Considerations for Architecture Level Trade Studies for Environmental Sensors

Craig Peterson[1]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Comparisons of key characteristics of environmental sensors such as technology readiness levels, mass, power, volume, and detection capabilities are essential for initial trade studies to determine likely candidates for further development and evaluation. However, these trade studies only provide part of the information necessary to make selection decisions. Ultimately, the sensors must be judged based on the overall system architectures and operational scenarios for which they are intended. This means that additional characteristics, such as architectural needs for redundancy, operational lifetime, ability to maintain calibration, and repair and replacement strategies, among others, must also be considered. Given that these characteristics can be extremely time-consuming and costly to obtain, careful planning is essential to minimize the effort involved. In this paper, an approach is explored for determining an effective yet comprehensive set of architecture level trades which is minimally impacted by the inevitable changes in operational (mission) scenarios. The approach will also identify and integrate the various facilities and opportunities required to obtain the desired architecture level trade information.

Nomenclature

AEMC = Advanced Environmental Monitoring and Control
CEV = Crew Exploration Vehicle
COTS = Commercial Off-the-Shelf
ENose = Electronic Nose
ESA = European Space Agency
FOM = Figure of Merit
FTIR = Fourier Transform Interferometer
GCMS = Gas Chromatograph/Mass Spectrometer
GEO = Geosynchronous Earth Orbit
ISS = International Space Station
LEO = Low Earth Orbit
MCA = Major Constituent Analyzer
MTBM = Mean Time Between Maintenance
MTTO = Mean Time to Operate
MTTR = Mean Time to Repair
NASA = National Aeronautics and Space Agency
PPM = Parts per Million
PPB = Parts per Billion
TAM = Technology Assessment Metric
TCM = Trace Contaminant Monitor
TRL = Technology Readiness Level
VOA = Volatile Organics Analyzer

I. Introduction

Trade studies of environmental monitoring sensors and instruments have been complicated by the recent adoption of the "Flexible Path" approach to manned missions and the corresponding increase in types of potential

[1] Technologist, Mission and Systems Concepts Section, 301-180, Senior.

manned missions. Detailed requirements for environmental monitoring sensors, instruments, and architectures have yet to be developed for these potential missions, although previously established requirements[1] (such as those for the space shuttle or International Space Station) may serve as bounding cases, where applicable.

The logical course to dealing with these complications has been to analyze the key characteristics of both the expanded "flexible path" mission set and their corresponding environmental monitoring sensors and instruments. This allows for development of an approach for an effective and reasonable review of post-fire oxygen sensors as a test case for evaluating environmental monitoring sensors and instruments (and ultimately overall architectures) in this new mission context. The end result is a charge to the reviewers that will attempt to capture not only the current state of applicable environmental monitoring sensors and instruments, but will also allow for determination of the potential for the selected environmental monitoring sensors, instruments, and architectures for further development to meet the requirements of other missions on the flexible path. This will include both assumed near term technology demonstrations and the more challenging and lengthy missions further down the "path".

II. Uncertainty in Trade Studies

All sensors and instruments that have not been flight proven have inherent uncertainties involved with their achievable performance, cost and schedule. Generally this can be expressed as a function of their technology readiness levels (TRL), where the uncertainty is inversely related to the TRL. Figure 1 illustrates this relationship by sizing the bubbles based on inverting the TRLs for International Space Station (ISS) air sensing instruments considered in a previous study to provide a relative measurement of uncertainty. In this illustration, the larger the bubble, the greater the relative uncertainty of achieving the desired performance within the given volume is for that instrument. Even flight proven hardware has uncertainties associated when it is being considered for inclusion in a new or different architecture (and mission) that may have different performance requirements, such as measurement sensitivity, accuracy, or lifetime.

