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Trade Study Considerations for Fire Detection, Suppression and Remediation Systems for Commercial Space Missions

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With the upcoming retirement of the International Space Station (ISS) and NASA's Moon to Mars campaign, NASA is actively building the United States space economy by engaging private industry in the design of vehicles and missions for human space flight. The future successes of commercial space endeavors rely on the ability to procure proven and effective life support equipment in the marketplace. Budgets and schedules for typical missions do not allow for individual companies to design and build flight hardware for all required systems in-house. They must rely either on re-creating NASA heritage designs (assuming that the design calculations, drawings, reports, and analyses are available through official resource requests) or purchasing commercially available systems that have been demonstrated on the ISS. The latter would be considered at Technology Readiness Level (TRL) 9 as they have been proven successful in an operational mission environment. The available alternatives can be expanded by procuring lower TRL systems (potentially as low as TRL 5), which require longer lead times and carry additional risks that may be reduced by extensive testing. This paper outlines a trade study methodology to identify and rank available hardware options for commercial space entities, in this case, for fire detection, suppression and remediation. This is a subset of the comprehensive Environmental Control and Life Support Systems (ECLSS) trade studies that have been done by Northrop Grumman. While this approach creates a suite of optimized hardware alternatives, the final choices for a given program will depend on the use case, priority, and budget of each individual mission or program.

Nomenclature

ATCO = ambient temperature catalytic oxidizer
COTS = commercial off-the-shelf
ECLSS = environmental control and life support systems
ICES = International Conference on Environmental Systems
ISS = International Space Station
LEO = low-Earth orbit
NASA = National Aeronautics and Space Administration
NDA = non-disclosure agreement
ORU = Orbital Replacement Unit
PFE = portable fire extinguisher
R & R = remove and replace
SBIR = small business innovation research
SWaP = Size Weight and Power
TRL = Technology Readiness Level

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I. Introduction

THE continuous presence of humans in low Earth orbit has spanned over twenty years, with the International Space Station (ISS) hosting over 260 individuals from twenty countries. While the ISS is expected to be retired in the coming decade, NASA seeks to facilitate a sustained human presence in low-Earth orbit (LEO) by awarding contracts to commercial space companies for future destinations. This active investment in a LEO economy is directed at developing a cost-effective approach to human spaceflight and increasing the number of commercial suppliers of spaceflight hardware within a competitive marketplace. This marketplace must include multiple options for purchasing environmental control and life support systems (ECLSS) equipment. Unfortunately, at the present time, these options are limited, and are mostly based on heritage designs that are currently used on ISS (these are at technology readiness level [TRL] 9 since they are flight-proven).

While it reduces program risk to choose ISS heritage equipment, there are multiple drawbacks, especially the age of these technologies. Many systems are workhorses that have performed satisfactorily for a decade or more, but others have been plagued by issues requiring the crew to troubleshoot and repair as they are able. Even the best ISS hardware can be improved and updated to reduce size, weight, and power (SWaP). However, the challenge has been justifying the funds, which are typically prioritized for more urgent technology gaps and completely new systems.

Some ECLSS hardware built in-house by NASA engineers could be re-created if the records (design calculations, drawings, reports, and analyses) are available. Official resource requests for this information from NASA by commercial space companies are not always fruitful because the records may not have been archived or electronic copies are not readily available. Vendors that originally built many of the the ECLSS items on ISS may offer versions of the heritage hardware for purchase, but typically they are not optimized to reduce SWaP, as the added effort would be costly and the resulting new version would not be flight-proven. In other instances, traditional vendors may be aligned with a particular commercial space entity and may not want to sell their item to a competing company. This may manifest itself as a refusal to sign a non-disclosure agreement (NDA), a ‘no-bid’ response, or a sudden and dramatic increase in price for the desired unit. Ideally, new companies with viable ECLSS technologies should be considered alongside the traditional ECLSS vendors. The technology readiness level (TRL) of these hardware options may be low, as they have never been demonstrated in an operational environment. Determining the correct TRL can be challenging and levels can be interpreted differently by different entities. Recent work describes objective evaluation methods beyond a single TRL determination, and references tools to aid in realistic assessments.[1]

