Outstanding Research Issues in Systematic Technology Prioritization for New Space Missions
Workshop Proceedings

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1. Workshop Objectives

A workshop entitled “Outstanding Research Issues In Systematic Technology Prioritization for New Space Missions” was held April 21-22, 2004 in San Diego, California on behalf of NASA Program Managers Robert Pearce (Code R Division of Strategic Planning) and Doug Craig (currently in the Human and Robotic Technology Program of Code T). The purpose of this meeting was to explore the state-of-the-art in decision analysis in the context of being able to objectively allocate constrained technical resources to enable future space missions and optimize science return.

The participants in this workshop are listed below:

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tr>
<td>John. D. Azzolini</td>
<td>Goddard Space Flight Center</td>
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<tr>
<td>Jacob Barhen</td>
<td>Oak Ridge National Laboratory</td>
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<td>David Bearden</td>
<td>Aerospace Corporation</td>
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<td>Doug Comstock</td>
<td>NASA HQ Code BX</td>
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<td>Jason Derleth</td>
<td>Jet Propulsion Laboratory</td>
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<td>Mark Drummond</td>
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<td>Alberto Elfes</td>
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<td>Joseph Fragola</td>
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<td>Jalal Mapar</td>
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<td>Othar Hansson</td>
<td>Thinkbank, Inc.</td>
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<td>Louis Lollar</td>
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<td>Guillermo Rodriguez</td>
<td>Jet Propulsion Laboratory</td>
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<td>Paul Schenker</td>
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<td>Jeffrey Smith</td>
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<td>Raphael Some</td>
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<tr>
<td>Mark Steiner</td>
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<tr>
<td>Charles Weisbin</td>
<td>Goddard Space Flight Center</td>
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<tr>
<td>Alan Wilhite</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>Giulio Varsi</td>
<td>Georgia Institute of Tech.</td>
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<tr>
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<td>NASA HQ Code S</td>
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2. Invited Talks

Several invited speakers presented their approach and results of recent experience to provide background for the ensuing group discussions.

The need for systematic technology assessment and prioritization was motivated in the talk entitled, “Strategic Investments Overview” by Doug Comstock, Director of Strategic Investments for NASA Code BX. Emphasis was on the demonstration of alignment of theme plans with the broader Agency Strategic Plan, and development of common analysis standards.

Then, each of the two mornings was comprised of presentations from the following speakers:

- **“Estimating the Risk of Technology Development,” Alan Wilhite**, Professor, Georgia Institute of Technology/National Institute of Aerospace. This talk discussed the characterization of risk through a matrix of probability and consequence. The probability was in turn, decomposed into probability of achieving technological maturity, and probability of achieving performance specifications, for a given resource allocation and schedule. An analytical hierarchical process is used to elicit data from experts. Specific case studies were used to illustrate these concepts.

- **“Technology Assessment of NASA Lidar Missions: A Pilot Study,” Mark Steiner**, NASA Goddard Space Flight Center. This is a technology investment case study leading to a next generation LIDAR instrument. Science measurements needs were determined, and physics models developed which would enable mapping between technology performance and instrument performance. Future extensions were suggested in terms of
broadening the entire architecture trade space and combining available data/tools into a unified system.

- **"The Atlas Decision Support System," Louis Lollar**, NASA Marshall Space Flight Center. This talk discussed plans for the ATLAS system, intended as a single (high level) desk top tool which would integrate information concerning missions, architectures, technologies etc. with coverage across the full life cycle, and would recommend relative ranking of technological candidates. The system currently uses system mass (surrogate for cost) as the major discriminator.

- **"The Earth Science System Analysis Model," Othar Hansson** (Thinkbank, Inc.). This talk presented a 3-part investment model of technology change, impact assessment, and prioritization in the framework of an influence network for improved reliability of weather prediction. The example included 13 candidate technologies as they influence 12 system characteristics (of the 13 x 12 = 156, only 18 are non-zero), with projected impact on 5 major system performance and cost metrics. An important consideration is that priorities depend on customer perspectives and there are often many different stakeholders (e.g. those interested in science, those interested in economics, those interested in safety etc.).

- **"Multi-Mission Strategic Technology Prioritization Study," Charles Weisbin**, Jet Propulsion Laboratory, California Institute of Technology. This is a comprehensive JPL study to date on technology assessment and prioritization. The START methodology described in section 1 demonstrated this approach can be used to assess a wide range of missions and technologies and is capable of inter-program trades. The study comprised 13 missions and 167 technology performance parameters in 23 technology areas. Technology investment recommendations were provided at technology task and technology area level as a function of resources available. At any level of resource investment, the likelihood of missions being technologically enabled was also presented.

The slides for these presentations are given in Appendix A.

### 3. Group Discussions

Each of the two afternoons was devoted to breakout sessions, addressing important questions and issues of current interest. Appendix B contains a detailed record of these discussions prepared by the breakout groups. Some of the more important highlights of these discussions are summarized below.

**Question 1:** In prioritizing technology development for missions, how should the relative values of the missions be assessed and quantified?

- **Should mission (= flight project) value be assessed at all?** Value is always assigned: current processes do this in a non-traceable, non-auditable way. It has to be done, so that we can improve on today's process. To do this, focus on functional objectives. The tool should allow for externally prescribed inputs about mission value.

There will always be a difference between valuation theory and results versus a final assessment by the decision-maker. In making a final assessment, the decision-maker can
augment the evaluation results with other factors external to the analysis. Identifying the decision analysis process as a tool for mission and technology portfolio selection reduces political sensitivity about the relative position in the launch queue.

- **Who should do it? Can it be done?** There is the problem of different stakeholders. Possible approaches are: (1) *Code B assesses relative value of missions* (they allocate resources to Enterprises). An example may be to consider the 18 theme areas and 3 mission areas, and given them each a high, medium, or low ranking; (2) Enterprises: *Code B apportions resources as a block to Enterprises. Enterprises prioritize missions*, with inputs from Science Groups and Project Managers; and (3) Executive Council, *Joint Strategic Assessment Committee performs the prioritization*.

- **How should it be done?** There were many alternative suggestions offered. Stakeholders can assess mission values in a process not unlike that used to rank departments at various academic institutions. Project managers can be surveyed to provide input to this process. Another option is to count the strategic goals within the NASA Strategic Plan that are satisfied, and use this as a factor in assessing mission value. In another option, mission cost can be used as a surrogate for value, and relative prioritization can be expressed through budget deltas by theme from year to year. Yet another option is to assign value on the basis of classifying missions into those that enable entirely new scientific discoveries, and those that enhance scientific knowledge about phenomena that have been previously discovered. *The NASA Strategic Plan should identify the “owner” of the prioritization process.*

**Question 2:** There are many architectural options to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?

- **It is possible to obtain mission capability requirements for missions that are at the early formulation stage.** In many cases, particularly where there may be a vast spectrum of previous missions from which to draw data, requirements for new undefined missions can often be obtained by projected evolution. One can assume an evolution from the technological state of the art (technology push) and iterate between what the technology might be able to achieve, and the corresponding new mission requirements that can be satisfied. *A functional decomposition is derived from mapping mission capability requirements to technology performance metrics*. The functional decompositions from each new advanced concept study might be stored in a NASA database. Capability requirements for missions can be obtained to whatever level of detail may be available. Mapping relevant technologies to capability requirements can identify technology gaps, and these gaps can be used to derive performance metrics for technologies. The fulfillment of requirements can be evaluated by modeling and simulation or by analyzing the degree to which relevant figures of merit are satisfied. *A relative value to various figures of merit may be assigned by parametric weighting of mission values and by conducting iterative sensitivity analysis. Don’t over-weigh optimizations but consider the level of precision; reserve some fraction for visionaries and spontaneous discoveries.* Consider approaches from other sectors (government, non-NASA, public, etc.).

- **There are advantages and disadvantages of establishing requirements.** “Requirements” are not ironclad, but have to be adaptive and negotiable. *Requirements have to be coupled*
with affordability and serve as a basis for negotiation among mission and system designers and the related technology developers. Requirements should ideally be expressed quantitatively. Requirements are different from specifications. Quantification of requirements can bring problems, but can also allow one to know when one is done.

- **Defining mission concepts involves working in a very large trade space.** How do you search it? Search trade space hierarchically, keeping the number of options low at each level. Delay decisions on final designs: NASA tends to dive into a specific point design too early. A more extensive assessment of the trade space, keeping uncertainties and options open, allows a broader, more valuable set of technologies to be developed. On the other hand, there are huge costs associated with keeping options open.

**Question 3:** How do we systematically acquire credible information, such as cost and performance estimates about technology development, which might seek to satisfy capability requirements.

- **Strive to make the data models and assumptions traceable and transparent.** One of the key features in achieving data quality is to undertake an independent review of the data, by a team external to the data generation process. Workshops can be used to enhance credibility of the data collected.

- **Strive to obtain statistically significant samples in the data set.** For high-risk or non-legacy technologies, the data should include estimates of uncertainty. In matching capability requirements to technology tasks, the data estimates should include as many valid viewpoints as possible to reduce the influence of inevitable uncertainties in individual data values. The larger the number of viewpoints represented in the data, the greater the robustness of the conclusions that can be drawn from it.

- **Strive to implement a data collection process that is sustainable.** The POP process is a good programmatic vehicle to request data generation and to implement incentives for proper response to such requests. Iterations should be easier than the first bounce. The process for data collection should be continually reevaluated. Quarterly reviews of the information should be conducted with researchers, technology developers, and mission experts.

**Question 4:** What is the best methodology to perform technical risk assessment, management and mitigation? Is the representation needed for risk management technologies fundamentally different to that needed for discipline-product technologies, such as sensing, manipulation, and thermal control?

- The representation and assessment of risk estimation and software technologies should be made consistent with those of the discipline product technologies (e.g., sensing, manipulation, mobility, etc.), in order to allow comparative analysis. It is important to have researchers state what kind of performance metrics they hope to impact; missions should provide goals.
• Risk manifests itself in terms of cost and schedule (as well as performance) and these impacts must be assessed in an integrated fashion. Software and hardware might be combined at a capability level as opposed to a discipline level.

• State of the art can be characterized, but the whole ‘ecosystem’ of software should be looked at, not just an algorithm, for instance.

