Systems Engineering Cost/Risk Analysis Capability Roadmap Progress Review

Stephen Cavanaugh, NASA Chair
Dr. Alan Wilhite, External Chair
April 6, 2005
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<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
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<tr>
<td>7:30</td>
<td>Continental Breakfast</td>
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<tr>
<td>8:00</td>
<td>Welcome and Review Process, Panel Chair &amp; NRC Staff</td>
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<td>8:15</td>
<td>NASA Capability Roadmap Activity</td>
<td>Vicki Regenie, NASA</td>
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<td>8:30</td>
<td>15.0 Systems Engineering Cost/Risk Analysis Overview</td>
<td>Stephen Cavanaugh, NASA</td>
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<td><em>-Sub-Team Presentations-</em></td>
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<tr>
<td>9:00</td>
<td>15.1 Systems Engineering</td>
<td>Dr. Alan Wilhite, Georgia Tech</td>
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<td><strong>- Break -</strong></td>
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<td>11:15</td>
<td>15.2 Life Cycle Costing</td>
<td>Dr. David Bearden, Aerospace Corporation</td>
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<td>12:00</td>
<td><strong>- Lunch -</strong></td>
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<td>12:45</td>
<td>15.3 Risk Management</td>
<td>Theodore Hammer, NASA</td>
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<td>1:30</td>
<td>15.4 Safety and Reliability Analysis</td>
<td>Dr. Homayoon Dezfuli, NASA</td>
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<tr>
<td>2:15</td>
<td>Concluding Summary</td>
<td>Stephen Cavanaugh, NASA</td>
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<td><strong>- Break -</strong></td>
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<tr>
<td>3:00</td>
<td>Open Discussion</td>
<td>NRC Panel</td>
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</tbody>
</table>
SE Capability Roadmap Team

Co-Chairs
NASA: Stephen Cavanaugh, LaRC
External: Dr. Alan Wilhite, Georgia Tech

Team Members

**Government**
- Dr. Michael Gilbert, LaRC
- Theodore Hammer, HQ
- Dr. Homayoon Dezfuli, HQ
- Stephen Creech, MSFC
- Phil Napala, HQ
- CAPT Daven Madsen, Navy/NSSO
- Dr. Steve Meier, NRO
- Richard Westermeyer, Navy/NSSO

**Industry**
- Dr. David Bearden, Aerospace
- Dr. Leonard Brownlow, Aerospace
- Gaspare Maggio, SAIC
- Steven Froncillo, SAIC

**Academia**
- Dr. Alan Wilhite, Georgia Tech

Consultants
- Stephen Kapurch, HQ
- David Graham, HQ
- Dale Thomas, MSFC
- Stephen Prusha, JPL
- Chuck Wiesbin, JPL
- Ron Moyer, HQ

Coordinators
- Directorate: Vicky Hwa, HQ Technical
- Doug Craig, HQ Integration
- Betsy Park, HQ Integration
- APIO: Victoria Regenie, DFRC
• **Systems engineering** is a robust approach to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk.

• **Life-Cycle Cost** is an integrated, process-centered, and disciplined approach to life cycle management of projects providing real and tangible benefits to all project stakeholders.

• **Risk Management** identifies potential problem areas early enough to allow development and implementation of mitigation strategies to control cost, schedule and mission success.

• **Safety and Reliability Analysis** maximizes Mission Success while managing safety risk and affordably meeting mission objectives.
This Capability Roadmap scope does not include performing the integration of all fifteen Capability Roadmaps. Roadmap coordinators (MD, Center, & APIO) comprise the Integration Team and facilitate the integration process by capturing Roadmap data and dependencies and documenting in relational database tool.
Need for Systems Engineering

• The President has challenged NASA to undertake exploration of the solar system
• In the face of tight budgets and mission risks, it is critical that these missions be executed flawlessly
  – Requires sound approach to Systems Engineering
    • Tools, methods, processes
      ▪ Continuous improvement
    • Best of industry and government
    • Standard processes
      ▪ All centers
      ▪ All missions
      ▪ All programs/projects
• System Engineering must be a “value added proposition” not an overhead burden
  – Consistent with the spirit of CAIB Recommendation

NASA’s new vision requires, more than ever, excellence in an integrated systems engineering cost/risk analysis capability
Four Systems Engineering Essentials

1st – Processes & Concepts (What)

2nd – Performance Aids (How)

3rd – Workforce (Who)

4th – How well organization implements and supports the framework with:

- Policies & Procedures
- Process Improvement
- Human Resources
- Training
- Milestone & Decision Gate Review Criteria
- Management of Quality
Complexity is a Major Issue

• Systems-of-Systems are Complex
  – As More Systems Are Added, the Interfaces Grow in a Non-Linear Fashion
  – Many of the Existing Systems Are Old and Not Built for These Interfaces
  – Conflicting or Missing Interface Standards Make It Hard to Define Interface Interactions

• Systems Engineering Must Deal With This Complexity
  – End-to-End Systems Engineering Is Needed, Including “Reengineering” Of Old Systems
  – Robust M&S, Verification And Validation Testing Are A Must
  – Need To Upgrade Modeling And Simulation Tools For Both Concept Definition And Verification And Validation Phases

Northrop Grumman Integrated Systems
September 21, 2004 Letter from the National Academies

Dear RADM Steidle:
At your request, the National Research Council recently established the Committee on Systems Integration for Project Constellation. The following quotes were taken from the report:

“Strengthening the state of systems engineering is also critical to the long-term success of Project Constellation. A competent systems engineering capability must be resident within the government and industry”.

“NASA’s human spaceflight systems engineering capability has eroded significantly as a result of declining engineering and development work, which has been replaced by operational responsibilities”.

“The demand for experienced systems engineers, who can function credibly in a system-of-systems environment, is particularly acute”.

“Plans should be developed for maintaining a satisfactory base of systems engineering throughout the duration of this program”.

“Systems Integration” Will Take Place At Multiple Tiers

- Tiers structured around functional responsibilities
- Must be prepared to support with maximum efficiency, minimum bureaucracy
- Need to support Directorate and Technology Themes, as well as Constellation
- SE&I authority should reside at lowest possible level

System-of-Systems Integration Demands Creative Solution

- No single model evaluated by NRC offers complete solution
- Complete expertise and competence is not available in any one sector
- Certain functions can only be executed by government personnel
- “Hybrid model” using government, FFRDC, and industry is attractive

ESMD SE&I Capability Will Be Phased-In Over Time

- Government will perform SE&I work needed to complete Spiral 1 SRR
- Near-term solution may evolve to different Long-term solution
Capability Roadmapping
Process & Approach

National Standards and State of Art Practices for SE, Risk, Cost, Safety

Develop Team Schedule And Deliverables

Develop Capability Model

Assess NASAs’ Capability Requirements

Identify Capability Readiness and Gaps

Develop Interrelationship Matrix with Strategic and Capability Roadmaps

Develop and Prioritize Mitigation Strategies

Define Development Schedule, Cost, Deliverables, and Readiness Maturity for Critical Capability Needs

Document Roadmap Plan

NASA Chief Engineer’s SE Study June 2005 Completion

Workshop 1 December 8-9, 2004

Workshop 2 February 1-2, 2005

SE Benchmarking Activity @ Fort Belvoir February 22-23, 2005

Workshop 3 March 2-3, 2005
Basis for Assessment

- **Quality Function Deployment (QFD)**
  - A quality system that implements elements of Systems Thinking (viewing the development process as a system) and Psychology (understanding customer needs)

- **Benchmarking** – Chief Engineers Fort Belvoir Workshop on February 22-23, 2005
  - Learning from the experience of others in Industry, DoD, and Other Agencies

- **Literature Search** – mostly Internet

- **Limitations of Assessment**
  - Budget limitations keep team small and limited in scope
  - QFD assessment limited to team size – small sample of NASA
  - Assessment more Qualitative vs. Quantitative
Capability readiness rating assignments are intended for future exploration missions and as such they should not be interpreted as capability ratings to perform the current missions.
Capability Team 15: Systems Engineering Top Level Capability Roadmap

Key Assumptions: Exploration & Science

2008 CEV Initial Flight

2011 James Webb

2013 Comet Surface Sample Return

2015 Prepare for Human Lunar Missions

Capability Roadmap 15: Systems Engineering Risk/Cost Analysis

15.1 Systems Engineering

Initial SE Implementation

Validated, Integrated SE Environment

Collaborative/Distributive PLEM Simulation-Based Capability

15.2 Life Cycle Cost

Agency-wide LCC Models & Process

Continuous Cost Risk Management

Integrated Life Cycle Cost Models

Life Cycle Cost linked to Project Management

15.3 Risk Management

Integrated Risk Tools and Mitigation plans

Standardized Simulation Based Risk Analysis

Probabilistic Risk Analysis and Mitigation

15.4 Safety & Reliability


Advanced Physics-based QRA

Next-generation Hazard Analysis Techniques

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

2005 2010 2015

Major Event / Accomplishment / Milestone

Legend

Major Decision

Ready to Use
**Major Assumptions:**

**Exploration & Science**

Key Assumptions: Exploration & Science
- 2018: Deep Drill & Completed Initial Human Landing
- 2025: Extended Lunar Capability & Life Finder Telescope
- 2030: Prepare for Human Mars Mission

**Capability Roadmap 15: Systems Engineering Risk/Cost Analysis**

15.1 Systems Engineering
- 2018: Initial International Collaborative Engineering / Management Simulation Based Capability

15.2 Life Cycle Cost
- 2018: Decisions based on Economic LCC Models
- 2025: LCC imbedded in all Agency Decisions

15.3 Risk Management
- 2018: Interdependent Systems Risk Analysis
- 2025: Interactive Risk Identification and Mitigation

15.4 Safety & Reliability
- 2018: Safety & Reliability Informed Decision making
- 2025: Virtual Safety and SE Analysis capability

**Legend**
- PLM – Product Life Cycle Management
- SBM – Simulation Based Modeling
- CMMI – Capability Maturity Model Integration
- QRA - Quantitative Risk Assessment
- LCC - Life Cycle Cost
Future State Required to Meet NASA Exploration Vision

- **Process (What)** – Need a common process for Systems Engineering, Cost, Risk and Safety. NASA Policy Requirements, guidelines and handbooks for this Capability need to be developed along with a need for an audible process.

- **Tools (How)** – Need a standardized approach for Systems Analysis. This includes a framework for advanced tools.

- **People (Who)** – Need qualified personnel. Training & Education programs including certification tied to job criteria and performance standards.

