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Advanced RLV Technologies Prioritization by the National Space Propulsion Synergy Team (SPST)

Milestone Deliverable
Contract NAS8-99060

April 30, 2001

Prepared for

Space Transportation Directorate
George C. Marshall Space Flight Center
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Prepared by

Science Applications International Corporation
6725 Odyssey Drive
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Pat R. Odom, Ph.D.
Kenneth W. Goode

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FOREWORD

The Space Propulsion Synergy Team (SPST) is a national volunteer organization of government, industry, and university experts in space propulsion and propulsion-related technologies that has provided specialized technologies assessment and prioritization support to the NASA Advanced Space Transportation Program (ASTP) for more than three years. In 1999 a process was conducted by the SPST that culminated in a workshop to assess and prioritize candidate advanced propulsion technologies for potential future applications to in-space robotic missions, including high thrust and low thrust earth orbital, lunar and planetary missions. In 2000 the process and workshop emphasis was on the prioritization of advanced propulsion technologies for potential application to third generation (Spaceliner 100) reusable launch vehicle (RLV) architectures. This year 2001, the effort culminated in a workshop to assess and prioritize potential technology solution areas derived from a SPST bottom-up assessment of impediments to achieving both third generation as well as second generation RLV system goals.

This report documents the results of the 2001 SPST workshop that was conducted during April 10 and 11 in the Collaborative Engineering Center (CEC) of the NASA Marshall Space Flight Center. The authors wish to acknowledge the input and support of the SPST leadership team in the preparation of this report including Walter Dankhoff, Executive Secretary of the SPST; David Christensen, Chairman of the SPST Steering Committee; Russel Rhodes, Leader of the Functional Requirements and Criteria Definition Team; Dan Levack, Leader of the Technologies Definition and Documentation Team; Dr. Jay Penn, Leader of the Bottom-Up Integrated Technology Team; John Robinson, Leader of the Architectures Assessment Team; and the entire team of technology evaluators who participated in the 2001 workshop and made it possible. Their names appear in this document. Finally, we acknowledge the special and dedicated expert assistance of Jordan Roddy, Brian Danylo, and Sandra Daniel, all of SAIC, in supporting the entire workshop process.

I would like to provide a special acknowledgement of the excellent work of (Kenneth W.) Wayne Goode in operating the facilitation software system during the workshop, and in processing and preparing all the data results for presentation in this document.

This report will be distributed primarily electronically, but paper copies will be made available to NASA and other interested parties by request.

Pat R. Odom
Workshop Facilitator

TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND

This document provides a summary of the results of the national Space Propulsion Synergy Team (SPST) sponsored workshop conducted on April 10 and 11, 2001, to prioritize a set of candidate technology areas to support the development of the next generations of America's reusable launch vehicle (RLV) systems. The workshop itself culminated a nine-month effort by the SPST to identify and define candidate technologies, recruit and orient a team of technology evaluators, and prepare for the use of a systematic, collaborative workshop process to facilitate the team's prioritization of the technologies.

This effort was undertaken originally to support the NASA Advanced Space Transportation Program (ASTP) Third Generation RLV (Hypersonics) technology investment planning inputs to the annual NASA budget cycle. However, the effort was partially funded by the Second Generation RLV program, and the results are applicable and should be useful to the Space Launch Initiative Second Generation RLV program.

The SPST strategy for identifying and prioritizing candidate propulsion and propulsion-related technology investments has included both top-down and bottom-up assessments. Top-down assessments represent the "technology pull" of advanced RLV system architectures and concepts. The bottom-up assessments derive from identification of the barriers or impediments to the development of advanced RLV systems that will be capable of meeting program goals. In April 2000 the national SPST conducted a workshop to prioritize a set of candidate propulsion technologies derived from a top-down assessment of potential architectures for third generation RLV systems. The April 2001 workshop was focused on the assessment and prioritization of propulsion-related technologies or technology areas identified as potential solutions to technical or operational impediments to achieving advanced RLV program goals.

In the sections to follow, the candidate technology areas assessed in the April 2001 workshop are identified (Section 2), the prioritization criteria are listed (Section 3), and the workshop participants are summarized (Section 4). An overview of the collaborative prioritization process and procedures used in the workshop is given in Section 5. Section 6 summarizes the results of the workshop. Section 7 provides an overall summary and conclusions to complete the report.

A list of references is provided as Section 8. Appendix A provides the baseline collaborative technologies prioritization results at the individual assessment criterion level as generated in the April 2001 workshop.