The final option for large space companies to procure ECLSS equipment is the investment of internal funds for engineering development to mature ECLSS hardware technologies that are either not available for purchase or not optimal to purchase from current vendors in the marketplace. This may include adapting commercial off-the-shelf (COTS) solutions, which are encouraged by NASA for LEO space stations. Overall, the selection of suitable hardware for commercial space missions must be evaluated with a strategic and uniform process. The scope of the trade study effort at Northrop Grumman was to identify currently available and emerging technologies that could be purchased or developed for use in commercial space missions. This is the first approach to determine program cost estimates and to define the initial design of the ECLSS system. This paper outlines the trade study methodology and its use for a subset of ECLSS hardware, namely, for fire detection, suppression and remediation. Results from these trades studies for Northrop Grumman commercial space programs are not disclosed in this paper.

II. Spacecraft Fire Safety

A spacecraft fire is considered to be one of the most catastrophic emergencies and may not be survivable. The performance of ISS fire safety equipment has never been tested by an actual fire. NASA has invested in research that has increased the understanding of this risk in microgravity by creating a relevant knowledge base versus relying solely on terrestrial fire safety practices and equipment.

A. NASA Investments

NASA has invested in both research and technology development in the area of spacecraft fire safety. The Smoke Measurement Experiment (SAME)[2,3,4] was performed twice on ISS to characterize both fresh and aged smoke from common spacecraft materials. Instruments in the experiment payload included both Shuttle and ISS smoke detectors to assess their performance. Subsequent ground experiments measured both of these types of smokes with aerosol reference instruments for higher fidelity results.[5,6,7,8] Consequently, the current target for detecting smoke in a spacecraft is the particle emissions from thermal decomposition or early overheating materials rather than combustion, because once flames are present, there is much less time to respond and fight the fire. This early smoke is well-characterized from ground experiments and has been used to evaluate smoke detector response and quantify acid gas emissions.[7,8,9,10,11,12] The current approach to fire safety equipment and its use is outlined in the NASA Human Integration Design Handbook and NASA Standard 3001, Volume 2, Rev. C.[13,14]

NASA has invested in ECLSS technology development based on roadmaps that chart the course to future missions. Gaps in the roadmaps are opportunities for new candidate technologies to be developed and flown as technology demonstrations on ISS. For example, the Spacecraft Fire Safety Experiments, called Saffire, included the first investment in the development of a "smoke eater" for post-fire cleanup.[15,16] Recent International Conference on Environmental Systems (ICES) papers outlining the ECLSS roadmaps and NASA funded activities state the fire safety technologies to be used on future missions will be developed mostly based on hardware used in previous spacecraft.[17,18] Unfortunately, fire response systems are not one-size-fits-all for every mission and vehicle. Even if innovation were prioritized, it would be difficult to disseminate a single set of requirements and expect a universal solution that would be widely applicable on all NASA and commercial missions.

NASA programs fund technology development directly through internal program funds and also through competitive opportunities that are open to many entities. The NASA Small Business Innovation Research (SBIR) program[19] has solicitations for different technology areas that have been historically aligned with the ECLSS roadmap needs. Some technologies have successfully reached TRL 9 after starting with Phase I SBIR grant awards, and, ideally, these would transfer into the commercial realm both for general consumers (if applicable) and for the space marketplace. The definition of a 'small business' according to the SBIR program encompasses multiple criteria, including company size, which is limited to 500 or fewer employees (including affiliates). An SBIR company may have as few as two employees, which can make subsequent technology transfer challenging. Even companies of ten to twenty employees may have difficulties navigating the transition from successful SBIR grant execution to performing as a supplier in the space marketplace. The required paperwork to verify cybersecurity, data and configuration management plans, and fulfilling the space mission design cycle is a burden researchers and engineers prefer to avoid, and these companies typically lack the funds to hire staff to fulfill these obligations. Beyond the SBIR program, NASA has funded industry partnerships such as the 'Tipping Point' and NextSTEP programs. Challenges through NASA Solve[20] can also provide large or smaller awards based on competitive proposals and down-selection activities followed by technology performance demonstrations. Spacecraft fire safety has not been a solicitation topic for these alternative funding sources because more urgent gaps in other ECLSS areas take priority. Nevertheless, it would be helpful to have more funding to foster additional competitors undertaking technology development in the fire safety equipment space to increase the options of flight-proven hardware available for purchase.