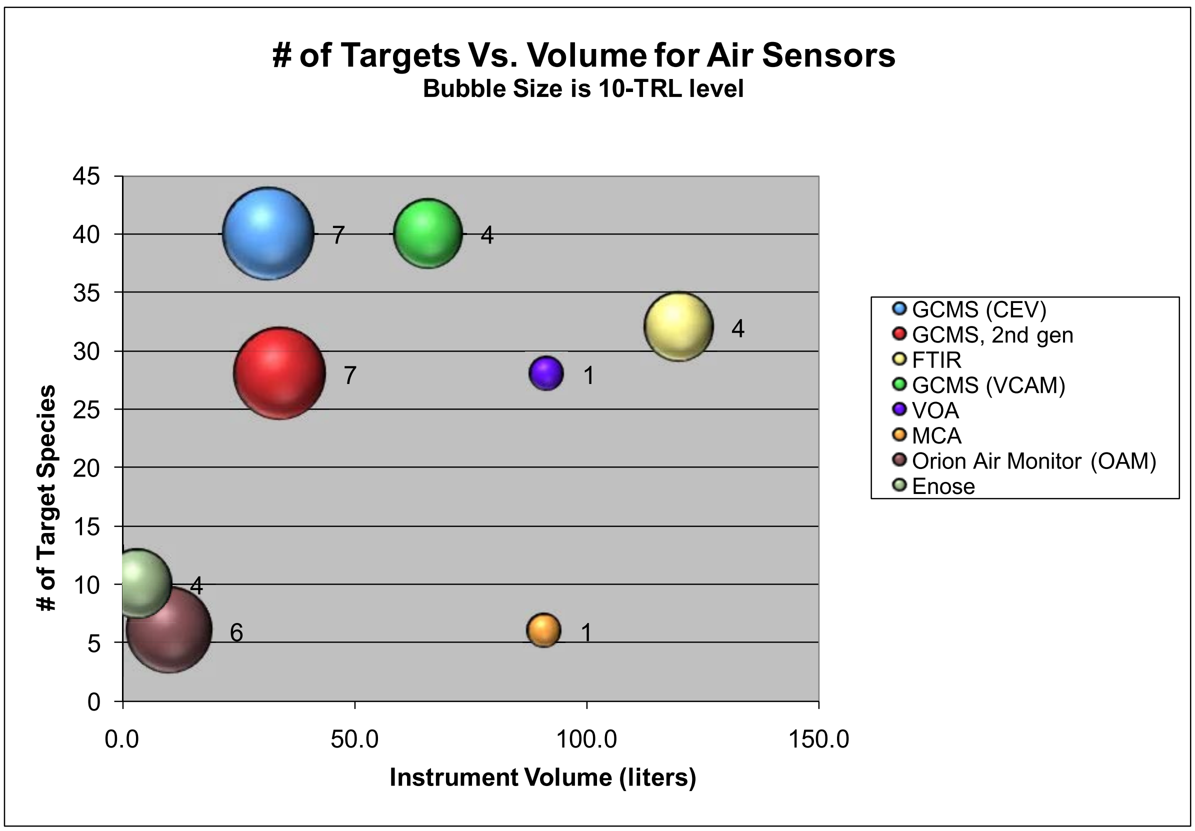

Figure 1. Illustration of Uncertainty as a Function of TRL (Bubble Size proportional to 10-TRL) for Candidate Air Quality Monitoring Instruments

The effect of these uncertainties is multiplied when there is additional uncertainty regarding the performance requirements. This is not as unusual as it may seem, as there is frequently some "play" in functional requirements where requirements may change as a result of later analyses showing that the requirement may be relaxed (or conversely, needs to be tightened). Budgetary considerations can result in requirement changes if the current requirement is perceived as unaffordable, even if it results in some loss of mission performance. When dealing with environmental monitoring and control requirements, there is still an evolving body of research on which requirements are based, as evidenced by the fact that 5 versions of the Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants[1,2] have been produced between 1994 and 2008.

While it is always desirable to reduce uncertainties as much as possible, it is clear that early trade studies must adopt an approach that accepts the existence of uncertainties and accounts for them in a useful fashion. The concept of "relative" uncertainty provides such an approach. In this context "relative" is defined by the number and the extent of the various uncertainties, where "extent" refers to the amount of work that would have to be undertaken to eliminate a given uncertainty, such as laboratory tests showing instrument resilience to selected environmental conditions (smoke or dust) or eventual development and test of a flight-qualifiable version of the subject instrument in a relevant environment (either ground or space).

In the case of post-fire oxygen sensors, two different technical approaches are being considered. One is the commercially mature laser spectroscopic approach (with no flight heritage) and a mini-GCMS. Most of the uncertainties associated with the laser spectroscope are those deriving from the need to develop a flight qualifiable version, whereas the mini-GCMS would have some additional development uncertainties but there may be a well-understood path to flight qualification, as several GCMS systems have been built and flown in other missions.