2. CANDIDATE TECHNOLOGIES

The SPST assigned an Integrated Technology Team (ITT) led by Jay Penn of the Aerospace Corporation to undertake a detailed bottom-up assessment of impediments and potential technology solutions in the development pathway toward achieving third generation RLV system goals. The team's approach emphasized traceability to second generation systems and technologies. The team used "structured brainstorming" to identify technologies and concept solutions that directly address system design criteria such as those developed over the past several years by the Functional Requirements Team of the SPST led by Russel Rhodes of the NASA Kennedy Space Center.

A technology response matrix was produced by the ITT that correlated candidate technology solution responses to design criteria. The technology responses were in the form of new or augmented technology developments or design guidelines (for concepts and technologies).

The ITT conducted their work primarily using regularly scheduled teleconferences and electronically shared excel spreadsheet forms to record and discuss results.

The results of the work of the ITT were provided to the SPST Technologies Definition and Documentation Team led by Dan Levack of Boeing Rocketdyne. The Technologies Team organized the complete set of identified technologies into six categories for convenience of assessment and documentation. The Team then prepared a white paper briefing, according to a standard template format, for each candidate technology for use in the April 2001 Technologies Prioritization Workshop. The Team elected to use Space Shuttle systems and practice as the pivot or reference technology against which all the candidate technologies would be assessed for prioritization in the workshop. A white paper briefing was prepared for the Shuttle reference technology.

The details of the approach and process used by the ITT in identifying the candidate technologies are summarized in Reference 1. The white paper briefings are all contained in Reference 2. The reader is cautioned that the specific names of the technology briefings contained in Reference 2 may vary from the exact titles used elsewhere in this report; but the key words in the titles should be consistent for briefing identification purposes.

The resulting 26 candidate technologies for assessment in the April 2001 workshop are listed as follows, organized into the six selected categories.

Technologies for Prioritization
At the April 2001 SPST Workshop

Pivot or Reference Technology: Current Space Shuttle System and Operations

IVHM Technologies

1. Critical Failures Identification – 100% IVHM data to identify all credible critical failures in adequate time to implement corrective action/abort.

2. Systems Health Verification – Provide totally integrated/automated functional health verification for all systems.

3. Automated Predictive Maintenance – Automated predictive maintenance capability designed-in as part of component development.

4. Preflight Checkout – IVHM does all preflight; visible check only required

Margin Technologies

5. Air-Breathing Main Propulsion – Develop all air-breathing concept (including ejector rocket, subsonic LACE, combined cycle) system alternatives that have benefit measured in payload to dry weight ratio and with an acceptable level of complexity. Solve as an integrated solution using comparable (to rocket) techniques.

6. Lightweight Subsystems – Develop lighter weight propulsion subsystems.

7. High Performance Subsystems – Develop higher performance propulsion subsystems (higher Isp, lower temperature, lower pump pressure, longer life subsystems).

Operations Technologies

8. Elimination of Support Systems – Development of critical technologies eliminating the need for support systems; e.g. self-contained engine valve and TVC actuators, eliminating requirement for distributive pneumatic and hydraulic systems.

9. Elimination of Turnaround Operations - Develop technologies that eliminate operation associated with turnaround of propulsion system (no purging/cleaning operations).

10. Leak Free Joints – Develop leak free joints in propulsion system (including H2).

11. Simplified Mating Operations – Develop simplified mating operations technologies (automated alignments, fluid connections, and interface checks).

12. Passive Aero Solutions – Develop technologies to utilize passive aerodynamics to minimize venting and purging requirements and eliminate the use of closed compartments.

13. Single Main Propellants – Use same main propellants in multiple stage vehicles.

14. Wireless Communication – Develop and mature wireless communication technology required to eliminate flight-to-flight and ground-to-ground umbilicals.

15. Cleaning Alternatives – Develop environmentally acceptable materials/cleaning alternatives that do not substantially compromise performance.

16. Cryogenic Conditioning – Minimize the need for cryogenic conditioning to start vehicle engines.

Safety Technologies

17. System Failures Tolerance – Develop the ability to tolerate credible system failures (e.g. contain an engine blade failure).

18. Pyrotechnics Elimination – Eliminate all pyrotechnic devices in favor of highly reliable, reusable mechanical devices.

Thermal Control Technologies

19. Active TPS Elimination – Develop use of ultra high temperature ceramics to eliminate active TPS and explore a wider range of TPS technologies in an operational environment including transpiration cooling, ablatives, heat sinks, passive aero techniques (search for fundamental thermodynamic technologies).

