Space Mission Concept Development Using Concept Maturity Levels

Randii R. Wessen, Chester Borden, John Ziemer, Johnny Kwok
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Over the past five years, pre-project formulation experts at the Jet Propulsion Laboratory (JPL) has developed and implemented a method for measuring and communicating the maturity of space mission concepts. Mission concept development teams use this method, and associated tools, prior to concepts entering their Formulation Phases (Phase A/B). The organizing structure is Concept Maturity Level (CML), which is a classification system for characterizing the various levels of a concept's maturity. The key strength of CMLs is the ability to evolve mission concepts guided by an incremental set of assessment needs. The CML definitions have been expanded into a matrix form to identify the breadth and depth of analysis needed for a concept to reach a specific level of maturity. This matrix enables improved assessment and communication by addressing the fundamental dimensions (e.g., science objectives, mission design, technical risk, project organization, cost, export compliance, etc.) associated with mission concept evolution. JPL's collaborative engineering, dedicated concept development, and proposal teams all use these and other CML-appropriate design tools to advance their mission concept designs.

This paper focuses on mission concept's early Pre-Phase A represented by CMLs 1- 4. The scope was limited due to the fact that CMLs 5 and 6 are already well defined based on the requirements documented in specific Announcement of Opportunities (AO) and Concept Study Report (CSR) guidelines, respectively, for competitive missions; and by NASA's Procedural Requirements NPR 7120.5E document for Projects in their Formulation Phase.

I. Introduction

JPL has been developing Concept Maturity Levels (CMLs) since 2008[3] when the Strategic Planning & Project Formulation Office's Chief Engineer first developed the concept. This terminology is used to objectively assess the technical progress that has been achieved for a mission concept during Pre-Phase A. Prior to the advent of CMLs, there were no methods available to 1) determine how much work was placed into a mission concept, 2) explicitly know when in a pre-project's lifecycle trade space exploration would be most advantageous to ensure that a mission concept is the most scientifically relevant and cost-effective, 3) determine which concepts had the same level of work and could be compared on the same terms, and 4) how much work a mission concept required to get to a subsequent level of maturity.

This paper will, for the first time, release the Concept Maturity Level Matrix externally to the non-JPL astronautics community. The authors and laboratory management have determined that the CML Matrix has reached a level of readiness that those outside of JPL could benefit from its use. The laboratory views this product as extremely valuable to NASA's Planetary Science Directorate (PSD) and its mission centers and is interested in collecting input from PSD and the other centers for broader use for spacecraft mission concepts. This point will be discussed in Section VII "Future Plans / Conclusions" section of this paper.

II. Concept Maturity Levels

Concept Maturity Levels (CMLs) provide a tool to effectively advance mission concept designs as well as to assess the current state of mission concepts. The CML vocabulary provides a standardized mechanism for describing and communicating the products / accomplishments required for achieving a given CML and for identifying work remaining to proceed to the next level. CMLs address the broad scope of engineering, science and

programmatic objectives and are useful for identifying analysis gaps and areas requiring more in-depth evaluation. Another use of CMLs is to provide a guideline / structure for internal concept reviews.

CMLs are defined as follows:

CML 1 *Cocktail Napkin* - The science questions have been well articulated, the type of science observations needed for addressing these questions have been proposed, and a rudimentary sketch of the mission concept and high-level objectives have been created. The essence of what makes the idea unique and meaningful have been captured.

CML 2 *Initial Feasibility* – The idea is expanded and questioned on the basis of feasibility, from a science, technical, and programmatic viewpoint. Lower-level objectives have been specified, key performance parameters quantified and basic calculations have been performed. These calculations, to first-order, determine the viability of the concept

CML 3 *Trade Space* - Exploration has been done around the science objectives and architectural trades between the spacecraft system, ground system and mission design to explore impacts on and understand the relationship between science return, cost, and risk

CML 4 *Point Design* – A specific design and cost that returns the desired science has been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Subsystems trades have been performed.

CML 5 *Baseline Concept* - Implementation approach has been defined including partners, contracting mode, integration and test approach, cost and schedule. This maturity level represents the level needed to write a NASA Step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects)

CML 6 *Integrated Concept* - Expanded details on the technical, management, cost and other elements of the mission concept have been defined and documented. A NASA Step 2 CSR is at this level of maturity. There is no corresponding milestone for assigned projects

CML 7 *Preliminary Implementation Baseline* - Preliminary system and subsystem level requirements & analyses, demonstrated (& acceptable) margins and reserves, prototyping & technology demonstrations, risk assessments and mitigation plans have been completed. This is the maturity level needed for competed missions to hold their Preliminary Mission System Review (PMSR) and for assigned projects to hold their Mission Definition Review (MDR)

CML 8 *PDR (Integrated Baseline)* — Design and planning commensurate for a Preliminary Design Review (PDR)

CML 9 *CDR* — Design and planning commensurate for a Critical Design Review (CDR)

This framework, to first order, is a sequential construct. It was developed to provide structure in Pre-Phase A where none existed before. It provides mission architects a way to communicate the amount of progress incorporated into a mission concept that allows the architects to know how much design work is needed to mature a concept to Phase A – The Concept & Technology Phase; and compare mission concepts with comparable levels of design effort.