“An immediate transformation imperative for all programs is to focus more attention on the application of Systems Engineering principles and practices throughout the system life cycle”

USAF Chief of Acquisition Memo, “Incentivizing Contractors for Better Systems Engineering, 9 Apr 03
Capability 15.1 Systems Engineering

Presenter:
Dr. Alan Wilhite
Benefits of Systems Engineering

- Requirements driven – build the right system
- Process driven – build the system right
- Integrated engineering and management for informed decisions
- Less cost / Less duration
Systems Engineering and Integration

Requirements, Requirements flowdown, Interfaces and Integration Performance, Specifications, Verification and Validation Technical Risk, Cost

Planning, Development, Production, Operations, Decision Analysis and Criteria, Cost and Schedule Risk

Technology Selection, Performance trades Requirements trades Min Performance Criteria, Investment Strategy, Best System, Verification and Validation, Technical Risk

Ref. GaTech AE 6322
**Scope of SE Standards**

- **IEEE 1220 Application & Management of the SE Process**
- **ANSI/EIA 632**
  - *Processes for Engineering Systems*
- **ISO/IEC 15288**
  - *System Life Cycle Processes*
- **MIL-STD-499B** *
  - *Systems Engineering*

**Breadth of Scope**

* Mil-Std-499C has more detail (similar to 15288) than Mil-Std 499B and has more breadth (similar to IEEE 1220)*
CMMI – DoD developed integrated model for systems engineering, software engineering, integrated product process development, and supplier sourcing

CMMI used as initial basis for strategic planning
Overview of the “State”

- The Standish Group (which exists solely to track IT successes and failures) surveyed 13,522 projects in 2003 and showed the following:
  - 34% of projects succeed (these projects are defined as those which deliver the contracted capabilities on time and on budget).
  - 15% of projects are out and out failures (these projects are defined as those abandoned midstream)
  - The rest (51%) are "challenged", meaning over budget, and/or over schedule, and/or deliver less capability / functionality than agreed upon and contracted for.

- According to a Lake & Sheard paper
  - Systems Engineering is practiced in a quagmire of SE Standards
    - MARC Proceedings 1999
- According to the AF Center for Systems Engineering:
  - “Systems Engineering is not broken.”
    - GEIA-G47 meeting January 2005

Systems Engineering is not broken but needs significant advancement to improve NASA’s program success rate
System Engineering Processes
## SE Capability Team Assessment

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<thead>
<tr>
<th>SE-CMMI</th>
<th>Team Assessment</th>
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<tbody>
<tr>
<td><strong>ENGINEERING</strong></td>
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<td>REQUIREMENTS DEVELOPMENT</td>
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<td>REQUIREMENTS MANAGEMENT</td>
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<td>TECHNICAL SOLUTION</td>
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<td>PRODUCT INTEGRATION</td>
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<td>VERIFICATION</td>
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<td>VALIDATION</td>
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<td><strong>PROJECT MANAGEMENT</strong></td>
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<td>PROJECT PLANNING</td>
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<td>PROJECT MONITORING AND CONTROL</td>
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<td>SUPPLIER AGREEMENT MANAGEMENT</td>
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<td>INTEGRATED PROJECT MANAGEMENT FOR IPPD</td>
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<td>RISK MANAGEMENT</td>
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<td>INTEGRATED TEAMING</td>
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<td>INTEGRATED SUPPLIER MANAGEMENT</td>
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<td>QUANTITATIVE PROJECT MANAGEMENT</td>
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<td><strong>SUPPORT</strong></td>
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<td>CONFIGURATION MANAGEMENT</td>
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<td>PROCESS AND PRODUCT QUALITY ASSURANCE</td>
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<td>MEASUREMENT AND ANALYSIS</td>
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<td>DECISION ANALYSIS AND RESOLUTION</td>
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<td>CAUSAL ANALYSIS AND RESOLUTION</td>
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<td><strong>PROCESS MANAGEMENT</strong></td>
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<td>ORGANIZATIONAL PROCESS DEFINITION</td>
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<td>ORGANIZATIONAL TRAINING</td>
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<td>ORGANIZATIONAL PROCESS PERFORMANCE</td>
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<tr>
<td>ORGANIZATIONAL INNOVATION AND DEPLOYMENT</td>
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**Integrated rollup of Importance and Present Capability**

- Critical Gap
- Significant Gap
- No or Minor Gap
Detail of Capability Assessment (Top 10% out of 187 processes)

- Establish Evaluation Criteria
- Identify and Analyze Risks
- Select Solutions
- Evaluate Alternatives
- INTEGRATED TEAMING
- Manage Corrective Action to Closure
- Establish Estimates
- Identify Alternative Solutions
- Objectively Evaluate Work Products and Services
- Evaluate Assembled Product Components
- Obtain an Understanding of Requirements
- ORGANIZATIONAL TRAINING
- Balance Team and Home Organization Responsibilities
- Identify Inconsistencies between Project Work and Requirements
- ORGANIZATIONAL INNOVATION AND DEPLOYMENT
- Establish Incentives for Integration
- Establish the Organization’s Shared Vision
- Establish Guidelines for Decision Analysis
### Other Identified SE Capability Gaps

<table>
<thead>
<tr>
<th>Capability</th>
<th>Status</th>
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<tbody>
<tr>
<td>Systems of Systems Integration</td>
<td>Critical Gap</td>
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<tr>
<td>Experienced SE Personnel</td>
<td>Critical Gap</td>
</tr>
<tr>
<td>Standard Process/Process Improvement</td>
<td>Significant Gap</td>
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<tr>
<td>Facilitate Advanced Technology</td>
<td>Significant Gap</td>
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<tr>
<td>Estimate and Manage Costs</td>
<td>Significant Gap</td>
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<tr>
<td>Acquisition Strategy</td>
<td>No or Minor Gap</td>
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<tr>
<td>Advanced Collaborative Environment</td>
<td>No or Minor Gap</td>
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</table>

**Refs.**

- NRC SE&I Study, 2004
- NASA SE Workshop, 2005
But SE standard writers can’t agree on what should be in a standard – Hence a quagmire!
Scope of SE Standards

- **MIL-STD-499B**: Systems Engineering
- **ISO/IEC 15288**: System Life Cycle Processes
- **ANSI/EIA 632**: Processes for Engineering Systems
- **IEEE 1220**: Application & Management of the SE Process
- **MIL-STD-499B**: Systems Engineering
- **CMMI/SE**:

**Level of Detail**

**Breadth of Scope**

* Mil-Std-499C has more detail (similar to 15288) than Mil-Std 499B and has more breadth (similar to IEEE 1220)

Ref: Lake Briefing at February 2005 Ft Belvoir NASA Chief Engineer Workshop
SE Gap Assessment indicates that CMMI Maturity Levels 2 and 3 should be developed in parallel for NASA.
Program Management
- Planning
- Organizing
- Directing
- Monitoring
  - Maintaining insight or assessing
- Control

Common Areas
- Risk Mgt
- Config Mgt
- Performance
- Evaluation
- Mission Assurance

Systems Engineering
- Requirements & Functional Analysis and Allocation
- Design Synthesis
- Systems Analysis & Control (Balance)
- Integration & Verification

SE Gap Assessment also agrees with CMMI that Systems Engineering and Program Management must be integrated for NASA
End state well defined
Engineered and developed within a fixed budget and cost
Well known schedule, technical, and benefit baseline
Often replaces a “legacy” System
Priority often
  – Technical/Security
  – Operational
  – Cost
  – Political

Dynamic end state Systems-of-Systems evolves over time
Subject to annual budget revisions
Facilitates Senior Decision Makers
Priority often
  – Political
  – Cost
  – Operational
  – Security
  – Technical

Competing Forces Addressed by Systems Engineering
• Tier 1: SE Agency Policy and Process Improvement Processes
  – Process application policy
  – Architecture, Base and General Processes
  – Knowledge Management and Continuous Process Improvement

• Tier 2: Process Area Procedures
  – Specific standards and references identified
  – Process interfaces (HQ-Center, HQ-Contractor, Center-Contractor)
  – System of Systems integration
  – Can be tailored to specific directorate

• Tier 3: Detailed Guidebooks
  Best practices of how to implement SE
  General tools and methods

• Tier 4: System Engineering Management Plans
  – Technical program
  – Specific plans on SE implementation
  – Engineering specialty integration
  – Specific tools and methods selected
  – Organizational and contract interfaces defined
<table>
<thead>
<tr>
<th>Typical Today</th>
<th>5-Year Vision</th>
<th>10-year Vision</th>
<th>15-Year Vision</th>
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</thead>
<tbody>
<tr>
<td>• national standard processes exist but in a quagmire of interfaces</td>
<td>• A systems engineering policy, guidelines, and implementation strategies based on national standards and NASA/DoD/contractor best practices has been developed</td>
<td>• A collaborative / distributive advanced engineering environment for product life-cycle engineering and management has been developed based on system engineer and management processes for systems development and workforce training</td>
<td>• an expert system for systems engineering exists to aid in the training and use of the validated advanced engineering environment for complex systems-of-systems developments</td>
</tr>
<tr>
<td>• NASA has a SE guideline (NASA SP-6105) that is only sporadically followed</td>
<td>• Annual audits of NASA's systems engineering process model ensures best practices are used and distributed</td>
<td>• Systems engineering, life-cycle cost, risk, and safety have been integrated for robust solutions of complex systems-of-systems development</td>
<td>• Knowledge management has revolutionized the startup of new programs with reuse of processes and tools</td>
</tr>
<tr>
<td>• no NASA-wide policy on systems engineering exists</td>
<td>• A systems engineering certification program requiring continual education and training has been institutionalized</td>
<td>• All NASA centers have achieved the top level of systems engineering maturity</td>
<td>• All decisions are based on validated simulations and virtual and surgical physical testing for performance, cost, safety, uncertainty, and risk (and politics!!)</td>
</tr>
<tr>
<td>• NASA, DoD, and contractor teams use different processes and terminology</td>
<td>• A knowledge management system for capturing and reuse of best practices and knowledge repository for cost, reliability, validated systems analyses and simulations, software, and hardware has been initiated</td>
<td>• A certified (educated, trained, and experienced) systems engineering staff exists for engineering, management, and decision making</td>
<td>• a completed integrated international organization is optimized for the collaborative distributed environment</td>
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<tr>
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<td>• A completely digital product life-cycle management system for systems engineering and management for program/project control has been developed</td>
<td>• the organization interfaces and throughput is optimized through dynamic simulations</td>
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Skills (Workforce)
• Definition of a Systems Engineering Architect/Expert
  – Architect network centric and systems of systems
  – System Integrator
  – Drives next generation of mission solutions

• Attributes
  – Experienced technical leader
  – Experienced in working with the customer, understand their needs and customer value and to serve as the customer’s primary technical interface
  – Expert in fundamentals – cost, schedule, risk, processes
  – System lifecycle experience from pre-proposal to logistics support
  – Understand hardware, software, mission and big picture
  – Solid interpersonal skills, verbal and written communications

• Lack of senior level experienced systems engineers/architects
  – Many self-proclaimed systems engineers
  – Exists both in industry and government
Degreed workforce is a shrinking pool.
The Resource Picture