Question 5: What are the criteria management will use to judge the results of a structured technology prioritization analysis?

The analysis and its results have to support and defend the eventual decision to stakeholders such as OMB, GAO, and others. The analysis should be traceable, transparent, understandable, and presented in a concise way. The analysis should document explicitly the important issues, assumptions and approximations, and should identify major uncertainties and other problem areas. The analysis has to address what the decision-maker cares about, including metrics and alternative options. The analysis should have the objective of providing decision-support tools and should provide options instead of point-solutions. The results should be cast as trades between risk and cost or between benefit and cost. The analysis should result in preferred recommendations and justifications spanning the decision space, not just negatives and consequences. The analysis products should be digestible and tuned for interpretation at the appropriate level.

4. Recommendations for Future Activities

The meeting concluded with a discussion of potential future activities, which included:

• Formulate and conduct a pilot application project, in partnership with a selected theme and program management representing mission, technology, and financial planning organizations. Increase the fidelity of the data and analysis, if necessary by initially narrowing the scope of mission and technology options

• Report on workshop results to the NASA multi-center System Analysis Consortia

• Provide input to POP guidance next February (e.g. types of inputs required)

• Provide additional organized opportunities for further technical discussion and exchange on such topics as risk assessment and decision analysis methods (e.g., partial completion of tasks, handling of reserves, etc.)

• Investigate potential concurrent applications of technology prioritization methods to other government agencies (e.g., Homeland Security). Address prototypical questions of potential benefit to others.
Appendix A: Slides of Invited Talks

- Doug Comstock

Strategic Investments Overview

Technology Prioritization Workshop

Doug Comstock
Director of Strategic Investments
April 21, 2004

Vision and Mission:
Our New Starting Point

The NASA Vision
To improve life here:
To extend life to there:
To find life beyond

The NASA Mission
To understand and protect our home planet:
To explore the universe and search for life:
To inspire the next generation of explorers as only NASA can.
The three volumes that make up the Congressional Submission are connected to the other elements of the NASA strategic management system.
Key Documents – FY 2005 Budget Request

President's Policy Directive

The Vision for Space Exploration

FY 2003 Performance and Accountability Report

Congressional Budget Justification

New Building Block Investments
Overcoming Barriers that Constrain Research and Discovery

<table>
<thead>
<tr>
<th>Technological Barriers</th>
<th>Ongoing Efforts</th>
<th>New Efforts</th>
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</table>
| Power                  | Nuclear Systems Initiative  
  • Greatly increased power for space science and exploration | Project Prometheus  
  • Nuclear Power and propulsion for revolutionary science and orbital capabilities  
  • First mission to Jupiter’s moons |
| Transportation         | Integrated Space Transportation Plan  
  • Orbital Space Plane  
  • Extended Shuttle operations  
  • Next-generation launch systems | Human Research Initiative  
  • Accelerate research to expand capabilities  
  • Enable 100+ day missions beyond low-Earth orbit |
| Human Capabilities     | In-Space Propulsion Program  
  • Efficient solar system transportation | Optical Communications  
  • Vastly improved communication transform science capability  
  • First demonstration from Mars |
| Communications         | Space Station Restructuring  
  • Research priority focused  
  • Management reforms  
  • Sound financial base |
The Strategic Organization

All performance must be tied to the NASA Vision and the 7 Goals tied to the Mission + 3 enabling Goals.

Performance: Accountability

**Vision**
All performance must be tied to the NASA Vision

**Strategic Plan**
One NASA: Many Themes support each of 3 NASA Missions

**Mission**
7 Goals tied to the Mission + 3 enabling Goals

**Goal**
What is to be accomplished, owned by a single Theme.

**Objective**
An important multi-year step on a Theme’s roadmap.

**Outcome**
Indicates annual progress towards achieving outcomes. Tied to a Theme’s budget investment.

**Performance Plan**

**Annual Performance Goal**
Code BX Products

Annual Budget Request – Integrated Budget and Performance Document (IBPD)
• Code BX led the design, development and integration of the IBPD
• Totally revamped Congressional justification – well received
• Page count less than half with more information than before
• Integrates budget with performance, setting government-wide benchmark

Performance and Accountability Report (PAR)
• Code BX leads the formulation, integration, production of the PAR
• Met aggressive OMB schedule
• On schedule for meeting even more aggressive OMB schedule this year

Strategic Plan
• Code BX led the formulation, integration and production of the plan
• High quality plan, seven months ahead of schedule

Integrated Planning
• Code BX developed and implemented the plan for integrated Agency planning in support of the Associate Deputy Administrator for Technical Programs
• Integrated set of planning documents being produced for the first time, including Enterprise Strategies and Center Implementation Plans
• A planning ‘community’ has been established with significantly improved communications
• Working with other Agencies to share best practices

Budget Amendments and Supplemental Requests
• Code BX leads/supports strategy, drafting, integration and advocacy
• FY 2003 Budget Amendment
  • Approved by OMB, adopted by appropriators
• FY 2004 Supplemental Request
  • Approved by OMB and now appropriated

Performance Plans
• Pre-IBPD FY 2003 performance plan was re-mapped to new strategic framework for the Agency
• FY 2004 performance plan revised to increase measurability of outcomes

Management Tool Development
• Code BX working with IFM Program and Chief Engineer to establish requirements and implementation plans for Erasmus
Systems Analysis

- The systems analysis community across the Agency is often called upon to assess investment strategies.
  - “How do we demonstrate alignment with the Agency Strategic Plan in a standard way?”
  - Wide range of analysis: ISTP, technology portfolios, cross Enterprise activities, spacecraft mission trades, etc.

- There are no “best practices” or common analysis standards to enable “apples to apples” comparisons of results.
  - Decision makers and analysts will both benefit from an open and transparent approach to performing and employing analysis products.
  - Have found that such standards are welcomed and encouraged.

- Code BX is seeking to catalyze a systems analysis ‘community’ among existing organizations dispersed across the Agency.
  - Budget process is a consumer of a great deal of Agency systems analysis products.
  - Currently engaged in dialog with systems analysis and systems engineering groups around the Agency on developing standards and a community.
  - Collecting inventory of tools, approaches, and environments from around the Centers.
  - Will conduct workshops and develop standards this year.
  - Goal is improved communications and strengthened capabilities, leading to better investment decisions.

Summary

Significant changes are underway
- Integration among the vision and mission, strategic plan, budget, and performance planning and reporting
  - Closer linkage of our budget estimates with our strategic plan, performance measures and institutional needs
  - Systems analysis efforts to improve linkage for better decisions

- Integrated budget and performance information in a single document, linked to strategic plan objectives through new budget structure arranged in “themes”
  - Ensures consistency among critical documents

- Annual and long-term performance measures directly traceable through the strategic plan to the vision and mission
  - Clear accountability for results through themes

- Defined agency goals requiring multiple enterprises and themes, with interdependencies and shared accountabilities
  - Reflects the One NASA philosophy

These changes will help NASA to achieve our Vision and Mission
When do you do risk analysis?

Risk analysis and response planning must be done during the initial planning phase of the project. Ideally, risk analysis and response planning is done during the project proposal phase and revisited on a regular basis.

"70% of a project's cost at completion is committed by the time the first 5% of the project's budget is actually spent."
The Elements of Risk

Risk is composed of TWO elements:

1.) The UNCERTAINTY (expressed as a probability (Pf) of achieving a project performance objective

   AND,

2.) The CONSEQUENCES (Cf) of a risk event

\[ \text{Risk} = Pf \times Cf \]

Caution is needed, of course in using this approach. It is necessary to be wary of multiplying 2 pieces of information together to produce a figure which may make an account's eyes light up but be of little practical value to a project manager.

Risk Assessment Matrix

<table>
<thead>
<tr>
<th>Probability of Failure (1 – Probability of Success)</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Renovation</td>
<td></td>
<td></td>
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<tr>
<td>Medium Renovation</td>
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<td></td>
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<tr>
<td>High Renovation</td>
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<td></td>
<td></td>
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<tr>
<td>Low Consequences Or Impact</td>
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<td></td>
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<tr>
<td>Medium Consequences Or Impact</td>
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<tr>
<td>High Consequences Or Impact</td>
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<tr>
<td>High Risk</td>
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<td></td>
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<tr>
<td>Medium Risk</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Low Risk</td>
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</table>

High Risk

Medium Risk

Low Risk
Characterization of Technology Risk
(utilization for system development)

- Probability of failure to:
  - Reach maturity for system integration
    (programmatic failure)
  - And meet Technical Performance Measures
    goals (technical failure)

- Impact on overall system performance of failing to meet TPM goals

Measures of Probability of Failure

- The Probability of Failure is measured by the three measures used for programs or projects - cost, schedule, and performance.
Measures of Programmatic Failure

- Development difficulty
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap

- Requirements, requirements flowdown, interface requirements, etc.

- Schedule
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone

- Cost
  - Defined cost for all milestones
  - Costs include NASA and contractor

- Management and technical team (experienced)

NASA's TECHNOLOGY READINESS LEVEL
(Scale for Tracking Risk Reduction)

9 - Actual system "flight proven" on operational flight
8 - Actual system completed and "flight qualified" through test and demonstration
7 - System prototype demonstrated in flight
6 - System/Subsystem (configuration) model or prototype demonstrated/validation in a relevant environment
5 - Component (or breadboard) verification in a relevant environment
4 - Component and/or breadboard test in a laboratory environment
3 - Analytical & experimental critical function, or characteristic proof-of-concept, or completed design
2 - Technology concept and/or application formulated (candidate selected)
1 - Basic principles observed and reported

Technology Readiness Level of 6 is usually required for Development
NASA’s Technology Readiness Levels (Software)

- **TRL 9**: Actual system “mission proven” through successful mission operations
  - Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.

- **TRL 8**: Actual system completed and “mission qualified” through test and demonstration in an operational environment
  - Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.

- **TRL 7**: Initial system demonstration in high-fidelity environment (parallel or shadow mode operation)
  - Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.

- **TRL 6**: System/subsystem prototype validated in a relevant end-to-end environment
  - Prototype implementations conform to target environment/interaces. Experiments with realistic problems. Simulated interfaces to existing systems.

- **TRL 5**: Module and/or subsystem qualified in relevant environment
  - Prototype implementations conform to target environment/interaces. Experiments with realistic problems. Simulated interfaces to existing systems.