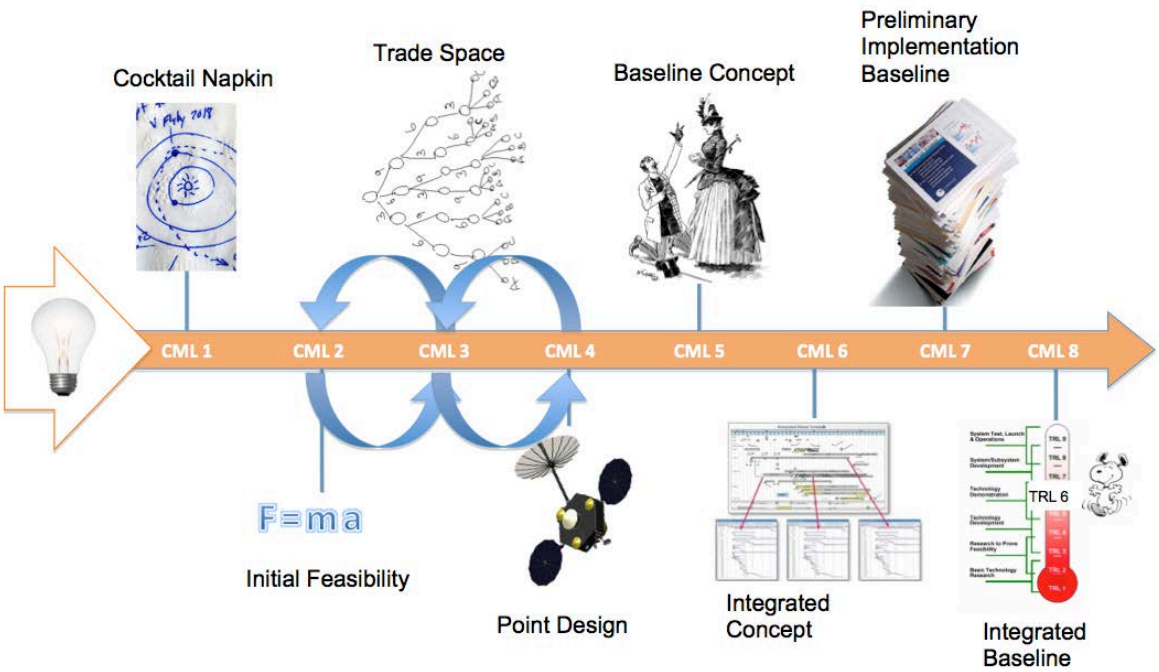

Figure 1. The Concept Maturity Level "spine" defining each step in the CML scale. This diagram illustrates how a mission concept matures as a function of time. Notice that between CMLs 2 – 4 there is an iterative nature between initial feasibility, trade space and point design. This highlights the fact that mission concept design is not usually a linear process, especially early on in a concept's development.

Figure 1 shows the sequential nature of CMLs. However there is a feedback loop between CMLs 2- 4. This is not a weakness of the CML scale but rather its strength. All too often mission concepts move forward without understanding the science partials, that is how science return changes as a function of some mission parameter (e.g., spacecraft mass, data volume, orbital period, etc.). This loop allows study teams to return to an earlier stage of concept development if mission design problems are encountered. Typically, study teams return from point design to trade space exploration to find an alternate approach for capturing the desired science. Trade space exploration is a key part of concept maturation and is needed to provide an increased likelihood that a global optimum is identified in the design of a viable concept. Prior to the development of CMLs, some study teams would move directly into point design with their mission concept without first having done sufficient trade space exploration. This resulted in mission concepts that 1) did not have a maximum science return, 2) had inefficient spacecraft and ground system designs, and 3) a less efficient overall mission concept because trades between science, mission, spacecraft, and ground system design for a particular cost point never occurred.

III. The Early CML Phases (CML 1 – 4)

The greatest challenge for mission architects in Pre-Phase A occurs at the start of the mission design process, rather than near the end. In the early stages of Pre-Phase A, a mission concept may have as little structure as a single science objective and perhaps a kernel of an idea of how to get accomplished. It is important that all major components of a mission concept be addressed at a high level and hopefully in parallel. It is at this time in the development of a concept that mission architects can have the most impact on the overall system design. Having a structure to refer to, such as the CML Matrix and the CML Checklists, would be a helpful tool for mission architects and program managers. At the end of Pre-Phase A, the study team is preparing for their Mission Concept Review (MCR) (for assigned projects) or their Step 1 proposal (for competed projects). Assigned projects have MCR

guidance from NASA's Procedural Requirements NPR 7120.5E document. Competed projects have guidance from NASA's Announcement of Opportunity (AO). As such, the early CML phases are the focus of this paper. For completeness, the CML Matrix goes from CML 1 – 7 and CML Checklists have been generated from CML 2 – 6. Since the mission concept must comply with NASA's Procedural Requirements NPR 7120.5E document for CML 7, the CML checklist does not duplicate that guidance. A complete discussion of CML Checklists will be discussed in section V of this paper.