- Degreed workforce is a shrinking pool
  - Many graduates are not US citizens
  - Total engineering enrollments continue to decrease
- 20-30 year cycle between major system developments and 10 year development cycle
  - Lack of SE experience on large complex systems
  - Experienced SE engineers are retiring faster than being trained
- NASA systems engineering for human spaceflight has eroded and systems of systems is particularly acute (NRC 2004 NASA Systems Integration Study)
- Existing university / industry partnerships are not having enough impact
  - SE is not a standard discipline (EE, ChemE, ME etc.)
  - More penetration at undergraduate level
- Need new ways to attract and develop system engineers
  - Additional learning
  - On-the-job experience
  - Virtual simulation
### NRO SE Certification Requirements

<table>
<thead>
<tr>
<th>Level</th>
<th>Experience</th>
<th>Training</th>
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<tbody>
<tr>
<td>I</td>
<td>2 yrs. SE</td>
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<tr>
<td></td>
<td></td>
<td>SE-501 Acquisition Systems Engineering and SE-502 Designing Space Missions</td>
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<td></td>
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<td>or 6 SE-related graduate credits</td>
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<td>or SPRDE Level II Certified</td>
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<tr>
<td>II</td>
<td>4 yrs. SE</td>
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<tr>
<td>III</td>
<td>7 yrs. SE</td>
<td>INCOSE Certification or</td>
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**NASA needs to develop a SE certification program to develop systems engineering to meet future program requirements.**
• Establish SE development policy including SE certification requirements for promotions

• Establish Government, industry, and academia SE education, training, and job experience partnerships

• Develop guidelines and process for SE graduated certification. Include integration with program management education and training

• Measure progress in SE workforce development and changes in program SE metrics
<table>
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<tr>
<td>&quot;erosion of knowledge, experience and skills&quot; in &quot;systems engineering, project management discipline, cost, schedule management, and technology management&quot;. &quot;particularly acute&quot; for systems of systems integration. (NRC Systems Integration for Project Constellation, 2004)</td>
<td>• A systems engineering certification program requiring continual education and training has been institutionalized</td>
<td>• Technological obsolescence of workforce virtually eliminated by a certified (educated, trained, and experienced) systems engineering staff for engineering, management, and decision making</td>
<td>• Systems Engineering experience gained through simulation and on-the-job training</td>
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<td>DOD has &quot;essentially eliminated its systems engineering capability&quot;. (NRC, 2004)</td>
<td>• just-in-time training via intelligent tutoring and advisory systems</td>
<td>• learning centers at each of NASA’s Collaborative Engineering Environment facilities</td>
<td>• Advanced Engineering Environment technologies and systems replicated at the university and used for maintaining a strong fundamental core course structure, with simultaneous links to the math and science departments and virtual links to industry and government laboratories</td>
</tr>
<tr>
<td>only a single capstone design course in undergraduate engineering</td>
<td>• training support using standard NASA and enterprise product and process models</td>
<td>• university use of collaborative, distributed- learning consortia</td>
<td>• national team teaching in engineering, math, science, management, and the humanities</td>
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<td>courses taught in traditional classrooms</td>
<td>• focused training tuned to new opportunities and the best match with different employee skills and working styles</td>
<td>• practical experience of new engineers using validated system simulations</td>
<td>• personal learning experience emphasized —anytime, anywhere via an advanced Internet with high bandwidth</td>
</tr>
<tr>
<td>some video and Web-based Courses</td>
<td></td>
<td>• technological obsolescence of workforce virtually eliminated</td>
<td>• just-in-time personal/virtual training and tutoring</td>
</tr>
</tbody>
</table>

Systems Engineering Tools and Methods
Effect of Requirements Definition Investment on Program Costs

Target Cost Overrun, Percent

Requirements Cost/Program Cost, percent

PAY NOW OR PAY LATER

PAY NOW OR PAY LATER

- GRO78
- OMV
- TDRSS
- IRAS
- Gali
- HST
- GOES I-M
- TETH
- LAND76
- EDO (recent start)
- ACTS
- MARS
- ERB77
- CHA.REC
- STS
- COBE
- SEASAT
- LAND78
- GRO82
- UARS
- VOYAGER
- DE
- EUVE/EP
- Ulysses
- SMM
- PIONVEN
- IUE
- HEAO
- ISEE
The Systems Engineering Process
(Ref. ANSI 499)

Process Input
- Customer Needs/Objectives/
  Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards

Requirements Analysis
- Analyze Missions & Environments
- Identify Functional Requirements
- Define/Refine Performance & Design Constraint Requirement

System Analysis & Control (Balance)
- Trade-Off Studies
- Effectiveness Analysis
- Risk Management
- Configuration Management
- Interface Management
- Performance Measurement
  - SEMS
  - TPM
  - Technical Reviews

Functional Analysis/Allocation
- Decompose to Lower-Level Functions
- Allocate Performance & Other Limiting Requirements to All Functional Levels
- Define/Refine Functional Interfaces (Internal/External)
- Define/Refine/Integrate Functional Architecture

Synthesis
- Transform Architectures (Functional to Physical)
- Define Alternative System Concepts, Configuration Items & System Elements
- Select Preferred Product & Process Solutions
- Define/Refine Physical Interfaces (Internal/External)

System Analysis and Simulation drive the entire Systems Engineering Process

Process Output
- Development Level Dependant
  - Decision Data Base
  - System/Configuration Item Architecture
  - Specification & Baseline
Integrated Systems Engineering and Life-Cycle Management

- System of System Management
  - Planning Process
  - Assessment Process
  - Control Process

- Acquisition & Supply
  - Supply Process
  - Acquisition Process

- System of System Design
  - Requirements Definition Process
  - Solution Definition Process

- Systems Realizations
  - Implementation Process
  - Transition to Use Process

- Systems of Systems Operations
  - Introduction Process
  - Integration Planning Process
  - Mission Ops Process

- System of System Technical Evaluation
  - Systems Analysis Process
  - Requirements Process
  - System Verification Process
  - SOS Validation Process
  - SOS Performance Process

Systems of Systems SE Processes

- Product Life-Cycle Management
- Knowledge Management
- Integrated Process Product Development
- Simulation Based Models
- Product Life Cycle Engineering and Management Focus
Integrated Product Process Development

**IPPD Defined:** A management process that integrates all activities from product concept through production/field support, using a multi-functional team, to simultaneously optimize the product and its manufacturing and sustainment processes to meet cost and performance objectives. Its key tenets are as follows:

- **Customer Focus**
- **Concurrent Development of Products and Processes**
- **Early and Continuous Life Cycle Planning**
- **Maximize Flexibility for Optimization**
- **Use of Contractor Unique Approaches**
- **Encourage Robust Design and Improved Process Capability**
- **Event Driven Scheduling**
- **Multidisciplinary Teamwork**
- **Empowerment**
- **Seamless Management Tools**
- **Proactive Identification and Management of Risk**
Product Lifecycle Management (PLM)

Product Life-Cycle Management
- Systems Requirements
- Configuration Items Specifications
- CAD/CAM Standard Database
- Change/Configuration Management
- Virtual/Real System Models
- V/R Production Models
- V/R Verification Requirements and Management
- V/R Validation Requirements and Management
- Comprehensive Production and Quality History
- Resource Management
- Supply Chain Management

Stakeholders
Contractors
Management
Engineering
SBSE: The Challenge of Contracted Elements

Fully Integrate Total NASA/Industry Systems Engineering and Management
| Engineering Discipline Tools | - Mostly very good for detailed analysis; however needs standards for multidisciplinary integration for design and speed increases for optimization and uncertainty analyses. |
| Specialty Engineering ("ilities") Tools | - Little confidence in prediction of causal relationships for reliability, maintainability, supportability, operability, availability, safety, etc. |
| Life Cycle Cost | - NASA has continually underestimated the life-cycle cost (technology, development, production, operations, logistics). Needs causal models to assist engineering system and lifecycle design. |
| Program/Project Management | - Many excellent tools available for cost, schedule, and configuration management; needs total integration including risk and engineering mitigation planning |
| Product Life-cycle Management | - Many new COTS capabilities are being developed. Need to assess and select for NASA applications. Integration with simulation based SE modeling required. NASA wide and industry integration required. |
Advanced Tools and Processes
- High Fidelity Numerical Simulations
- Non-Traditional Methods
- Rapid Synthesis Methods
- Life Cycle Frameworks
- Life Cycle Cost Simulations
- Risk Simulations

System of Systems
Life-Cycle Simulation and Modeling

Requirements, Flowdown, Trades, Sensitivities, and Validation
- Risk
- Sustainability
- Cost
- Informed Decisions
- Performance
- Schedule
- Safety
- Reliability

Requirements
Concept Development
Design/Development
Test
Manufacturing
Integration/Verification
Ops/Maintenance
Disposal
Integration of risk analysis with decision processes.

Risk-informed Decision-making
(Integrated Consideration of all Performance Measures and Deliberation)

Key Uncertainties

Decision Option

INTEGRATION OF QUALITATIVE AND QUANTITATIVE SYSTEM SAFETY ANALYSIS

TECHNICAL RISK

Risk Metric (Loss of Crew)
Risk Metric (Loss of Science)
Risk Metric (Injury to Public)
Risk Metric (Schedule)
Risk Metric (Cost)

Performance Measures (Quantities of interest to Decision-Maker)

FM EFFECT CR
Device A Fails Loss of X 1
Device B Fails Loss of Y 3

Risk-informed Decision-making
(Integrated Consideration of all Performance Measures and Deliberation)
<table>
<thead>
<tr>
<th>Performance</th>
<th>Probability of Success</th>
<th>Schedule</th>
<th>Safety</th>
<th>R&amp;D Costs</th>
<th>Ops Costs</th>
<th>Growth Potential</th>
<th>Delivery Costs</th>
<th>Critical Development Problem Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EOR</strong></td>
<td>15300</td>
<td>14.5 (w/spare)</td>
<td>Aug 1969</td>
<td>18.2</td>
<td>$6490 E6</td>
<td>$1240</td>
<td>12</td>
<td>$88.4 E6</td>
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<td>a. Earth orbit rendezvous</td>
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<td>c. C-5 launch vehicle</td>
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<td>d. standard apollo capsule</td>
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<td><strong>LOR</strong></td>
<td>12,600 5,000 LEM</td>
<td>19.1</td>
<td>Feb 1969</td>
<td>16.1 (CM)</td>
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<td>$620</td>
<td>10*</td>
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<td>22.0 (LEM)</td>
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<td>a. lunar orbit rendezvous</td>
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<td>b. LEM and personnel transfer</td>
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<td>d. standard apollo capsule</td>
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<td><strong>C-5 Direct</strong></td>
<td>9210</td>
<td>21.9</td>
<td>Oct 1968</td>
<td>16.7</td>
<td>$5690 E6</td>
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<td>c. C-5 launch vehicle</td>
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<td><strong>Nova Direct</strong></td>
<td>15300</td>
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<td>May 1970</td>
<td>18.0</td>
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<td>$630</td>
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<td>a. Nova launch vehicle</td>
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<td>b. standard apollo capsule</td>
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</tbody>
</table>
Objectives:
- Schedule
- Budget
- Reduce LCC
- Increase Affordability
- Increase Safety
- Increase Sustainability