Determination of the relative uncertainty requires expert evaluation and judgment, such as experienced members of a review panel. Review panels have previously been used several times to evaluate advanced environmental technology[3,4,5,6,7,8]. Before such a review panel can begin its work, some context regarding the key characteristics of the target mission and the subject instruments will need to be communicated to ensure the reviewers are comparing "apples to apples". This will keep discussions focused on the "tall tent poles" remaining in maturing the subject instruments for the missions under consideration.

III. Consideration of Key Characteristics

Given the uncertainty in overall performance requirements and the current lack of specific timeframes for development of flight systems and missions for destinations on the "flexible path", reviewers can provide the most benefit by not only ranking the candidate sensors in terms of their current capability, but also by identifying gaps and pointing out development path[s] as remedies. This guidance may include identifying performance improvements that could be achieved with additional investment along with potential risks to improving sensor and system performance. Table 1 shows selected key characteristics of the various target locations on the flexible path and the importance of selected Environmental Monitoring and Control Characteristics for those targets. While these characteristics are currently expressed in qualitative terms, they can still be used provide a relative rating that can be used by reviewers to discriminate among candidate sensors.

Table 1. Key Characteristics

		Target Vehicle/Habitat									
		ISS	**LEO (tech demo)**	**GEO (tech demo)**	**Lunar Orbiter**	**Lunar Lander**	**Lunar Outpost**	**Lagrange Points (Earth-Sun)**	**Asteroid**	**Phobos (Mars Orbiter)**	**Mars Lander**
Target Key Characteristics	Lifetime - occupied	years	days-months	days-months	weeks	weeks	years	months	months-years	years	weeks
	Lifetime - vacant		days-months	days-months		days-weeks	weeks - months				years
	resupply opportunity	frequent	None	frequent	None	None	infrequent/ expensive	infrequent/ expensive	None	None	None
	mass restrictions	moderate	moderate	high	high	high	high	extreme	extreme	extreme	extreme
	power restrictions	moderate	moderate	moderate	moderate	high	moderate	high	high	high	high
	volume restrictions	moderate	moderate	moderate	moderate	high	moderate?	high	high	high	extreme
	Dust	none	none	low	low	moderate	high	low	low	low	high
	Radiation	low	low	moderate	moderate	moderate	high	high	high	high	high
	Gravity*	micro	micro	micro	micro	micro to 1/6g	1/6 g	micro	micro	micro	micro to 1/3 g
Environmental Montioring and Control Key Characteristics Importance	High Sensitivity (health)	high	moderate	high	high	high	extreme	extreme	extreme	extreme	extreme
	High Sensitivity (control)	moderate	high	high	high	high	moderate?	high	high	high	high
	Post Fire Recovery	yes	V2V**	V2V	V2V	V2V	yes	yes	yes	yes	yes
	Reliability/lifetime***	moderate	moderate	high	high	high	extreme	extreme	extreme	extreme	extreme
	low mass	moderate	moderate	high	high	high	extreme	extreme	extreme	extreme	extreme
	low power	moderate	moderate	moderate	moderate	high	moderate	high	high	high	high
	low volume	moderate	moderate	moderate	moderate	high	moderate?	high	high	high	extreme
	(*) Does not include launch loads or propulsive maneuvers										
	(**) Vent to vacuum										
	(***) Can be traded against mass/power/volume										

Desired performance improvements will likely include increased sensitivity, improved accuracy and stability, increased lifetime, reductions in crew-time required for operation, repair or replacement, decreased mass, power, and/or volume, and decreased cost of the flight qualified-sensor. Potential roadblocks range from fundamental limitations of the sensor physics or a drastic (i.e., expensive) re-design to achieve a flight-qualified sensor. Table 2 has a list of flight sensor characteristics that can be considered in terms of either improvements or roadblocks. While several of the characteristics would normally be quantifiable (e.g., mass, volume, power, etc.), it may be necessary to rate them more qualitatively at their early stage of development. One approach would be to invert these metrics and consider their evaluation in terms of efficiency: which sensor is most efficient (i.e., provides the same or better performance with less mass, power, and volume) and ranking them accordingly. This efficiency metric could also be normalized to a "per unit mass" or "per unit power" for the sake of comparisons. This allows for a consistent metric where high values are always desirable and low values are always undesirable. As has been done in the past[3,4,5,6,7,8], qualitative rankings can be assigned numerical ranks (technology assessment metrics or TAMs), allowing overall scores to be constructed by the reviewers.