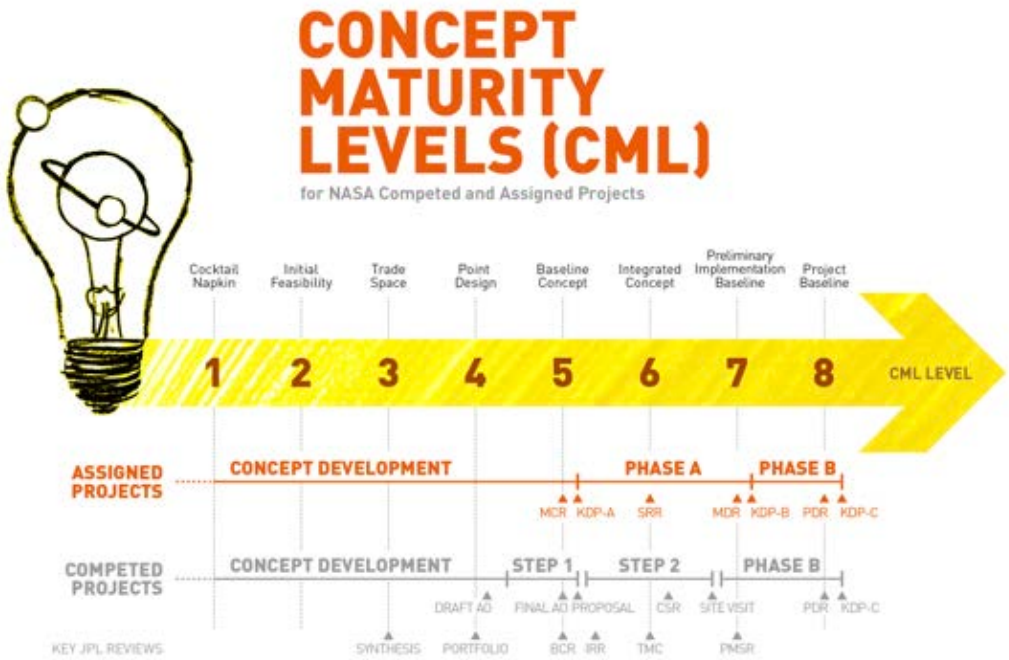

Figure 2. Concept Maturity Levels for NASA Assigned and Competed Projects. This diagram shows how CMLs align with NASA's project milestones. By the middle of Phase B, there is not an assigned project and a competed project lifecycle but rather a single project lifecycle.

Figure 2 shows the major NASA and JPL reviews as a function of CML. Concept Maturity Levels provide an efficient shorthand for describing the maturity of a mission concept and what level of maturity is needed for a particular portion of a project lifecycle. As an example, an Assigned Projects should have a mission concept at CML 5 by the time of their Mission Concept Review (MCR); and for competed proposals, a mission concept should have a maturity of CML 5 by the time of their Baseline Commitment Review (BCR). In both cases, if the content of a mission concept is known, mission architects can compare the state of their concept to that identified in the CML 5 Checklist. The result is an explicit list of areas where the concept is at the desired level of maturity and a list of deficiencies. Armed with that information, the study team can efficiently marshal its resources to get their mission concept up to the desired level of maturity in time for their reviews.

IV. Concept Maturity Level Matrix

The CML Matrix contains 7 columns (for CML 1 – 7) and 24 rows. These rows are binned into a set of Science rows (2), Technical rows (13), Management rows (5), a Cost row (1), and 3 "Other" rows. These bins are aligned with the way NASA evaluates mission concepts. NASA first holds a science review followed by a TMCO Review. TMCO is an acronym for Technical, Management, Cost and Other.

The CML Matrix was not designed to contain every mission design attribute at all possible levels of fidelity. Rather it is a high-level guide for study and proposal teams through the early stages of mission design. There are two high-level approaches for using this matrix. The first is as a way to determine the content of a mission concept at the time of a particular review. As an example, by looking at the contents of the cells in the CML 5 column, a mission architect can quickly see the material that is needed for a study team to pass their Mission

Concept Review. Of course, the matrix only identifies what is needed at each CML, not what is necessary to achieve a winning proposal. An alternate approach is to look across a row. As an example, if you are a project's Mission Assurance Manager (MAM), then by reviewing the "Mission Assurance Management" row, the MAM can easily see the products required as a function of time.

Because of the large size of the CML Matrix (24 rows), for this paper the matrix has been divided into 5 smaller matrices (i.e., Science, Technical, Management, Costing, and Other) (Figure 3 – 7)

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Name	Cocktail Napkin	Initial Feasibility	Trade Space	Point Design	Baseline Concept	Integrated Concept	Preliminary Implementation Baseline
Life Cycle Gate	—	—	—	Concept Gate (Draft AO Out / Mission Study Report)	Baseline Commitment Gate / MCR	Step 2 Submittal	PMSR / MDR
Science							
Attribute							
Science Objectives & System Requirements	Science objectives described in one sentence	Objectives described to levels that allow comparison with previous investigations and NASA science community documents	Objectives linked to investigations and measurements Science return as a function of cost, risk and programmatics quantified	Produce draft Science Traceability Matrix Initial Level 1 requirements considered Specifying one Baseline and one Threshold Science investigation Key Performance Parameters listed	Science Traceability Matrix (or equivalent) produced Preliminary PLRA produced (assigned projects)	Proposed Level 1 requirements documented Level 2 & 3 driving requirements listed Full and minimum success criteria defined Baseline PLRA submitted @ SRR (assigned projects)	Update PLRA if necessary Preliminary Level 2 & 3 requirements listed
Science Data System	—	Identify science data drivers	Science data rates and volume included in trade space analysis	Science data system sizing	Science data processing architecture, release and archive approach defined	Science data management approach (includes Level 0, 1, 2 data products) defined	Same as for CML 6

Figure 3. The two science rows of the CML Matrix. These rows capture both ends of the mission concept process, namely the science objectives (the why are we doing this mission?) and the science data products (the what will be produced?) portions of the mission concept. The science portion of the mission design is typically the entire reason for proposing this mission and must be included in all system trades.

