

The NASA Standard for Models and Simulations: Deployment Experience

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**Standards in Modeling and Simulation Workshop:
The Next 10 Years**

**Virginia Modeling Analysis and Simulation Center
March 31–April 2, 2010**



Outline

- **Drivers**
- **Key Features**
- **Deployment Experiences**

- **Supplementary Material**
 - References
 - Need
 - Scope
 - Requirements
 - Credibility Assessment Scale
 - Development Process



Drivers



NASA Chief Engineer on Need

- **“Multiple reviews (including the CAIB) and advisory bodies have recommended that NASA needs a standard for Models and Simulations”**
- **“We are increasingly reliant on modeling and simulation to verify our systems, including many places where end-to-end or even major element tests are difficult at best”**





Drivers for M&S Standard

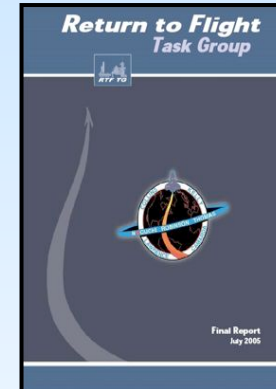
Columbia Accident Investigation Board (CAIB)



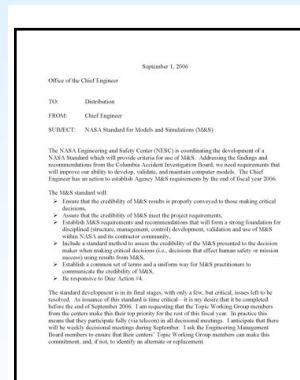
A Renewed Commitment to Excellence (Diaz Report)



Return-to-Flight Task Group (Stafford-Covey Report)



NASA Chief Engineer Memo, Sept. 2006





Pre-Issuance Summary

- **M&S Standard development started in May 2005 in response to Diaz Action #4**
- **The interim NASA M&S Standard was issued by the NASA Chief Engineer on Dec. 1, 2006 as NASA-STD-(I)-7009**
- **Agency-wide review of the Interim M&S Standard was conducted May–August 2007**
- **Numerous changes were made as a result**
- **Additional changes were made as a result of the January–May 2008 review by the EMB and the OCE**
- **The permanent NASA M&S Standard was issued by the NASA Chief Engineer on July 11, 2008 as NASA-STD-7009**



Key Features



Theme of NASA-STD-7009

- **Ensure that the credibility of the results from M&S is properly conveyed to those making critical decisions**
- **Critical decisions based on M&S results, as defined by this standard, are those technical decisions related to design, development, manufacturing, ground, or flight operations that may impact human safety or program/project-defined mission success criteria.**



Risk-informed Scope Guidance

- *Program and project management in collaboration with the Technical Authority have the responsibility to ... identify and document the critical decisions to be addressed with M&S and to determine which M&S are in scope. The latter determination should be based upon the risk posed by the anticipated use of the M&S.*

M&S Risk Assessment Matrix

M&S Results Influence	5: Controlling	(G)	(Y)	(R)	(R)
	4: Significant	(G)	(Y)	(R)	(R)
	3: Moderate	(G)	(Y)	(Y)	(R)
	2: Minor	(G)	(G)	(Y)	(Y)
	1: Negligible	(G)	(G)	(G)	(G)
		IV: Negligible	III: Marginal	II: Critical	I: Catastrophic
		Decision Consequence			



Content of NASA-STD-7009

- **NASA-STD-7009 contains requirements, not guidance**
- **At present, NASA-STD-7009 is not a mandatory standard**
 - It is the program's decision, not the institution's decision, on whether NASA-STD-7009 is an applicable document



Requirement Categories

- 4.1 Programmatic Requirements**
- 4.2 Models**
- 4.3 Simulations and Analyses**
- 4.4 Verification, Validation and Uncertainty Quantification**
- 4.5 Development and Use of Recommended Practices**
- 4.6 Training**
- 4.7 Assessing the Credibility of Models and Simulations**
- 4.8 Reporting Results to Decision Makers**

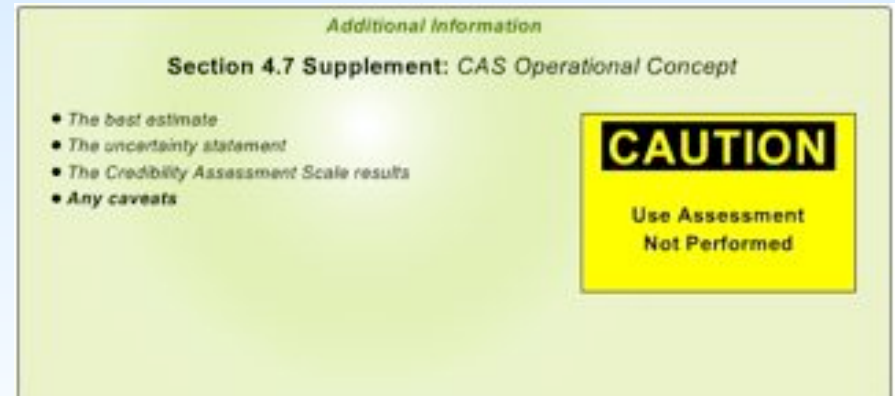
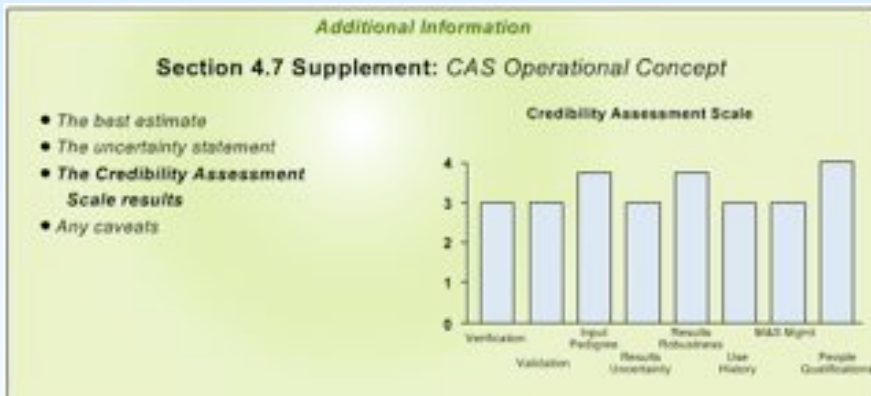
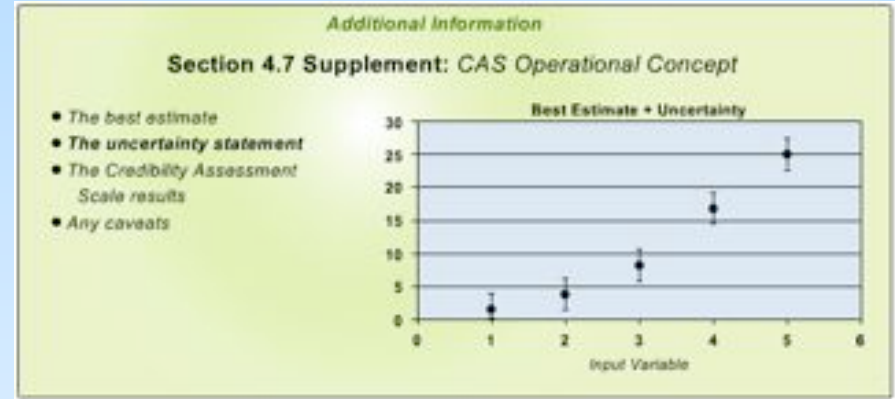
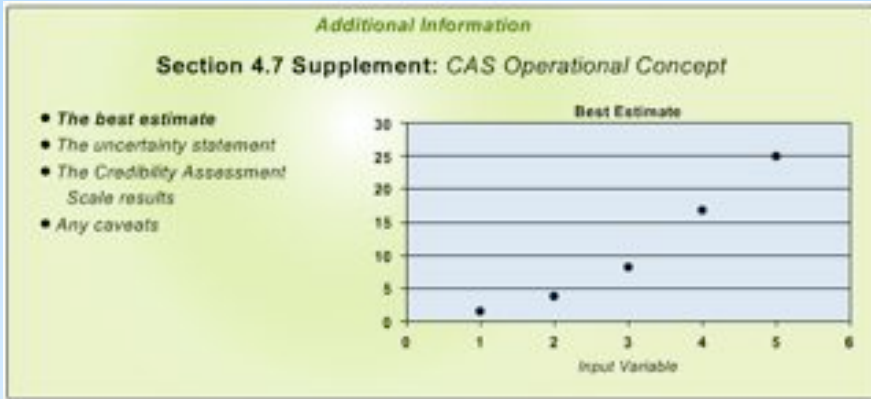


4.8 Reporting Results to Decision Makers

	Requirement
4.8.1	Report explicit caveats for any of 6 critical areas
4.8.2	Report uncertainty estimate (and basis for this estimate)
4.8.3	Report evaluation of the results on the Scale