- **TRL 4**: Module and/or subsystem qualified in laboratory environment
  - Standalone prototype implementations. Experiments with full scale problems or data sets.

- **TRL 3**: Analytical and experimental critical function and/or characteristic proof-of-concept

- **TRL 2**: Technology concept and/or application formulated
  - Basic principles coded. Experiments with synthetic data. Mostly applied research.

- **TRL 1**: Basic principles observed and reported
  - Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.

**Measures of Programmatic Failure**

- **Development difficulty**
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap

- **Requirements, requirements flowdown, interface requirements, etc.**

- **Schedule**
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone

- **Cost**
  - Defined cost for all milestones
  - Costs include NASA and contractor

- **Management and technical team (experienced)**
Research and Development
Degree of Difficulty (RD³)

R&D³
I. A very low degree of difficulty is anticipated in achieving research and development objectives for this technology.
   Probability of Success in "Normal" R&D Effort > 99%

II. A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology.
    Probability of Success in "Normal" R&D Effort > 90%

III. A high degree of difficulty anticipated in achieving R&D objectives for this technology.
    Probability of Success in "Normal" R&D Effort > 80%

IV. A very high degree of difficulty anticipated in achieving R&D objectives for this technology.
    Probability of Success in "Normal" R&D Effort > 50%

V. The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required.
   Probability of Success in "Normal" R&D Effort > 20%

Measures of Programmatic Failure

- Development difficulty
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap

- Requirements, requirements flowdown, interface requirements, etc.

- Schedule
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone

- Cost
  - Defined cost for all milestones
  - Costs include NASA and contractor

- Management and technical team (experienced)
Measures of Programmatic Failure

- Development difficulty
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap

- Requirements, requirements flowdown, interface requirements, etc.

- Schedule
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone

- Cost
  - Defined cost for all milestones
  - Basis of costs (FTEs, facilities, hardware, etc.)

- Management and technical team (experienced)

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Low NOx Combustor

1-Pager Work Logic
# Low NOx Combustor

## 1-Pager Work Logic Description

### 1.0.2.1 LPP Subcomponent Eval
- Many cups tested
- Feeds sector test program
- Continues during sector test program
- Used for sector design refinement
- Essentially complete by FY95
- GE/NASA

### 1.0.2.2 CFP Rectangular Sector Eval
- Combines components for integrated evals
- 3 configurations tested
- Primary feed to annular test program design
- Secondary feed to core combustor test program design
- Uses non EPM materials
- GE/NASA

### 1.0.2.3 LPP Curved Sector Evaluation
- Added shape fidelity over rectangular evals
- Two test series of single configuration
- Feed core combustor test program design
- GE

### 1.0.2.4 LPP Sector Transient Test
- Evaluation of rectangular sector configurations
- Primary feed to annular test program design

### 1.0.2.5 RQL Sector Combustion Rig
- 3 generation tests of progressively complex design
- Gen I tests and Gen II design from separate contract
- P&W test feed annular rig test program design
- NASA test feed core combusor test program
- Uses non EPM materials
- P&W/NASA

### 1.0.2.6 Enhanced Quench Zone Mixing
- Applies to RQL configuration
- P&W/NASA participation
- Feeds annular rig test program design

### 1.0.2.7 Quench Zone Diagnostics
- Same as 1.0.2.6
- P&W participation

### 1.0.2.8 Analytical Code Dev
- Feed products to test programs as developed
- NASA

### 1.0.2.9 Emission Minimizing Fuel Combustor
- Feed products to test programs as developed
- NASA

### 1.0.2.10 Grants
- Feed products to test programs as developed
- Universities

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## Low NOx Combustor

### 1-Pager Work Schedule

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<tr>
<td>Rectangular Sector Eval</td>
<td>GE</td>
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<td>LPP at RQL</td>
<td>GE/PW</td>
<td>1</td>
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<th>Designed</th>
<th>Failed</th>
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<th>Analysis</th>
<th>Completed</th>
<th>Production</th>
<th>Completed</th>
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<td>1.1.2</td>
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</tr>
</tbody>
</table>

---

22
Low NOx Combustor

1-Pager Cost Distribution

Minimal Technology Data Sheet

Impact
Cost and Credibility
Difficulty
Meets architecture
ATP schedule

23
Assessing Technology Risk Using AHP
(Analytical Hierarchical Process)

- The AHP is based on the hierarchical decomposition of the prioritization or forecasting criteria down to the level at which the decision or forecast alternatives can be pair-wise compared for relative strength against the criteria.

- The pair-wise comparisons are made by the participating experts and translated onto a numerical ratio scale.

- The AHP mathematical model then uses the input pair-wise comparisons data to compute priorities or forecast distributions as appropriate.

### Analytical Hierarchical Process

#### Individual Assessment

<table>
<thead>
<tr>
<th>Metric Interval</th>
<th>Most Likely</th>
<th>Relative Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 25 Units</td>
<td>5%</td>
<td>As likely as 35 to 40</td>
</tr>
<tr>
<td>25 to 30</td>
<td>25%</td>
<td>As likely as 35 to 40</td>
</tr>
<tr>
<td>30 to 35</td>
<td>75%</td>
<td>As likely as 35 to 40</td>
</tr>
<tr>
<td>35 to 40</td>
<td>100%</td>
<td>Most likely interval</td>
</tr>
<tr>
<td>45 to 50</td>
<td>10%</td>
<td>As likely as 35 to 40</td>
</tr>
</tbody>
</table>

#### Integrated Group Assessment
# Technology Risk Assessment – Phase 3
## Summary Of Airframe Risk Assessments

<table>
<thead>
<tr>
<th>TA</th>
<th>TECHNOLOGY PROJECT</th>
<th>COST</th>
<th>SCHED</th>
<th>TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>STRUCTURAL HEALTH MONITORING – NORTHROP GRUMMAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>METALLIC CRYOTANK - BOEING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CERAMIC MATRIX HOT STRUCTURES - MRD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>DURABLE ACREAGE CERAMIC TPS - BOEING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>DURABLE ACREAGE METALLIC TPS - OCEANEERING</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>INTEGRATED AERO-THERMAL &amp; STRUCTURAL THERMAL ANALYSIS - NASA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>STRUCTURAL &amp; MATERIALS/TANK/TPS INTEGRATION - NASA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>STAGE SEP &amp; ASCENT AERO-THERMODYNAMICS - NASA</td>
<td></td>
<td></td>
<td>No Data</td>
</tr>
<tr>
<td>2</td>
<td>MATERIALS &amp; ADVANCED MANUFACTURING: PERMEABILITY RESISTANCE - NASA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>LIGHTWEIGHT INFORMED MICRO-METEOROID RESISTANT TPS - NASA</td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>ULTRA HIGH TEMPERATURE SHARP EDGE TPS - LMC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CERAMIC MATRIX COMPOSITE – SOUTHERN RESEARCH</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# Technology Risk Assessment – Phase 3
## Structural Health Monitoring (Shm)

### TA-2 Airframe

**Northrop Grumman**

**MAJOR RISKS**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Schedule</th>
<th>Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost – Cost of 8,000 sensors for full scale SHM could be very high, but is understood.</td>
<td>Schedule – Critical schedule issue is availability of Composite Cryo-tank for testing. SHM starting at TRL 4 in 2002. No development issues affecting schedule.</td>
<td>Technical – Reliability – Integration of 8,000 sensors into one reliable SHM is a risk. Testability - Availability of Full Scale Composite Cryo-tank for testing to achieve TRL 6.</td>
</tr>
</tbody>
</table>

**CONTINGENCY PLAN SUGGESTION**

Use a subscale tank (18 to 20 ft diameter) to test SHM system.

**NOTE:** Only new or updated comments are contained in this report. Refer to Phase 2 report for complete evaluation. No significant change in evaluation from Phase 2.

Show Stopper – Lack of Funding for Composite Cryo-tank for Testing

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Structural Health Monitoring (Northrop Grumman)
Development Schedule

1. They should meet this goal based on present information.

2. NGC is starting with the SHM technology at a TRL level of 4 in 2002. They have plans to develop a structural health monitoring system and integrate it into a full-scale composite cryotank and complete test in 2009 timeframe. So the critical element of this is really having available a full-scale composite tank with this system integrated into it in 2002. That's the biggest concern because the funding level could get cut on the full-scale development of a composite tank that is in a separate technology development funding under GEN2. So, there are no major issues with respect to developing the SHM system that NGC is proposing here. The issue is with respect to the availability of a full-scale composite cryotanks in 2005/2006 which could face some serious funding issues given that GEN2 is probably not going to carry two tanks to TRL = 6 (metallic and composite).

5. If funding is maintained for the duration of the project, it is probable that it will come in on schedule.

7. There is a trade-off that should be made between the amount of health monitoring and robustness of design/analysis. As the vehicle is used for repeated flights some of the health monitoring sensors will become inoperative and others will produce data that has increasing errors. At some point a decision will need to be made relative to how many flights can be achieved before the health monitoring system itself must be inspected and checked out for adequate performance. The cost of maintaining the health monitoring system should be weighed against the cost of increasing the robustness of design thereby reducing the need for health monitoring. The reliability of the health monitoring system must consider the sensors, the data system and everything that is needed to transfer the data from the sensor to the data system. The lowest reliability part of the system may be the vehicle installed data transmission lines (quite a nest of lines) which must pass through the vehicle requiring compromises to be made in other disciplines of the vehicle design.

---

Technology Success Data

<table>
<thead>
<tr>
<th>Metric</th>
<th>Units</th>
<th>Weight</th>
<th>Low</th>
<th>High</th>
<th>Goal</th>
<th>EV</th>
<th>EV Dev</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Cost</td>
<td>Million $</td>
<td>0.50</td>
<td>85</td>
<td>235</td>
<td>115</td>
<td>137</td>
<td>19%</td>
<td>12%</td>
</tr>
<tr>
<td>Development Schedule</td>
<td>years</td>
<td>0.50</td>
<td>2005</td>
<td>2007</td>
<td>2006</td>
<td>2005.9</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>

**Weighted Programmatic Success:** 31%

- External Inspection Interval: missions 0.09 0 10 20 5 86 31% 30%
- Flight Mission Life: missions 0.13 0 10 20 5 232 42% 15%
- Internal Inspection Interval: missions 0.05 0 10 20 5 60 42% 26%
- Leak Rate: SCIM 0.1 1200 2000 399 -100% 28%
- Operating Pressure: PSI 0.1 0 100 50.0 50.0 30.7 2% 58%
- Reliability: % 0.1 99.9990 100.0000 99.9990 99.9952 0% 52%
- Weight: lb/cu ft 0.19 0 100 0.090 0.220 0.376 71% 13%

**Weighted Technical Success:** 31%

1. Combined Weighted Success: 31%

---

Assumption: The Low to High range contains 100% of the possible values of the metric.