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Technical							
Attribute							
Mission Development	One sentence description of unique mission & system characteristics	Key mission concept parameters and performance requirements quantified Rudimentary calculations & comparisons to mission analogues performed Gross characterization of space environment	Alternative set of mission architectures evaluated against science objectives, cost & risk Quantitatively bounded hazards of space environment	Driving requirements, initial high-level scenarios, timelines and operational modes documented Propellant load and delta-V budget determined Power, telecom, data processing approach defined Descopes & backup options identified as needed	Concept is complete, viable & stable Mission phases documented to level for illustrating how science objectives will be met Mission traceability matrix created Resource utilization consistent with scenarios and ops modes A mission categorization and risk classification determined	Expand description of mission phases to illustrate critical s/c/ ground functions Delta-V & maneuver strategy (for s/c projects), communications approach & ground station needs determined	Key driving mission scenarios, timelines and modes documented in detail
Spacecraft System Design	—	Key flight elements, design parameters & performance requirements listed High-level comparison to similar flight systems documented	Unique features that distinguish one flight system architecture from another evaluated Perform sensitivity studies to bound performance within trade space performed	System architecture with mechanical configuration drawings, block diagrams & descope options compiled	Subsystem designs to enable external evaluation & costing documented System contingencies & margins established	Major architectural trades complete and incorporated All key LV, s/c, and payload I/F qualitatively defined	System & subsystem designs and external I/F defined Plans for closing open design issues finalized Plans for maturing technology, long-lead items, and prototyping engineering developments in place
Instrument System Design	—	One sentence description of potential measurement technique(s) Perform high-level comparison to similar measurement technique(s)	Key instrument performance requirements, measurement techniques and instruments selected against science / mission objectives, cost & risk Sensitivity studies to bound performance within trade space performed	Instrument design with mechanical configuration drawings, block diagrams & descope options compiled (Earth Science & Astrophysics concepts), Instrument performance requirements traced to level 1 requirements	Instrument designs sufficient to enable external evaluation & costing developed (competed projects) Initial Instrument accommodations noted Plans for maturing technology, long-lead items, and prototyping engineering developments in place Science data Quantity, Quality, Continuity & Latency (QQCL) requirements, instrument contingencies & margins established	Major payload trades complete and incorporated Final instrument designs & accommodations specified	Instrument design, accommodation, open issues & external I/F defined
Ground System / Mission Operations System Design	—	Mission ops approaches defined	Mission ops drivers and sensitivities assessed Major flight / ground trades identified New ground system capabilities identified	MOS / GDS architecture based on ops scenarios described	Major MOS responsibilities, block diagrams, facilities & I/Fs with science community defined MOS based on operations complexity sized Approach for acquiring & returning critical events data documented	MOS diagrams with proposed inheritance compiled Major flight / ground trades complete Operational roles, responsibilities & data flow elaborated	MOS implementation w/ mission unique items defined Plans for upgrading facilities, software & hardware complete

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Technical Risk Assessment & Management	—	Identify risks Identify areas of major concerns	Compare risks across the various architectures Identify mitigation stategies for key risks	Risk drivers listed A 5 x 5 matrix with relevant risk drivers (include selected mitigation / development options) used	Risks and mitigation plans incorporated into the baseline Selected pre- and post mitigation likelihood and consequence of baseline detailed Identification of prototyping plans for mitigating highest risks Strategies for control, allocation & release of technical margins & cost reserves determined	Risks reassessed Risk list expanded to include second tier subsystem and / or instrument risks Initial prototyping results known Baseline Risk Management Plan submitted @ SRR (assigned projects)	Update Risk Management Plan if necessary Project risk management process implemented Update plans based on ongoing protoyping
Technology	—	Identify enabling technologies and / or significant engineering developments required to get to TRL 6 by PDR	Compare technologies & major developments required for design options across the trade space	Technology options characterized Baseline options selected & justified Explain rationale for TRL (See TRL table) Fallback options for all new technologies identified	A technology evaluation for each baseline option (Include maturation approach for new technologies) completed Baseline Technology Development Plan submitted (assigned projects)	Update Technology Development Plan if necessary Invest in key technologies	Technology assessment, residual risks and recommended closures provided Update plans to assure TRL 6 by PDR (CDR for technology missions)
Inheritance	—	Identify source of assumed inheritance	Early evaluation of Inheritance options, benefits and risks across trade space	Major inherited assembly items tentatively selected	For design driving assemblies and components, confirm availability, status and document	Reconfirm availability and applicability of inherited items Check for parts obsolescence and pedigre	Same as for CML 6
Master Equipment Lists	—	—	Mass of major elements quantified based on subsystem estimates	MEL documented to assembly level (e.g., antenna, propellant tank, star tracker, etc.)	Expand / update MEL consistent with heritage	MEL selectively expanded to component level for minor modifications to heritage assemblies or for components needed in extreme environments	Same as for CML 6
Technical Margins	—	Identify high risk areas that need significant margin Assess uncertainty	Use institutional margins where applicable Analysize best and worst case scenarios	Institutional margin policies followed Critical margins estimated	Resources defined, tracked & actively managed	Same as for CML 5	Same as for CML 5
System Engineering	—	Initial generation of trade space options	Capture the relative merits of performance, cost and technical risk over a broad range of architectures Subsystem dependencies identified	High leverage science, spacecraft and ground system trades completed	Architecture finalized System Engineering approach documented Additional system trades and approach for closure identified	System trades complete Identify subsystem trades Baseline System Engineering Implementation Plan written (assigned projects)	Update System Engineering Implementation Plan if necessary Known subsystem trades complete
Launch Services	—	Launch approach and performance identified	Perform trades for candidate launch vehicles demonstrating compatibility with performance and fairing size	Preliminary launch vehicles & backup documented NASA Launch Services acquisition process is being used	Recommended launch vehicle requirements & capabilities established, including non-standard services Launch services has been contacted	Confirm launch vehicle assumptions	Identify mission unique launch needs (e.g., injection covariance study, contamination control, special access, etc.)