Subject to:
- Design & Environmental Constraints
  - Subject to Economic & Discipline Uncertainties
  - Subject to Impact of New Technologies-Performance & Schedule Risk

Robust Solutions:
- Schedule
- Budget
- Reduce LCC
- Increase Affordability
- Increase Safety
- Increase Sustainability

Customer Satisfaction
Technology Trends

Innovation Focus Throughout the Life Cycle

Optimizing the re-use of Data and Corporate Knowledge

Tomorrow's savings
Integrated Virtual and Real Design, Test, Production, and Operations

Knowledge Capture and Management

Product Life-Cycle Modeling

Systems Engineering Evolution

Manual SE Integration

2D

3D

Design & Manufacturing

Integrated SE Processes

Integrated Virtual and Real Design, Test, Production, and Operations
Rapid (Virtual and Real) Prototyping

- Early Requirements Development
- Analysis of Alternatives
- Reconfigurable Designs
- Real/Virtual Integration
- Human/Machine Performance
- Safety, Reliability, Cost Trades
- Systems of System Integrated Performance and Decision Analysis

Rapid Validation of Virtual Models for Confident Decision Analysis
Define, Monitor, and Control the Physical World

VIRTUAL

Product & Process Knowledge

INTELLECTUAL PROPERTY

PHYSICAL

Production

REAL OPERATIONS
• Design is Authored as Models

• Simulation Verifies the Design

• Physical Test Verifies the Simulation

Better Decisions / Shorter Development Times
Virtual Simulation to Keep and Reuse Workforce Knowledge

Validated virtual simulation may compensate for lack of physical Systems Engineering experience.
Simulation Based Modeling (SBM) Build Progression

1. Subjective Assessments
   - QFD / AHP
   - System Engineering Tools

2. Engineer in the Loop
   - Conceptual/Prelim Engineering
   - Risk – Flight, Development, RMS
   - Cost – Complete Life-Cycle

3. Operator in the Loop
   - Ground Operations
   - Mission Operations
   - Supply Chain Management

4. Hardware/Software in the Loop
   - Test Program Def & Refinement
   - Hardware & Software Testing
   - System Integration Modeling

5. Pilot in the Loop
   - Ground and Flight Sims
   - Validate Engr Concepts & Techs

6. Manufacturer/Tester in the Loop
   - Technology / Producibility Plan
   - Factory Layout / Tooling
   - Virtual/Real Test Integration

2 - Management in Loop
   - Architecture and Technology Trade Studies
   - Requirements Definition

2 - Organizations in Loop
   - Requirements Validation
   - Contractor Source Evaluation
   - System Optimization/Robust Design

Integration and Testing

2 - Organizations in Loop
   - Operations Analysis
   - Logistic Planning
   - Mission Planning
   - Flight Readiness Validation
A geographically distributed, integrated, secure, collaborative environment which enables life cycle design and analysis capability, enabling world-class engineering and science applications.
**Modeling Management Structure**

For STS Logistics, Management and Planning ~70%

---

**Direct (Visible) Work**

“Tip of the Iceberg”

Support (Hidden) + Recurring Ops

---

**STS Budget “Pyramid”**

(FY 1994 Access to Space Study)

<table>
<thead>
<tr>
<th>Generic Operations Function</th>
<th>Total $M FY94</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elem. Receipt &amp; Accept.</td>
<td>1.4</td>
<td>0.0%</td>
</tr>
<tr>
<td>Landing/Recovery</td>
<td>19.6</td>
<td>0.6%</td>
</tr>
<tr>
<td>Veh Assy &amp; Integ</td>
<td>27.1</td>
<td>0.8%</td>
</tr>
<tr>
<td>Launch</td>
<td>51.5</td>
<td>1.5%</td>
</tr>
<tr>
<td>Offline Payload/Crew</td>
<td>75.9</td>
<td>2.3%</td>
</tr>
<tr>
<td>Turnaround</td>
<td>112.3</td>
<td>3.3%</td>
</tr>
<tr>
<td>Vehicle Depot Maint.</td>
<td>237.5</td>
<td>7.1%</td>
</tr>
<tr>
<td>Traffic/Flight Control</td>
<td>199.4</td>
<td>5.9%</td>
</tr>
<tr>
<td>Operations Support Infra</td>
<td>318.6</td>
<td>9.5%</td>
</tr>
<tr>
<td>Concept-Uniq Logistics</td>
<td>842.7</td>
<td>25.1%</td>
</tr>
<tr>
<td>STS Ops Plan’g &amp; Mgmnt</td>
<td>1477.4</td>
<td>43.9%</td>
</tr>
<tr>
<td><strong>Total ($M FY94)</strong></td>
<td><strong>3363.4</strong></td>
<td><strong>100.0%</strong></td>
</tr>
<tr>
<td><strong>Percent</strong></td>
<td></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

CM McCleskey/NASA KSC
Management and Organization integration is a major percentage of program costs.

Information flow, decision paths, and process graphs can be stochastically modeled for duration, human capital, and impact on total program costs.

Currently, no organizational model has been developed to analyze NASA program organizational performance.

Validated organizational simulations may have as much impact as system simulation and optimization.
### Steps in the Design and Development of Products and Processes

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>• high-level systems engineering analysis</td>
<td>• traditional systems engineering methods / non-standard application across NASA</td>
<td>• establishment of NASA-wide policy and guidelines for systems engineering</td>
<td>• integrated systems engineering and management systems for technical and programmatic risk</td>
<td>• all life-cycle engineering functions are seamlessly integrated for system design, development, manufacture, and operation</td>
</tr>
<tr>
<td>• stakeholder/mission requirements definition</td>
<td>• little integration and reuse of engineering analyses</td>
<td>• integrated life-cycle analysis tools for system and requirements trades for acquisition</td>
<td>• validated life-cycle simulation of all mission requirements</td>
<td>• all mission and enterprise requirements can be traded with functional and physical models for the systems of systems environment</td>
</tr>
<tr>
<td></td>
<td>• late trades of requirements versus system specs, performance, and cost</td>
<td>• systems of systems requirements are understood and validated</td>
<td>• seamless transitioning of technical simulations to management and control simulation</td>
<td>• complete emersion of stakeholder in the design/requirements process</td>
</tr>
</tbody>
</table>

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>• product strategy</td>
<td>• competitive comparisons</td>
<td>• complete linkage of customer requirements, functional requirements, physical architecture, and operational requirements</td>
<td>• knowledge base for construction of systems analyses for a proposal with a &quot;selected&quot; level risk</td>
<td>• reliable “batch of one” methods for unique products</td>
</tr>
<tr>
<td>• voice of the customer</td>
<td>• projections of future products</td>
<td>• virtual prototypes for specification validation</td>
<td>• reliable specifications even for first-of-a-kind products</td>
<td>• product created on demand</td>
</tr>
<tr>
<td>• environmental and other regulatory requirements</td>
<td>• interviews and focus groups of customers and others</td>
<td>• strategic decision models and analyses based on uncertainty and risk</td>
<td>• ability to write in preferences and requests</td>
<td>• maximum reuse of hardware, software, infrastructure, and knowledge for the enterprise</td>
</tr>
<tr>
<td>• planned product specification</td>
<td>• demonstrations</td>
<td>• product life-cycle model for management of complete digital product database</td>
<td>• systems of systems impact of specifications are known</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• output is written documentation</td>
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</tbody>
</table>

### Systems Engineering Tools and Methods
**Assessment and Vision**

<table>
<thead>
<tr>
<th>Steps in the Design and Development of Products and Processes</th>
<th>Typical Today</th>
<th>5-Year Vision</th>
<th>10-year Vision</th>
<th>15-Year Vision</th>
<th>Steps 3, 4, and 5 combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Concept Development</td>
<td>• iterative, largely manual, bottom-up, non-optimized</td>
<td>• integrated, predictive life-cycle cost and profitability models</td>
<td>• complete life-cycle optimizations trading safety, performance, life-cycle cost, technical/performance risk, and schedule</td>
<td></td>
<td>• concept is optimized to meet mission and enterprise requirements (hardware, software, and knowledge reuse known)</td>
</tr>
<tr>
<td></td>
<td>• expert opinion for concept initiation</td>
<td>• optimization of shared resources</td>
<td>• full automation of subsystem and component tracking and trade-offs</td>
<td></td>
<td>- sensitivities, robustness, uncertainties are automatically generated for decision analysis</td>
</tr>
<tr>
<td></td>
<td>• rules of thumb</td>
<td>• better models of cost and &quot;ilities&quot; for concept trades with customer requirements</td>
<td>• collaborative engineering environment for complete enterprise participation in engineering and management with contractors</td>
<td></td>
<td>• expert system generates alternatives</td>
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<tr>
<td></td>
<td>• innovation relies on experienced practitioners</td>
<td></td>
<td>• virtual prototyping for manufacturing, integration, testing, ground and fight operations</td>
<td></td>
<td>• optimized, top-down concept development process</td>
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<td></td>
<td>• automatic analytical evaluation of all product and process attributes (including risk and uncertainty)</td>
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<td></td>
<td></td>
<td>• global collaborative engineering environment</td>
</tr>
</tbody>
</table>

### Systems Engineering Tools and Methods Assessment and Vision

<table>
<thead>
<tr>
<th>Steps in the Design and Development of Products and Processes</th>
<th>Typical Today</th>
<th>5-Year Vision</th>
<th>10-year Vision</th>
<th>15-Year Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4. Preliminary Product and Process Design</strong></td>
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<td></td>
</tr>
<tr>
<td>• high-level definition of product and process designs</td>
<td>• iterative, largely manual, largely bottom-up, heuristic</td>
<td>• rapid iteration of product and process design</td>
<td>• some degree of iteration implied, but guided by optimization capability</td>
<td>• single-pass product and process design and concurrent evaluation with multifunction optimization and automatic cascade to next lower level of design</td>
</tr>
<tr>
<td>• evaluation of product and process designs vs. targets</td>
<td>• derivations of existing designs</td>
<td>• object-oriented models scalable from macro to micro levels</td>
<td>• analytical evaluation of all attributes, 200 to 300 times faster than current methods</td>
<td>• automated generation of details about component and subsystem design and manufacturing details from high-level descriptions and desired attributes</td>
</tr>
<tr>
<td>• high-level system trade-offs</td>
<td>• progressive definition</td>
<td>• single interoperable data set</td>
<td>• integrated; single data source</td>
<td>• single product life-cycle data source</td>
</tr>
<tr>
<td></td>
<td>• coarse definition, mostly manual from scratch</td>
<td>• automated process model creation</td>
<td>• full automation of subsystem and component tracking and trade-offs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• unequal levels of definition for new and reused parts</td>
<td>• analytical evaluation of all attributes, including cost and producibility</td>
<td>• virtual manufacturing</td>
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<td>• 20% of product and process attributes evaluated analytically using simplified models</td>
<td>• multifunctional optimization</td>
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<td></td>
<td>• reliance on physical prototypes</td>
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</tbody>
</table>