---

EXAMPLE

**Expected Value – Mean or average value of the estimated probability distribution.** It is the value of the metric expected by the evaluators.

**Expected Value Deviation – Deviation of the EV from the goal, calculated as follows:**

**Absolute Value: EV - Goal**

**Goal**

A minus sign in front of the calculated value indicates that the EV is worse than the goal.

---

**EV Deviation show by how much the EV misses the goal.** It is defined for certain metrics.

**Weighted Success is the average success probability of the metrics.**

**Combined Weighted Success is average of technical and programmatic Weighted Success.**

---

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Risk Assessment Matrix

Launch Vehicle Propulsion Technology Selection

<table>
<thead>
<tr>
<th>Technology</th>
<th>Delta Isp, sec</th>
<th>Cost</th>
<th>Delta Isp/Cost</th>
<th>TRL</th>
<th>RDA</th>
<th>Probability of Failure</th>
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<tbody>
<tr>
<td>Metalized Hydrogen</td>
<td>15</td>
<td>200</td>
<td>0.075</td>
<td>2</td>
<td>5</td>
<td>25</td>
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<tr>
<td>Advanced Materials</td>
<td>10</td>
<td>150</td>
<td>0.067</td>
<td>3</td>
<td>4</td>
<td>16</td>
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<tr>
<td>Chamber Pressure</td>
<td>8</td>
<td>100</td>
<td>0.080</td>
<td>3</td>
<td>4</td>
<td>16</td>
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<tr>
<td>Combustion Efficiency</td>
<td>6</td>
<td>90</td>
<td>0.067</td>
<td>4</td>
<td>3</td>
<td>9</td>
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<tr>
<td>Nozzle Efficiency</td>
<td>4</td>
<td>50</td>
<td>0.080</td>
<td>4</td>
<td>2</td>
<td>6</td>
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<tr>
<td>O/F Ratio</td>
<td>2</td>
<td>65</td>
<td>0.031</td>
<td>5</td>
<td>2</td>
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</table>

What is the your investment order?
Weighted Technology Impact Ranking
(Quantitative assessment after tech portfolio selected and funded)

**Requirements**

<table>
<thead>
<tr>
<th>Safety (45%)</th>
<th>Loss of Crew</th>
<th>Loss of Vehicle</th>
<th>Loss of Mission</th>
<th>Loss of Payload</th>
<th>Cost ($/lb) (35%)</th>
<th>Launch Availability</th>
<th>DDT&amp;E - Average</th>
<th>1st Unit Prod. Cost</th>
<th>Annual Ops Cost</th>
<th>Facilities Cost (10%)</th>
<th>Technical (20%)</th>
<th>Vehicle Empty We</th>
<th>Vehicle GLOW</th>
<th>Total Weighted Score</th>
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<tbody>
<tr>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
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**Technologies**

<table>
<thead>
<tr>
<th>Rapid Turn Around TP5</th>
<th>TP5 Block</th>
<th>Tank Block</th>
<th>Tank NG</th>
<th>Op LMC</th>
<th>PEP</th>
<th>MPB</th>
<th>LIMC MAS/ARC</th>
<th>MAB</th>
<th>MPS-Crossed Block</th>
<th>MET-Crossed Block</th>
<th>MET-Pro</th>
<th>MET-CryoTank Block</th>
<th>MET-Exist</th>
<th>LOX</th>
<th>LOX Ethanol Booster</th>
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<tr>
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<td>0.18</td>
<td>0.18</td>
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<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
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</tbody>
</table>

**Impact Assessment**

- **High**
- **Medium**
- **Low**

**Comments on Investment Strategy and Impact Assessment Method**

- Very poor choice of technology portfolio (~two-thirds of technologies have low or negative impact)
- Wrong requirements were developed
- Systems analysis did not model the technologies correctly
High impact (enabling) technologies can have low ROI.

### Technology Risk Assessment

#### Impact on Requirements (weighted value functions)

- **Engine Technologies**

- Should be considered for funding based on cost and expert opinion

#### Probability of Failure

(TRL, RD^3, Cost, Schedule)
Technology Agency Impact Model

Requirements Flowdown

- Enterprise Strategic
  Priority of missions within an Enterprise
- Missions / Program
  Percentage of total missions that architectures are utilized
- Architecture
  Percentage of proposed architectures that capability impacts
- Capability
  Indexed technology impact on capabilities computed by systems analysis (not yet available for all Architectures) or by expert opinion

Technology = Capability * Architecture * Mission * Enterprise Impact

Summary
Technology Risk Assessment

- Technology risk is based on the probability of technology development success versus the impact of the technology on the system
- Technology development probability of failure is similar to any project. Should have defined WBS, requirements, schedule, cost, etc.
- Expert opinion is used for assessment; AHP is one method to obtain and integrate the opinions.
- Expert opinion or systems analysis can be used to define the impact of the technology on the system.
- For total Agency impact, future enterprise missions need to be prioritized to assess technology global impact and risk.
Introduction

How do we integrate systematic technology investment planning into the process of architecting NASA’s new space missions?

- GSFC perspective based on:
  - Exploration Initiative and current mission planning environment
  - FY 2003 Lidar Technology Pilot Study w/ LaRC
  - FY 2004 TAA study w/ JPL
- Goddard’s vision as to what needs to be done next
Engineering and Technology Support Across Life Cycle

Strategic technology investment analysis enhances...

Pre-formulation/Formulation
- Roadmap generation and review
- Advanced concept development and review
- Refinement of roadmaps, advanced concepts, technologies, etc.
- Proposal development and review
  - Risk management
  - Project/Program cross-coordination and cross-coupling
  - Independent technical/management review
  - Lessons Learned Identification & Feedback

Cross Life Cycle Activities
- Technology development and review
- Tracking and execution of roadmaps, advanced concepts, technologies, etc.
- Requirements and Systems Analysis

Implementation & Decommissioning
- Requirements management
- Design and development of missions, instruments, systems, technologies, etc.
- Product and service delivery
- Integration & test
- Launch, early-orbit check-out
- Operations & sustaining engineering
- Technology Commercialization

Approval
- Technology planning
- Approval review engineering and product support
- Program/Project plan support

... sound decisions across mission and program life cycles.
Lidar Pilot Study: Charter from Code R

Code R tasked GSFC and LaRC to perform a technology assessment study of Lidar missions with the following objectives:

1. Develop a process for assessing the system-level benefits of new technology investments to guide program investment decisions.
2. Establish performance goals for evaluating the progress of technology development & risk relative to the state of the art.
3. Identify high-payoff crosscutting technologies that are enabling for sets of future mission concepts with similar scientific objectives.

GSFC and LaRC performed this Technology Assessment Analysis (TAA) pilot study 2003
- Used system engineering approach to determine expected return on technology investments that could ultimately be used at the mission, enterprise, or agency level
- Allowed specific technologies to be evaluated for their impact on life cycle cost

Study Flow - 1

Captured science goals for aerosol Lidar -

- Examined ESTIPS database to establish science objectives for next generation Lidar and found that more detailed information was needed.
- Performed survey of aerosol-climate community and Lidar experts to fully populate domain of science measurement goals (e.g., detect aerosols and clouds and obtain their optical characteristics).

Derived science measurement needs that drove the integrated instrument performance requirements (such as SNR for atmospheric area of interest).
Captured technology options that would improve Lidar performance

Surveyed technologists and grouped results into generic Lidar system component options.

Developed model of aerosol and cloud Lidar instruments: maps technical performance into instrument performance in area of atmosphere to be measured.

Developed technology development model (from starting TRL to TRL 6): maps development risk and investment plan to technology performance over time.
Linked models and used them to trade off cost, development risk, and instrument performance to optimize technology investment plan.
Technology Development Modeling

Technology Development Model (from starting TRL to TRL 6) maps development risk and investment plan (estimated schedule and budget) to technology performance over time.

System Performance Model maps technology performance into system performance.

Link models and use them to trade off cost, development risk, and system performance to optimize technology investment plan.

Systems Dynamic Modeling – Technology Development
The Study Methodology Enables

... to determine return on investment ...

Combining lidar technology development modeling ...

... and lidar performance modeling ...

and provide best estimate as to which group of technologies would enable the mission, reduce cost, and be most likely to enhance overall value.
Iidnr.
Pilot Stl,d,l/
Fyo,3:

Develop an approach to maximize the value of NASA's technology investments.