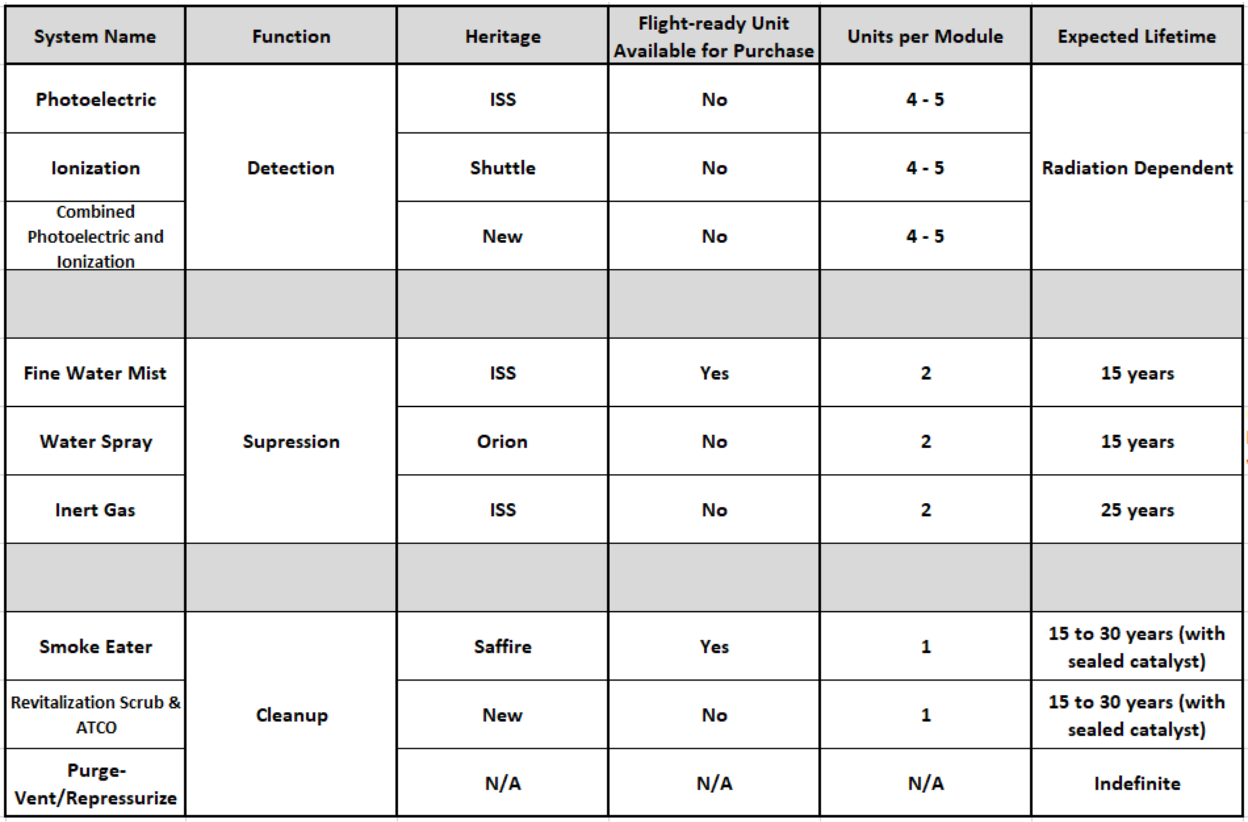
B. Candidate Technologies

The fire safety hardware alternatives considered for this trade study are shown in Table 1. Fire detectors that have been used on ISS and Shuttle were chosen based on the latest terrestrial technologies at the time. Ionization smoke detectors, which were used on the Shuttle, have been in use for decades and are able to detect smoke particles from flaming combustion, which tend to be smaller. Photoelectric smoke detectors, such as the ones on ISS, are based on light scattering and they are better at detecting smoke from smoldering or overheating materials. A third option is combining these two detection methods in a dual sensor fire detector that provides additional sensitivity to a wider range of smoke particle sizes and fire conditions.