Information Reported to Decision-maker





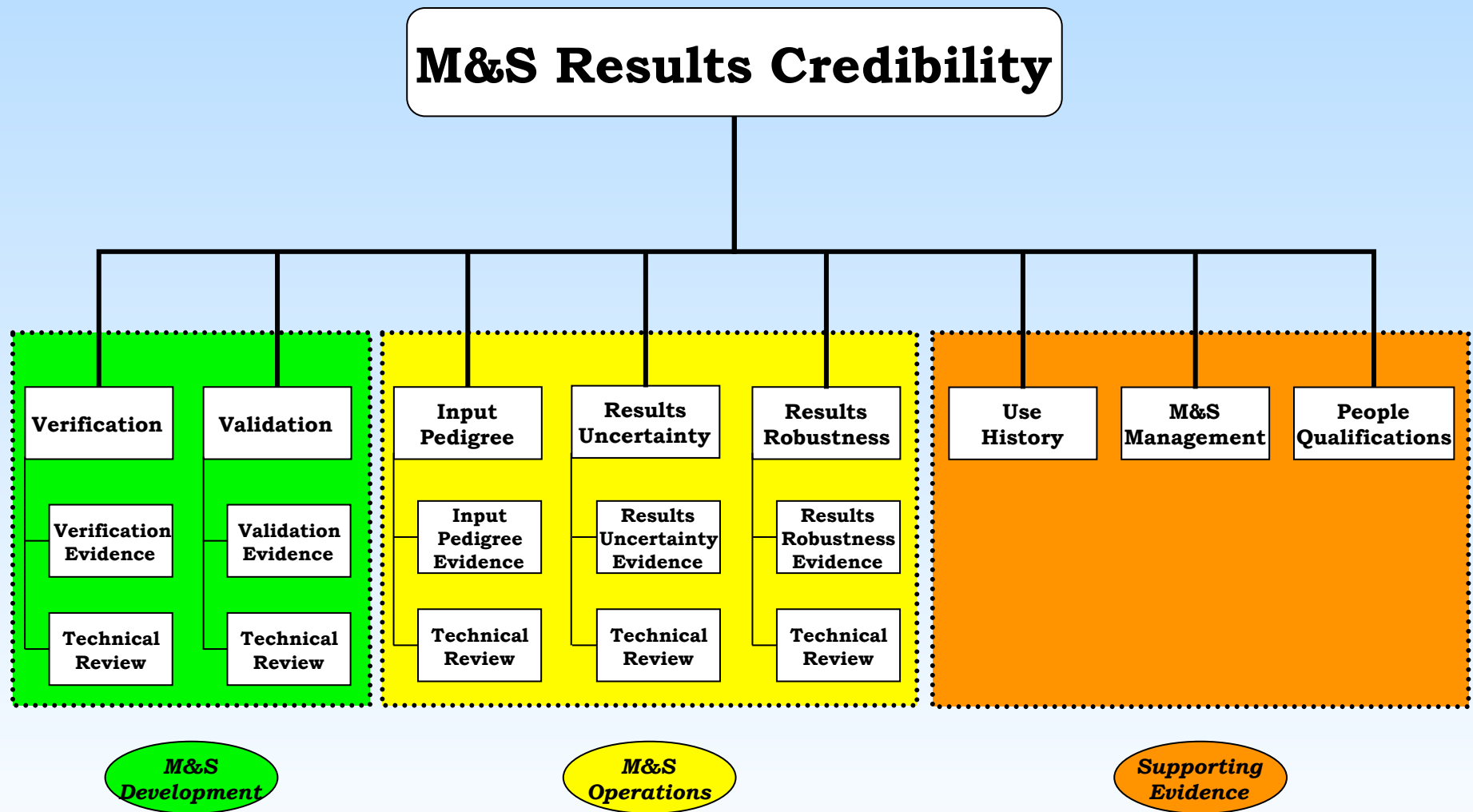
Required Uncertainty Report

- **Req. 4.8.2 – Reports to decision makers of M&S results shall include an estimate of their uncertainty and a description of any processes used to obtain this estimate as defined in Req. 4.4.7 and Req. 4.4.8.**

- **a. Reported uncertainty estimates shall include one of the following:**
 - (1) A quantitative estimate of the uncertainty in the M&S results, or
 - (2) A qualitative estimate of the uncertainty in the M&S results, or
 - (3) A clear statement that no quantitative or qualitative estimate of uncertainty is available



Credibility Assessment Scale Structure





Role of the Credibility Assessment Scale

- **The Scale just frames the discussion of credibility in the same way that a risk matrix frames the discussion of risk**
- **[From introductory text of Sect. 4.7]**
 - “Just to emphasize this fundamental point, the credibility assessment scale does not purport to measure credibility; rather, it assesses the M&S results, and the rigor of the processes used to produce them, against key factors that affect the credibility judgment.”
 - “The fundamental premise of this approach is that as a general rule, the more rigorous the key processes used for generating the M&S results, the greater the credibility of the M&S results, all else (including the estimated uncertainty) being equal.”



Deployment Experiences



Initial Center Objections

- **In 2008 the 10 NASA Centers were asked whether they concurred or non-concurred with adoption of the proposed NASA-STD-7009**
 - 5 concurred
 - 5 non-concurred
- **Principal objections**
 - Scope is unclear
 - No scale should be included
 - Documentation burden is heavy
 - Have guidance not requirements



Issuance Decision

- **In May 2008 the issues were discussed at a meeting of the NASA Engineering Management Board**
- **The NASA Chief Engineer and the NASA Chief of Safety and Mission Assurance (2 of the 3 signers of the Certificate of Flight Readiness for NASA launches) spoke strongly in favor of having a standard**
- **Responses to objections**
 - The Risk Assessment Matrix was added
 - Chief Engineer was adamant on inclusion of the scale
 - Documentation burden is only heavy for those with immature M&S development processes
 - Having only guidance would be unresponsive to the drivers
- **The M&S Standard was issued, but not as a “mandatory standard” for the time being**



2008 Post-Issuance Events

- **Interim M&S Standard levied on Lockheed-Martin's Orion contract**
- **Ares I-X CDR, Pt. 2 RFA on M&S Standard (July 2008)**
- **Diaz Action #4 Officially Closed (August 2008)**
- **JPL Implementation Plan (Sept. 2008)**
- **Training Module released (October 2008)**
- **NESC Final Report approved (November 2008)**
- **Lockheed-Martin assessment of impact of (permanent) M&S Standard**



2009 Post-Issuance Events

- **Lockheed-Martin assessment of impact of (permanent) M&S Standard**
- **NESC Systems Analysis Team (February 2009)**
- **Ares I Tailoring Plan (March 2009)**
- **Aerospace Safety Advisory Panel comments (Fall 2008, Fall 2009)**
- **Mission Assurance Improvement Workshop (MIAW) [NRO, SMC, NASA, MDA, Aerospace Corp., industry] initiates development of a guidance document for a Program Modeling and Simulation Plan (Fall 2009)**
- **NASA Engineering and Safety Center (NESC) initiates development of a Recommended Practices Guide for M&S Standard (January 2010)**



Reception of the CAS

- **The Credibility Assessment Scale totally dominates any discussion of the M&S Standard**
 - Some object to any kind of scale
 - Some prefer some other approach, e.g., a checklist
 - Some object to specific factors in the CAS
 - Some find the CAS too vague
 - Some alter the CAS for their own use
- **But, senior NASA managers are adamant that NASA have a scale and that it be uniform across the Agency**



Documentation Burden Observations

- **NASA JSC requested Lockheed-Martin to estimate the additional cost imposed by compliance with the M&S Standard**
 - Lockheed-Martin estimated that the cost to its M&S projects would be an extra 1%
 - Lockheed-Martin is CMMI Level 5
- **NASA centers/projects are quite willing to impose the NASA M&S Standard on its contractors**
- **NASA centers are very reluctant to comply with the NASA M&S Standard on its in-house work**



Ares I-X M&S Scope Assessment



- A - GN&C
- B - Structures
- C - Thermal
- D - Trajectory
- E - Aerodynamics

- F - OML
- G - Mass Properties
- H - Vibro-Acoustics
- I - System ProE

5: Controlling			H	A, B
4: Significant			E, F	
3: Moderate		D	C, G	
2: Minor		I		
1: Negligible				
	IV Negligible	III Moderate	II Critical	I Catastrophic



Training Module — Examples

Dr. Mike Ryschkewitsch: NASA Chief Engineer



4.2 Models

Req. 4.2.5 – Shall document the limits of operation of models.

Additional Information

knowledge of operations is captured in the user interface	test verification and validation, certification	documentation, configuration management, and quality assurance	training or certification requirements	test management, maintenance, and obsolescence	user feedback when results appear unrealistic	method to assess the credibility of the M&S
G		Y				

Traceability Matrix

The term "limits of operation" is defined as "The boundary of the set of parameters for which an M&S result is acceptable based on the program/project-required outcomes of verification, validation, and uncertainty quantification."



Additional Information

This section contains information of a general or explanatory nature that may be helpful but is not mandatory.

ARES 1-X M&S Risk Assessment Matrix

Color Coding

"Red" category are within scope

"Yellow" category are at the project discretion

"Green" category are not within scope

5: Controlling	D	H	A, B
4: Significant	I	E, F	
3: Moderate		C, G	
2: Minor			
1: Negligible			
	IV: Negligible	III: Moderate	II: Critical I: Catastrophic

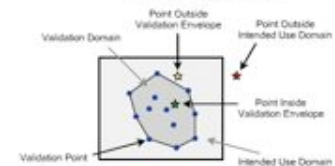
- A - GN&C
- B - Structures
- C - Thermal
- D - Trajectory
- E - Aerodynamics

- F - OML
- G - Mass Properties
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- I - System ProE

Additional Information

This section contains information of a general or explanatory nature that may be helpful but is not mandatory.

Limits of Operation



This diagram illustrates limits of operation from the perspective of validation for the case of a model with two parameters. The dark blue circles illustrate the points at which validation has been performed. The domain of validation is denoted by the dark gray region bounded by the envelope of the validation points. The light gray rectangle indicates the domain of intended use. The three stars represent points in the input parameter space at which simulations were performed. In this example both the green star and the yellow star correspond to simulations within the limits of operation, whereas the red star denotes a point outside the limits of operation of the model.

In this example the limits of operation are broader than the domain of validation. According to Requirement 4.2.5, the limits of operation must be documented, including the rationale for the specific choice of these limits in terms of the validation results (per Requirement 4.4.4), the verification results (per Requirement 4.4.1) and the uncertainty quantification results (per Requirement 4.4.8); furthermore, the documentation should include the key assumptions made in determining these limits (see Recommendation (b) of Section 4.8).