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Planetary Protection	—	Identify need for Planetary Protection requirements	Evaluate expected Planetary Protection implementation options	Planetary Protection approach defined	Letter from NASA's Planetary Protection Officer with provisional Planetary Protection Categorization obtained	Same as for CML 5	Final Planetary Protection Certification received
Verification & Validation	—	—	Identify any major or unique V&V activities	Approach for verifying new & enabling functions of the chosen architecture defined System testbeds, & prototype models identified Consider how V&V will be supported Number of CD&H functions identified	V&V approach and schedule defined Testbeds and prototype model equipment list produced Number of flight system interfaces identified	V&V schedule integrated with IMS Update number of C&DH functions and flight system interfaces	Preliminary Project V&V Plan complete Testbed and prototype model equipment list finalized

Figure 4. The 13 technical rows of the CML Matrix are listed in this figure. One key aspect of this portion of the matrix is the concurrent design of the mission with both the spacecraft and ground systems included as an integrated system.

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
	Management						
Attribute							
Acquisition & Surveillance	—	—	Survey international and domestic capabilities for alternate architectures Idenitification of key make-buy decisions	Business Decision Memorandum completed (AO projects) Solicit RFI(s) for Industry input if necessary) System-level In-house versus out-of-house decision made	Partner MOU completed (AO projects) Identify long-lead procurements Strawman list of subsystem sources for each item in MEL	Industry Contractor placed on contract for Step 2 (AO projects) Project procurement reqmts package prepared (Assigned projects)	Contracts or Bounded Cost-Risk negotiated Preliminary Project Acquisition Plan written Update list of subsystem sources Phase B Task Plan completed
Project Organization, Implementation Mode & Partnering	—	—	Identify partnership options Implementation mode (in-house or system contract) trades performed	PI, Science team & key partners identified Program Office approved PI (Competed proposals only) Organizational options identified Project structure created	Project Personnel (PM, PSE, FSM and / or Instrument Mgr) named Implementation mode final decision made Foreign partners & other NASA centers identified Roles & responsibilities of key partners defined Draft org chart developed Proposed contributions & cooperative agreements listed Project Formulation Authorization document ready to sign (assigned projects) Phase A Formulation Agreement submitted (assigned projects)	PM, PSE, and FSM in place Remaining Core Project Team identified Agreements from "Doing" organizations written Key project management policies incorporated into CSR (AO projects)	Project Organization documented in Preliminary Project Plan Subsystem contractors identified Core Project Team in place Work agreements for Phase B in place, Preliminary agreements for Phase C/D negotiated Key project management policies finalized Baseline Formulation Agreement for Phase B submitted

Schedules	Identify time frame	Potential launch opportunities identified Use Schedule & Cost Rules-of-Thumb to estimate lifecycle duration	Assess variations and risks to science, development schedule and impacts to mission duration	Top-level Gantt chart generated	Gantt Chart to 1-month resolution with key deliverables, system reviews, technology developments, instruments, models & simulators, long lead procurements, I&T and critical path developed - Funded schedule reserves added to schedule Preliminary Integrated Lifecycle Network Schedule with key system milestones produced (assigned projects)	Top-level Gantt Chart & Preliminary Integrated Lifecycle Network Schedule (with critical path and funded schedule reserve) updated	Preliminary Integrated Lifecycle Network Schedule with key subsystem milestones produced Range of schedule estimates and confidence levels produced
Work Breakdown Structure	—	—	NASA Standard WBS & Dictionary (down to level 2 and level 3 for spacecraft and payload) used	NASA Standard WBS & Dictionary down to level 3 (system level) and level 4 (for spacecraft and payload) used Project scope assessed by major WBS elements	Tailored WBS and dictionary approved	Same as for CML 5	Same as for CML 5
Mission Assurance Management	—	—	—	—	Mission assurance approach tailored to mission risk class	Mission assurance plan expanded (described in CSR for competed projects, actual plan for assigned projects)	Preliminary Mission Assurance Plan written

Figure 5. The 5 Management rows of the CML Matrix. In some cases, mission concepts omit some programmatic portion of the concept that results in either an entire mission concept redesign or an unacceptable growth of the overall mission lifecycle cost. This matrix will help to minimize the likelihood of omitting these areas.

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Cost							
Attribute							
Cost Estimation and Cost Risk	—	Cost estimate range provided based on analogous missions Cost uncertainity quantified	Cost sensitivities explored across trade space as a function of major drivers Initial estimate down to level 2 and level 3 for spacecraft and payload Cost uncertainity quantified System cost risks identified	Initial estimate down to level 3 (system level) and level 4 for spacecraft and payload. Recommended reserve level based on known project risks Cost risks identified at subsystem level Ensure budget is consistent with NASA funding profile	Validate the CML 4 cost estimate using at least 2 model-based estimates Validate recommended reserves based on two independent methods	Develop a fully supportable cost estimate (i.e., BOEs and cost and pricing data at the lowest required WBS level) for Phase B Cost estimate can be a combination of grass roots and model-based cost estimates for Phase C/D/E Determine reserve levels based on risk posture of the project Validate recommended reserves based on two independent methods Develop a probabilistic cost estimate Obtain institutional	Refine and validate approved baseline Range of estimates and confidence levels produced

Figure 6. The Cost rows of the CML Matrix. This row captures the need for a mission concept cost estimate as well as the cost uncertainty, the cost sensitivities across the trade space, and the validation of the cost estimate and its associated level of reserve.