20. Active Thermal Control Elimination – Develop generic technologies that eliminate active thermal management systems.

Technologies to Reduce the Number of Systems

21. All Rocket Cycle – Use of all rocket cycle propulsion technologies.

22. Integrated Propulsion/Thermal/Power – Use of technologies to

integrate Reaction Control System (RCS), Orbital Maneuvering System (OMS), Main Propulsion System (MPS), Thermal Management, and Power Generation into one system.

23. Integrated RCS/OMS/MPS – Use of technologies to integrate RCS, OMS, and MPS into one system.

24. Integrated RCS/OMS – Use of technologies to integrate RCS and OMS into one system.

25. Residual Gases Utilization – Component development to allow use of unusable residual gases for propulsion functions.

26. MPS Low Thrust Mode for OMS – Use of a very low thrust MPS mode for the OMS propulsion function.

3. PRIORITIZATION CRITERIA

This section summarizes the technical and programmatic criteria identified and defined by the national Space Propulsion Synergy Team over the past several years (Ref. 3) for use in assessing and prioritizing candidate propulsion (and propulsion related) technologies for the development of advanced RLV systems. These criteria have been weighted by the SPST Functional Requirements (and Criteria Definition) Team led by Russel Rhodes of the NASA Kennedy Space Center using a structured Quality Function Deployment (QFD) process. All the criteria and their weights were loaded into the facilitation software used by the evaluation team at the April 2001 Technologies Prioritization Workshop.

The evaluation team in the workshop assessed and scored each candidate technology area identified in the preceding section of this report against each of the technical and programmatic criteria as described in Section 5. For each candidate technology area, the evaluator considered the question, "What is the potential of this technology area compared to current Shuttle technology or practice, to positively contribute to achieving the given technical or programmatic criterion for advanced RLV systems?"

The 25 technical criteria and their weights are listed as follows where the plus or minus sign indicates the "direction of goodness"; i.e. a plus indicates that "more is better", and a minus indicates "less is better".

Technical Criteria

Criterion	Weight (%)
Number of different propulsion systems (-)	6.48
Number of active components required to function including flight ops (-)	5.87
System margin (+)	5.66
Number of toxic fluids (-)	5.51
Percentage of propulsion system automated (+)	5.43
Number of unique stages (flight and ground) (-)	5.38
Design variability (-)	5.17
Number of active on-board space systems required for propulsion (-)	5.06
On-board propellant storage and management difficulty in space (-)	5.04

Technology readiness level (-)	4.73
Number of different fluids in system (-)	4.50
Number of propulsion subsystems with fault tolerance (+)	4.43
Mass fraction required (-)	4.31
Increased (Average) Isp on reference trajectory (+)	3.45
Number of umbilicals required to launch the vehicle (-)	3.07
Number of engines (-)	3.05
Resistance to space environment (+)	2.98
Number of active engine systems required to function (-)	2.75
Integral structure with propulsion systems (+)	2.66
Number of modes or cycles (-)	2.53
Number of ground power systems (-)	2.52
Amount of energy release from unplanned reaction of propellant (-)	2.44
Margin, mass fraction (+)	2.39
Margin, thrust level / engine chamber pressure (+)	2.35
Number of engine restarts required (-)	2.24
Total	100.00 %

The programmatic criteria are divided into two subsets: Program Acquisition Phase criteria and Technology R&D Phase criteria. The SPST Functional Requirements Team working with the NASA customer has separately weighted each of these subsets of criteria. The criteria and their weights are as follows:

Program Acquisition Phase Criteria

Criterion	Weight (%)
Number of major new technology development items (-)	20

Technology readiness at program acquisition milestone: TRL 6 + margin (+)	16
Time required to establish infrastructure (schedule of R&D phase) (-)	12
Total system DDT&E concept development and implementation cost (-)	12
Infrastructure cost: Initial system implementation (capital investment) (-)	12
Technology capability margin (performance as fraction of ultimate) (+)	11
Number of other options available (+)	10
Items requiring major ground test articles and demonstration (-)	7
Total	100%

Technology R&D Phase Criteria

Number of technology breakthroughs required to develop and demonstrate (-)	14
Estimated time to reach TRL 6 from start of R&D (-)	13
Number of operational effectiveness attributes addressed for improvement (+)	13
Current TRL (+)	11
Number of full-scale ground or flight demonstrations required	11
Cost to reach TRL 6 (-)	10
Number of operational effectiveness attributes previously demonstrated (+)	9
Number of related technology databases available (+)	7
Number of new facilities required costing over $2M (-)	7
Total annual funding by item at peak dollar requirements (-)	4
Number of multi-use applications including space transportation (+)	3
Total	102%

Note: The R&D Phase assessment criteria weights sum to 102% due to rounding to the nearest percent values. The weights were re-normalized in the final prioritization calculations based on the workshop input data.