Understand process of gathering information, developing models, and presenting results:

Develop a general approach for optimizing technology investments and apply to LIDAR measurements

Expansion in FY04:

- Partner with JPL to extend process to space architect's Design Reference Missions
- Work with other centers (LaRC, ARC) to broaden technology databases, share processes, share results
- Extend performance modeling to include instrument accommodations (spacecraft and ground system)

Unified Agency-Wide Technology Assessment Framework

Unified Technology Assessment Framework

Features

- Toolbox approach
- Each tool is unique
- Different views based on same data
- Each tool optimizes over a specific dimension, depending on question being asked
- Convergence results in Unified Process and helps V&V tools

Quantifiable and Risk Based Technology Investment Strategy
### Reference Missions & Grand Challenges

<table>
<thead>
<tr>
<th>Reference Missions (not listed in order of priority)</th>
<th>Grand Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Aggregation and Space Infrastructure Systems (OASIS)</td>
<td>Modular, Distributed Structures, Human Protection, Robotic Assembly</td>
</tr>
<tr>
<td>Mars Surface Missions (e.g. Mars Science Laboratory; Astrobiology Field Lab; etc.)</td>
<td>Long-Range Mobility on Ice; Deep Drilling; Automated Return Launch; Risk Mitigation (Pre-Phase A)</td>
</tr>
<tr>
<td>Lunar Survey Study Mission</td>
<td>Sensor Webs &amp; Data Fusion: Lidar/Radar Instrument Systems; Multi-Spectral Scanner; Model-Driven Multi-Measurement-Validated Data Reduction</td>
</tr>
<tr>
<td>Earth Biomass (surface, mid-canopy, and canopy heights.)</td>
<td>Lidar/Radar Instrument Systems; Multi-Spectral Scanner</td>
</tr>
<tr>
<td>Sensor Webs &amp; Data Fusion</td>
<td>Model-Driven, Multi-Measurement-Validated, Data Reduction</td>
</tr>
<tr>
<td>RASC - L2 Earth Observing Telescope</td>
<td>Large deployable mirrors, membrane type shape control, formation flying</td>
</tr>
<tr>
<td>Venus Surface Missions</td>
<td>Extreme Environments (460C temp; 90 bar pressure; sulfuric acid clouds at 50 km)</td>
</tr>
<tr>
<td>Generic Critical Design Review requirements derived from Pathfinder, Space Station or other recent mission</td>
<td>Quantify mission-level impact of ECS technologies, such as risk management and human organization, whose primary contribution is to the design process, and that are not necessarily embodied within a hardware or software flight system</td>
</tr>
</tbody>
</table>

**NOTE:** GSFC and JPL will share performance data on all reference missions.

---

### Study Data Gathering

- **Have developed a technology list in cooperation with JPL**
  - Shows who will gather technology information in which areas
- **Have common technology data gathering template, based heavily on Space Architect work**
- **Common technology data template and sharing of this and the reference mission performance information will allow JPL and GSFC to run common data through both sets of tools and provide results for comparison**
- **Analyze differences between tools, since view problem from different but complementary angles:**
  - JPL – good for matrixing many technologies across many mission sets
  - GSFC – good for in-depth analysis of technology development within particular mission (performance parameter) set
Integration of Risk into Technology Planning

- Risk
  - Tools and methodology
- Technology Databases
  - NTI, ESTO, Aeronautical DB, ...
- System Analysis Tools
  - TAPS, JPL Tool, ...

Ideas for an Integrated Approach

Guesswork/Gut Feel Replaced with Integrated System Analysis
Considerations for NASA

Currently -

- We conduct deterministic and probabilistic assessment of existing systems based on mission requirements
  - Probabilistic sensitivity analysis for point solutions (Shuttle, Station, …)
    - *system decision trees are often complex and may not capture everything*

Future -

- Assessment of entire architecture trade space to include technology development risk, programmatic risk, operational risk (vehicle, etc.) and cost
  - Effect of technology on system design/development/cost/schedule
- Models to develop probability distribution of expected outcome
  - Probability based Genome Model will integrate TRL to provide a powerful view into future mission strategies and architectures.

Next Steps for NASA

- Get all technology players to play together
- Integrate processes and tools as makes sense to answer questions at the appropriate level
- NASA Technology Assessment Technical Committee??

Unified Agency-Wide Technology Assessment Framework
“ATLAS”
Advanced Technology Life-cycle Analysis System

April 2004

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Development Programs Division
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NASA/Marshall Space Flight Center
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Contents

• Overview
• ATLAS Conceptual Diagram
• ATLAS Architectural Overview
• Notional Example
• Summary
Overview

• Making good decisions concerning research and development portfolios—and concerning the best systems concepts to pursue—as early as possible in the life cycle of advanced technologies is a key goal of R&D management.

• This goal depends upon the effective integration of information from a wide variety of sources as well as focused, high-level analyses intended to inform such decisions.

• The presentation provides a summary of the Advanced Technology Life-cycle Analysis System (ATLAS) methodology and tool kit...
  - ATLAS encompasses a wide range of methods and tools
  - A key foundation for ATLAS is the NASA-created Technology Readiness Level (TRL) systems
  - The toolkit is largely spreadsheet based (as of August 2003)

• This product is being funded by the Human and Robotics Technology Program Office, Office of Exploration Systems, NASA Headquarters, Washington D.C. and is being integrated by Dan O'Neil of the Advanced Projects Office, NASA/MSFC, Huntsville, AL.

“ATLAS” Approach
Advanced Technology Life-cycle Analysis System
Notional Example Analysis
Lunar Rover to Collect Ice from the Lunar Craters

- **Notional Scenario**
  - Launch elements to LEO for construction
  - LEO to Lunar Orbit
  - Base system/Rover to "Edge of Crater"
  - Rover descends into the crater to retrieve some ice
  - Rover brings the ice back to the base unit

- **Analyst chooses (with help from ATLAS)**
  - Launch Vehicle
  - LEO Base Configuration
  - Orbital Transfer Vehicle
  - Base Vehicle
  - Lunar Rover

- **Output Data from ATLAS**
  - Mass statement(s) for each subsystem and/or 18 subsystems
  - DDT & E (6 year cycle)
  - Cost for each system and/or 18 subsystems
  - Theoretical first unit cost
  - Life cycle costs
  - Views of the intermediate steps of the process
Summary

- A central challenge in the management of innovation lies in making good decisions in the absence of complete information
  - The conundrum is that the earliest decisions have the greatest affect on project outcomes, and yet they must be made at the time when there is the least detailed information available

- The ATLAS modeling system is being developed to contribute to the resolution of this challenge
  - By providing a single (high-level), desk-top tool that integrates information on, and analytical relationships among various missions, architectures, systems, technologies and associated metrics, and costs

- Although considerable work remains, it appears likely that ATLAS will begin operations—and to make meaningful contributions to Agency decisions—during FY 2004
The CICT Earth Science Systems Analysis Model

Barney Pell, Joe Coughlan, Bryan Biegel, Ken Stevens, Othar Hansson, Jordan Hayes

NASA Ames Research Center & Thinkbank, Inc.
April 2004

The ESSA Team

- Task leads:
  Barney Pell (Lead), Bryan Biegel (Co-lead), Joe Coughlan (Science Lead), Walt Brooks (Science Co-Lead)

- Subcontractor:
  Othar Hansson & Jordan Hayes, Thinkbank

- ARC team:
  Ken Stevens, Peter Cheeseman, Chris Henze, Samson Cheung, et al.
Enough About Me


- PhD (Computer Science), Berkeley. Using decision analysis techniques for search control decisions in science planning/scheduling systems.

- Thinkbank: custom software development, software architecture consulting, technology due-diligence for investors.

Agenda

CICT Systems Analysis

Our modeling approach
- a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned
Systems Analysis in CICT

- Demonstrate "systematic and thorough investment decision process" to HQ, OMB and Congressional Decision Makers
- Increase awareness and substantiate CICT's impact to missions. Road map CICT projects to missions and measurement systems
- 4 teams in FY03:
  - 2 pilot studies (Earth Science [me]; Space Science [Weisbin]): explore models for ROI of IT.
  - TEAM: map from NASA Strategic Plan to IT capability requirement; technology impact assessment
  - Systems Analysis Tools (COTS/GOTS)

Earth Science Pilot Study

How do we characterize and quantify a science process?

Can we build a model of how CICT technology investments impact ROI in a NASA science process?

What modeling approach is suitable for making such analyses understandable and repeatable?
Current State

What have we learned? (FY03)

- Decision analysis modeling techniques can be applied to systems analysis of CICT project areas.
- Built model of weather-prediction data pipeline.

What don’t we know? (FY04)

- How much time/expense needed to build a full model
- How such a full model fits into a real NASA program context
  (CDS: Collaborative Decision Systems)

Pilot Study Focus

- Criteria for science process to study
  - Important to a major customer base,
  - Significantly drives technology investments
  - Generalizes to a class of related processes
  - Amenable to quantitative analysis.

- 2010 Weather Prediction process
  - Critical Earth Science process with relevance not only to NASA scientists but to the nation at large.
  - Stretch goals require technology breakthroughs.
  - Strong technology driver for other science problems
  - Starting point: analyses from ESE computational technology requirements workshop (4/02)
Pilot Study Accomplishments

- Identified modeling formalism (influence diagrams)
  - Clear semantics accessible to both ES & CICT experts
  - Tools exist for sensitivity analysis, decision-making, etc.
    We chose Analytica as our modeling tool.
  - Successfully transferred/applied to Space Science pilot study as well.
- Built a model with an understandable, simple structure (after much research and many iterations).
- Demonstrated the kinds of analyses made possible by the model

Agenda

CICT Systems Analysis

Our modeling approach
  - a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned
Methodology: Decision Model

Q1: Which technology investments should I make?

Q2: How does each technology investment improve overall system/mission value (including cost considerations)? Choose investments with highest value.

Filling in the Decision Model

System value is a function of a set of metrics (accuracy, fidelity, cost, etc.). We can model the priority among the metrics independent of the technologies used.

Technology investments have value in that they improve these metrics.
The metrics can be modeled in terms of abstract system characteristics (data volume, algorithm accuracy, processing speed, model fidelity, ...).

Technology investments, together with some mission-specific parameters, influence the system characteristics. A technology investment (such as data visualization research) has value in that it improves system characteristics (such as model fidelity).
Methodology: Influence Diagrams

We’ve sketched an “influence diagram” model of the decision.

Q: What tech. investments maximize expected overall system value?
Q: Value of model refinement: How sensitive to assumption A?
Q: Value of information: what if we knew that project P would succeed?
Q: Value of control: what if we could reduce risk of project P failing?

Influence diagram tools (such as Analytica) allow you to specify and evaluate these models. Diagram structure and decision analysis techniques speed specification of required parameters.

“What-if” and optimization questions reduce to the problem of computing functions of conditional prob. distributions: “best” technology investment is:

\[
\text{argmax } [E(\text{Overall System Value} | \text{Technology Investments})]
\]
Agenda

CICT Systems Analysis

Our modeling approach
– a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned

The ESSA Model

Our set of 5 metrics include:
dervelopment cost, operations cost, accuracy, model fidelity, etc.
Our 12 System Characteristics include: observation density, assimilation efficiency, cpu efficiency, etc.

Our 13 technology investments include: data-mining, launching a new data source, targeted observing, etc.

Each represents a research area, summarizing a range of individual research tasks or proposals.
System-Assessment Model: the most stable part of the model, owned/design by a customer domain expert who understands the behavior of the system/mission being analyzed.