Life Cycle Phase	Pre-Phase A					Phase A	
	Advanced Studies			Concept Development		Early Formulation	
CML	1	2	3	4	5	6	7
Other							
Attribute							
Launch Approval	—	—	—	—	NASA's designated launch approval organization notified about proposed concept Launch approval requirements defined	Launch approval requirements documented	Baseline Launch Approval Engineering Plan completed
NEPA Compliance	—	Identify any nuclear material or public safety issues	Explore options (e.g., non-nuclear options for nuclear power missions)	Evaluate Project NEPA requirements (per NPR 8580.1)	NEPA requirements documented and NASA's designated NEPA organization notified about proposed concept	NEPA requirements reassessed	Same as for CML 6
Export Compliance	—	—	—	If detailed technical discussions with foreign partners are contemplated, contact Export Compliance Office	Same as for CML 4	Export authorization in place if needed for detailed technical discussions	Export authorization finalized Preliminary Export Compliance Management Plan completed

Figure 7. The "Other" rows of the CML Matrix. In many cases, these areas are considered after-the-fact and can lead to cost growth or worse, the inability to implement the particular mission concept in the manner conceived.

V. Concept Maturity Level Checklists

Once the CML Matrix was developed, it became immediately obvious that a tool to assist in CML evaluation was required. To be most helpful to the study teams, an evaluation tool should be able to be applied quickly and generate an assessment of gaps for the various CMLs. Specifically, such a tool should be able to 1) quickly measure the concept's maturity, 2) be repeatable (i.e., be able to be applied to many proposals and provide the same level of maturity score for concepts with the same level of maturity) and, 3) provide clear information as to what areas of the concept need additional work to get to the overall mission concept to the desired level of maturity.

The checklists themselves are based on the products identified in the specified column of the CML Matrix. CML Checklists have been generated for CMLs 2 – 6. No checklist was created for CML 1 due to the free-form nature of a mission concept design very early in the design process. In addition, at CML 1, the concept design is driven more by the objectives of the mission and myriad of implementation possibilities. This is not to say that there are no required mission design attributes at CML 1, but rather the emphasis is on the original concept and returning the desired science. CML 1 highlights what is novel about the mission concept and its motivation. The only areas considered in CML 1 are 1) the science objective, 2) the unique mission characteristics, 3) an approximate timeframe for the launch of the mission, and 4) target cost class. On the other side of the spectrum, there were no checklists created for CML 7 or greater due to the fact that CML 7 is well into a Project's Phase A's Concept & Technology Development phase. By the CML 7 (and in reality, by the start of CML 6), the mission concept must comply with NASA's Procedural Requirements NPR 7120.5E document and no longer needs the guidance provided by CMLs.

As for the use of checklists, these provide guidelines for proposal and study teams to correct areas that are found deficient by this tool. The tool provides an independent check on where the concept is weak and where work should be applied to make the mission concept implementable and robust. Once maturity is assessed, the proposal and study teams are faced with a choice. Of the areas that are identified as "not at the desired maturity level," where should the team's limited resources be applied to help their overall concept's maturity? In most cases, teams do not have the resources (i.e., time, funds, and personnel) to correct all deficiencies found by the tool. It is a decision for the Principal Investigator, Capture Lead, Proposal Manager, Study Lead, System Engineer and/or any other key team personnel to decide how best to apply the team's limited resources to most efficiently correct the most critical omissions.

Figures 8a, 8b and 8c show the CML 4 Checklist as an example. The checklist has three columns and consists of 1) functional area, 2) criteria, and 3) status. Each cell in the status column can be given a color to represent the status of each attribute. The color of a cell is interpreted as follows: green (G) = completed, yellow (Y) = in the process of being completed, or red (R) = not yet started. A mission concept is considered to be at a particular concept maturity level if 80% of the attributes in that column have been completed (green). Of course there is nothing special about 80%. A mission concept coming in with a maturity assessment of 78% "green" is probably at the desired level of maturity. On the other hand, it would be difficult to consider a mission concept complete and robust if it is assessed as at 90% completeness but is missing their Science Traceability Matrix, Level 1 requirements, and Master Equipment List. Engineering judgment must be applied when interpreting results of each maturity assessment.

	CML 4 Checklist Sheet	
	2013 April 11	
Functional Area	**Criteria**	**Status (RYG)**
	SCIENCE	
Science Objectives & Driving Requirements	o Draft Science Traceability Matrix produced	G
	o Initial Level 1 requirements considered	G
	o One Baseline and one Threshold Science investigation specified	G
	o Key Performance Parameters listed	G
Science Data System	o Science data system sized	R
	TECHNICAL	
Mission Development	o Driving requirements documented	G
	o Initital high-level scenarios, timelines and operational modes documented	G
	o Propellant load and delta-V requirements determined	G
	o Power generation and distribution approach defined	G
	o Telecommunication approach defined	G
	o Data processing approach documented	Y
	o Descope and backup options identified as needed	G
	o Launch period is 20 days long	G
Spacecraft or Instrument System Design	o System architecture & instrument designs (Earth Science & Astrophysics missions only) described by mechanical configuration drawings	G
	o System architecture & instrument designs (Earth Science & Astrophysics missions only) described by block diagrams	Y
	o Descope options compiled	G
	o Instrument performance requirements traced to level 1 requirements	Y
Ground System & Mission Operations System Design	o MOS / GDS architecture based on ops scenarios described	
Technical Risk Assessment & Management	o Risk drivers listed	
	o Top risks documented in 5 x 5 matrix (includes selected mitigation options)	
Technology	o Technology options characterized and baseline options selections and justified	
	o TRL for new technologies explained	
	o Fallback options for all new technologies identified	
Inheritance	o Major inherited assembly items tentatively selected	
Master Equipment Lists	o Assembly level (e.g., antenna, propellant tank, star tracker, etc.) MEL documented	

Figure 8a. The first part of a partially completed CML 4 Checklist. This is an example of a CML 4 maturity level assessment of a collaborative design team's mission point design effort.