For fire suppression, there have been three types of portable fire extinguishers (PFEs) in use in recent missions. The ISS historically has CO2 fire extinguishers, which are based on the principle of displacing the oxygen that enables combustion, essentially starving the fire. The drawbacks of the inert gas PFE include the increased risk of asphyxiation and discharging the extinguisher exacerbates the existing challenge of removing CO2 from the cabin air. The inert gas PFE was recently supplemented with a fine water mist unit, which contains six pounds of water and can extinguish both laptop fires and fires behind racks. The water spray PFE, developed for the Orion spacecraft, is a variant of the fine water mist PFE with a different nozzle that sprays larger droplets. Other types of PFEs, such as those containing Halons, are not considered safe for spacecraft as it adds a foreign substance to the atmosphere, which can be difficult to clean up after spraying and can potentially damage hardware such as a water processor. Water and inert gases are already present and the means to remove them from the atmosphere are likely part of every ECLS system.

The post-fire cleanup options include one operational approach and two types of hardware. A smoke eater filters smoke particles and captures both acid gases and carbon monoxide in adsorbents which are not regenerable on orbit. The current post-fire cleanup procedure for ISS involves activating all available atmosphere scrubbers and an option of crew setting up and activating an ambient temperature catalytic oxidizer (ATCO) canister, a LiOH canister, and an activated charcoal canister. LiOH canisters remove CO2 and acid gases and a charcoal canister removes volatile organic compounds, while the ATCO converts CO into CO2. Practically speaking, these canisters are not regenerable on orbit. The most drastic but also very effective option to rapidly clean the cabin after a fire is to vent the entire gaseous contents out to the vacuum of space by depressurization. This would be followed by repressurization of the cabin with stored nitrogen and oxygen. This option does not require crew to set up additional hardware to execute as the pressure relief valve is built into the vehicle, but a large supply of nitrogen and oxygen must be available in tanks to repressurize the spacecraft. Note the expected lifetimes for post-fire cleanup hardware in Table 1 assume the catalysts and canisters are properly sealed and handling and storage protocols have been perfected for longevity.

Table 1. Fire Safety Technology Alternatives



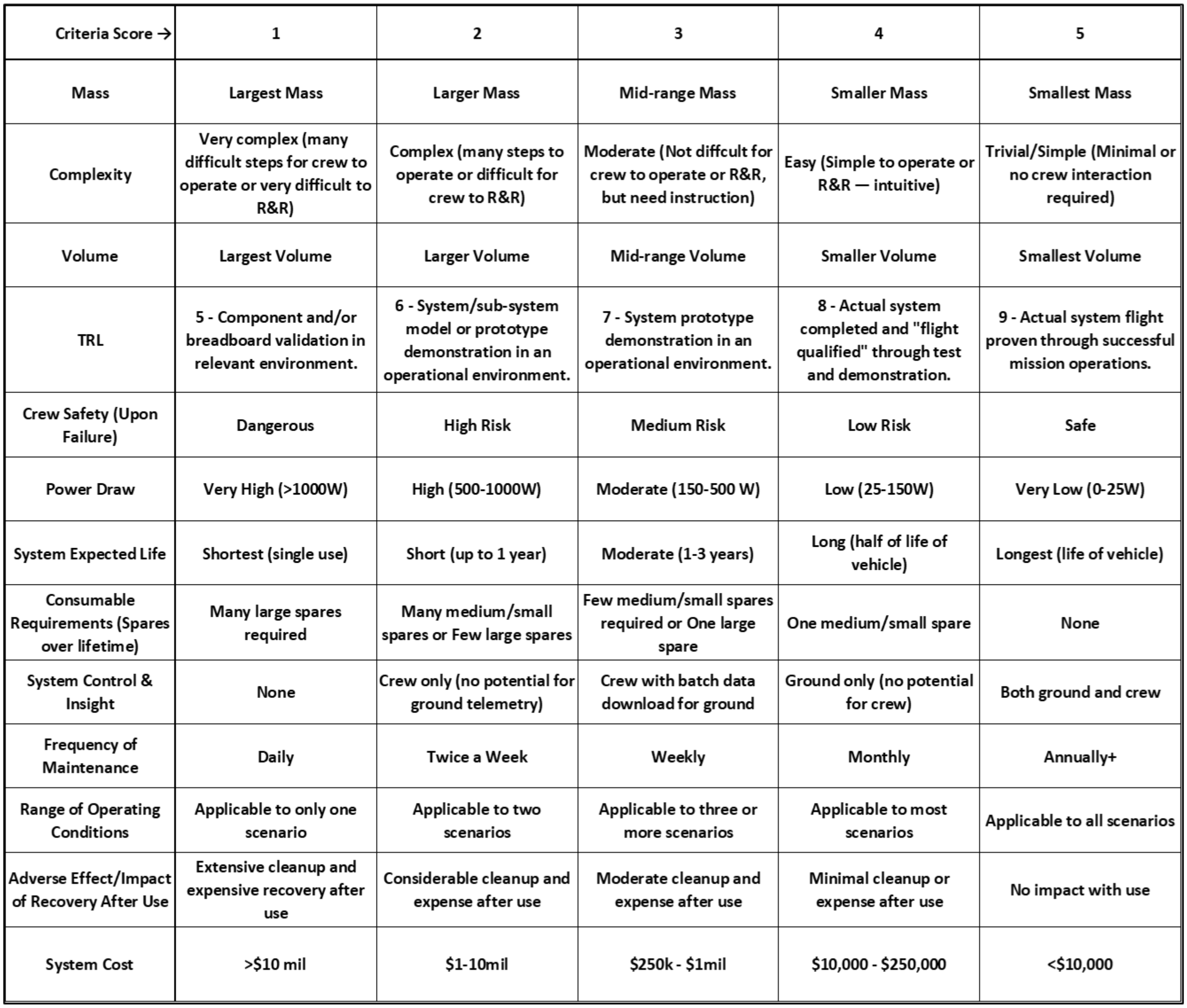
System Name	Function	Heritage	Flight-ready Unit Available for Purchase	Units per Module	Expected Lifetime
Photoelectric	Detection	ISS	No	4 - 5	Radiation Dependent
Ionization		Shuttle	No	4 - 5	
Combined Photoelectric and Ionization		New	No	4 - 5	
Fine Water Mist	Supression	ISS	Yes	2	15 years
Water Spray		Orion	No	2	15 years
Inert Gas		ISS	No	2	25 years
Smoke Eater	Cleanup	Saffire	Yes	1	15 to 30 years (with sealed catalyst)
Revitalization Scrub & ATCO		New	No	1	15 to 30 years (with sealed catalyst)
Purge-Vent/Repressurize		N/A	N/A	N/A	Indefinite