JPL Comments on the M&S Standard

- **The NASA Model and Simulation Standard is heavily focused on documentation requirements**
 - Developing a Modeling/Simulation Plan (Rqmt 4.1.4) is one of the best recommendations noted in the standard
 - Most JPL projects have already been developing these plans, even though it is not formally required on the JPL Gate Product List
 - Documentation associated with input parameters was an obvious factor to include. But, it needs further consideration as many comments from JPL and other NASA Centers have indicated that with 1000's of parameters this is a challenging task
- **Credibility Scale**
 - The 8 factors noted in the credibility scale, provide excellent coverage for evaluating a simulation. However, there is a strong desire at JPL to review numerical results over the mapping to the qualitative levels



Model Review Certification Record (MRCR) [JPL's "Checklist"]

Model Review Certification Record (MRCR)

Project:		Delivery ID:		Model Configuration ID:			MRCR Number:					
Assembly / Subsystem / System Scenario		<input type="checkbox"/> Preliminary Design <input type="checkbox"/> Final Design (CDR) <input type="checkbox"/> System Verification (II&T)		Model Cognizant Engineer			HW CogE or System Engineer		Date			
CHECK APPLICABLE ANSWER. IF "N" OR "N/A" PROVIDE EXPLANATION				YES	NO	N/A	DATA ATTACHMENTS					
							Reference verified repository location.					
Requirements							Model Planning Documentation (requirements, stakeholders, validation plans) (items 1, 2, 9)					
1. Are model requirements complete and sufficient for this point in the life cycle?												
Stakeholders & Inputs							All Model input documentation - List controlled documents, attach all others. (items 3, 4)					
2. Are user stakeholders, their roles and responsibilities documented? Have they met responsibilities given for this stage in the lifecycle?							Design & review records (items 6,7)					
3. Have all known necessary inputs been identified. Have all planned inputs been received and placed under configuration management?							Model validation test results or other validation records (items 10, 11)					
4. Final Maturity & later: Are relevant design documents identified (i.e. MICD, IICD, Phasing ...), complete, approved, released and under change control?							Device as-built records (i.e. calibration) - trace to EIDP					
5. For all inputs, but particularly preliminary documentation, are caveats and qualifications documented?							Documentation of known model deficiencies, caveats and qualifications. (items 5, 8, 12, 14)					
Design							REMARKS					
6. Have all effects been identified and analyzed for relevance to this model? Is this list, the related analyses and decisions documented?												
7. Has the model been reviewed by the function provider and all identified user stakeholders to assure it meets its objectives, is complete, is using all inputs correctly and has correctly modeled all relevant attributes?												
8. All Maturity Levels: Are all known design shortcomings identified and adequately documented?												
Validation							APPROVALS (Bold are required; Model Lead may tailor others.)					
9. Preliminary Maturity: Has final validation approach been outlined? Do test plans adequately support model validation?							Model Lead		Date	Model Co-Lead		Date
10. Maturity Levels prior to System Verification: Are model validation records complete?												
11. Sys. Verif. Maturity: Is model validation complete and documented? Are validation test procedures, results and analyses recorded?												
12. All Maturity Levels: Are all model known validation shortcomings identified and adequately documented?												
Delivery & Closeout							Systems Engineering		Date	Function Provider		Date
13. Is planned model delivery documentation complete? Are test cases for each user stakeholder application and platform documented?							User Stakeholder		Date	User Stakeholder		Date
14. Are there any model caveats or qualifications that are not addressed in earlier questions? If so document and attach.							User Stakeholder		Date	User Stakeholder		Date
15. Has there been a previous MRCR for this model? If yes, provide a description of any differences.							User Stakeholder		Date	User Stakeholder		Date
16. Is this model ready for its intended use?												



Uncertainty Quantification Concern

- **The requirement to present an uncertainty statement is a source of much concern amongst NASA centers and contractors**
- **Lockheed-Martin's evaluation for JSC included the concern that they did not see how to present an uncertainty statement in the context of their current processes**
- **However, the standard permits one to state that no uncertainty estimate is available**
- **Of course, engineers are most reluctant to do this**
- **Getting a score above 0 on the Results Uncertainty factor of the CAS requires a non-trivial uncertainty statement**
- **NASA needs to provide guidance (and tools) to its engineers for uncertainty quantification of M&S results**



Recommendation R-2: Coordination (in NESC Final Report on M&S Standard)

- **NASA should coordinate with other organizations and professional societies to further mature the M&S Standard.**
 - The development and operation of M&S, the analysis and presentation of M&S results, the proper training of M&S practitioners, the identification of recommended practices, and the need for assessing and conveying the credibility of M&S results to decision makers are not unique to NASA. These aspects of the M&S process are common to many other organizations. NASA should participate in activities directed towards standards that serve a broader M&S community.
 - *NPD 8070.6B: Support the development of, formally adopt, and use domestic and international voluntary consensus standards, as defined and required by Public Law 104-113 and by OMB Circular A-119, in preference to Government standards to accomplish NASA's mission wherever practical, technically appropriate, and consistent with laws and regulations.*
 - *There is broad interest in the M&S Standard outside NASA, e.g., ASME, SISO, DoD*
 - *Similar scales have been developed by (parts of) DoD (MSCO) and DoE (Sandia)*



Recommendation R-8: RPGs (in NESC Final Report on M&S Standard)

- **NASA should sponsor the development of Recommended Practices Guides along disciplinary lines. This responsibility might best be delegated to the NASA Technical Fellows.**
 - While some M&S have well established and documented procedures, many others do not. Furthermore, existing guidelines may not cover new applications of the M&S. For example, models often require calibration, or numerical parameters need to be tuned for new problems. Knowledge of these procedures, calibrations, and tunings often resides in a small subset of workers. NASA should identify M&S domains that need Recommended Practice Guides and coordinate with professional societies, academia, commercial and international partners to develop them.
 - ***This recommendation is the key to successful deployment of the NASA M&S Standard***



External Consultants

- **Aegis**

- Alleen Bray
- Lisa Caine
- Bobby Hartway
- Danny Thomas
- Bill Waite

- **QTEC**

- Audrey Milroy

- **“DMSO”**

- Scott Harmon
- Simone Youngblood

- **Sandia,
Albuquerque**

- Bill Oberkamp
- Dave Peercy
- Marty Pilch
- Tim Trucano

- **Academia**

- Osman Balci (VPI&SU)
- Sankharan Mahadevan (Vanderbilt)
- David Nicol (U. Illinois)



What's Next?

- **In the near term, use of the M&S Standard is optional**
- **Evaluations of the M&S Standard are in progress**
- **A Recommended Practices Guide is under development**
- **The M&S Standard will be revisited by a future team within 5 years (as are all NASA standards)—**
 - probably much sooner than 5 years
 - likely immediately following the RPG
- **A decision will eventually be made on whether to include the M&S Standard on the list of mandatory NASA standards**



Backup



References



References 1

- **CAIB Report:**
 - <http://caib.nasa.gov/>
- **Diaz Report:**
 - *No longer on-line*
- **Stafford-Covey Report:**
 - http://www.nasa.gov/pdf/125343main_RTFTF_final_081705.pdf
- **NASA-STD-7009:**
 - http://standards.nasa.gov/released/NASA/NASA_STD_7009_APPROVED_2008_07_11.pdf

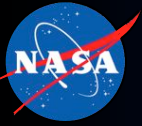


References 2

- **Online Training Module (inside NASA firewall)**
 - <http://standards.nasa.gov/Training/NASA-STD-7009/index.html>
- **NESC Final Report (RP-08-118_06-005)**
 - <http://www.nasa.gov/offices/nesc/reports/index.html>
- **ASAB Report**
 - http://www.hq.nasa.gov/office/oer/asap/documents/2008_ASAP_Annual_Report.pdf
- **2009 Aerospace Sciences Papers**
 - Blattnig, S.R. et al, “NASA Standard for Models and Simulations: Philosophy and Requirements Overview,” AIAA Paper 2009-1010,
 - Babula, M. et al, “NASA Standard for Models and Simulations: Credibility Assessment Scale,” AIAA Paper 2009-1011
- **SIW Spring 2008 Paper**
 - Bertch, W.J., Zang, T.A. and Steele, M.J., “Development of NASA’s Models and Simulations Standard”, SISO 2008 Spring Simulation Interoperability Workshop [SIWZIE Award]
- **SIW Spring 2009 JPL Paper**
 - Bertch, W.J., “Jet Propulsion Laboratory (JPL) Approach to the NASA’s Standard for Models and Simulations and VV&A,” SISO 2009 Spring Simulation Interoperability Workshop