Given the existence of uncertainties, relative numerical scores are most useful in identifying the more extreme outliers and removing them from further consideration, so that more attention can be paid to those whose scores are more comparable. In the rare case where one candidate is consistently better than or equal to another candidate in every characteristic (and has comparable technical development uncertainty) then the lower scoring candidate could also be removed from consideration. However, in most cases, the overall scores will reflect a mixture of greater and lesser performance on differing characteristics with differing uncertainties, so reliance on the purely numerical scores would be unwise.

Some of the characteristics are highly sensor dependent, such as the need for replacement units, any consumables, and any additional hardware required for replacement or repair of the unit, which add to the overall mass and volume requirement for a given sensor. The secondary impacts for a given target (in terms of the ripple effects such as those of the sensor power needs on mission power system mass, or the mass of

Table 2. Sensor Characteristics

Performance
Measurement Range
Sensitivity
Selectivity
Resolution
Response Time
Sampling Frequency
Linearity
Accuracy
Drift
Verification Requirements met (safety, launch, etc.)
Number of Active Units required (per 10 day mission)
Number of Replacement Units required (per 10 day mission)
Total Mass All Units (kg)
Sensor/Instrument
Consumables
Repair/Replacement Kit
Interface HW
Total Volume (cc) All Units
Sensor/Instrument
Consumables
Repair/Replacement Kit
Interface HW
Power
one unit per 24 hrs (whr)
all units per 24 hrs (whr)
one unit peak (w)
all units peak (w)
Thermal (waste heat)
one unit per 24 hrs (whr)
all units per 24 hrs (whr)
one unit peak (w)
all units peak (w)
Environmental Tolerance
Crew Time required (crew hrs per 24 hours) (includes calibration and operation)
Mean Time to Operate (MTTO) (crew hrs/24hrs)
Mean Time to Repair/Replace (MTTR) (hrs)
Mean Time between Maintenance (MTBM) (per 24 hrs)
Cost (FY10 k$)
one unit
all units
Technology Readiness Level

support structure required to integrate the sensor[9]) can also be considered. The amount of crew time involved with calibration, operation, replacement of consumables, sensor repair and/or replacement and the frequency of those activities is also an important consideration. Other considerations include the ability of the sensors to tolerate lengthy storage periods, either pre- or post-launch. Habitats may be unoccupied and unpowered for lengthy periods, and the ability to start, stop, or restart sensors without crew involvement may be necessary. Some level of analysis of the most likely failure modes of the sensors will be necessary in order to in order to quantify these characteristics.

Consider the case of postfire oxygen sensors and instruments. While some of the target environments do not require them, those with longer mission durations generally will require postfire monitoring and corresponding sensors and instruments. There has been considerable discussion within NASA on the appropriate O_2 detection limits. Several performance requirements exist currently, tied to specific missions and crewed vehicles and their designs for life support. While the actual requirement values for O_2 detection accuracy may be X ppm, for control systems with time constants, the typical engineering request is to measure significantly better, say X/5 ppm or even X/10 ppm in order to provide robustness in the combined monitoring and control system. One desired outcome of a review panel is an analysis that would allow easy selection of candidates based on specific missions with postfire O_2 measurement needs, once those needs are quantitatively established. In the case of the mini-GCMS and laser spectroscope sensors mentioned above, the number and extent of changes that would be needed to achieve improved performances would need to be captured. In the case of the mini-GCMS, this might include extending the length of the GC and MS portions of the instrument (with the potential for increasing sensor mass and power), whereas for the laser spectroscope it could involve increased laser power, improved detector performance, or a larger sample cell.

Emphasis would be placed on those missions that would be more likely to be near term, such as an International Space Station (ISS) technology demonstration, or a technology demonstration in some form of habitat either in LEO or GEO. While such technology demonstration missions would impose less severe constraints on mass, volume, power, and reliability, it will still be necessary to evaluate whether a given sensor has the capability of achieving needed improvements in those areas, and the steps necessary to make those improvements, to insure that there is a viable roadmap from the current sensor to the desired mission flight sensor. Technology demonstrations in LEO or GEO can also provide flexibility in their mission scenarios while reducing risk to the crews by providing the capability for either exceptions from the planned demonstration (such as recovering from a fire by venting atmosphere to vacuum and restoring it from stored supplies if a fire suppression and recovery system fails during test) or even evacuation of the crew to the ISS or Earth in the case of serious hazard.