III. Trade Study Methodology and Criteria

In the space mission arena, assessing the array of ECLSS hardware options (or lack thereof) is a complex problem. A trade study is an analytical approach to making objective decisions and also documents the assumptions and priorities that lead to the final hardware choices.[21,22]

The thirteen critera categories shown in Table 2 were chosen for the trade study, but are not an exhaustive list. The scores from one (worst) to five (best) are summed for each category with the maximum possible of 65. The relative importance of each category is reflected in a tailored weighting system that emphasizes the most important attributes for a specific program. For example, if the period of performance for a mission is shorter, then TRL will be weighted more heavily versus a long-lead time project. While space launch costs have come down in recent decades, they continue to be a major cost driver, so mass and volume are emphasized with a higher weighting. The criteria weights are initially assessed for a specific mission but may change throughout the program lifecycle. If program funding or priorities change, or new information arises, the relative criteria weightings should be reassessed and trade results reinterpreted to see if a change in direction is warranted.

Table 2. Trade Study Criteria and Scores



Criteria Score →	1	2	3	4	5
Mass	Largest Mass	Larger Mass	Mid-range Mass	Smaller Mass	Smallest Mass
Complexity	Very complex (many difficult steps for crew to operate or very difficult to R&R)	Complex (many steps to operate or difficult for crew to R&R)	Moderate (Not diffcult for crew to operate or R&R, but need instruction)	Easy (Simple to operate or R&R — intuitive)	Trivial/Simple (Minimal or no crew interaction required)
Volume	Largest Volume	Larger Volume	Mid-range Volume	Smaller Volume	Smallest Volume
TRL	5 - Component and/or breadboard validation in relevant environment.	6 - System/sub-system model or prototype demonstration in an operational environment.	7 - System prototype demonstration in an operational environment.	8 - Actual system completed and "flight qualified" through test and demonstration.	9 - Actual system flight proven through successful mission operations.
Crew Safety (Upon Failure)	Dangerous	High Risk	Medium Risk	Low Risk	Safe
Power Draw	Very High (>1000W)	High (500-1000W)	Moderate (150-500 W)	Low (25-150W)	Very Low (0-25W)
System Expected Life	Shortest (single use)	Short (up to 1 year)	Moderate (1-3 years)	Long (half of life of vehicle)	Longest (life of vehicle)
Consumable Requirements (Spares over lifetime)	Many large spares required	Many medium/small spares or Few large spares	Few medium/small spares required or One large spare	One medium/small spare	None
System Control & Insight	None	Crew only (no potential for ground telemetry)	Crew with batch data download for ground	Ground only (no potential for crew)	Both ground and crew
Frequency of Maintenance	Daily	Twice a Week	Weekly	Monthly	Annually+
Range of Operating Conditions	Applicable to only one scenario	Applicable to two scenarios	Applicable to three or more scenarios	Applicable to most scenarios	Applicable to all scenarios
Adverse Effect/Impact of Recovery After Use	Extensive cleanup and expensive recovery after use	Considerable cleanup and expense after use	Moderate cleanup and expense after use	Minimal cleanup or expense after use	No impact with use
System Cost	>$10 mil	$1-10mil	$250k - $1mil	$10,000 - $250,000	<$10,000