4. WORKSHOP PARTICIPANTS

The team of 18 evaluators who participated in the April 2001 Technologies Prioritization Workshop was divided into a Technical subteam and a Programmatic subteam. David Christensen, Chairman of the SPST Steering Committee, recruited the Technical evaluators from across government, industry, and academia. Walter Dankhoff, Executive Secretary of the SPST, recruited the Programmatic evaluators for the workshop. The Technical evaluators assessed the candidate technology areas identified in Section 2 against the technical criteria listed in Section 3 of this report. The Programmatic evaluators assessed the candidate technology areas against the programmatic criteria listed in Section 3. The overall team was composed of six programmatic and twelve technical evaluators listed as follows:

Programmatic Evaluators

Ben Donahue
The Boeing Company

Vic Giuliano
Pratt & Whitney

Dave Goracke
Boeing Rocketdyne

Dr. John Hutt
NASA Marshall Space Flight Center

Pete Mitchell
SAIC

Phil Sumrall
NASA Headquarters

Technical Evaluators

Drew DeGeorge
Air Force Research Laboratory

Dr. Clark Hawk
University of Alabama in Huntsville

Larry Hunt
NASA Langley Research Center

Dave McGrath
Thiokol

Dr. Charles Merkle
University of Tennessee Space Institute

Scott Miller
General Dynamics

Dr. John Olds
Georgia Institute of Technology

Dr. Jay Penn
Aerospace Corporation

W. T. Powers
NASA Marshall Space Flight Center

John Robinson
Boeing Space and Communications

Costante Salvador
Pratt & Whitney

Larry Talafuse
Lockheed Martin

5. WORKSHOP PROCESS AND PROCEDURES

5.1 Prioritization Process Overview

The team of 18 technical and programmatic evaluators used a modified Analytic Hierarchy Process (AHP) to collaboratively prioritize the candidate technology areas within each of the six technology area categories as listed in Section 2 of this document. The AHP is a well-established (both by theory and wide applications) multi-criteria methodology for the prioritization of decision alternatives. In the current application, the decision alternatives are the set of candidate advanced RLV technology investment areas for consideration in NASA budget planning.

The AHP is based on establishing a hierarchy of technical and programmatic evaluation criteria (Fig. 5.1-1) that provide a basis for assessing and prioritizing the candidate technology areas. The criteria are defined to measure the potential of each candidate technology area to contribute to the achievement of third generation RLV program goals. The results should be also applicable to the achievement of second generation RLV program goals.

The criteria are weighted based on SPST assessments of their relative technical or programmatic importance in establishing the priorities of candidate technologies. As stated in Section 3 the SPST Functional Requirements task team has established these weights using Quality Function Deployment (QFD) techniques working with the NASA customer.