Technical Margins * Margins can be relaxed down to PNSR levels if accepted of 5	o Institutional margin policies followed (margins defined by DP Section 6.3)	
	o Critical margins estimated	
S/C Dry Mass (Mass growth allowance & margin)	o >= 35%*	
Power	o >= 35%*	
Propellants	o N/A	
Data Storage	o N/A	
Attitude Control	o N/A	
Energy	o >= 35%*	
Flight S/W (CPU timing & memory)	o >= 100%	
Telecom	o >= 3 dB (for deep space); >=6 dB (for proximity links)	
System Engineering	o High leverage science, spacecraft and ground system trades completed	
Launch Services	o Preliminary launch vehicle and backup documented	
	o NASA Launch Services acquistion process is being used	
Planetary Protection	o Planetary Protection approach documented	
Verification & Validation	o Approach for verifying new & enabling functions of the chosen architecture defined	
	o System testbeds, & prototype models identified;	
	o Consider how V&V will be supported;	
	o Number of CD&H functions identified	

Figure 8b. The second part of the CML 4 Checklist. This contains the last portion of the technical attributes of the checklist. Notice that there are no requirements for propellant, data storage and attitude control technical margins at CML 4, as those are not required by the AO.

MANAGEMENT		
Acquisition & Surveillance	o Business Decision Memorandum completed (AO projects)	
	o Solicit RFI(s) for Industry input (if necessary)	
	o System-level In-house versus out-of-house decision made	
Project Organization, Implementation Mode & Partnering	o PI, Science Team and key partners identified	
	o Associate Director for PF&S approved industry partner and system contractors (Competed proposals only)	
	o Organizational options identified	
	o Project structure created	
Schedules	o Top-level Gantt chart generated	
	o Schedule margin calculated using DP 6.1.2.2 formula	
Work Breakdown Structure	o NASA WBS & Dictionary down to level 3 (system level) and level 4 (for spacecraft & payload) used	
	o Project scope assessed by major WBS elements	
Mission Assurance Management	o (None identified at this time)	
COST		
Cost Estimation & Risk	o Initial estimate down to level 3 (system level) and level 4 for spacecraft and payload	
	o Recommended reserve level based on known project risks	
	o Cost risks identified at subsystem level	
	o Budget is consistent with NASA funding profile	
OTHER		
Launch Approval	o (None identified at this time)	
NEPA Compliance	o Project NEPA requirements evaluated (per NPR 8580.1)	
Export Compliance	o (None identified at this time)	

Figure 8c. The third and final part of the CML 4 Checklist. This contains the management, cost and "other" portions of the checklist. The "Other" portion of the checklist contains those programmatic areas that extend past the pre-project itself and must be coordinated with other NASA organizations.

There are three other caveats about the CML Checklist tool that need to be clearly articulated. They are 1) the tool does not measure the quality of a particular attribute; it just measures the state of completeness. As such, if a proposal team states they have completed their Draft Science Traceability Matrix, there is no attempt to determine how well that traceability matrix was done. Rigorous engineering analysis needs to be performed on each mission concept attribute to determine its quality. Next, 2) there is no attempt to weight the relative value of different attributes. As such, the tool cannot distinguish the difference in maturity between a team that does not have their Key Performance Parameters completed over their Telecom Approach defined. And finally, 3) it is very dangerous to let proposal and study teams "self assess." An independent assessor should have a half-hour discussion with key members of the study (at least the Proposal Manager and System Engineer). Self-assessments have a tendency to result in overly optimistic scores.

VI. How CMLs are used at JPL to Advance Concept Design Maturity

JPL uses CMLs for its mission studies in Pre-Phase A. These studies encompass both new concepts and innovative variations of previous mission concepts. These variations may include changes to the mission design, science investigations or payload, subsystem technologies or programmatic options (e.g., foreign partnership, in-house (JPL) or out-of-house implementation, distributed operations or centralized, etc.). The earliest stages of the

CML process (CMLs 1-3) are typically addressed by JPL's A-Team. The A-Team enables study of high-leverage, open-ended ideas that are not ready for a Team X (CML 4) point design study. The scope of the A-Team's responsibilities include idea generation, feasibility assessment, architecture trade space evaluation, science traceability, technology infusion, and strategic evaluation. The intent of the CML 1-3 process is to create innovative missions that respond to the science and programmatic (e.g., cost cap) needs and evaluate them to a sufficient level of detail that the most promising mission concept "seeds" are available for additional analysis.

The A-Team typically conducts one or more collaborative sessions in response to customer needs, based on an agreed-to study plan. The sessions are facilitated to enable rapid, broad investigations. Subject matter experts participate to provide innovative concept generation and technical analysis expertise. A number of technical products can be generated ranging from mission design (trajectory) evaluations, science traceability, cost & risk studies, technology assessments, etc.

The A-Team develops and utilizes engineering analysis and costing tools for each CML for its internal use. In this way, the A-Team can apply the right tool for each level of maturity. For example, a CML 2 cost tool will have large uncertainties due to the low fidelity of the estimate. However, these tools are designed to be of a sufficient fidelity that they support the level of decision-making consistent with the CML (e.g. at CML 2, a costing tool should be able to adequately model and determine which cost class a mission concept is in). The A-Team's strength is the team's small size, diversity of participation by subject matter experts having significant mission experience, and emphasis on systems engineering and integration. It is designed to rapidly and inexpensively explore the design space to identify the mission concepts that can return the type of desired science for the particular mission's class (e.g., Explorer, Discovery, New Frontiers, or Flagship).