System-Assessment model computes System Metrics from System Characteristics.
**Example System Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assimilation efficiency</td>
<td>0-1 scale: how much information is retained despite approximations in data assimilation?</td>
</tr>
<tr>
<td>CPU efficiency</td>
<td>&gt;0: percentage speedup in CPUs due to R&amp;D investments</td>
</tr>
<tr>
<td>Data efficiency</td>
<td>0-1 scale: how much information is present in each bit of data selected?</td>
</tr>
<tr>
<td>Ensemble efficiency</td>
<td>0-1 scale: how much improvement in forecast skill do we get from using ensemble algorithms?</td>
</tr>
<tr>
<td>Model framework</td>
<td>0-1 scale: how much fidelity is present in our models?</td>
</tr>
<tr>
<td>Observation density</td>
<td>0-1 scale: how many of the available observations do we make?</td>
</tr>
<tr>
<td>Postprocessing effectiveness</td>
<td>0-1 scale: how much improvement in forecast skill do we get from using post-processing?</td>
</tr>
<tr>
<td>Simulation efficiency</td>
<td>&gt;0: percentage speedups in simulation due to R&amp;D investments</td>
</tr>
</tbody>
</table>

**Instantiating the Model**

System-Change Model: owned/designed by a program manager who understands the feasibility and impact of different research areas.

System-Change model computes System Characteristics from the set of Technology Investments chosen (and system/mission config parameters)
System-Change Model

- "Impact matrix" quantifies the changes to system characteristics that will occur if individual research projects succeed.
- "Cost matrix" quantifies cost breakdown for each research area.
- Portfolio of research areas determines what impacts will be felt.
- (In an extended model, cost and impact could vary over time.)

System-Change: Research Areas

- **Data-efficient simulations (same data size)**
  choose a more informative set of observations to improve forecast skill at the same computational cost
- **Data-efficient simulations (less data)**
  reduce number of observations (and reduce computational cost) w/o reducing forecast skill
- **Targeted Observing**
  ditto, but also gather more targeted observations based on ensemble accuracy estimates (e.g., the SensorWeb concept)
- **Adaptive grid methods**
  reduce number of grid points by using regional forecast as boundary conditions
- **Improvements in ensemble methods**
  reduce number of ensembles needed to get similar accuracy estimates (e.g., through use of particle filter technology)
- **Data-mining of model outputs**
  increased skill from same model output via data analysis & visualization (intelligent data understanding)
**System-Change: Research Areas**

- **Modeling tools**
  ESMF and other initiatives to make modeling efforts more productive

- **System Management/Tuning tools**
  Auto or Semi-Automatic Parallelization tools, Benchmarking, Cluster management, etc.

- **Instrument models**
  tools for creating more accurate instrument models.

- **Launch new data source**
  collect additional types of observation data by launching a new instrument.

- **Launch replacement data source**
  collect a new type of observation data, but keep the total amount of data processed the same.

- **Higher resolution models**
  develop higher resolution models and move to higher resolution simulation

**Research Area Impact**

Impact matrix has a value for each pair (13 research areas x 12 system characteristics): 156 possible, but only 18 are nonzero.

Impact can be positive or negative:

- Impact(targeted observing, observation density) = low neg.
- Impact(launch new data source, observation density) = low

Some more examples:

- Impact(targeted observing, targeting efficiency) = low
- Impact(system mgmt/tuning, cpu efficiency) = low
- Impact(adaptive grid, simulation efficiency) = medium
### Impact Matrix

<table>
<thead>
<tr>
<th></th>
<th>Assimilation efficiency</th>
<th>Assimilation density</th>
<th>Cpu efficiency</th>
<th>Data efficiency</th>
<th>Downlink density</th>
<th>Ensemble efficiency</th>
<th>Model framework</th>
<th>Observation density</th>
<th>Postprocessing effectiveness</th>
<th>Simulation efficiency</th>
<th>Targeting efficiency</th>
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<td>data-efficient simulations (same data size)</td>
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### Qualitative → Quantitative

Impact is parameterized qualitatively (lo, med, hi). This qualitative scale is then quantified inside the model.

Each of the parameters has a different interpretation under the four scenarios (pessimistic, consensus, optimistic, ideal). This allows us to compare in a best-case vs. worst-case manner.

<table>
<thead>
<tr>
<th></th>
<th>pess.</th>
<th>cons.</th>
<th>optim.</th>
<th>ideal</th>
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<tbody>
<tr>
<td>Lo</td>
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<td>1.0</td>
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<tr>
<td>Med</td>
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<td>.3</td>
<td>.4</td>
<td>1.0</td>
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<tr>
<td>Hi</td>
<td>.3</td>
<td>.5</td>
<td>.7</td>
<td>1.0</td>
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</table>
Instantiating the Model

System Priorities Model: designed/owned by program manager cognizant of NASA priorities

System Priorities Model computes overall System Value given the System Metrics.
Review: Combining the Models

Remember: results (evaluations, ROI, etc.) must be understood as a function of the inputs used to calculate the results:

\[ f(\text{model, assumptions, priorities}) \]

Priorities depend on perspective:
we model basic (science value only) versus applied (economic value only)

Results: Caveat
Evaluating Research Areas

- Basic: launch new data source (35M) & targeted observing (22M)
- Applied: data-mining (2.5B) & improved ensemble methods (1.5B)
**Sensitivity Analysis**

Sensitivity to “optimism” variable: two research areas have vastly higher potential impact under ideal assumptions. Pessimistic view of data-mining exceeds optimistic assessment of other areas.

**Synergy Between Research Areas**

We can look for synergies by finding pairs of research areas with much higher value than the two areas individually...

Under the applied research focus:

**Biggest synergies**

- Launch new data source ($1.5B) + targeted observing ($1B) yields a synergy of $700MM

- Launch new data source ($1.5B) + data-efficient simulations ($800MM) yields a synergy of $400MM
Understanding the Model

BLUE OVALS summarize the way that system changes flow through the assessment model. We can diagnose our assumptions by analyzing how these variables vary as we vary research area.

Agenda

CICT Systems Analysis

Our modeling approach
   – a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned
Modeling lessons learned...

Model and modeling technology should be:
- understandable and easy to use

and should support:
- varying levels of detail (qualitative→quantitative)
- varying scope
  (cross-cutting value as well as mission-specific value)
- development of models by distributed stakeholders
- multiple uses / answer multiple questions
- varying assumptions/priorities
- communication/debate/collaboration

Lessons learned...

- Model preferences of different stakeholders explicitly
- Allow for easy variation in assumptions ("what if our model is wrong? ...our estimates overly optimistic?")
- Compare impact of each technology to a no-investment baseline
- Make models modular and decoupled:
  technology investments →
  system characteristics →
  performance metrics →
  "return" or "mission value"
  (three arrows == three submodels)
End of workshop talk...

Full report is available at http://support.thinkbank.com/essa-final
Multi-Mission Strategic Technology Prioritization Study


"Systematic Technology Prioritization For New Space Missions"

Humphrey's Half Moon Inn, San Diego, CA

Jet Propulsion Laboratory
California Institute of Technology
April 22, 2004

Acknowledgements

• C. Moore, Y. Gawdiak, D. Craig, M. Hirschbein for encouragement and support in undertaking this study

• M. Steiner, J. Azzolini for providing data about remote observation instrument technology

• P. Troutman for assisting in collection of data for the OASIS reference missions, and E. Kolawa for data about extreme environments

• S. Prusha for assisting in selection of ECS technologies to analyze; M. Feather for providing information about correlations of tasks and needs
Study Staff & Roles

➢ JPL

- J. Derleth, Mission & Technology Portfolio Optimization
- A. Elfes, ECS Data & Analysis
- B. Kennedy, ECT Data & Analysis
- R. Manvi, Tech Life Cycle & Risk Management Model
- K. Shelton, Mission & Technology Data Base
- J. H. Smith, Integrated Risk Analysis
- G. Rodriguez, System Analysis

➢ GSFC staff (M. Steiner, J. Azzolini, J. Mapar, C. Stromgren)

Study Objectives

- Perform a pilot study of sufficient breadth which demonstrates in an auditable fashion how advanced space technology development can best impact future NASA missions
  - Include wide spectrum of missions & technologies
  - Can add new missions & technologies easily
  - Optimize technology portfolios
  - Lead to rapidly prototyped example

- Show an approach to deal effectively with inter-program analysis trades

- Explore the limits of these approaches and tools in terms of what can be realistically achieved (scope, detail, schedule, etc.)
Technology Portfolio Optimization Approach

- Collect performance data for many individual technologies; each data input is viewed as a statistical sample representing an expert assessment
- Group the technological data into a tree-like hierarchical model to predict "integrated" system, mission, and multi-mission impact of individual technologies
- Search computationally for technology portfolios with optimal science return, risk and cost impact
- Investigate sensitivity of the optimal portfolio to changes in available budget levels

Major Study Challenges

- **Reference Missions**: assess mission value; characterize capability requirements
- **Technology Projections**: characterize performance; manage widely dispersed and non-uniform data
- **Uncertainty**: incorporate & manage widespread uncertainty
- **ROI Measures**: formulate suitable value function for portfolio analysis
- **Layers of Abstraction**: choose and maintain appropriate level of analytical abstraction
- **Technological Boundaries**: boundaries of technology domains not clearly marked
- **Many Scales**: large differences in cost and performance scales for different technologies
- **Performance Parameters**: not fully understood for some technologies
- ...
Implementation Approach

- Iterative in three phases (keep eye on big picture early, and continuously)
  - Phase 1 minimalist multi-mission set; ECT/ECS technologies
  - Phase 2 more extensive set of missions & technologies (June 04)
  - Phase 3 completion of full study (December 04)

- Maintain high degree of connectivity
  - Space Architect
  - Revolutionary Mission Concepts
  - Advanced Space Technology Programs
  - Enterprises
  - Centers
  - Etc.