The trade studies start with the review of published technical whitepapers, particularly ICES papers, which are the main source of up-to-date information for ECLSS hardware development projects and advancements in TRL. Unfortunately, an ICES paper touting hardware development at the outset of a funded project may not have a follow-on conference paper to report the results and lessons learned throughout the effort, including potential future improvements. ICES papers may be written by a NASA technical monitor on behalf of a company building the hardware or employees of the company may initiate and write ICES papers on their own. NASA may not choose to continue funding some projects beyond a certain SBIR phase or TRL so there may be no stakeholder or potential ICES author to generate a follow-on paper. Incomplete information from ICES papers can be misleading because in the commercial marketplace, a company may portray their own hardware as TRL 9 because it was included in a flight project, but it may not have performed as expected or outcomes were not fully successful. Therefore, this initial research on relevant ICES papers should be carefully interpreted. The ICES literature review phase resulted in identification of potential suppliers and further research of company websites. Vendors were contacted and meetings covered by NDAs resulted in technical data that further modified the hardware options and attributes based on information exchange. An important distinction in the generation of hardware options is whether systems are independent (meaning they can operate without other hardware interaction), or dependent (meaning hardware must be paired with other sytems or equipment to provide a solution). The fire safety trade study was simple in that respect, as it did not include any dependent systems. It is recommended the candidate hardware options in a trade study should be limited to four or less, but in the fire safety arena this was not a challenge as the choices were limited. Finally, assessment criteria for evaluating alternatives were chosen and the weighted scores systematically determined the best option.

Each of the trade study criteria are discussed below with pertinent information on the fire safety hardware options.

A. Mass

The mass of a candidate hardware entry is a relative ranking of the alternatives, ordered from 'smallest mass' to 'largest mass.' When masses are similar, all are scored the same. Note the physical weight of a piece of equipment is not a factor for its use in the LEO microgravity environment because of weightlessness, but it is a significant factor for launch costs at the beginning of a mission. One example of an option scoring poorly for mass score is the venting and repressurization option for post-fire cleanup. While this is an operational approach, it requires spare tanks of nitrogen and oxygen to restore a habitable atmosphere in the vehicle. It is not trivial to launch the additional tanks required to repressurize a vehicle and thus it scored lowest.

B. Complexity

The complexity of a piece of ECLSS equipment can vary from trivial or simple to complex. Trivial or simple hardware items require little or no crew interaction, whereas complex hardware requires significant effort by the crew to operate and/or to remove and replace (R & R) failed components. Additional considerations for this criterion include whether training is required to operate the hardware or a significant number of steps are necessary for startup or maintenance. Most options were very similar or equal in complexity, with the exception of the air revitalization scrub and ATCO for post-fire cleanup, since that approach had more elements and procedures than the other options.

C. Volume

The volume criterion may seem similar to the mass, however, it refers to how much space the system occupies inside the vehicle. For example, rack space is not abundant on a spacecraft so the smaller the installed volume of the ECLSS equipment, the more space is available for habitation. The smaller the vehicle for a given mission, the more weight this criterion receives. Note that this does not include the volume of required spares, commonly known as orbital replacement units (ORUs). The fire safety equipment in this trade study did not have a significant spread in scores in this category.