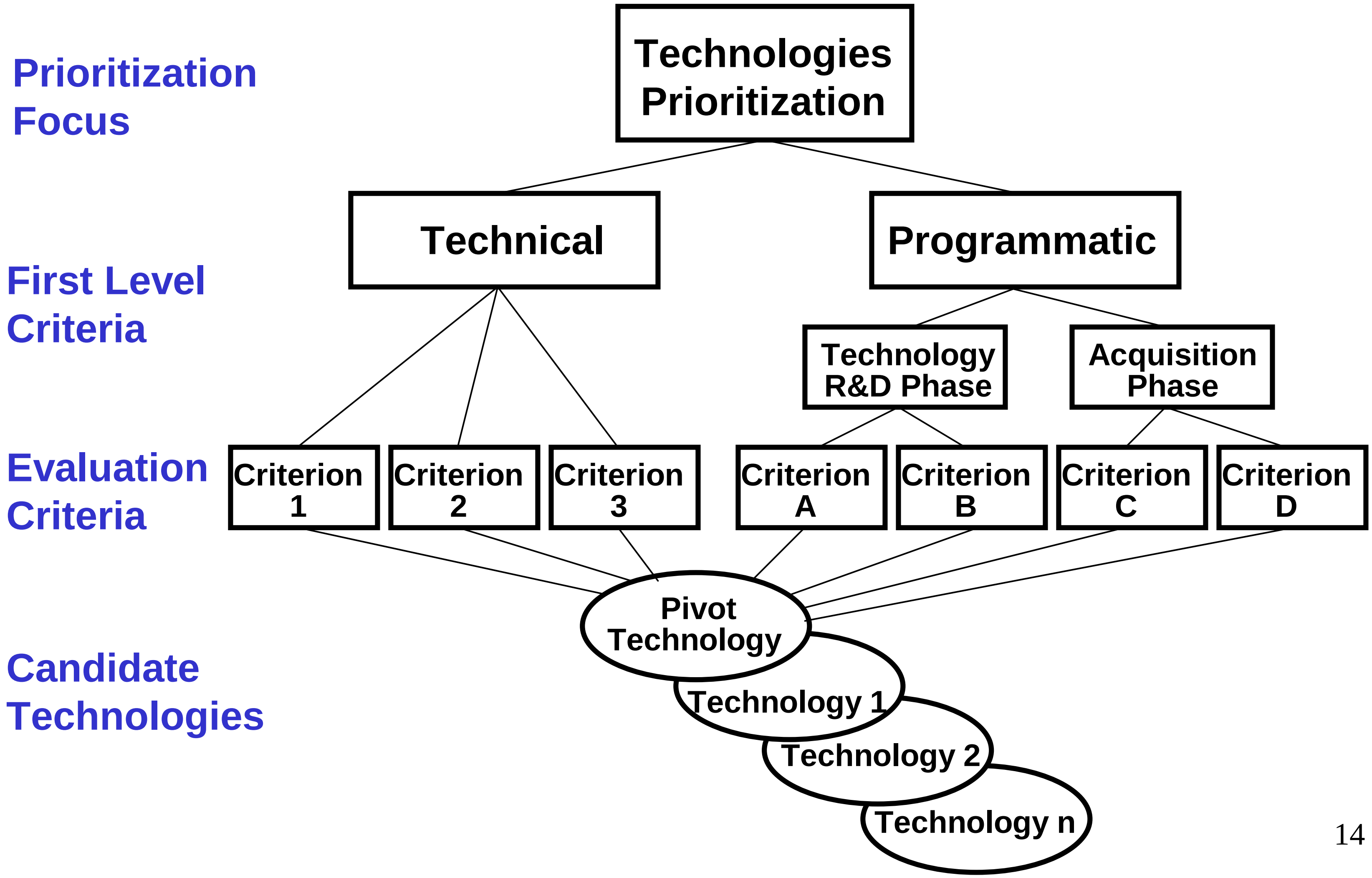
In order for the evaluators at the workshop to assess candidate technologies against the defined prioritization criteria, they must be provided with appropriate information about each of the technologies or technology areas. Such information was provided to the April 2001 workshop in the form of structured briefings on each candidate technology area prepared by the SPST Technologies Definition and Documentation Team led by Dan Levack of Boeing Rocketdyne. The Shuttle reference or pivot technology was briefed as a baseline for assessment of the potential contributions of the candidate technologies being prioritized.

All the briefings were posted and made available on the NASA Virtual Research Center (VRC) web site hosted at the Marshall Space Flight Center. Ten days before the workshop the evaluators were mailed an orientation package describing the prioritization process and procedures to be used at the workshop, defining the criteria to be used, and how to access the information on the VRC web site.

Given the candidate technology areas, and the definitions and weighting of the evaluation criteria, what remained was the requirement to collaboratively assess the candidate technology areas within each category. This was done on a pairwise basis relative to current Shuttle practice against the technical and programmatic criteria, and to roll up the weighted results to establish priorities. The computer-based AHP method developed by SAIC for the NASA Advanced Space Transportation Program (ASTP)

Figure 5.1-1

Analytic Hierarchy for Technologies Prioritization



provides a structured process to do the needed pairwise assessments (Fig. 5.2-1). The process asks each of the evaluators to systematically compare Candidate Technology Area A with the pivot or reference technology (Space Shuttle practice) against each evaluation criterion using the information contained in the technology briefings given at the workshop and the team discussions after each briefing. The purpose of the discussions is to share and level knowledge and understanding, address pertinent questions or issues, and provide a common basis for each evaluator's assessment of the candidate technology area. Each evaluator entered the pairwise comparison of Technology A versus Shuttle practice against each evaluation criterion into his computer software interface using a strength-of-comparison scale. Technology B was then compared to the reference (pivot) technology; then technology C was compared to the reference; then D, and so on until all technology areas in a given category were assessed. The facilitation software called ITIPS (Internet Accessible Technology Investment Prioritization System) processes all the team's inputs to produce prioritization results for review and post-processing into various formats for use by NASA.