### Systems Engineering Tools and Methods

#### Assessment and Vision

- automatic verification of the system and processes generated within the NASA advanced engineering environment
- immersive design and evaluation environment from the total NASA/contractor engineers, managers, and decision makers
- international distributed, collaborative processes

#### Steps in the Design and Development of Products and Processes

<table>
<thead>
<tr>
<th>5. Refinement and Verification of Detailed Product and Process Designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>development of designs for components, subsystems, and manufacturing processes</td>
</tr>
<tr>
<td>geometry creation</td>
</tr>
<tr>
<td>prediction and evaluation of all product and process attributes</td>
</tr>
<tr>
<td>tracking and trade-offs of subsystems and components</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5-Year Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>distributed, collaborative processes within NASA</td>
</tr>
<tr>
<td>physical prototypes essentially eliminated</td>
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<tr>
<td>real-time sharing of design information</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>10-year Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>automatic configuration control and tracking of system and processes</td>
</tr>
<tr>
<td>distributed, collaborative processes (NASA and contractors)</td>
</tr>
<tr>
<td>design advisors</td>
</tr>
<tr>
<td>minimal, “surgical” testing</td>
</tr>
<tr>
<td>no late trade-offs and no errors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15-Year Vision</th>
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<tbody>
<tr>
<td>automatic verification of the system and processes generated within the NASA advanced engineering environment</td>
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<tr>
<td>immersive design and evaluation environment from the total NASA/contractor engineers, managers, and decision makers</td>
</tr>
<tr>
<td>international distributed, collaborative processes</td>
</tr>
</tbody>
</table>

#### Typical Today

- detailed process and product definition mostly manual and from scratch
- limited reuse of design geometries for new parts
- analytical evaluation of one-third of product and process attributes using detailed models
- some model sharing
- reliance on physical prototypes
- attribute prediction and evaluation partially automated, but not integrated with design evolution

### Systems Engineering Tools and Methods Assessment and Vision

<table>
<thead>
<tr>
<th>Steps in the Design and Development of Products and Processes</th>
<th>Typical Today</th>
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<th>10-year Vision</th>
<th>15-Year Vision</th>
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</thead>
<tbody>
<tr>
<td><strong>6. System Prototype Development</strong></td>
<td>• experimental refinement of product attributes that do not meet targets</td>
<td>• integrated database for development of rapid prototypes</td>
<td>• complete virtual prototyping of system, systems, manufacturing, integration, tests, and operations</td>
<td>• validated virtual models - limited experiments required</td>
</tr>
<tr>
<td></td>
<td>• analytical evaluation required for more than half of all product attributes</td>
<td>• virtual prototypes becoming the norm for NASA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• real and virtual prototypes available for form, fit, and function demonstrations and tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>7. Production, Testing, Certification, and Delivery</strong></td>
<td>• virtual shop floor modeled</td>
<td>• product life-cycle model used to integrate production with resources, supply chain, workforce, and management</td>
<td>• all production hardware, software, infrastructure, workforce, and processes developed and tested virtually</td>
<td>• complete integrated virtual environment for supply chain, production, integration, verification, and validation</td>
</tr>
<tr>
<td></td>
<td>• discrete event optimized production flow</td>
<td>• products with 100% quality—getting it right the first time</td>
<td>• complete supply chain modeled and integrated with production</td>
<td>• virtual design and manufacturing process with zero defects</td>
</tr>
<tr>
<td></td>
<td>• on-line statistical process control</td>
<td></td>
<td>• off-line robust design</td>
<td>• only minor facility reconfigurations required for single product runs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• lean, agile manufacturing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• design for manufacturing: fewer parts, more compatibility, and easier assembly processes</td>
<td></td>
</tr>
</tbody>
</table>

### Steps in the Design and Development of Products and Processes

<table>
<thead>
<tr>
<th>8. Operation, Support, Decommissioning, and Disposal</th>
<th>Typical Today</th>
<th>5-Year Vision</th>
<th>10-Year Vision</th>
<th>15-Year Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>• sequential, historically based modeling approach</td>
<td>• consideration of remanufacturing in design</td>
<td>• autonomous systems</td>
<td>• autonomous systems</td>
<td>• autonomous systems</td>
</tr>
<tr>
<td>• a lot of manual operations</td>
<td>• limited autonomous systems</td>
<td>• operations driven supply chain fully modeled and managed</td>
<td>• self-healing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• simulation models based on operational processes</td>
<td>• design for easy repair</td>
<td>• self-disassembly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• improved automation of support activities</td>
<td>• design for disassembly</td>
<td>• self-disassembly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• supply chain modeled for impacts on design</td>
<td>• design for reuse and remanufacture</td>
<td>• self-disposal</td>
<td></td>
</tr>
</tbody>
</table>

Capability 15.1 Systems Engineering Roadmap

Key Assumptions: Exploration & Science

2008 CEV Initial Flight
2011 James Webb
2013 Comet Surface Sample Return
2015 Prepare for Human Lunar Missions

Capability Roadmap 15: Systems Engineering Risk/Cost Analysis

Initial Life-Cycle Management Capability
Integrated System Engineering and Management Capability
Collaborative/Distributive PLEM Simulation-Based Capability

15.1 Systems Engineering

15.1.1 Processes
NASA HQ SE Policy
NASA HQ SE Standard With Systems of Systems
Integrated SE, PM, & RM (CMMI Level 3)
CMMI Level 5
National NASA/Industry SE Integration

15.1.2 Skills
SE Certification Policy & Program
Initial Certified Class
Initial Skilled SE Architects
Distributed SE’s Throughout NASA

15.1.3 Tools and Methods
Initial PLM Implementation
SBM Build 1
SBM Build 2
Validated PLM
Integrated PLM
Integrated PLM

Validated, Integrated SE Environment
Collaborative/Distributive PLEM Simulation-Based Capability

Legend
PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost
Capability 15.1 Systems Engineering Roadmap

**Key Assumptions:**
- Exploration & Science

**2018**
- Deep Drill & Completed Initial Human Landing

**2025**
- Extended Lunar Capability & Life Finder Telescope

**2030**
- Prepare for Human Mars Mission

---

**Capability Roadmap 15: Systems Engineering Risk/Cost Analysis**

**15.1 Systems Engineering**

- **15.1.1 Processes**
- **15.1.2 Skills**
- **15.1.3 Tools and Methods**

- International SE Standards
- International Certified SE’s
- Validated SE L5 PLM Environment
- International Collaborative Total PLM Environment

---

**Legend**
- PLM – Product Life Cycle Management
- SBM – Simulation Based Modeling
- CMMI – Capability Maturity Model Integration
- QRA - Quantitative Risk Assessment
- LCC - Life Cycle Cost

---

**Major Decision**

**Major Event / Accomplishment / Milestone**

**Ready to Use**
Summary

• Systems Engineering in NASA needs to be improved for large complex systems of systems projects

• Standard system engineering policy needs to be developed at the Agency level for guidance to Centers

• The training and education of systems engineering needs to be institutionalized

• Advanced Engineering Environment can greatly enhance program execution, workforce training, and search for innovation and improved science
Capability - 15.2 Life Cycle Cost

Presenter:
Dr. David Bearden
What is a Life Cycle Cost (LCC)?

• An integrated, process-centered, and disciplined approach to life cycle management of projects provides real and tangible benefits to all project stakeholders.

• A LCC estimate includes total cost of ownership over the system life cycle, all project feasibility, project definition, system definition, preliminary and final design, fabrication and integration, deployment, operations and disposal efforts.

• A LCC estimate provides an exhaustive and structured accounting of all resources necessary to identify all cost elements including development, deployment, operation and support and disposal costs.

* Definitions provided by the NASA Cost Estimation Handbook, 2004
Benefits of the Life Cycle Cost

- “Ensure cost realism and accuracy”
  - The President’s Commission

- Improve confidence in selection process
  - Enables better budgeting

- Predict cost impact of change

- Limit potential for significant overruns
  - Increases mission success

- Gauge economic impact of decisions
Cost Team Process

- Evaluated current Capability Readiness Level (CRL) of cost discipline, at the lowest cost team WBS level
  - Cost Analysts at NASA HQ, MSFC, JPL, SAIC and The Aerospace Corporation evaluated the readiness level and importance of the current State of the Practice
  - Scored Robotic Spacecraft and Human Space Flight separately

- Interviewed Agency cost estimating leaders for current status / initiatives

- Identified remaining near-term gaps after implementation of current initiatives
  - Recommended additional measures for near-term

- Envisioned ideal state for cost estimating
  - Five and twenty year horizons
Current State-of-the-Practice for Life Cycle Cost

• **Tools**
  - Primarily system level parametric models with broad application
  - Medium fidelity models for development and operations
  - Low fidelity requirements (Physics) based models for instruments
  - High fidelity component models limited in application
  - Immature technology development capability
  - Scattered, sparsely-populated databases deployed across centers and industry
  - Databases with limited content, pre full-cost accounting and not normalized

• **Skills**
  - Limited formal cost training in academia
  - Limited career path

• **Process**
  - Program costs rolled up from several models
  - Costs validated through comparison of bottom’s up to parametric (top down)
  - Periodic intersection of cost estimation with project development
  - Immature linkage to Schedule Analysis
  - Minimal understanding of relationship of LCC to mission risk and safety
<table>
<thead>
<tr>
<th>Maturity Level – State of the Practice for 15.2 Life Cycle Cost</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Robotic Spacecraft</strong></th>
<th>Tools</th>
<th>Skills</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate Life Cycle Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Maturation</td>
<td><strong>Red</strong></td>
<td><strong>Red</strong></td>
<td><strong>Red</strong></td>
</tr>
<tr>
<td>Development</td>
<td><strong>Green</strong></td>
<td><strong>Green</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Production</td>
<td><strong>Green</strong></td>
<td><strong>Green</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Operations</td>
<td><strong>Yellow</strong></td>
<td><strong>Yellow</strong></td>
<td><strong>Yellow</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Human Spaceflight</strong></th>
<th>Tools</th>
<th>Skills</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate Life Cycle Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Maturation</td>
<td><strong>Red</strong></td>
<td><strong>Yellow</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Development</td>
<td><strong>Yellow</strong></td>
<td><strong>Yellow</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Production</td>
<td><strong>Yellow</strong></td>
<td><strong>Yellow</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Operations</td>
<td><strong>Yellow</strong></td>
<td><strong>Yellow</strong></td>
<td><strong>Green</strong></td>
</tr>
</tbody>
</table>