Pilot Study Reference Missions

(Organized by Science-Site Location)

- Inner Solar System
  - Venus Surface (1-site land)
  - Venus Surface (Multi-site-land)
  - Comet Sample Return

- Earth Observation
  - Biomass**

- Earth’s Moon
  - OASIS*
  - Lunar Sample Return
  - Remote Lunar Survey**
  - LunarPrecursor Resource Survey

- Mars
  - Mars Science Lab
  - Mars Scout Line
  - Mars Astrobiology Lab
  - Mars Sample Return

- Outer Solar System
  - Titan Surface
  - Europa Lander

➢ Initial reference mission set as of April 15, 2004
➢ More missions and enabling technologies will be added throughout the period of performance of the study

* OASIS is a near Earth transportation infrastructure that enables access to the Moon. It consists of: a Hybrid Propellant Module, a Chemical Propulsion Module, a Solar Electric Propulsion Module, and a Crew Transport Vehicle.

** GSFC contribution to this study focuses on these missions
## Reference Missions & Major Challenges
(Minimalist Mission Set for PHASE I)

### Reference Mission Classes (not listed in order of priority)

<table>
<thead>
<tr>
<th>Earth’s Moon: Orbital Aggregation and Space Infrastructure Systems (OASIS); Lunar Remote Survey; Lunar Surface Missions; etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Challenges</td>
</tr>
<tr>
<td>Deep Space Robotic Rendezvous &amp; Docking; Long Term Cryogenic Fuel Storage in Space (&gt;2 years); Long Life Ion Engines (&gt;15 K-hours)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mars Surface: (e.g. Mars Science Laboratory; Astrobiology Field Lab; Mars Sample Return; etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Challenges</td>
</tr>
<tr>
<td>Long-Range, Long-Life Mobility (10’s of kilometers, &gt;600 sols); Substantive Sample Collection and Return (&gt;1kg, 0&lt;depth&lt;100m subsurface)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Earth Observation: Biomass</th>
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</thead>
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<td>Major Challenges</td>
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<tr>
<td>Lidar/Radar Instrument Systems; Multi-Spectral Scanner; Sensor Webs &amp; Data Fusion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outer Solar System: Titan Surface; Europa Lander</th>
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<tbody>
<tr>
<td>Major Challenges</td>
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<table>
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<tr>
<th>Inner Solar System: Venus surface; comet sample return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Challenges</td>
</tr>
</tbody>
</table>

- Technologies to be evaluated will include:
  - Technological products in several discipline fields (aimed at operational flight system implementation (e.g. advanced materials, structures, etc.)
  - Risk assessment tools and infrastructure to allow for risk quantification, and risk mitigation during an entire mission life-cycle, but that do not necessarily appear in the flight system implementation (e.g. risk management methods)  

## Enabling Technologies for Which Data Has Been Collected to Date

- Extreme Temp & Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics (Venus)

- Electric & Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage & Control; Syntactic Foams, Formation Flying (OASIS)

- Entry Descent & Landing; Surface, Aerial, Subsurface Mobility; Manipulation, Drilling, Sampling (Mars, Titan, Comet, Lunar Surface)

- In-Space Inspection, Maintenance, Assembly (OASIS, Large Observatory Platform, Gateway, Space Solar Power)

- Risk Methods, Tools and Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization & Visualization; etc. (All Reference Missions)
Enabling Technology Areas
(for which data has been collected to date)

<table>
<thead>
<tr>
<th>Enabling Technology Areas</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric &amp; Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage &amp; Control; Syntactic Foams, Formation Flying; In-Space Robotic Inspection, Maintenance, Assembly</td>
<td>OASIS</td>
</tr>
<tr>
<td>Entry Descent &amp; Landing; Surface, Aerial, Subsurface Mobility; Manipulation, Drilling, Sampling</td>
<td>Mars, Earth’s Moon, Titan, Comet</td>
</tr>
<tr>
<td>Risk Methods, Tools &amp; Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization &amp; Visualization; etc.</td>
<td>All</td>
</tr>
<tr>
<td>Extreme Temp &amp; Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics</td>
<td>Venus, Titan, Europa</td>
</tr>
</tbody>
</table>

Technology Areas are Decomposed into Many Sub-Areas & Performance Parameters

<table>
<thead>
<tr>
<th>A Few Typical Technology Areas</th>
<th>A Few Typical Technology Sub-Areas</th>
<th>A Few Typical Performance Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Function Structures</td>
<td>Modular, Distributed Structures, Deployable Structures, etc.</td>
<td>Contract/Extend (cm), Power per Mass (W/kg), etc.</td>
</tr>
<tr>
<td>Fuel Storage &amp; Control</td>
<td>On Orbit Cryogenic Fuel Transfer, Tank Pressure Control, Fuel Storage, etc.</td>
<td>Flow Rate (kg/min), Pressure (kPa), Time (yrs), etc.</td>
</tr>
<tr>
<td>Subsurface Ice Mobility</td>
<td>Range, Radiation Dose, Payload Capacity, Ambient Pressure, etc.</td>
<td>Distance (km, mRads), Mass (kg), Pressure (atm), etc.</td>
</tr>
<tr>
<td>Extreme Temperature &amp; Pressure Components</td>
<td>High Temperature Electronics, Permanent Magnets, Energy Storage, etc.</td>
<td>Temperature (Celsius), Pressure (Bars), Energy Density (Whr/l), etc.</td>
</tr>
<tr>
<td>Risk Methods, Tools &amp; Workstation</td>
<td>Model Based Risk Analysis, Mission Risk Profiling Capability, etc.</td>
<td>Accessibility, applicability to multiple mission phases, risk mitigation coverage</td>
</tr>
</tbody>
</table>

This is an early draft for April 19th, 2004. Please do not distribute.
### Mission & Technology Data Base

--- Current Size Summary ---

- **Size of Mission & Technology Capability Data Base (as of April 15, 2004)**
  - 13 missions covering wide spectrum of NASA strategic plans
  - 23 technology areas (structures, energetics, extreme environments, surface mobility, etc.)
  - 86 technology sub-areas (batteries, payload capacity, thermal control, etc.)
  - 167 technological performance parameters (power density, operating temperature, etc.)

- **Remarks About Data Base**
  - Current data set is more detailed in some areas than in others
  - More technologies & detail will be collected in subsequent phases
  - Our analysis methods can handle data sets with non-uniform detail

---

This is an early draft for April 15th, 2004. Please do not distribute.
Risk Related Requirements
(from Point of View of a Project Manager)

- **Risk Management Must:**
  - Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules; estimate and rank risk levels
  - Provide ways to visualize risk elements, time profile, and mitigation strategies
  - Assure that the systems and trade analysis includes cost, performance, and risk
  - Provide auditable benefit/cost of implementing begin-to-end risk mitigation strategies

Connecting Risk Technologies to Requirements

**Requirements:**
- Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules; estimate and rank risk levels
- Provide ways to visualize risk elements, time profile, and mitigation strategies
- Assure that a substantial portion of the design space is explored including cost, performance, and risk
- Provide auditable benefit/cost of implementing end to end risk mitigation strategies

**ECS: Engineering of Complex Systems**
- SRRM: System Reasoning and Risk Management
  - KESS: Knowledge Engineering for Safety and Success
  - RSO: Resilient Systems and Operations
### System Reasoning and Risk Management (SRRM) Project Executive Summary

**Goals**
- Advance scientific and engineering understanding of system risk, complexity, and failure.
- Develop processes & tools to identify, characterize, mitigate, trade, and track full lifecycle mission risks.

**Objectives**
- Better identification and characterization of system risks and their relationship to components.
- Improve design through early identification and trading of risk during the early cycle.
- Improve breadth and accuracy of risk analysis and methods.
- Combine disparate data, models, and risk assessment tools and capability.

**Challenges**
- Risks not well understood or well characterized, especially in early design phases.
- Risk not an inherent resource in design tradeoffs.
- Data and interactions in complex systems are difficult to model and visualize.
- Integration of tools & data of differing detail, context, and pedigree for variety of decision-makers.

**Approach**
- Analyze & model events and interactions which have lead to system mishaps and failures.
- Develop capability to fully characterize and model risk signatures early and consistently.
- Mature & improve fidelity of subsystem models to capture failure modes and consequences.
- Broaden the design space by fully integrating models and demonstrating the utility of risk as a tradable resource.

**Technology Performance Attributes**
- **Accessibility of historical risk event data**
- **Potential to understand and reduce design risks and optimize resources to retire risks**
- **Risk model enhancement (potential for better model credibility)**
- **End-to-end risk integration for breadth of domain**
- **Degree of Alignment (Effectiveness in percent)**

#### Attribute Definitions

<table>
<thead>
<tr>
<th>Attribute Definition</th>
<th>Best Case</th>
<th>Worst Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility of risk data</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Easy to use DB spans multiple mission/projects with risk events categorized for search. DB may be limited to specific category or series of missions. Supporting data/verifications are anecdotal (narrative) format without categories of risk events for easy search. May require further processing to another format.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential to reduce design risks</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Technology helps to identify and reduce risks during early phases of project (Phase A/B) with potential to dramatically reduce overall project costs by reducing rework. Technology helps identify/ reduce mission risks for Phase C/D; Large potential cost benefits if used. Provides a screen that limits potential risks from passing CDR. Technology helps identify technology development or subsystem risks, but may or may not influence overall system risk.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk model enhancement</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Technology provides new approach for addressing design risk life-cycle or part of life-cycle not previously addressed (e.g., mgmt, org, risks) Technology either provides new, more effective approach for risk analysis or fills missing gap in temporal or breadth of risk analyses (but not both) Technology does not address missing gap in design life-cycle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-to-end risk integration</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Technology provides synergistic integration with other tools and databases fully compatible with emerging design environments (temporal and breadth). Risk technology allows interaction with common databases but cannot be integrated with other stand-alone applications. Technology is stand-alone; focused, narrow; little breadth or temporal range, databases are separated with little or no connectivity. Integration difficult.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
All SRRM Technology Areas Are Included for the Pilot Study