In the Analytic Hierarchy Process, the strength-of-comparison scale measures the potential degree of advance over the current Space Shuttle state-of-the-art that a given candidate technology offers relative to a given assessment criterion. The scale is defined by both adjective levels and corresponding numerical values from 1 (no potential advance) up to 9 (potential for an exceptional advance over the current state-of-the-art). These inputs from the workshop evaluators were processed in a central database using the AHP algorithm, to calculate a collaborative, weighted priority vector for each set of candidate technology areas within a given category. The priority vector looks very much like a probability distribution with a component value for each candidate technology area such that the sum of the values equals one. The higher the value, the higher is the relative priority of the technology area being assessed.

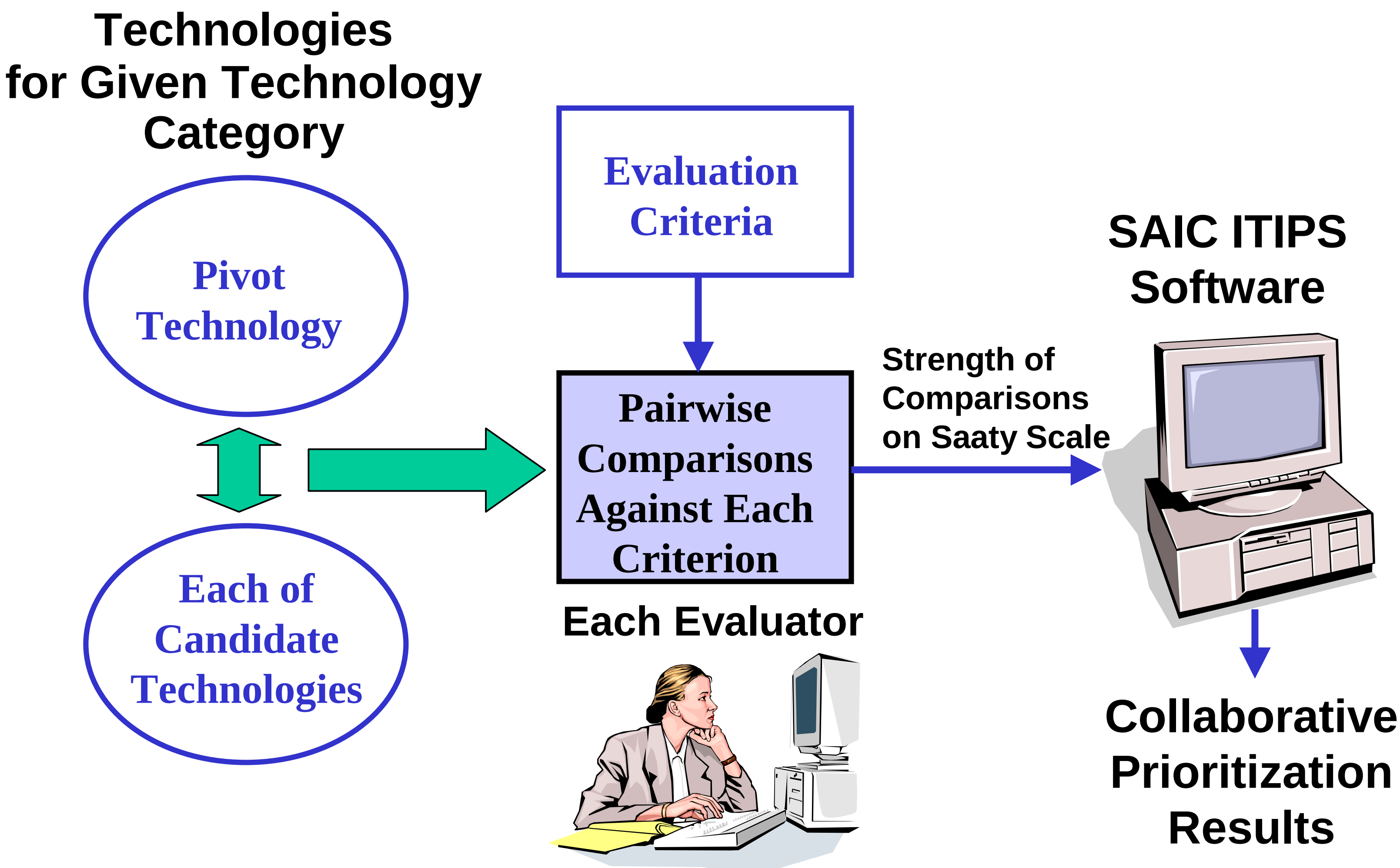
For example, assume that the workshop team's collaborative assessments of the four candidate technology areas A, B, C, and D in a given category are computed to be the priority vector (.243, .467, .096, .194). The highest priority technology area is B, followed by A and D clustered second and third priority. Technology Area C is a clear fourth priority. The priority component numbers sum to 1. Priority ratios are formed by dividing each priority component number by the highest priority number, .467. The resulting ratios are (.520, 1.0, .206, .415). Technology Area A has a priority 52% of the highest priority technology (Technology Area B). Technology Area C has a priority of only about 21% that of B; and Technology Area D has a priority 42%that of B. This provides a measure of the relative strength of the priorities computed by the collaborative inputs of the evaluation team.