Critical Gap | Significant Gap | No or Minor Gap

Results indicate a strong need for Technology Maturation Cost Estimation Capabilities
Capability ratings trended higher for Robotic Spacecraft than Human Spaceflight primarily because of better data availability (function of more recent, relevant missions)

Capability ratings for Technology maturation cost estimating low in all areas

Production and Development estimating limited by data available in Human Spaceflight area

Operations cost estimating readiness low due to less mature tools and processes and availability of fewer estimators
Missions Driving Requirements

- Primarily driven by ESMD
  - Prometheus
  - Crew Exploration Vehicle
  - Human Exploration of Moon/Mars
- Large SMD Projects
  - James Webb Space Telescope
- Scale of large ESMD and SMD projects increases budgetary impact of overruns, poor estimation, and requirements creep

Additional reports that drive capability

- NPR 7120.5C
Elements of LCC Roadmap

• Tools
  – One NASA Cost Engineering (ONCE) Database
  – Technology Development Estimation Capability
  – Integrated Cost, Risk, & Schedule Models
  – Integrated Life Cycle Models with Improved Operations Models
  – Requirements (Physics) based Models
  – Economic Modeling

• Skills
  – Continuous Development
  – Formal Academic Education

• Process
  – CADRe (Cost Analysis Data Requirement) feeds data to ONCE
  – CCRM (Continuous Cost Risk Management)
  – Standard WBS
  – CAIG-like (Cost Analysis Improvement Group) implementation
"Enable a more agile cost estimating capability that interacts effectively with the project management function"

- Improved models
  - Representative Initiative: Integrated Life Cycle parametric system level models
  - Remaining Gap: Importance of accurate cost information justifies more investment to build higher fidelity integrated models

- Improved database
  - Representative Initiative: CADRe -> ONCE
  - Remaining Gap: Better coordination and cooperation by data owners (data sharing by centers/involved parties), data availability is a long-term problem

- Enhanced process to enable use of LCC estimating as an input to the project management function
  - Representative Initiative: CCRM
  - Remaining Gap: CCRM implementation will be challenging
Capability 15.2 Life Cycle Cost Roadmap

Key Assumptions: Exploration & Science

2008 CEV Initial Flight
2011 James Webb
2013 Comet Surface Sample Return
2015 Prepare for Human Lunar Missions

Capability Roadmap 15: Systems Engineering Risk/Cost Analysis

15.2 Life Cycle Cost
15.2.1 Tools
15.2.2 Skills
15.2.3 Process

Agency-wide LCC Models & Process
Continuous Cost Risk Management
Integrated Life Cycle Cost Models
Life Cycle Cost linked to Project Management

Initial Integrated LCC Tool
Continuous Cost Management
Life Cycle Technology Models
Requirements Based
dSafety Based

ONCE start
ONCE IOC
Industry Databases Linked
Expanded ONCE IOC

Current Center Databases Linked
ONCE IOC

Training program established
Std. WBS
Continuous Cost Risk Management Established
Expanding CADRe Start

CADRe & CCRM start
Experienced teams at HQ
Expanded teams at Centers

Major Assumptions:
Exploration & Science
2008 CEV Initial Flight
2011 James Webb
2013 Comet Surface Sample Return
2015 Prepare for Human Lunar Missions

2005 2010 2015

Major Decision Major Event / Accomplishment / Milestone Ready to Use

Academic Offering
Cost in SE Curriculum

Initial Integrated LCC Tool
Continuous Cost Management
Life Cycle Technology Models
Requirements Based
Safety Based
“Create a cost estimating capability that simulates the economic system and interacts seamlessly with management and systems engineering throughout the project”

- Understand the whole economic system and simulate to understand the effects of design and programmatic decisions have at the industry base level
  - Model not only design solution, but economic business case for industry

- Link the project management and systems engineering process with cost analysis
  - Simulate technology changes, process changes, etc.

- Improve tools and databases to allow for high-fidelity analysis
  - Cost as a function of safety, risk, schedule, and technology
Capability 15.2 Life Cycle Cost Roadmap

Key Assumptions:
- Exploration & Science

2018: Deep Drill & Completed Initial Human Landing
- Economic LCC Models
- Closed Economic based LCC models
- Linked LCC Models for all phases of project
- Higher Fidelity Databases Available

2025: Extended Lunar Capability & Life Finder Telescope
- Open Economic based LCC models

2030: Prepare for Human Mars Mission
- International Collaborative Engineering / Management Simulation Based Capability

15.2 Life Cycle Cost
- Decisions based on Economic LCC Models
- Linked LCC Models for all phases of project
- Higher Fidelity Databases Available
- LCC Skills readily available
- Continuous cost risk analysis broadly used within agency
- LCC used for all Agency decisions

Major Decision
- Ready to Use

Major Event / Accomplishment / Milestone
## Life Cycle Cost Goals

<table>
<thead>
<tr>
<th>Capability</th>
<th>Year 5</th>
<th>Year 10</th>
<th>Year 25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MODELS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost Accuracy</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Schedule Accuracy</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>DATABASE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of Programs w/ Complete CADRe</td>
<td>50%</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>SKILLS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Staff w/ Formal Training within NASA</td>
<td>50%</td>
<td>75%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>PROCESS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Programs implementing full CCRM process</td>
<td>30%</td>
<td>60%</td>
<td>90%</td>
</tr>
</tbody>
</table>
Summary

• Evaluated current capability of cost estimation discipline

• Envisioned ideal future state for cost estimating

• Performed gap analysis taking into account current initiatives

• Developed roadmap from current state-of-practice to envisioned state
Capability – 15.3 Risk Management

Presenter:
Theodore Hammer
Risk Management identifies potential problem areas early enough to allow development and implementation of mitigation strategies. This includes contingency planning, descope approaches, and qualitative and quantitative assessments. As complexity of systems grows the importance of risk analysis increases in managing cost, schedule and mission success.

The Risk Management sub-element needs to be thoroughly integrated with other aspects of systems engineering.

Risk management includes tools, processes, and skills.
Key Points/Benefits

- Risk Management most effective when integrated with program/project and technical management

- Gaps exist within the present risk management state of the practice

- First End State targets elimination of existing gaps

- End States target delivery of capabilities five years prior to a milestone

- Regular evaluation critical

- A formal integrated risk management capability benefits implementation of highly complex systems by
  - Enabling cost effective implementation and problem avoidance
  - Increasing probability of mission success
  - Reducing programmatic problems (e.g., cost and schedule)
Current State-of-the-Practice for Risk Management Within NASA

- Risk Management policy and requirements exist
- Conduct annual NASA Risk Management conference
- Risk Management planning widely used
- Assessments are highly qualitative
- Quantitative assessments using such tools as PRA are limited
- Risk mitigation planning and implementation widely used, but not well integrated into the project planning (e.g., cost/work breakdown, integrated schedules)
- Various risk management tools have been used, however, based on NASA trade studies ESMD has selected a state-of-the-art risk tool as the Directorate standard: Active Risk Manager (Strategic Thought, LLP)
- Formal risk management training exists based on Software Engineering Institute risk management process

Evaluation based on OSMA and NASA Center RM POC assessments.
### Evaluation of Risk Management

**State of the Practice**

#### Risk Management

<table>
<thead>
<tr>
<th>Prepare for Risk Management</th>
<th>Skill</th>
<th>Tool</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine Risk Sources and Categories</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define Risk Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Establish a Risk Management Strategy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Identify and Analyze Risks</th>
<th>Skill</th>
<th>Tool</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify Risks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantitative</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualitative</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate, Categorize, and Prioritize Risks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track/Control/Communicate</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mitigate Risks</th>
<th>Skill</th>
<th>Tool</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop Risk Mitigation Plans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implement Risk Mitigation Plans</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

#### Critical Gap

- Determine Risk Sources and Categories
- Define Risk Parameters
- Establish a Risk Management Strategy

#### Significant Gap

- Identify and Analyze Risks
- Mitigate Risks

#### No or Minor Gap

- Prepare for Risk Management
Gaps

- **Prepare R**
  - Insufficient level of integration of risk management and risk assessment with other capabilities
  - Lack of regular collection of data to assess the level of compliance and practice of risk management and assessment
  - Limited skill, tools and process for in-depth identification of risk sources
  - Limited skill, tools and process for an integrated risk strategy

- **Identify R**
  - Lack of standardization in risk management tools used
  - Inconsistent level of skill and knowledge for Risk Management practitioners
  - Insufficient application of quantitative techniques to identify risks, and limited qualitative assessment skills
  - Insufficient skills and tools for a consistent approach to monitoring, tracking, control/feedback and communication (e.g., external) of risks

- **Mitigate Y**
  - Limited skill and tools for mitigation planning
  - Limited skill, tools and process for the implementation of mitigation activities
Key Assumption is capability to support key milestones must be in place 5 years prior:

- 2011 James Webb Telescope
- 2015 Prepare for Human Lunar Missions
- 2018 Initial Human Lunar Landings
- 2025 Extended Lunar Capability
- 2030 Prepare for Human Mars Mission

Requirements and assumptions for increased risk management capabilities

- Increased complexity of systems
- Increased inter-dependency of complex systems
- Distributed implementing organizations
- Environment uncertainty
- Longer mission durations/complex logistics requirements
- Tougher science requirements
- Challenge of implementation and verification of advanced instrument technology (e.g., increased detector sensitivity)
- Increase future IT capabilities at lower costs
FY 2010 Lunar Support

• **Prepare**
  – Change process and skills to effect integration of risk management
  – Regular collection of self assessment data
  – Institute skills, tools and process for:
    • In-depth identification of risk sources
    • Integrated risk strategies

• **Identify**
  – Standardize risk management tools used
  – Define skills/knowledge criteria for risk practitioners; conduct training
    • Including quantitative techniques
  – Institute skills, tools: Monitoring, tracking, control/feedback and communication (e.g., external) of risks

• **Mitigate**
  – Institute skill and tools for mitigation planning
  – Institute skill, tools and process for the implementation of mitigation activities
Integration of risk analysis with decision processes

Risk-informed Decision-making
(Integrated Consideration of all Performance Measures and Deliberation)

Key Uncertainties

Decision Option

Risk Metric (Loss of Crew)
Risk Metric (Loss of Science)
Risk Metric (Injury to Public)
Risk Metric (Schedule)
Risk Metric (Cost)

Performance Measures (Quantities of Interest to Decision-Maker)

INTEGRATION OF
QUALITATIVE AND
QUANTITATIVE SYSTEM SAFETY ANALYSIS

FM EFFECT CR
Device A Falls Loss of X 1
Device B Falls Loss of Y 3
FY 2014 Human Lunar Landing Support

- **Prepare**
  - Improved risk source identification; expanded to include routine operational environment challenges
  - Risk sensitivity analysis for interdependent complex systems