D. TRL

TRL definitions for the trade study were taken from the NASA definitions.[23] TRL 5 is the minimum level considered for most programs. A lower TRL could significantly affect cost and schedule, and further development may not eliminate all the risk. The use of COTS is not ruled out by this criterion, as many terrestrial solutions can be up to TRL 6 (prototype demonstration in an operational environment, that is, surviving and operating in critical environmental conditions). However, even if the operating principle does not depend on gravity, there are differences in both heat and fluid transfer in space missions. Creative thermal solutions can compensate for the lack of buoyant cooling in microgravity and the field of low-g plumbing has been advanced to include options for adapting terrestrial designs for flight.[24] There is risk associated with accelerating the introduction of technologies that have not been flown on ISS. However, many times the incremental advancement in performance overcomes the drawbacks of decades-old low TRL hardware that is not optimized for SWaP.

E. Crew Safety

This criterion addresses what happens when an item fails on orbit. If it fails (or when), is it dangerous to the crew? The goal is to choose systems, components, fluids, etc. that are nominally as safe for crew as possible but can still accomplish the intended purpose. For example, CO2 PFEs are considered more dangerous than water PFEs if they malfunctioned and the contents were released into the cabin. Also, the depressurization/repressurization option for post-fire cleanup may endanger the crew if the operation were to malfunction. Not only is the act of depressurization itself potentially dangerous, but a malfunction in the pressurized gas tanks needed to repressurize the vehicle to an appropriate pressure and mixture is also an issue.

F. Power Draw

The power criterion has a very large range, in excess of 1000 watts, for the lowest score. This was based on the full ECLSS trade study methodology that surveyed the broad variety of equipment that is historically or currently in use on ISS or flown on other vehicles. The 'very low' power draw score was less than 25 watts, an extremely broad range for the fire safety equipment, which is miniscule compared to most ISS ECLSS hardware (particularly regenerative systems). The power draw scores were identical for all the smoke detection and PFE options however, post-fire cleanup alternatives did have some differences in power draw, particularly for the fans to operate the smoke eater and the regenerative ATCO options.

G. System Expected Life

The system expected life category ranges from single-use hardware (lowest score for non-regenerable or disposable items) to lasting the full life of the vehicle (highest score for no expected maintenance or replacement). The intermediate scores cover ranges in-between, from short life (up to one year), moderate life (one to three years), and long life (half of the life of the vehicle). Many times there are components that are replaced on a maintenance schedule, but these did not necessarily lower the score significantly because this criterion addressed longevity (such as avoiding a full system R & R). Consumables are covered in a separate category. For fire safety equipment, scores were nearly equal in this category, whereas other ECLSS items in other trade studies had more significant differences.

H. Consumable Requirements

Consumable requirements, also known as 'spares over lifetime' or necessary ORUs, can significantly affect operations in a spacecraft. The worst score is given for many large volume spares, with incrementally better levels for fewer medium or smaller spares, and the highest score is given for no required spares over the lifetime of the mission or vehicle. This criterion mainly considers the stowage issues in the spacecraft, but other associated costs are upmass of spares and crew time for maintenance to replace items. The amount of stowage required for spares depends on the resupply cycle. If more frequent cargo vehicles are scheduled, fewer spares are required to be stowed in the vehicle at a time. Most items cannot be stored outside the vehicle, except potentially high pressure gas tanks. The difficulty of replacing consumables is covered in the complexity category and the frequency of maintenance is also related, but has its own category.

I. System Control and Insight

The system control and insight criterion evaluates the availability of information from the system. This includes health and system status, error information or flags, failure lights, and internal sensor data. The crew can look at an integrated screen on the unit or a linked electronic tablet, there can be telemetry to the ground, or the hardware design can incorporate both levels of insight. Similarly, the options for controlling the system were considered including turning the system on/off or changing its operational parameters. The worst score is given for no control or insight, for example a desiccant canister that cannot show how full it is or at what rate humidity is adsorbed received the lowest score. The next score is given to systems limited to on orbit crew insight only, which can result in the tedious practice of reading numerical values into a microphone for the ground to be informed. A step better is given to systems when crew can see the information and data can be transmitted in batches to the ground. It is considered even better when the ground has full insight and control, while the crew has none, aside from potentially touching an item or hearing an internal fan running. This is an improvement because the crew should be occupied with many activities during waking hours and they cannot monitor equipment while they sleep. Another scenario needing this level of control and insight would be periods of uncrewed operation, which are now in the concept of operations for multiple future missions. Ultimately, the best scenario is when both the ground and crew have full insight and control. If the crew happened to be sleeping or incapacitated during a contingency scenario, the ground should have continuous access to all the information and system control to appropriately manage the contingency. Conversely, if there is a loss of communication with the ground, then the crew can know the status and command the hardware. The smoke detection and suppression alternatives all scored equally in this category, while the post-fire venting operation had the lowest score.