JPL's Team X is also using the CML approach and terminology to generate tools and to define consistent products when Team-X evaluates mission concepts. Team-X is a team that initiated the collaborative engineering capability within NASA. JPL's Team X was created in 1995, in response to an era of tighter federal budgets. Since then, Team X has conducted over 1000 studies. Mission point design studies (CML 4) support early concept development and are the primary focus of Team X. This includes support for proposals for new work (e.g., responding to Discovery or New Frontiers Announcements of Opportunity) and limited design trades. To accomplish this, the team typically conducts a small number of collaborative design sessions (usually 3 over the span of a week) and generates a set of mission design, spacecraft design and cost and risk results. In addition, Team X is evolving to provide a variety of new analysis capabilities (e.g., engineering and cost review) consistent with the CML 4 point design level of fidelity.

VII. Future Plans / Conclusions

CMLs, the CML Matrix and the CML Checklists are not the entire answer to advancing concept maturity and fidelity. As JPL gains more and more experience with CMLs, we see that there are other factors that can directly impact a mission concept's maturity. One such factor is complexity. Mission complexity can have a large bearing on a project's maturity as well as on its risk posture and overall lifecycle cost. But complexity is difficult to determine in Pre-Phase A due to the lack of information. In addition, complexity can be further obscured by whether the engineering required for this concept has been developed before. A future effort to address the issues of weighting elements of the CML Checklist and complexity is planned.

Due to the success of CMLs, JPL is now beginning the process of introducing CMLs and the CML tool set (i.e., the CML terminology, matrix and checklists) to other potential users. The National Research Council's Planetary Science Decadal Survey panels used the CML terminology and found it very useful for comparing mission concepts. To make these tool accessible to a larger community, the laboratory is in the process of placing them on an externally available website. Members of JPL's Innovation Foundry have modified the tool's content to make it generally applicable for other NASA Centers, rather than being JPL-specific. Once the site becomes operational, individuals can use these CML tools as they see fit. However, these web-based tools are still based on JPL developed methodologies. JPL and its Innovation Foundry believe that CMLs should have a much broader appeal and could benefit from adding mission design experience from other NASA centers. To this end, JPL is interested in working with NASA's Planetary Science Division to develop such a task. This task would require forming a working group from across NASA (e.g., ARC, JPL, GSFC) and its partners (e.g., Johns Hopkins' APL, Aerospace Corporation, etc.) to work together to expand the CML tools from a JPL-specific tool set to one that can be used across the industry.

The CML tools are just now reaching a level of readiness that makes the time right for a broader use outside of JPL. For over five years, JPL has been developing this tool set and applying them to various mission

concepts in the various programmatic areas (i.e., Earth, Mars, Solar System and Astrophysics). The value of the CML tool set in evaluating concept maturity and recommending actions to improve lagging elements of the concept has been demonstrated in practice. The detailed definition and applications of the CML tool set will continue to evolve as they gain wider acceptance outside of JPL. We expect that the use of CMLs will facilitate discussions of concept maturity, provide a basis for improved concept development practices, and help establish reasonable expectations based on the maturity of the concepts in consideration.

VIII. Acronyms

AO – Announcement of Opportunity
APL – Applied Physics Laboratory (John Hopkins University)
ARC – Ames Research Center (NASA)
BCR - Baseline Commitment Review
BOE – Basis of Estimate
C&DH – Command & Data Handling
CDR – Critical Design Review
CML – Concept Maturity Level
CSR – Concept Study Report
dB - Decibels
FSM – Flight System Manager
GDS – Ground Data System
GSFC – Goddard Space Flight Center (NASA)
I/F – Interface
I&T – Integration & Test
JPL - Jet Propulsion Laboratory (NASA)
L/V – Launch Vehicle
MAM - Mission Assurance Manager
MCR – Mission Concept Review
MDR – Mission Definition Review
MEL – Master Equipment List
MOS – Mission Operations System
MOU – Memorandum of Understanding
NASA – National Aeronautics and Space Administration
NEPA – NASA Environmental Policy Act
NPR - NASA's Procedural Requirements
PDR – Preliminary Design Review
PF&S – Project Formulation & Strategy
PI – Principal Investigator
PLRA
PM – Project Manager
PMSR – Project Mission System Review
PSD - Planetary Science Directorate
PSE – Project System Engineer
QQCL – Quantity, Quality, Continuity and Latency
RFI – Request for Information
S/C- Spacecraft
SRR – System Requirements Review
TMCO - Technical, Management, Cost and Other
TRL – Technology Readiness Level
V&V – Verification and Validation
WBS – Work Breakdown Structure

Acknowledgment

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Copyright 2013 California Institute of Technology
Government sponsorship acknowledged

References

1. "NASA Space Flight Program and Project Management Requirements", NASA Procedural Requirements NPR: 7120.5E, 2012 August 14.

2. "NASA Research and Technology Program and Project Management Requirements", NASA Procedural Requirements NPR: 7120.8, Appendix J. Technology Readiness Levels (TRLs), 2008 February 5.

3. Wessen, Randii R., Adler, Mark, Leising, Charles J., Sherwood, Brent, "Measuring the Maturity of Robotic Planetary Mission Concepts", AIAA 2009 Conference

4. Wessen, Randii R., Adler, Mark, Leising, Charles J., Sherwood, Brent, "Measuring the Maturity of Robotic Planetary Mission Concepts II", SpaceOps 2010 Conference

5. Sherwood, Brent, McCleese, Daniel J., "JPL Innovation Foundry", Acta Astronautica, 2013 April 17, pages 236 - 247