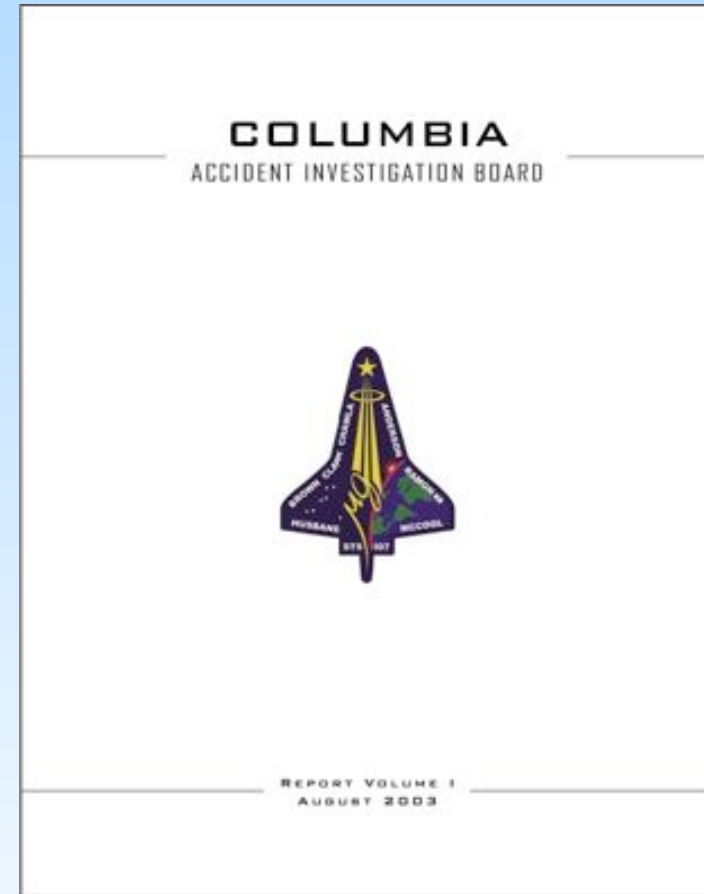


Need



CAIB Recommendation R3.8-2

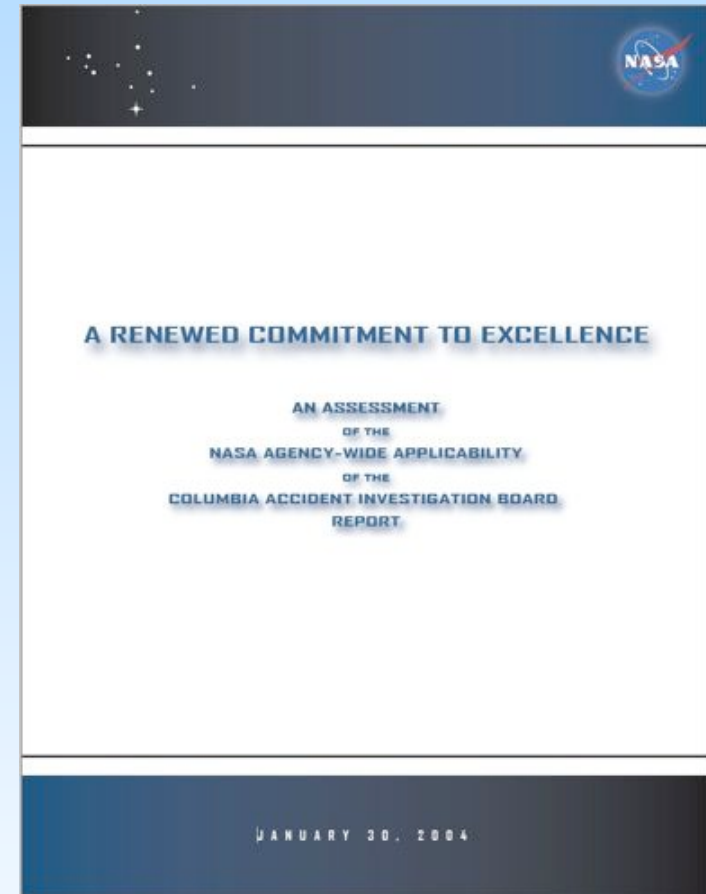
- **Develop, validate, and maintain physics-based computer models to evaluate Thermal Protection System damage from debris impacts. These tools should provide realistic and timely estimates of any impact damage from possible debris from any source that may ultimately impact the Orbiter. Establish impact damage thresholds that trigger responsive corrective action, such as on-orbit inspection and repair, when indicated**





Diaz Team Conclusion

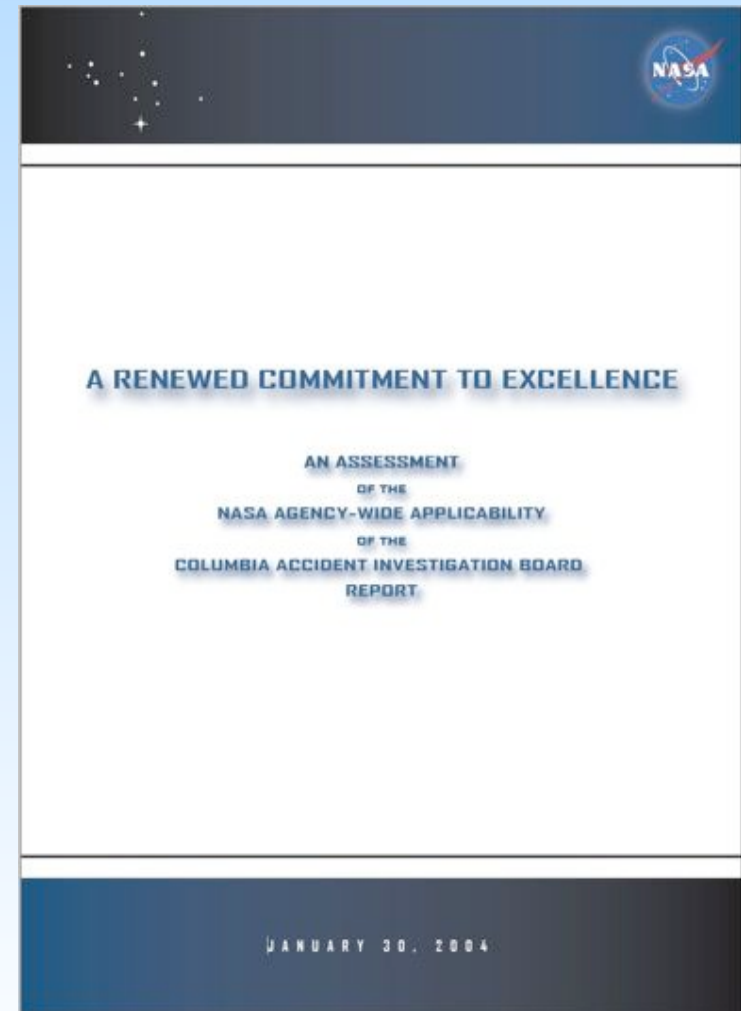
- **All programs should produce, maintain, and validate models to assess the state of their systems and components. These models should be continually updated and validated against experimental and operational data to determine appropriate courses of action and repair. The value of the models should be assessed with respect to their ability to support decision making in a timely way so as not to lead the decision maker to a conflict between costly action versus effective action in the interest of safety or mission success.**





Diaz Action #4 Summary

- **Develop a standard for the development, documentation, and operation of models and simulations:**
 - documentation, configuration management, and quality assurance
 - verification and validation, operational data and trending
 - tool management, maintenance, and obsolescence
 - training requirements
 - best practices for user interfaces
 - user feedback when results appear unrealistic





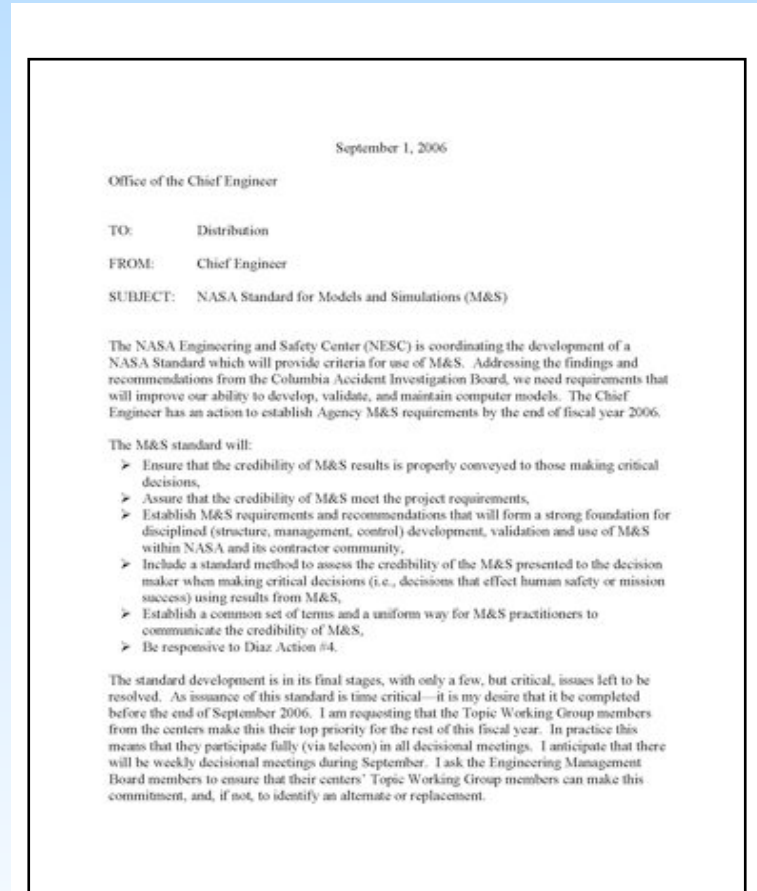
Diaz Action #4 Details

- **Develop a standard for the development, documentation, and operation of models and simulations**
 - Identify **best practices** to ensure that knowledge of operations is captured in the user interfaces (e.g. users are not able to enter parameters that are out of bounds)
 - Develop process for tool **verification and validation, certification, reverification, revalidation, and recertification** based on operational data and trending
 - Develop standard for **documentation, configuration management, and quality assurance**
 - Identify any **training or certification requirements** to ensure proper operational capabilities
 - Provide a plan for **tool management, maintenance, and obsolescence** consistent with modeling/ simulation environments and the aging or changing of the modeled platform or system
 - Develop a **process for user feedback** when results appear unrealistic or defy explanation