J. Frequency of Maintenance

This criterion addresses the need for doing maintenance. This includes changing filters or other components, such as sensor heads, zeolite beds, etc. or performing calibrations. Regularly scheduled housekeeping is not considered maintenance for this trade study. The score ranges were formulated for all ECLSS hardware based on what is currently required for ISS systems. All fire detection, suppression and remediation candidates had the highest possible score in this category because ISS smoke detectors have a long history of operation without failure or required scheduled maintenance.

K. Range of Operating Conditions

Not every technology solution or approach is applicable for every scenario. For example, ionization smoke detectors are most effective with smaller smoke particles whereas photoelectric smoke detectors are optimal for larger diameter particles. The combined photoelectric and ionization smoke detector option scored the highest for this category as it would have the best ability to detect smoke, regardless of the emission source (flaming or overheating/smoldering material).

L. Adverse Effect and/or Impact of Recovery after Use

Some technology options have unfavorable effects after implementation in a fire scenario. The best example is fire suppression where there are different consequences for spraying water in a module to fight a fire vs. filling the module with CO_2. The presence of water is benign to humans and can be cleaned up, but may have lasting impacts on hardware that could lead to R&R. Corrosion and microbial growth may be longer-term consequences in the event the water is not completely removed in a reasonable time frame. The level of cleanup depends on each vehicle design. For example, rack faces conceal open spaces that can collect larger droplets from the water spray PFE. If the spray droplets, which are larger than the fine water mist droplets, were to collect and combine behind panels, evaporation could be hampered. The smaller droplets from the fine water mist PFE can evaporate faster, so less water is likely to collect in dead spaces behind wall panels. If a fire is suppressed with an inert gas PFE, the physical cleanup is negligible. However, a breathable atmosphere must be restored restored by scrubbing the CO2 and increasing O2 levels either through an oxygen generator or oxygen supply tanks.

M. System Cost

The cost levels in this trade study were created for all ECLSS hardware, which can exceed $10 million for some complex systems. The combined cost of an item and all ORUs for the vehicle lifetime were considered. The fire detection, suppression and remediation alternatives all scored the same in this category, with the exception of the post-fire cleanup by venting and repressurizing, which was the most expensive option.

IV. Trade Study Scores

For the fire safety subset of trade studies performed for Northrop Grumman ECLSS hardware, many options ranked very closely, which required additional attention to scoring and weighting of criteria. Some mission scenarios made differentiation much more obvious, but in general, the fire safety systems did not have wide ranges in ranking scores compared to other hardware for air revitalization or water purification. If two alternatives had nearly the same score, sensitivity analyses were performed to check the final result.

The averages and standard deviations of the final ranking scores were sufficient to determine an optimal choice. The post-fire cleanup options had the widest spread in scores before weighting, and the final weighted scores had an average of 3.26 with a standard deviation of 0.28. Fire suppression options were closer in score, with an average of 4.06 and a standard deviation of 0.16. Finally, the smoke detector options ranked very similarly before weighting and had an average of 4.53 and a standard deviation of 0.10. While the final scores of all three categories were in the 3 to 5 range, it is interesting to note that the lowest score was for post-fire cleanup options, showing that the choices were less than ideal.

V. Conclusion

This paper describes a subset of the trade study efforts at Northrop Grumman for commercial space missions, covering fire detection, suppression, and remediation equipment alternatives. The attributes and criteria for evaluating hardware solutions are discussed, but ultimately, the availability of items for purchase is a key point that affects the cost and schedule of commercial space missions. The competition between commercial space companies and the terms of vendor NDAs preclude the sharing of trade study results in this paper. Further investment by NASA and other space agencies to expand options on the market would be helpful. Future efforts should consider helping smaller businesses and new participants join in the space marketplace in order to increase competition. This approach will eventually drive down costs while building the space economy.

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