IV. Desired Review Results

Reviewers at this early stage are posed several challenges, due to the uncertainties in both requirements and sensor capabilities. While checklists and scoring forms can help structure and guide their efforts (perhaps a separate set for each potential habitat targeted for analysis), ultimately it will be their expertise that must be brought to bear to determine not only the current state and suitability of the candidates, but whether there is a path that can ensure the continued applicability of the candidates to new target environments. Simply providing a list of the activities that are needed to progress along the development path for a given target environment would be very useful. Grading these activities in terms of importance and/or difficulty adds another dimension of useful information and could be used to construct a score to represent the relative uncertainty for a given sensor's potential for achieving the development goals. The field of Decision Analysis[11] has developed several useful approaches for constructing such scores in a relatively rigorous fashion, even when uncertainties play a larger role. Figure 2 provides a notional example of how the results of such a review might be graphically presented.

As can be seen in Fig. 2, for Mission Target X, both Sensor A and Sensor B have similar overall rankings, but whether Sensor B can actually achieve that performance is somewhat more uncertain than Sensor A. Assuming Mission Targets X, Y, and Z are listed in the order in which they may be addressed over time and represent increasingly demanding environments, it is not surprising that the uncertainties for most sensors increase accordingly. Of course care must be taken to not to make selection decisions based solely on such graphical representations, although they may be useful in eliminating the most obviously low performers (perhaps Sensor C) so that more attention can be spent on the more promising candidates. The fact that Sensor B's uncertainty remains relatively constant may be an indication that there is a consistent development path for Sensor B, regardless of target environment. That may make it more attractive than a sensor that doesn't require much modification in the near term, but would require substantial development for targets in the long term.

In considering the post-fire sensors mentioned in the previous paragraphs sensor B could be the laser spectroscope who's primary uncertainty is developing the flight qualified version of a commercial sensor, whereas sensor A could be a min-GCMS that could rely on flight heritage for the early mission targets, but may need redesign to meet the more demanding requirements for the later mission targets. Or the driving requirement could be increasing lifetime from mission target X to Z, so the need for solvents for the mini-GCMS (sensor B in this case) will increase as a function of mission lifetime, increasing its mass and reducing its relative rank, while the need to improve laser lifetime for the laser spectroscope (sensor A) may be the driving uncertainty but without impacting the relative rank of the sensor. As always, such depictions should be used to provide feedback to the reviewers and any results that seem inconsistent or illogical should be taken as an indication that more scrutiny is required before decisions can be made.

Notional architectures based on previous work[9,10] can also provide a guide for determining the functional environment in which the candidate sensors might be integrated and perhaps more importantly, provide a sense of the operational complexities which will be involved. The current monitoring and control architecture of the ISS, at the least, can provide context for evaluation of the sensors. Lunar-based architectures previously developed could also usefully serve as a surrogate for whatever new architectures may be eventually developed.