NASA Chief Engineer Memo

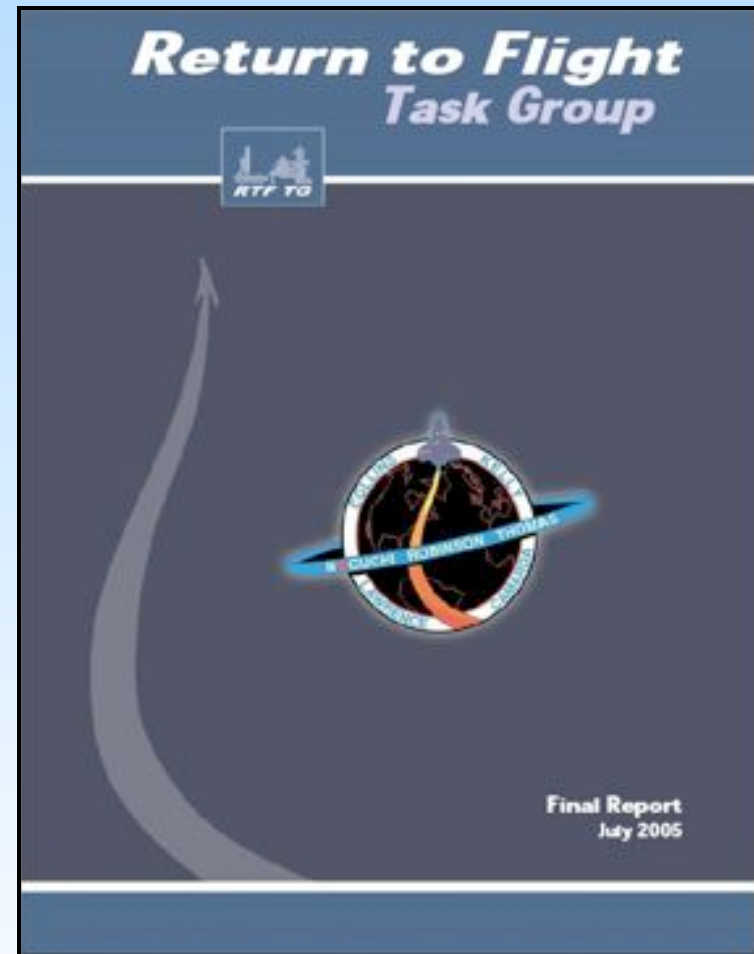
- **The M&S standard will:**
 - Ensure that the credibility of M&S results is properly conveyed to those making critical decisions,
 - Assure that the credibility of M&S meets the project requirements,
 - Establish M&S requirements and recommendations that will form a strong foundation for disciplined (structure, management, control) development, validation and use of M&S within NASA and its contractor community,
 - **Include a standard method to assess the credibility of the M&S presented to the decision maker when making critical decisions** (i.e., decisions that effect human safety or mission success) using results from M&S,
 - Establish a common set of terms and a uniform way for M&S practitioners to communicate the credibility of M&S,
 - Be responsive to Diaz Action #4.





Stafford-Covey Report

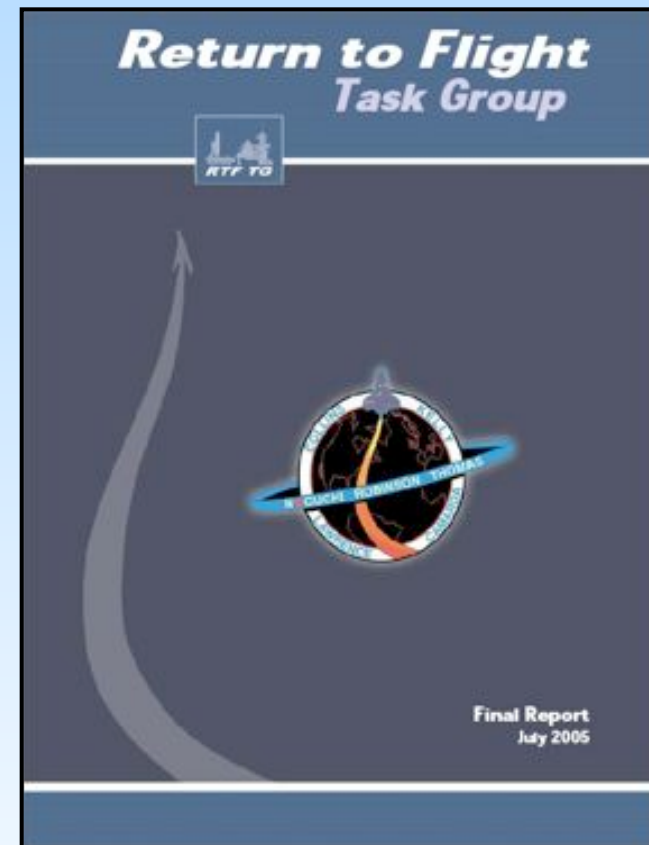
- **Employ formal development, verification and validation, and outside review plans**
- **Assumptions should be written down and consistently applied**
- **Sensitivity Analysis**
- **Careful Analysis of Uncertainty**





Stafford-Covey Annex A2 Quote

“The uncertainties in one model (or system) inherently feeds into and compounds the uncertainty in the second model (or system), and so on. It appears, however, that NASA largely designed these five classes of models without the attention to the interdependencies between the models necessary for a complete understanding of the end-to-end result. Understanding the characteristics of, and validating and verifying, one type of model without examining the implications for the end-to-end result is not sufficient. ... But, as the Columbia accident showed, in a high risk environment that involves many unknowns like human space flight, **experience and instinct are poor substitutes for careful analysis of uncertainty.**”

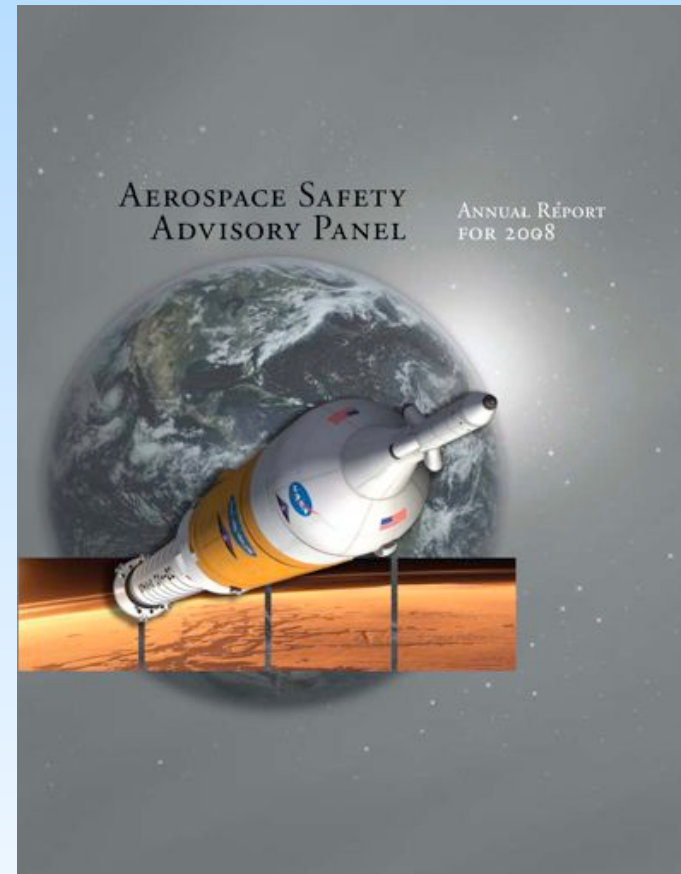




Aerospace Safety Advisory Panel

· Rec #: 2008-02-03 Modeling and Simulation.

- Description of Recommendation: On modeling and simulation, a NASA-wide matrix should be created to color-classify models as green, yellow, and red so that a statement of high confidence means the same thing from one NASA Center to another.
- Status: Open* (* Updates and ASAP monitoring are required)



http://www.hq.nasa.gov/office/oer/asap/documents/2008_ASAP_Annual_Report.pdf



ASAP Excerpts 1

- ***“The Chief Engineer is playing a central role in developing and implementing interim, test version, and consensus performance standards as well as using new modeling and simulation standards to establish a consistent basis for comparing and assessing the risks of applying simulation results (e.g., level of confidence; boundaries of regions in which the simulations are expected to, or do not, apply).”***
- ***“The Panel expressed satisfaction with the release of Document 7009 on Modeling and Simulation standards, the first mandatory [sic] NASA standard applicable to all simulations; that standard is now in beta testing. The Panel agreed the approach being taken would give program managers and chief engineers a consistent basis on which to compare and assess the risk of adopting results from simulations.”***



ASAP Excerpts 2

- ***“Mr. Frost praised the work done on modeling and simulation, saying it was among the best he had seen: if one were to make ‘life and death’ decisions based on models, it was well to know what level of confidence could be assigned to them. The modeling and simulation proposal called for the creation of a matrix that would classify models as ‘green,’ ‘yellow’ and ‘red.’ “***
- ***“Dr. McErlean said it ‘extremely important’ that common and universally accepted definitions be established as to what each matrix block meant; if an engineer at one center described a risk level as a ‘3,’ this should conjure a shared image with engineers elsewhere.”***



ASAP Members in 2008

- **Vice Admiral Joseph W. Dyer, USN (Ret.), Chair**
- **Dr. James P. Bagian**
- **Major General Charles F. Bolden, Jr.**
- **Deborah L. Grubbe, P.E.**
- **John C. Marshall**
- **John C. Frost**
- **Joyce A. McDevitt, P.E.**
- **Dr. Donald P. McErlean**
- **Brock R. “Randy” Stone**



Scope



NASA-STD-7009 Covers

- **Development and operation (or execution) of M&S as well as the processes of analysis and presentation of the results from the M&S.**



NASA-STD-7009 Does Not Cover

- **Controls Software: Software that implements algorithms for controlling systems and subsystems**
- **Display Software: Software that implements algorithms for user interaction with control systems.**
- **M&S that are embedded in control software, emulation software, and stimulation environments**
- **STD 7009 does not cover these because:**
 - Extensive guidance on such software already exists, e.g. in NPR 7150.2, and NASA STD-8719.13.