- **Identify**
  - Simulation-based risk identification
  - Increased depth and fidelity of quantitative techniques
  - Improved risk communication, including risk uncertainties

- **Mitigate**
  - Integration of mitigation activities into project schedules
FY 2020 Extended Lunar Support

- **Prepare**
  - Risk sensitivity analysis techniques for interdependent systems
  - Improved risk source identification; plans for expanded extended lunar operational environment challenges

- **Identify**
  - Predictive risk capability and tools
  - Interactive risk identification; knowledge based providing a connection to risk decisions made in the past

- **Mitigate**
  - Capture of risk mitigation successes/failures to predict mitigation approach probability
FY 2025 Human Mars Support

- **Prepare**
  - Improved risk sensitivity analysis techniques for interdependent complex systems
  - Improved risk source identification; plans for expanded Mars operational environment challenges

- **Identify**
  - Improved predictive risk capability and tools
Capability 15.3 Risk Management Roadmap

Key Assumptions: Exploration & Science

2008 CEV Initial Flight
2011 James Webb
2013 Comet Surface Sample Return
2015 Prepare for Human Lunar Missions

Capability Roadmap 15: Systems Engineering Risk/Cost Analysis

Integrated Risk Tools and Mitigation plans
Integrated System Engineering and Management Capability
Collaborative/Distributive PLEM Simulation-Based Capability

15.3 Risk Management

15.3.1 Prepare
Integrated Risk Process
Data base of Self Assessment Established
Generic Risk Strategies Data Base Developed
Operational Environment included in Risk Analysis

15.3.2 Identify
Risk ID Tools Developed
Standardized Risk Tools Used
Simulation Based Risk Identification
Probabilistic/Sensitivity Analysis Risk Identification

15.3.3 Mitigate
Risk Mitigation Plans Routinely Used
Risk Mitigations Tracked against Identified Risks
Risk Mitigations Integrated into Project Schedules

Legend
PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Major Decision
Major Event / Accomplishment / Milestone
Ready to Use

2005
2010
2015
Capability 15.3 Risk Management Roadmap

Key Assumptions: Exploration & Science

2018 Deep Drill & Completed Initial Human Landing

2025 Extended Lunar Capability & Life Finder Telescope

2030 Prepare for Human Mars Mission

Capability Roadmap 15: Systems Engineering Risk/Cost Analysis

15.3 Interdependent Risk Analysis

15.3 Interactive Risk Identification and Mitigation

15.3 Risk Management

15.3.1 Prepare

15.3.2 Identify

15.3.3 Mitigate

Interdependent Systems Risk analysis

Predictive tools/Processes

Generic Risk Mitigations data base developed

Extra-terrestrial operational environments included in risk analysis

Interdependent System of Systems Risk analysis

Interactive Risk Identification

Interactive Risk Identification and Mitigation

Accurate Risk Analysis in Uncertain Environments

2020

2025

2030

Legend
PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Extra-terrestrial operational environments included in risk analysis

Accurate Risk Analysis in Uncertain Environments

International Collaborative Engineering / Management Simulation Based Capability

Initial International Collaborative Engineering / Management Simulation Based Capability

International Collaborative Engineering / Management Simulation Based Capability
## Maturity Goals

### RISK MANAGEMENT

#### Prepare for Risk Management

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change process and skills to effect integration of RM</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Regular collection of self assessment data</td>
<td>1/YR</td>
<td>1/YR</td>
<td>1/YR</td>
<td>1/YR</td>
</tr>
<tr>
<td>Institute skills, tools and process</td>
<td>80%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Improved risk source identification</td>
<td>6</td>
<td>7</td>
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<td>Improved risk source id; extended lunar operations</td>
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#### Identify and Analyze Risks

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<td>Standardize risk management tools used</td>
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<td>Define skills/knowledge criteria for risk practitioners</td>
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<td>Institute skills, tools: Monitoring, tracking, control/feedback and communication</td>
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<td>Increased depth and fidelity of quantitative techniques</td>
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<td>Improved risk communication, including risk uncertainties</td>
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<td>Interactive risk identification; knowledge based connection to risk decisions made in the past</td>
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<td>Improved predictive risk capability and tools</td>
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#### Mitigate Risks

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<td>Institute skills and tools for mitigation planning</td>
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<td>Institute skill, tools and process for the implementation of mitigation activities</td>
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<td>Integration of mitigation activities into project schedules</td>
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<td>Capture of risk mitigation successes/failures to predict mitigation approach probability</td>
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Summary

- Risk Management most effective when integrated with program/project and technical management

- First End State targets achieving RM integration with program/project and technical management, and elimination of existing gaps

- End States target delivery of capabilities five years prior to milestone that would benefit most from those capabilities

- Regular evaluation critical to determining capability maturity and success in meeting end state objectives
Capability - 15.4 Safety & Reliability Analysis

Presenter:
Homayoon Dezfuli, Ph.D, NASA
Team Lead
Objectives of System Safety & Reliability Analysis

• Evaluation and management of
  – Safety risk
  – Mission success

• Includes processes and techniques used to provide organized, disciplined approach to:
  – Identify and resolve risks as effectively as possible
    • Personnel
    • Equipment
    • Mission success
  – Assess safety and reliability through all phases of the life cycle
  – Risk-informed management of safety & reliability

• Assessment tools and processes should provide integrated evaluation of the entire system:
  – Hardware
  – Software
  – Physical environments
  – Operations
  – Human
  – Interactions of systems
Ensuring Safety and Mission Success in an Ideal Decision-making Framework

Ensure Safety and Mission Success

- Protect the Safety and Health of the Public
- Protect the Safety and Health of our Partners
- Protect those Assets the Nation Entrusted to us

Develop and Meet Requirements & Standards

- Develop and Meet Requirements & Standards
- Meet Federal Laws and Regulations (e.g., OSHA)
- Meet States Laws and Regulations
- Transition of Requirements into Contracts

Monitor Performance and Analyze Operating Experience

- Monitor Performance and Analyze Operating Experience
- Trend and Precursor Analysis
- Inspection, Audit, & Review to Detect Noncompliance

Conduct Test, Research, and Assessments to Reduce Uncertainties

- Conduct Test, Research, and Independent Assessments and Reviews
- Conduct System Safety and Reliability Analysis and Manage Risk

Conduct System Safety and Reliability, and Manage Risk

- System Safety
- Reliability Analysis
- Safety and Mission Risk Management

The Focus of this Presentation

- Dissemination of Lessons Learned
- Inspection, Audit, & Review to Detect Noncompliance
- Trend and Precursor Analysis

The Focus of this Presentation

PREREQUISITE: A SAFETY CULTURE IN WHICH MISSION OBJECTIVES ARE CLEARLY STATED AND PROMOTES QUALITY, ACCOUNTABILITY, COLLABORATION, AND COMMUNICATION
• Benefit: Ensure safety and mission success while affordably meeting program objectives

• This benefit will be realized when safety, reliability and risk analyses are standardized and are integrated with decision processes under a single decision-making framework
  – Integrate information on safety, reliability and risk under one umbrella (integration)
    • Elimination of organizational and process barriers
  – Systematize the hazard identification process (modeling standardization)
  – Analyze safety and mission risk (measurement of safety and mission performance)
    • Assessment of aggregate risks
    • Identification of weaknesses and vulnerabilities
    • Identification and assessment of uncertainties
  – Manage safety and mission risk (decision-making)
    • Performance of trade-off studies
    • Development of risk reduction strategies
Current State-of-the-practice for 15.4 Safety & Reliability Analysis

- **Hazard analysis is widely used**
  - Focuses on specific contributors
  - Limited applicability to complex systems-of-systems
    - generally the result of brainstorming

- **Fault Tree Analysis and Failure Modes and Effects Analysis are widely used**
  - Typically applied when completed design information is available
  - Primarily applied at subsystem level
  - Limited ability to affect early design decisions

- **Risk Matrix is widely used**
  - Applied to top-level risk issues
  - Interaction between risk items is difficult to discern
  - Is unsuitable for combining risks to obtain aggregate risk
  - Uncertainties are not formally accounted for
• A Typical State-of-Practice System Safety Assessment Technique
  – Analyst postulates a failure or a deviation and assesses its consequences
    • Typically one failure or deviation is analyzed at a time
  – Analyst qualitatively judges how often a failure or deviation can occur
  – Analyst qualitatively judges the severity of the outcome or assumes the worst-case outcome
  – Analyst maps each analyzed failure into one of three risk categories (Green, Yellow, Red)
The state-of-practice safety analyses do not readily reveal whether safety is improving, declining, or staying the same:

- Not designed to measure safety
- Without safety performance measures (safety risk metrics) one cannot manage safety risk effectively in the design and operational phases of a system.

System safety and risk analyses are organizationally remote from design. They are add-on to traditional engineering analysis.
“System safety engineering and management is separated from mainstream engineering, is not vigorous enough to have an impact on system design, and is hidden in the other safety disciplines at NASA Headquarters.”
• NASA has begun applying probabilistic risk assessment (PRA) techniques for evaluating safety performance
  – PRA is shown to be an effective tool
    • To integrate qualitative and quantitative safety models
    • To quantify risk metrics relating to the likelihood and severity of events adverse to safety or mission success including gaining an understanding of uncertainties

• Probabilistic risk models have not yet been used for design decisions
  – Models for software-intensive systems, unique space environment, and human decision-making and human-automation interactions have not been fully developed
  – Model developments are hampered by lack of PRA skills and limited and fragmented safety-related reliability databases
Robust and effective Safety and Reliability Assessment will be necessary to safely and affordably meet all the goals in the mission framework

- ~ 14 launches FY05 - FY10 (not including Shuttle and ISS)
- Over a hundred launches between FY10 - FY 30
- Planetary missions using nuclear technology
- Human mission to Mars by 2030
- Sample & return missions to Mars in 2014
- Potential for 3 month stay on the Moon
- Complex science missions (telescopes and solar exploration)

Not limited to human safety and crew survival,
- Must include loss of mission, loss of equipment, and adverse environmental impacts
# Maturity Level – Capabilities for 15.4 Safety & Reliability Analysis

## Skills, Tools, Processes

<table>
<thead>
<tr>
<th>Category</th>
<th>Skills</th>
<th>Tools</th>
<th>Processes</th>
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<tbody>
<tr>
<td><strong>Risk and Safety Management</strong></td>
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<td>Risk Tradeoffs, Risk Acceptance</td>
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<td>and Risk Communication</td>
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<td>Appreciation and Quantification</td>
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<td>of Uncertainties</td>
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<td>Mishap Investigation</td>
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<td>Analysis (hardware, software,</td>
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<td>Reliability Prediction Models</td>
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<tr>
<td>Reliability Database</td>
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</table>

### Key:
- **Minor or No Gap**
- **Significant Gap**
- **Critical Gap**
- Text in red indicates a gap
Objective: Integration of qualitative and probabilistic methods to support design evaluation

- Integrated qualitative and probabilistic methods are usually not conducted until late in the system life-cycle