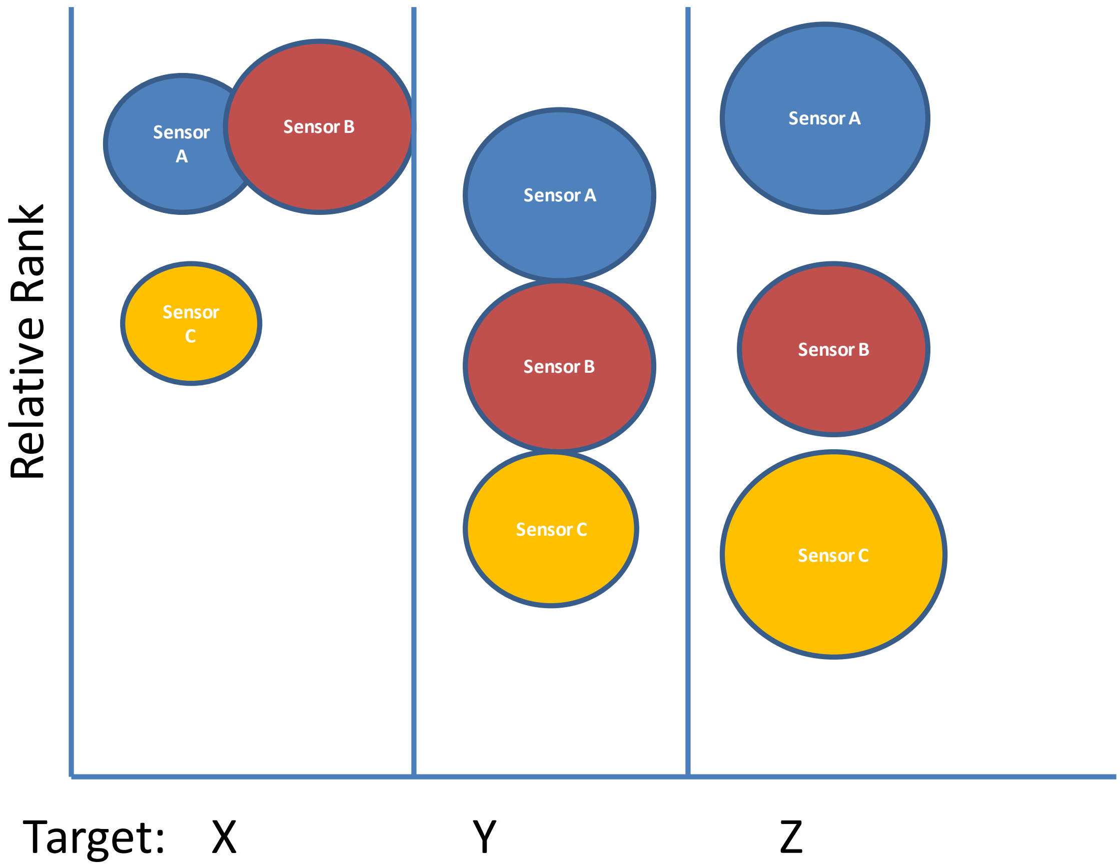

Figure 2. Notional Example of Review Results (Bubble Size is Relative Uncertainty)

Once the relative rankings for the sensors for the various target environments and architectures have been determined, and the potential roadmaps (and roadblocks) for future development have been captured and rated in terms of their relative importance, the panel's works is still not complete. To obtain the maximum benefit from the review, consideration of needed facilities and techniques for verification of sensor operation prior to their use in flight technology demonstrations will be required. Recommendations for test chambers, ground-based habitat simulators, or other facilities will be invaluable in planning for the future.

Once all this information (checklists, score sheets, development uncertainty, etc.) is captured, correlated, displayed, discussed, and decisions made (hopefully reached by consensus of the review team) the immediate work of the review team is complete. However, all this effort will be in vain if the information is not preserved in a form that will allow for easy revision from time to time as requirements become more firmly established and architectures are further defined and developed to reflect the selected "path". If the records of the review are properly maintained, it may not even be necessary to reconvene the reviewers to update the results. Reviewers can be provided with the requirement or architecture updates along with their previous assessments, allowing them to modify their assessments to reflect the changes, which then can be collated with the other reviewers' changes to provide an updated assessment. These collated results can then be circulated among the reviewers for their concurrence or comment. While this process may be somewhat more time consuming (in elapsed time) than reconvening the review panel, it reduces the problems involved with scheduling a reconvened review and will take less of the reviewers' time, since no travel would be involved.

V. Conclusion

Uncertainties are inherent in any technology development until the matured technology is successfully incorporated in practice. Even then, application of a mature technology to a new environment introduces new uncertainties. When the requirements for the target mission are also uncertain, it would seem to be an intractable problem. Yet investment decisions must be made in a timely fashion to allow development to complete in time for target missions to incorporate them into their overall design. The only recourse is to develop a review strategy that allows for determination of the relative performance and uncertainties associated with a specific technology (such as environmental monitoring sensors), along with the capability to rapidly update the results as uncertainties are reduced or eliminated.

Checklists and spreadsheets can provide the mechanism for both guiding the review and capturing the results of the individual reviewers. Qualitative assessments can be converted into numerical scores, allowing for graphical display of the candidate technologies. Low performing technologies can be eliminated from further consideration, while promising candidates can then be taken to the next level of scrutiny, where the potential impediments to their maturation for the target missions can be detailed in a way that can be fed back to the technology developers for their consideration (assuming their selection.) If the review materials are properly archived, they can be rapidly retrieved and revised when further definition of requirements and target mission architectures becomes available, allowing for course corrections or further down-selection of technology developments. It may even be practical to introduce emerging technology developments not previously considered during the formal review into this process, although if the emerging technology is sufficiently novel, it may be necessary to reconvene the reviewers. However, even in this case, having all the previously derived information on the other candidates ready to hand would likely result in a much speedier and effective review.

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