M&S Risk Assessment Matrix

5: Controlling	G	Y	R	R
4: Significant	G	Y	R	R
3: Moderate	G	Y	Y	R
2: Minor	G	G	Y	Y
1: Negligible	G	G	G	G
	IV	III	II	I
	Negligible	Moderate	Critical	Catastrophic

- **Decision Consequence - Consequence classifications assess the impact of a decision that proves incorrect.**
 - Class I - Catastrophic
 - Class II - Critical
 - Class III - Moderate
 - Class IV – Negligible
- **M&S Results Influence - Influence estimates the degree to which M&S results influence program/project engineering decisions.**
 - Influence 1 - Negligible
 - Influence 2 - Minor
 - Influence 3 - Moderate
 - Influence 4 - Significant
 - Influence 5 - Controlling



Decision Consequence

- **Catastrophic.** A poor decision may result in death or permanently disabling injury, facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission; schedule slippage causing launch window to be missed; cost overrun greater than 50 percent of planned cost; most (more than 75 percent) mission success criteria not met due to severe performance degradations.
- **Critical.** A poor decision may result in severe injury or occupational illness, or major property damage to facilities, systems, equipment, or flight hardware; schedule slippage causing launch date to be missed; cost overrun between 15 percent and not exceeding 50 percent of planned; many (between 25 percent and 75 percent) mission success criteria not met due to substantial performance degradations.
- **Moderate.** A poor decision may result in minor injury or occupational illness, or minor property damage to facilities, systems, equipment, or flight hardware; internal schedule slip that does not impact launch date; cost overrun between 2 percent and not exceeding 15 percent of planned cost; a few (up to 25 percent) mission success criteria not met due to performance degradations.
- **Negligible.** A poor decision may result in the need for minor first aid treatment but would not adversely affect personal safety or health; damage to facilities, equipment, or flight hardware more than normal wear and tear level; internal schedule slip that does not impact internal development milestones; cost overrun less than 2 percent of planned cost; all mission success criteria met, with at worst minor performance degradations.



M&S Results Influence

- **Negligible.** Results from the M&S are a negligible factor in engineering decisions. This includes research on M&S methods, and M&S used in research projects that have no direct bearing on program/project decisions (for NASA missions).
- **Minor.** M&S results are only a minor factor in any program/project decisions. Ample flight or test data for the real system in the real environment are available, and M&S results are used just as supplementary information.
- **Moderate.** M&S results are at most a moderate factor in any program/project decisions. Limited flight or test data for the real system in the real environment are available, but ample flight or test data for similar systems in similar environments are available.
- **Significant.** M&S results are a significant factor in some program/project decisions, but not the sole factor for any program/project decisions. Ample flight or test data for similar systems in similar environments are available.
- **Controlling.** M&S results are the controlling factor in some program/project decisions. Neither flight nor test data are available for essential aspects of the system and/or the environment.



Requirements



Project and TA Responsibilities

Responsibility
Jointly identify the responsible parties for the requirements
Jointly identify the level of documentation required
Jointly identify the critical decisions to be made with M&S
Jointly determine which M&S are in scope based on a risk assessment
TA ensures objectives & requirements for the M&S are appropriately defined



4.1 Programmatic Requirements

	Requirement
4.1.1	Document the Scope risk assessment
4.1.2	Identify & document which M&S are in scope
4.1.3	Define objectives and requirements for M&S products
4.1.4	Develop plan for acquisition, development, operation, and maintenance of M&S used for critical decisions
4.1.5	<i>Document technical reviews</i>
4.1.6	Document M&S waiver process
4.1.7	Document M&S Management evidence

Requirements in bold in 4.1–4.8 are to be interpreted as meaning that the activity in question is not required per se, but that whatever was done is to be documented, and if nothing was done a clear statement to that effect is to be documented.



4.2 Models

	Requirement
4.2.1	Document assumptions and abstractions of the conceptual model
4.2.2	Document basic structure and mathematics of model
4.2.3	Document data sets and supporting software for model development & input
4.2.4	Document units and reference frames
4.2.5	Document limits of operation of models
4.2.6	<i>Document uncertainty in model-development data</i>
4.2.7	Document guidance on proper use of model
4.2.8	<i>Document parameter calibrations</i>
4.2.9	Document updates of the model
4.2.10	Document obsolescence criteria
4.2.11	Provide a feedback for unusual results
4.2.12	Maintain models & documentation in configuration management system
4.2.13	Maintain data sets and supporting software configuration management system



4.3 Simulations and Analyses

	Requirement
4.3.1	Ensure simulations are not used outside limits or provide warning
4.3.2	Document and explain observed execution warning and error messages
4.3.3	Document which models were used
4.3.4	Document versions of M&S
4.3.5	Document data used as input and it's pedigree
4.3.6	<i>Document any unique computational requirements</i>
4.3.7	Document processes for conducting analysis, simulation, and uncertainty quantification
4.3.8	Document the use history of M&S
4.3.9	Document the use assessment
4.3.10	Document rationale for setup and execution



4.4 Verification, Validation, and Uncertainty Quantification

	Requirement
4.4.1	<i>Document verification techniques & domain of verification</i>
4.4.2	<i>Document numerical error estimates</i>
4.4.3	Document verification status
4.4.4	<i>Document validation techniques & domain of validation</i>
4.4.5	<i>Document validation metrics, referents and data sets</i>
4.4.6	<i>Document validation studies and results</i>
4.4.7	<i>Document uncertainty quantification processes</i>
4.4.8	<i>Document quantified uncertainties</i>
4.4.9	<i>Document sensitivity analyses</i>



4.5 Development and Use of Recommended Practices

	Requirement
4.5.1	Identify existing Recommended Practices that apply



4.6 Training

	Requirement
4.6.1	Determine depth of required training
4.6.2	Document training topics, training process & training verification
4.6.3	Determine qualifications of developers, operators & analysts



4.7 Assessing Credibility

	Requirement
4.7.1	Assess credibility of results using the 8 factors in the Scale
4.7.2	Justify and document the credibility assessment
4.7.3	Perform roll-up to an overall score on the Scale



4.8 Reporting Results to Decision Makers

	Requirement
4.8.1	Report explicit caveats for any of 6 critical areas
4.8.2	Report uncertainty estimate (and basis for this estimate)
4.8.3	Report evaluation of the results on the Scale



Credibility Assessment Scale



Considerations for the CAS

- **Does it cover the key issues from CAIB/Diaz/Stafford-Covey?**
- **What did the decision-makers whom the TWG interviewed consider important?**
- **The results on the CAS should be as independent as possible from project requirements to enable a “common language” for decision makers across all projects**



Perspectives

- **The Scale is meant to facilitate the discussion of M&S credibility, not to provide a cookbook answer**
- **The Scale is meant to be a uniform, NASA-wide measure of rigor and not a relative measure, i.e., viz a viz specific project requirements**
 - There is one exception to this—the “favorable agreement” criteria



Summary of Scale

Level	Verification*	Validation*	Input Pedigree*	Results Uncertainty*	Results Robustness*	Use History	M&S Management	People Qualifications
4	Numerical errors small for all important features	Results agree with real-world data	Input data agree with real-world data	Non-deterministic & numerical analysis	Sensitivity known for most parameters; key sensitivities identified	De facto standard	Continual process improvement	Extensive experience in and use of recommended practices for this particular M&S
3	Formal numerical error estimation	Results agree with experimental data for problems of interest	Input data agree with experimental data for problems of interest	Non-deterministic analysis	Sensitivity known for many parameters	Previous predictions were later validated by mission data	Predictable process	Advanced degree or extensive M&S experience, and recommended practice knowledge
2	Unit & regression testing of key code features	Results agree with experimental data or other M&S on unit problems	Input data traceable to formal documentation	Deterministic analysis or expert opinion	Sensitivity known for a few parameters	Used before for critical decisions	Established process	Formal M&S training and experience, and recommended practice training
1	Conceptual & mathematical models verified	Conceptual and mathematical models agree with simple referents	Input data traceable to informal documentation	Qualitative estimates	Qualitative estimates	Passes simple tests	Managed process	Engineering or science degree
0	Insufficient evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence

*This factor has a Technical Review subfactor

NASA M&S Standard



M&S Development Level Defns

Level	Verification Evidence	Validation Evidence
4	Reliable error estimation methods are used to quantitatively assess numerical errors. These estimates show that the errors are small from test suites, which exercise all important algorithms, all important features and capabilities, and all important couplings (physics, modules, etc.) of the full computational model.	M&S results compare favorably for the real-world system at validation points by comparison of M&S results to an acceptable referent, which is measurements on the real-world system.
3	Some formal method is used to assess numerical errors associated with unit testing with significant coverage of the code.	M&S results compare favorably for problems of interest at validation points by comparison of M&S results to an acceptable referent, which is experimental measurements on problems of interest.
2	Favorable results from unit and regression testing of key features of the computational model.	M&S results compare favorably for unit problems at validation points by comparison of M&S results to an acceptable referent, which is either experimental measurements or higher-fidelity M&S results.
1	Favorable evidence of verification for conceptual and mathematical models.	M&S conceptual and mathematical models compare favorably with “general problem” and “textbook” referents.
0	Insufficient evidence.	Insufficient evidence.

- The project decides *a priori* what constitutes “favorable” agreement



M&S Operations Level Defns

Level	Input Pedigree Evidence	Results Uncertainty Evidence	Results Robustness Evidence
4	The input data compare favorably with measured data from the real-world system, or the input data came from M&S with a summary credibility rating above 3.5. Uncertainty associated with the input data is known.	Uncertainty estimates are quantitative and based upon nondeterministic and numerical analysis.	Sensitivity of the M&S results for the real-world system is quantitatively known for most of the variables and parameters, including all of the most sensitive variables and parameters.
3	The input data compare favorably with acceptable measured referent data from problems of interest, or the input data came from M&S with a summary credibility rating above 3.0. Uncertainty associated with the input data is known.	Uncertainty estimates are quantitative and based upon nondeterministic analysis.	Sensitivity of the M&S results for the real-world system is quantitatively known for many variables and parameters.
2	The input data is traceable to formal documentation, or the input data came from M&S with a summary credibility rating above 2.0.	Uncertainty estimates are quantitative and based upon deterministic analysis or expert opinion.	Sensitivity of the M&S results for the real-world system is quantitatively known for a few variables and parameters.
1	The input data is traceable to informal documentation, or the input data came from M&S with a summary credibility rating above 1.0.	Uncertainty estimates are qualitative.	Sensitivity of M&S results for the real-world system is estimated by analogy with the quantified sensitivity of similar problems of interest.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

- The project decides *a priori* what constitutes “favorable” agreement



Technical Review Level Defns

Level	Technical Review
4	Favorable external peer review accompanied by independent <i>factor evaluation</i> .
3	Favorable external peer review.
2	Favorable formal internal peer review.
1	Favorable informal internal peer review.
0	Insufficient evidence.