Applying integrated system safety and reliability analyses for assessment and trade-off studies early in the design process to improve the effectiveness of decision-making
Integration of risk analysis with decision processes

Risk-informed Decision-making
(Integrated Consideration of all Performance Measures and Deliberation)

TECHNICAL RISK

Risk Metric (Loss of Crew)
Risk Metric (Loss of Science)
Risk Metric (Injury to Public)
Risk Metric (Schedule)
Risk Metric (Cost)

INTEGRATION OF QUALITATIVE AND QUANTITATIVE SYSTEM SAFETY ANALYSIS

FM EFFECT CR
Device A Fails Loss of X 1
Device B Fails Loss of Y 3

FY10
Top-level Objective for FY10 15.4
Safety & Reliability Analysis (Continued)

MAKING A DECISION: Consideration of all pertinent performance measure with their appropriate importance and their interrelationships

With Knowledge of
- Requirements,
- Engineering Insights,
- Engineering Standards and Operational Experience

With Knowledge of
- Technical Risk Metrics,
- Their Uncertainties, and
- Stakeholders' Preferences (relative weights of performance indicators)

Assess the Impact of Each Decision Option on Performance Measures (Quantities of Interest to Decision-maker)

Decision
Choose the most suitable option or reduce uncertainty (do more research)

Stakeholders Deliberation

Analysis

Decision Options

Metric for Crew Safety
Metric for Public Safety
Metric for Mission Success
Metric for schedule
Metric for cost
FY15 Vision for 15.4 Safety & Reliability Analysis

- Safety, consistent with mission requirements, is designed into the system in a timely and cost-effective manner
  - Standardization of safety and reliability analyses and processes and their integration with systems engineering process
  - Ability to trade safety & reliability against performance, cost, design options, diverse management paths
  - Extend analysis philosophy to development stages of system design
  - Developing risk acceptance process and criteria
  - Ability to assess and quantify uncertainties
  - Ability to perform trend and precursor analysis
  - Systems knowledgeable safety experts

- Physics-based Probabilistic Risk Assessment Models that fully integrate all elements of risk; including technical, organizational, and cost
  - Centralize existing safety, reliability, system design/operating limitations, and risk focused database
  - Assessing expected performance of a design / operational strategy, based on probabilistic simulation of time histories and explicit evaluation of performance (risk) metrics for those time histories
  - User-friendly, intuitive safety & reliability tool interfaces
  - Risk models linked directly to database with automated evaluation updates
Defining acceptable risk regions specific to the program

Risk assessment of decision options

Assessment of uncertainties

consideration of risk results including their uncertainties in decision-making
Example Integrated Future Capability

Inputs

Architectural Definition
Mission Profile
Operational Parameters

Outputs

Failure Modeling

Probability Aggregation

Failure Event Response Model

Data Analysis

Reliability Database

Mission Profile

Loss-of-Crew (LOC) Probability Distribution
Loss-of-Vehicle (LOV) Probability Distribution
Loss-of-Mission (LOM) Probability Distribution
Other Risk Metrics
• System safety and reliability activities incorporated in a risk-informed decision-making framework, capable of
  – Responding to mishaps in real time
  – Allocating resources (presents solutions, evaluates mitigation options)
  – Effective communication of safety issues
  – Monitoring performance using well defined risk metrics

• Virtual life-cycle simulation model of safety & reliability
  – Next-generation hazard analysis techniques that evaluate
    • New hardware technology
    • Software
    • human performance
    • Organizational factors
  – Safety and reliability models that interface with
    • Quality control processes
    • Testing processes
    • Assembly and manufacturing
    • Maintenance and operational processes
Example of a Simulation-based Risk Model

Branch Points (BP)
- System Hardware State BP
- Physical Variables BP
- Human Action BP
- Software BP
- End State

$P_i = $ Branch Probability

Prob.(End State) = $P_1 P_2 P_3 P_4 P_5$

Source: UMD Presentation: April 04
15.4 Safety & Reliability Analysis

Key Assumptions:
Exploration & Science

2018 Deep Drill & Completed
Initial Human Landing

2025 Extended Lunar Capability
& Life Finder Telescope

2030 Prepare for
Human Mars Mission

Capability Roadmap
15: Systems
Engineering Risk/Cost
Analysis

Initial International Collaborative
Engineering / Management Simulation
Based Capability

Integrated Virtual Safety and
SE analysis capability

15.4 Safety & Reliability

Next Generation of Safety &
Reliability Management System

Virtual Safety and SE
Analysis capability

15.4.1 System Safety

Engine for Integrated Predictive Safety &
Reliability model-based analysis

Integrated Virtual Safety and
SE analysis capability

15.4.2 System Reliability

Engine for Integrated Predictive SE & Safety
& Reliability model-based analysis

15.4.3 Safety Management

Virtual Safety analysis capability

Legend:
PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Major Event / Accomplishment / Milestone
Ready to Use

Major Decision
Concluding Summary

Presenter:
Stephen Cavanaugh
### Systems Engineering

<table>
<thead>
<tr>
<th>Capability</th>
<th>SE-CMMI</th>
<th>Team Assessment</th>
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<td><strong>Engineering</strong></td>
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<td>Technical Solution</td>
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<td>Supplier Agreement Management</td>
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<td>Integrated Project Management for EFPD</td>
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<td>Risk Management</td>
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<td>Integrated Supplier Management</td>
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<td><strong>Support</strong></td>
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<td>Organizational Environment for Integration</td>
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<td>Organizational Process Performance</td>
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<td>Organizational Innovation and Deployment</td>
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#### Risk Management

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<th>Step</th>
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<tr>
<td>Prepare for Risk Management</td>
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<td>Determine Risk Sources and Categories</td>
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<td>Define Risk Parameters</td>
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<td>Establish a Risk Management Strategy</td>
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<td>Identify and Analyze Risks</td>
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<td>Identify Risks</td>
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<td>Qualitative</td>
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<td>Evaluate, Categorize, and Prioritize Risks</td>
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<td>Planning</td>
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<td>Track/Control/Communicate</td>
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<td>Mitigate Risks</td>
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<td>Develop Risk Mitigation Plans</td>
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<td>Implement Risk Mitigation Plans</td>
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### Life Cycle Costing

#### Robotic Spacecraft

- Estimate Life Cycle Cost
- Technology Maturation
- Development
- Production
- Operations

#### Human Spaceflight

- Estimate Life Cycle Cost
- Technology Maturation
- Development
- Production
- Operations

### Safety & Reliability Analysis

#### Risk and Safety Management
- Risk Tradeoffs, Risk Acceptance and Risk Communication
- Appreciation and Quantification of Uncertainties
- Mishap Investigation
- Trend and Precursor Analysis
- Dissemination of Lessons Learned

#### Systems Safety
- Qualitative Systems Safety Analysis (hardware, software, phenomenological, human)
- Quantitative Systems Safety Analysis (hardware, software, phenomenological, human)

#### System Reliability
- Reliability Prediction Models
- Reliability Database

### Key
- Minor or No Gap
- Significant Gap
- Critical Gap

Text in red indicates a gap.
Systems Engineering Cost/Risk Analysis Roadmap Metrics

• Development Metrics (process, skills, tools)
  – Annual SE NASA modified CMMI audit of maturity (levels 1-5) and capability readiness (levels 1-5)
  – Number of NASA certified engineers in Systems Engineering, Life-Cycle Costing, Risk Management, and Safety
  – Percentage of programs using integrated Systems Engineering, Project Management, Life-Cycle Costing, Risk Management, and Safety tools

• Performance Metrics (implementation)
  – Number of cancelled programs and termination reviews per year
  – Average percent cost of overrun per year
  – Accuracy of cost and schedule predictions
  – Percent of program cost dedicated to Systems Engineering
  – Number of mission failures per total number of missions
  – Number of hits (requests) from Knowledge Management databases in Cost, Reliability, Safety, Risk, and Systems Engineering
Do the Capability Roadmaps provide a clear path way to technology and capability development?
  - Yes. All Roadmap sections address skills, tools (including Database creation from which Models are developed to address current gaps), and new process.

Are technology maturity levels accurately conveyed and used?
  - Yes. CRL were assessed by the community, and programs created to address areas with low level CRLs.

Are proper metrics for measuring advancement of technical maturity included?
  - Yes. The development and performance metrics assigned are appropriate to measure progress towards increasing the validity of the discipline, and reflect current Government criticism.

Do the Capability Roadmaps have connection point to each other when appropriate?
  - Yes. The capability is a discipline which connects to all other roadmaps.
An active Senior Sponsor is **absolutely essential** due to the complexity of future NASA Exploration missions.

Develop an Integrated organization of Systems Engineering, Cost, Risk, & Safety.

- Application needs to be strategic and tactical implementation
- Capability to integrate across Agency are currently uneven

Develop a Systems Engineering, Cost, Risk and Safety Professional Certification program to develop a qualified skill base.

- Require SE certification level for all SE positions
- Require as a performance objective in personnel reviews
- Reward progress

Establish an independent review process for each program that provides a gate keeping processes to ensure project success.

Create a centralized archival database with best practices, skill base, processes, and lessons learned.

The state of systems engineering as practiced at NASA needs to be improved to successfully achieve the Exploration Vision.
DoD Partnering Possibilities

- Both part of the U.S. government with all the general rules, regulations and procedures that entails
- Share a common industrial base
- Anticipate a large turn over of the workforce in the near future
- Funding constraints, including uncertainties from budget cuts
- Moving towards capabilities-based acquisition and evolutionary development
- Increasing complexity with more system-of-systems and families-of-systems
- Share some technology overlap
- Need a strong role of Systems Engineering Systems Engineering, Cost, Risk and Safety within our programs to be successful

Opportunity exists to collaborate with DoD & NROs Systems Engineering Professional Development Program and the established Systems Engineering Education programs at DAU & AFIT.
Next Steps/Forward Work

Make changes to roadmaps based on NRC feedback
Review and Assess all applicable Strategic Roadmaps and their requirements for Systems Engineering capabilities
- Suggest possible opportunities for Strategic Roadmaps

Make changes to roadmaps to ensure consistency with Strategic Roadmaps requirements
- Additional metrics to determine if achievements will be reached

Continue to work with other Capability roadmaps to ensure consistency and completeness

Develop rough order of magnitude cost estimates for the Systems Engineering, Cost, Risk and Safety Capability Roadmap

Prepare for 2nd NRC Review which will address 4 additional questions:
- Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
- Do the capability roadmaps articulate a clear sense of priorities among various elements?
- Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
- Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?
Click to add title

SE Back Up Slides
7 – Commercial processes/tools widely used by industry and NASA

6 – Commercial processes/tools sparsely used by NASA

5 – Specialized NASA developed processes/tools used in current programs

3 – Processes/tools under development for existing projects/programs

1 – Ideas of processes/tools that could enhance NASAs Systems Engineering