5.2 Workshop Procedures

Mr. Bob Sackheim, Associate Director for Propulsion at the NASA Marshall Space Flight Center, welcomed all the technology evaluators, observers, the SPST leadership, and the facilitation team to the workshop, and stated the importance of the workshop team's input to MSFC. The workshop was conducted in the Collaborative Engineering Center

Figure 5.2-1

Collaborative AHP Data Entry



(CEC) at the Marshall Space Flight Center on April 10 and 11, 2001 from 8:00 am to 5:00 pm each day.

David Christensen, Chairman of the SPST Steering Committee, welcomed all participants and had everyone introduce themselves and their affiliation. The logistics and overall plan for the week, including the all-day national meeting of the SPST on April 12, following the two-day workshop was briefly discussed.

Dr. Pat Odom, the SAIC workshop facilitator provided an orientation briefing to all participants and reviewed the workshop agenda. Dan Levack of Boeing Rocketdyne, and leader of the SPST Technologies Team, gave an overview of the candidate technology areas to be assessed at the workshop. He briefly reviewed the process used by the SPST Bottom-Up Integrated Technologies team (ITT) in identifying the technology areas under consideration in the workshop. Dr. Jay Penn of the Aerospace Corporation led the ITT.

Russel Rhodes of the NASA Kennedy Space Center then provided a briefing on the technical and programmatic criteria to be used in the workshop. He answered questions concerning the criteria, their origin, their definition, and how they should be used in the technology area assessments.

The team then moved into the process of receiving the pivot technology briefing and then the technology area briefings, discussing them, and providing their prioritization assessments into the facilitation software. Each technology area was systematically assessed and prioritized within each of the six technology area categories as summarized in Section 2. The order of the six technology area categories followed the listing in Section 2, except that the IVHM briefings and assessments were moved from first to third in the sequence to enable Clyde Dennison of Northrop Grumman Corporation to provide the briefings at the start of the second day of the workshop. All the other technology area briefings were given to the workshop evaluators by Dan Levack of Boeing Rocketdyne, based on the work of his SPST Technologies Team.

Following the assessment of all the candidate technology areas across the six categories, the workshop team performed a prioritization of the six categories themselves based on the potential of each category of technologies to enable the achievement of third and second generation RLV program goals.

A final assessment was performed by the workshop team to do a top level evaluation of all the 26 candidate technology areas against each of two general criteria: (1) their potential to enable the achievement of third and second generation <u>safety goals</u>, and (2) their potential to enable the achievement of <u>cost goals</u>.

The results of all the assessments performed at the workshop are summarized in the next section of the report.

6. WORKSHOP RESULTS

This section summarizes the results of the April 2001 Technologies Prioritization Workshop. Subsection 6.1 introduces the detailed prioritization results at the criterion level (technical and programmatic) with the large database of charts included in this report as Appendix A. Subsection 6.2 presents the integrated prioritization results across all the technical assessment criteria. Subsection 6.3 presents the corresponding integrated results for the programmatic criteria. Subsection 6.4 provides the combined technical and programmatic prioritization results based on different weightings between the technical and programmatic criteria.

Subsection 6.5 presents the results of the collaborative prioritization or weighting of the six technology area categories themselves. Subsection 6.6 then provides the global prioritization results for all 26 candidate technology areas across both the technical and programmatic evaluation criteria.

Subsection 6.7 summarizes the results of the separate exercise to assess all 26 candidate technology areas against their potential to (1) reduce costs, and (2) increase safety of advanced RLV systems, as performed at the end of the workshop. Data are presented to enable comparisons of these data with the baseline technical and programmatic prioritization data. The results of combining the baseline data with these separate cost and safety assessments are included.

Subsection 6.8 provides graphic displays of the technical versus programmatic priorities resulting from the workshop as a decision support input to NASA.