- **Technical Review is an important part of NASA process**
- **Technical Review can adjust the score by at most one level**



Supporting Evidence Level Defns

Level	Use History	M&S Management	People Qualifications
4	De facto standard.	Continuing Process Improvement: The M&S effort is using measurements on M&S processes to improve the repeatability of the M&S results.	Possesses an advanced engineering or science degree or extensive work experience in M&S, has extensive experience with the development and use of the M&S being reviewed, and has employed specific recommended practices relevant to current application.
3	Post-decision real-world events have been accurately represented in results (e.g., validated by mission data).	Predictable Process: The M&S effort is measuring repeatability of the M&S results generated by the M&S processes.	Possesses an advanced engineering or science degree or extensive work experience, has general M&S training, has specific experience with the M&S being reviewed, and has been trained on specific recommended practices relevant to the current application.
2	Used previously to perform analysis upon which critical decisions have been made.	Established Process: The M&S effort has established a documented process for M&S development and operations.	Possesses an engineering or science degree, has received formal training in formulation of M&S and generic training in recommended practices for M&S, and has developed M&S products.
1	Specific scenarios have been created to test application, or results compare favorably with outputs from other similar tools.	Managed Process: The M&S roles and responsibilities have been defined.	Possesses an engineering or science degree, has been introduced to the topic of M&S, and has been exposed to generic recommended practices in M&S.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

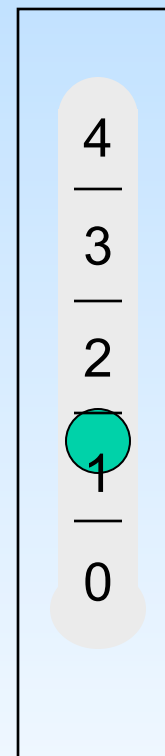
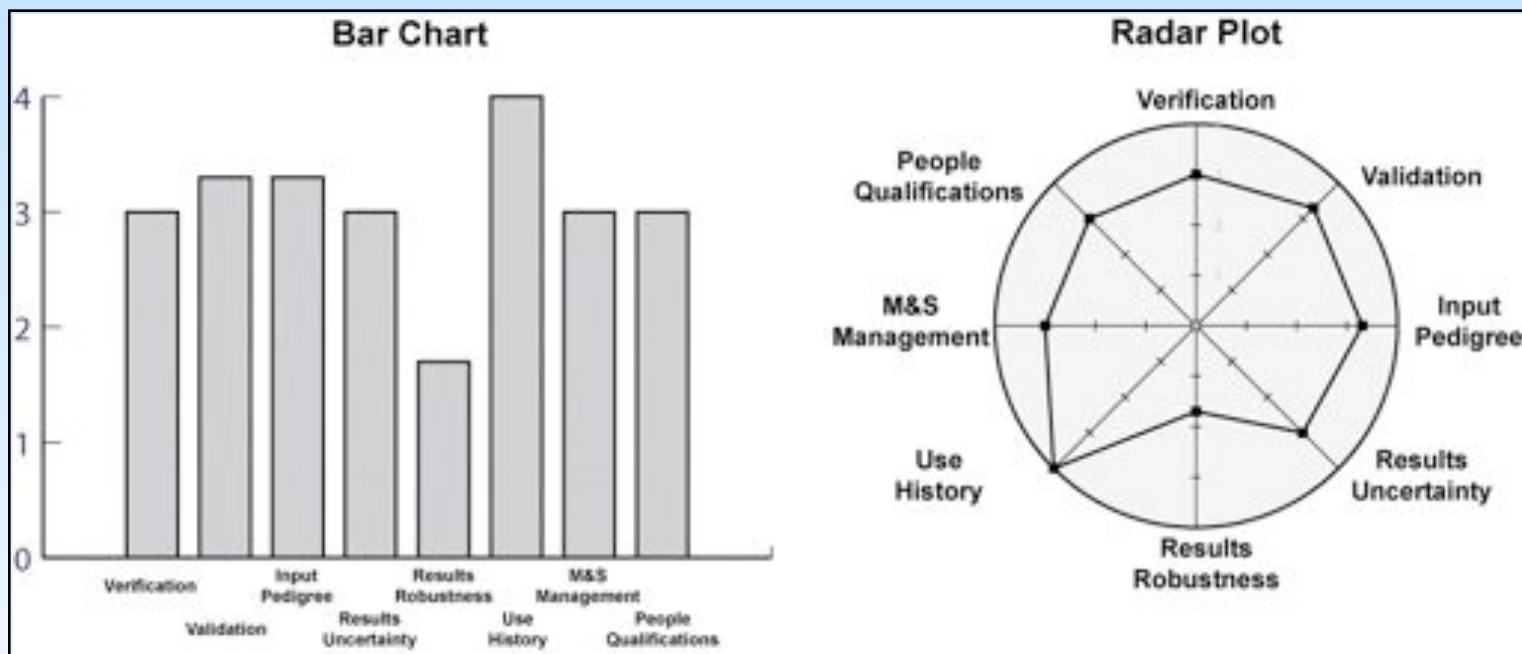
- **M&S Mgmt & People Qualification are driven by CAIB/Diaz**
- **Use History (“heritage”) is important to NASA decision makers**



Sample Report Formats

Individual Factor Scores

Overall Score

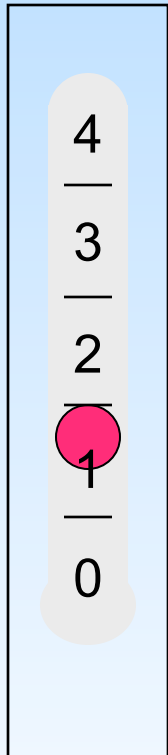
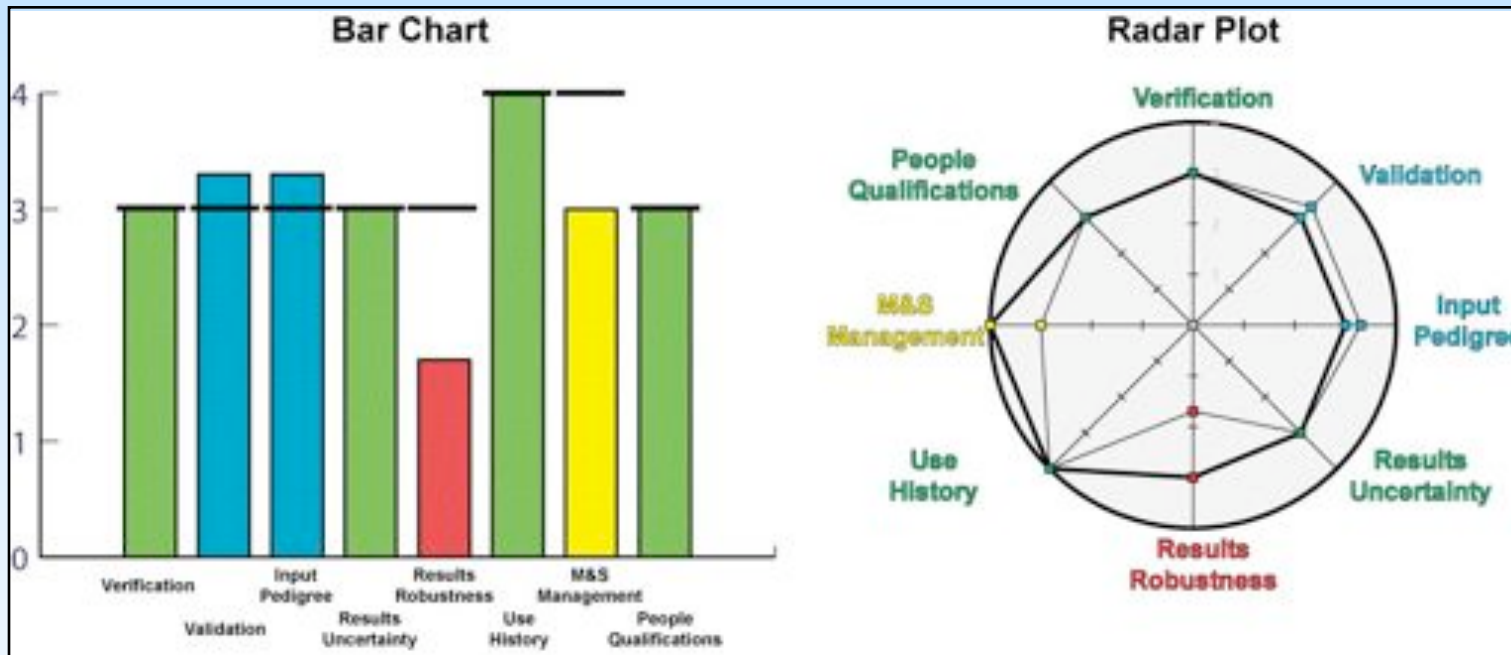




Comparison with Thresholds

Individual Factor Scores

Overall Score





Questions Answered by Various Scales

- **DMSO/MSCO VPMM**
 - How mature is your validation process?
 - *A narrow question (but answered extremely well)*
- **MSFC (CFD) SRL**
 - How ready are we to meet your program's CFD needs?
 - *The right question for negotiating program funding*
- **Sandia PCMM**
 - How rigorous can you be in ideal circumstances?
 - *The right question for a research organization or research program*
- **NASA CAS**
 - How rigorous were the processes used to produce today's results?
 - *The right question for M&S support for development and operations decisions*
- **JPL MRCR**
 - Were the requirements for the M&S on this project met?