1. Risk Methods/Tools (RMT)
2. Risk Workstation (RWS)
3. Mishap/Anomaly Database (MAIS)
4. Model-Based Hazard Analysis (MBHA)
5. System Complex Research (SCR)
6. Risk Characterization/Visualization (RCV)
7. Risk-Based Design (RBDO)
8. Data Mining Research (DMR)
9. Investigation Methods/Tools (IMT)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Level</th>
<th>Metric</th>
<th>Unit</th>
<th>Polarity</th>
<th>SOA</th>
<th>Low</th>
<th>ML</th>
<th>High</th>
<th>$M</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECS</td>
<td>1</td>
<td>How performance is measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRRM</td>
<td>2</td>
<td>Accessibility of Historical Risk Event Data</td>
<td>0-10</td>
<td>+</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>RISK Methods &amp; Tools</td>
<td>4</td>
<td>Potential to Understand and Reduce Design Risks and Optimize Resources to Retire Risk</td>
<td>0-10</td>
<td>+</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Risk Model Enhancement (Potential for Better Model Credibility)</td>
<td>0-10</td>
<td>+</td>
<td>2</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>End-to-end Risk Integration for Breadth of Domain</td>
<td>0-10</td>
<td>+</td>
<td>2</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extent of Needs Covered</td>
<td>0-1</td>
<td>+</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

*SRRM data cast in same format used for all other technologies (shown in slide 14)
## Mission-Technology Complexity Map

### Analysis Options Used to Get Typical Results in Slides 25-30

<table>
<thead>
<tr>
<th>Analysis Options Used</th>
<th>Other Options Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform science-return value for all missions</td>
<td>Can assign non-uniform science return value (user prescribed)</td>
</tr>
<tr>
<td>Uniform value for all technologies at the same hierarchical level; “democratic” hierarchy</td>
<td>Can prescribe general technology organizations; based for example on mission and system decomposition</td>
</tr>
<tr>
<td>Technology correlations and co-dependencies set to zero</td>
<td>Can explicitly include correlation &amp; co-dependency parameters when available</td>
</tr>
<tr>
<td>Risk estimates based only on performance uncertainty</td>
<td>Can include cost, schedule and other risk factors</td>
</tr>
<tr>
<td>Identical development time (~10 yrs) for all technologies</td>
<td>Can vary technology development time as a model parameter</td>
</tr>
<tr>
<td>TRL data not included in technology projections</td>
<td>Can analyze TRL data within existing analysis framework</td>
</tr>
</tbody>
</table>
Estimated Impact of Technology Budgets on Missions Enabled

High funding

Medium funding

Low funding

Combined est. Mission Success % and Tech Area investment Suggestion

In Space Assembly
Surface Technologies
OASIS
ECS Technologies
Extreme environments
Average % to enable all missions:

Approximate Average % chance of enabling all missions
Concluding Remarks

• Study Results to Date (January-March, 2004)
  – Initial data base for 13 missions and 167 technology performance parameters in 23 technical areas, representing Code T,S,M,Y enterprises
  – Rapidly prototyped analysis capability to evaluate impact of technological investment on science and exploration return

• Work Remaining (April-December, 2004)
  – Expand data base to include more enabling missions and technologies (e.g. modular distributed structures, etc.)
  – Conduct more in-depth analysis of the representation and fidelity of the existing data set, and a more detailed treatment of the consistency and integration across program elements
  – Calibrate data base and analysis with extensive WHAT-IF computational
Appendix B: Records of Group Discussions

Questions for Working Groups

1. In prioritizing technology development for missions, how should the relative values of the missions be assessed and quantified? (one measure of relative worth is the value that NASA is willing to pay for these missions, but there may be better figures of merit in terms of information returned? How do you compare value of technology supporting Station to that supporting Mission to Planet Earth? Within Space Science, how would the value technology contribution to a Mars sample Return be compared to that which supports a Europa mission?

Possible Answers

1. Should mission (= flight project) value be assessed at all?
   - Value is always assigned: current processes do this in a non-traceable, non-auditable way.
   - Has to be done, so that we can improve on today’s process.
   - Difference between valuation theory and results vs. x decision-makers final assessment.

2. Who should do it? Can it be done? (problem of different stakeholders)
   - Code B assesses relative value of missions (they allocate resources to Enterprises):
     - Ex: 18 theme areas and 3 mission areas: high, medium, low ranking.
   - Enterprises: Code B apportions resources as a block to Enterprises
     - Enterprises prioritize missions
   - Executive Council, Joint Strategic Assessment Committee.
     - Science Groups/Project Managers: Prioritize missions.
Possible Answers

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Questions for Working Groups

2. There are many architectures that might purport to enable a mission concept, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?

   - How do we get functional requirements at pre-phase A stage?
   - Are there better ways to define the science/ops interface than fitting the boxes a posteriori?
Possible Answers

1. **Is it possible to obtain mission capability requirements at this stage?**
   
   - Science mission concepts are typically more mature/have clearer objectives than human missions.
   - Assume new undefined missions requirements can be drawn from a spectrum of past missions
   - Assume that the requirements evolve from the technological state of the art (technology push) and iterate

2. **Advantages and disadvantages of requirements**
   
   - "Requirements" are not ironclad, have to be negotiable. Requirements have to be coupled with affordability and serve as a basis for negotiation.
   - Requirements should be expressed quantitatively. Requirements are different from specs. Quantification of requirements brings problems, but also allows one to know when one is done.

3. **Defining mission concepts involves working in a very large trade space. How do you search it?**
   
   - Search trade space hierarchically, keeping the number of options low at each level.
   - Delay decisions on final designs: NASA tends to dive into a specific point design too early. A more extensive assessment of the trade space, keeping uncertainties and open options, allows a broader, more valuable set of technologies to be developed. On the other hand, there are huge costs associated with keeping options open.

4. **What technologies should be funded?**
   
   - General technology areas can be extracted from early mission concepts, and these should be funded.
   - Insist that each mission concept study provides one or more functional decompositions (stored in a database). Since there is only a limited number of feasible architectures, they can be specified and a common set of relevant technologies extracted. Also identify key enabling technologies and perform gap analysis.
   - Sustainability is essential, not just affordability. Reusability: define/develop technology building blocks that can be "robust" and used across different missions. Avoid cutting off early promising technology paths. Temporal impact of technologies has to be taken into account.
Questions for Working Groups

3. How do we systematically acquire credible information on technology development (cost/performance estimates and associated uncertainty, temporal and functional correlations etc.) which might seek to satisfy capability requirements.

Possible Answers

➢ Add extra fields as part of the Technology Inventory collection process

➢ Augment the existing CRAI activity with independent review.

➢ Examine the limits of what might be feasible; remember to strive for plausibility not perfect accuracy

➢ Have NASA pay for this data acquisition as part of system studies

➢ Develop models based on historical data
Questions for Working Groups

4. What is the best methodology to perform technical risk assessments and mitigations; is the evaluation of these fundamentally different from the discipline product technologies (e.g. sensing, manipulation, mobility etc.).

Possible Answers

- Based on experience, assess the objectivity and usefulness of quantitatively measuring relative reliability gain associated with improved risk methodologies
- Based on mission experience, determine whether new risk methodologies are needed.
- Risk technologies Can/Cannot be blended uniformly into a prioritization methodology
Questions for Working Groups

5. What are the criteria management needs to take and use the results of such a structured analysis.

Possible Answers

- Need a sense of confidence in the overall mission requirements and technological characterization
- Consistency with the unstated policies from NASA (re: value, pull/push, etc.)
- Timely response
- Data acquisition process needs to be feasible from the viewpoint of overall effort.
Questions – Day 1

How do we systematically acquire credible information on technology development (cost/performance estimates and associated uncertainty, temporal and functional correlations, etc.) which might seek to satisfy capability requirements?

- Credible: presentation would be plausible as seen by an independent review team

Are the data models and assumptions traceable and transparent?
- Workshop for credibility review
- Peer reviews/third party teams
- Explicit inclusion of uncertainty for high risk or non-legacy items
- Matching capability requirements to technology tasks

Sustainable process? (i.e., are iterations easier than first bounce?)
- POP process as a vehicle for data generation -- incentives for proper behavior
- Continuing reevaluating process
- Quarterly review with researchers and mission experts

Are all valid viewpoints considered?
Do you have an estimate of the robustness of the conclusions?
Do independent review teams have recommendations?
B. What is the best methodology...

- How can the representation and assessment of risk estimation/software technologies be made consistent with those of the discipline product technologies (e.g., sensing, manipulation, mobility, etc.)?
  - Important to have researchers state what kind of metric they hope to impact; missions should provide goals
  - Look at cost impacts as well as performance impacts
  - Combine software and hardware at a capability level as opposed to a discipline level
  - State-of-the-art can be characterized, but perhaps the whole 'ecosystem' of software should be looked at, not, for instance, an algorithm...

C. What are the criteria that management needs...

- What are the criteria that management needs to take and use the results of such a structured analysis?
  - Analysis has to support/defend the eventual decision to OMB and GAO and others
    - Traceable, transparent, understandable, presented in a concise way
    - Make issues explicit, identify problem areas
  - Analysis has to address what the decision maker cares about -- metrics, alternatives, etc.
  - Context is decision support
    - Cast as risk vs. cost; benefit vs. cost;
    - Provide options - not point solutions
      - Preferably with recommendations and justifications (not just negatives and consequences); span decision space
    - Digestible products tuned to appropriate level
In prioritizing technology development for missions, how should the relative values of the mission be assessed or quantified?

There are many architectures that might purport to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?
There are many architectures that might purport to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?

- Missions map to technologies that map to metrics
- Architectures are snapshots of different technology metric sets
- Compare the architectures indirectly by evaluating their technology portfolios and costs.

Functional decomposition derived from mapping of mission capability requirements to technology metrics.

1. Obtain capability requirements from mission(s) to level available
2. Get technology gaps from mission
3. Map relevant technologies to capability requirements
4. Derive performance metrics for technologies
5. Evaluate fulfillment of requirements by performance (simulation, modeling, figures of merit)
6. Weight by parametric mission values; sensitivity analysis

- Don’t over-weigh optimizations but consider level of precision; reserve some fraction for visionaries and spontaneous discoveries
- Consider approaches from other sectors (gov’t., non-NASA, public, etc.)
A workshop entitled, "Outstanding Research Issues in Systematic Technology Prioritization for New Space Missions," was convened on April 21-22, 2004 in San Diego, California to review the status of methods for objective resource allocation, to discuss the research barriers remaining, and to formulate recommendations for future development and application. The workshop explored the state-of-the-art in decision analysis in the context of being able to objectively allocate constrained technical resources to enable future space missions and optimize science return. This article summarizes the highlights of the meeting results.