Development Process

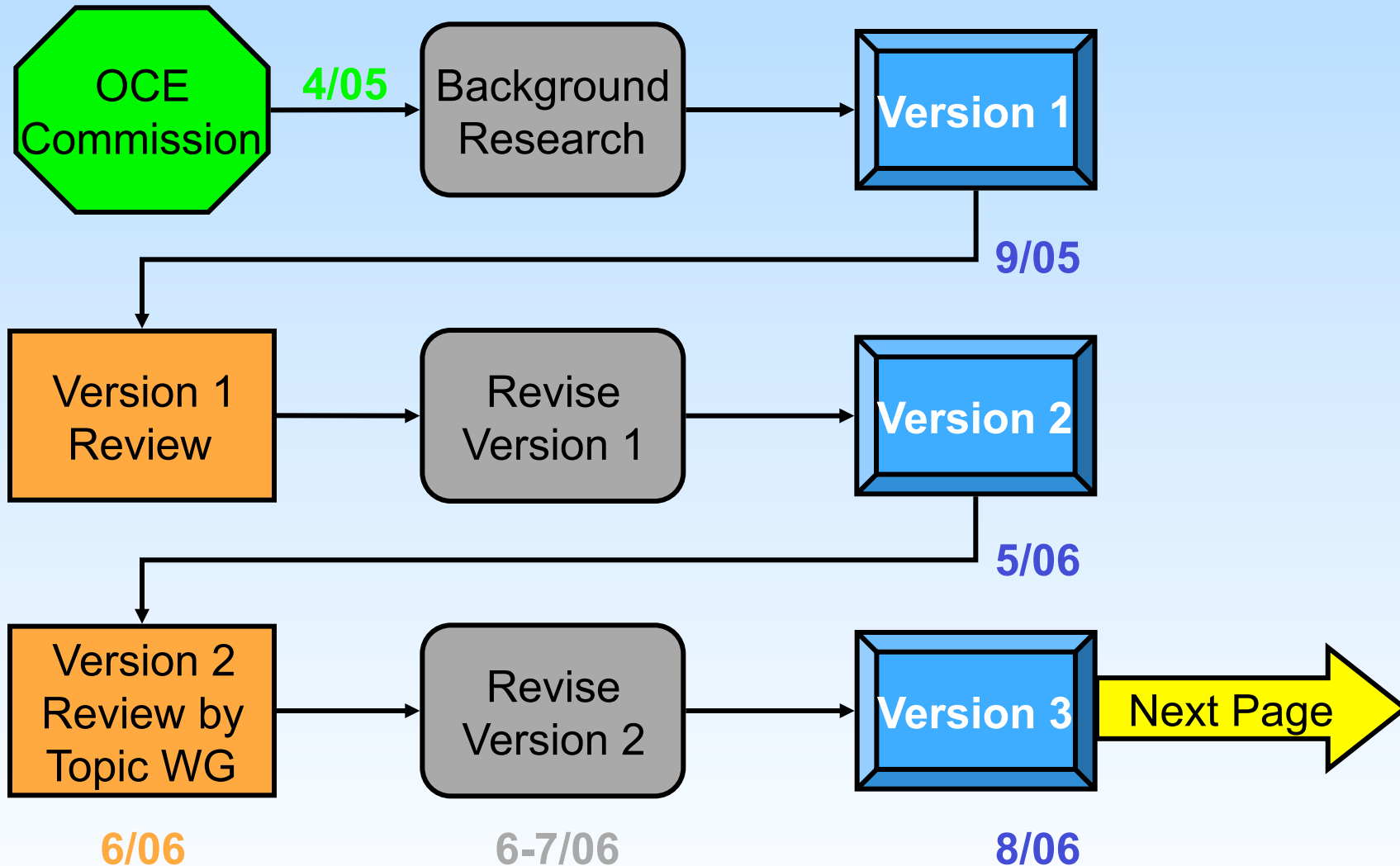


Participants in Development

- **Development Team [NASA LaRC]**
 - Developed initial 3 versions of Standard (2005-2006)
 - Provided recommendations to Topic Working Group on changes to Version 3
- **Topic Working Group (TWG) [all Centers but DFRC]**
 - Provided comments on Version 2
 - Modified Version 3 and approved Version 4 (Interim Standard)
 - Decided disposition of comments from Agency-wide review (2007)
 - Advised on disposition of comments from EMB review (2008)
- **Technical Standards Working Group (TSWG)**
 - Oversees formal input from all NASA centers for permanent standard
- **Engineering Management Board (EMB)**
 - Reviewed draft permanent standard
- **NASA Chief Engineer**
 - Issues standard

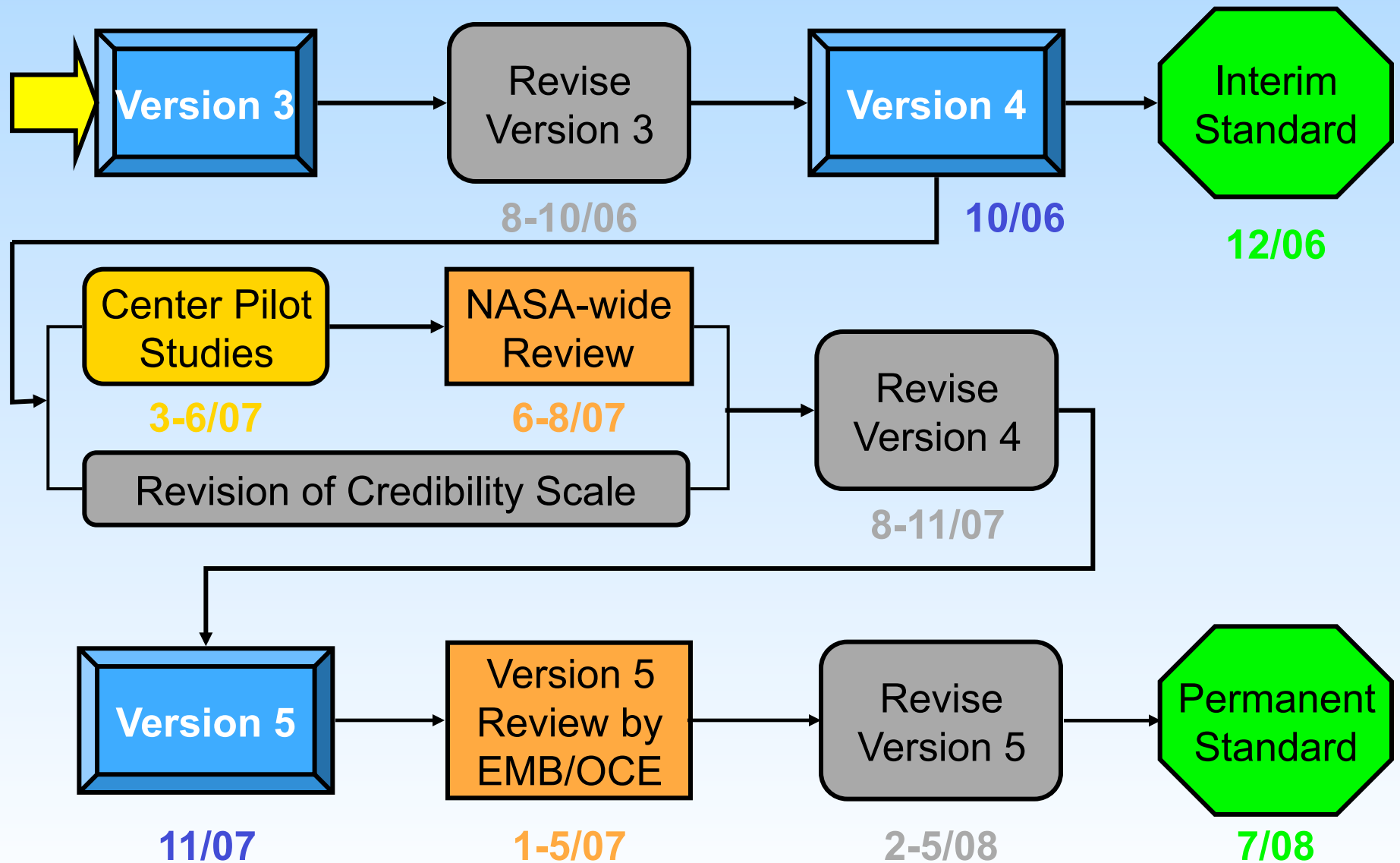


M&S Standard Development Process 1





M&S Standard Development Process 2





Development Team (NASA LaRC)

- **Steve R. Blattnig**
- **Lawrence L. Green**
- **Michael J. Hemsch**
- **James M. Luckring**
- **Joseph H. Morrison**
- **Ram K. Tripathi**
- **Thomas A. Zang**



Topic Working Group

- **ARC:** Unmeel Mehta: Fluid Dynamics
- **DFRC:** *none*
- **GRC:** Maria Babula (Jeff Rusick): Mission Analysis (S&MA)
- **JSC:** Andre Sylvester (Galen Overstreet): Simulation (Structures)
- **GSFC** Gary Mosier: Controls
- **JPL:** Bill Bertch: Space Science Missions
- **KSC:** Martin Steele: Discrete Event Simulation
- **LaRC:** Larry Green (Dick Davis): Systems Analysis (Instruments)
- **MSFC:** Joe Hale: Constellation IM&S
- **SSC:** Jody Woods: Systems Analysis–Fluids, Structures, Thermal

- **Chair:** Tom Zang: Systems Analysis