Interpreting the AHP Data

Before proceeding to look at the workshop results, it is important that the reader understand a fundamental premise underlying the Analytic Hierarchy Process and on the basis of that premise, how to interpret the data that comes out of the process.

In applying the multi-criteria decision analysis method known as the Analytic Hierarchy Process (AHP), one understands or assumes that the decision alternatives being assessed are competing alternatives. That is, the alternatives being prioritized for the decision maker(s) are expected to be competitive with one another. That, in fact, is what makes the process worth doing. Because it is difficult to discriminate among the alternatives, a prioritization process is needed.

One implication of this is that the AHP typically should not be applied where the decision alternatives may be more than an order of magnitude apart in priority. If that is the case, an AHP is probably not needed to distinguish between the alternatives; they are not really competitive. Typically, one should expect to see a spread of the highest to lowest priorities in the range of 2 or 3 to 1 for a sizeable set of alternatives. Spreads up to 9 to 1 are possible but rare in the assessment of competing advanced technologies.

How does all this apply to the SPST workshop results? First, it is assumed the bottom-up SPST assessment process identified a set of competing technology solution areas to potentially address impediments to achieving third or second generation RLV system goals. Therefore the AHP should be applicable to the prioritization of these potential technology area investments. Therefore In reviewing the results it should not be surprising to see limited separation among priorities, especially when there is only two or three competing technology areas being assessed in a given technology category. In categories where there are more candidate technology solutions, one should expect to see a greater top to bottom spread in priorities based on the team assessments. This should also be seen in the global prioritization results across all 26 technology areas assessed in the SPST workshop.

It should be kept in mind that the collaborative AHP prioritization results directly represent the combined inputs of the evaluation team against the criteria defined by the SPST. And as in any decision support methodology, the quality of the results depend directly on the quality of both the decision criteria and the assessment inputs.

The baseline data presented in the following subsections will be provided in a standard format adopted for this report. A chart will be provided for each category of technologies or the global set of candidate technologies being prioritized indicating the criterion or criteria against which the prioritization was done. The collaborative results are shown on each chart in three standard forms. The first column shows the priority vector produced by the evaluation team inputs. The priority vector component values sum to one. The higher the component value the higher the relative priority of the candidate technology.

The second column in each chart shows the priority ratios for the candidate technologies or technology areas where each priority vector component is divided through by the highest priority value. Thirdly, the horizontal bars on the chart provide a graphical display of the priority ratios to give a quick sense of the prioritization results.

6.1 Prioritization at the Criterion Level

The collaborative results of the prioritization of the candidate technology areas at the criterion level provides the master baseline database for the April 2001 SPST Technologies Prioritization Workshop. These data provide an "audit trail" of results from the collaborative inputs of the evaluation team to show why the integrated results at the technical and programmatic levels come out like they do. In effect, these data show the prioritization strengths and weaknesses of each of the candidate technology areas with respect to all of the assessment criteria.

Because of the level of detail of these data charts and their large number, they have been included in this report as Appendix A. The first 150 charts present the collaborative priorities of the candidate technology areas in each of the six categories for each of the 25 technical evaluation criteria (6 technology area categories times the 25 technical criteria each = 150 charts). The next 114 charts present the collaborative priorities of the technology areas in each of the six categories for each of the 19 programmatic evaluation criteria (6 categories times the 19 programmatic criteria = 114 charts).

Appendix A includes an index by page numbers to assist the reader in locating specific prioritization data at the individual criterion level.

6.2 Integrated Technical Prioritization

Charts 6.2-1 through 6.2-6 present the integrated prioritization of the candidate technology areas by category across the 25 weighted technical evaluation criteria. Chart 6.2-1 shows the relative prioritization data for the four candidate technology areas in the IVHM Technologies Category. As introduced in the beginning of this section, the collaborative results are presented in three standard forms on the chart. The first column shows the priority vector produced by the technical evaluation team inputs. The priority vector values for each of the candidate technology areas sum to one. The higher the component value, the higher is the relative priority of the candidate technology area.

The second column shows the priority ratios for the candidate technology areas where each priority vector component is divided through by the highest priority value. The bars on the chart provide a graphical display of the priority ratios.

The data on Chart 6.2-1 show that all four of the technology areas scored approximately equally, with the Critical Failures Identification and Automated Predictive Maintenance technologies having marginally higher priorities than the Systems Health verification and Preflight Checkout technologies. This indicates that the team judged all four of these technology areas, relative to each other, to be important to achieving advanced RLV program goals. This result is consistent with the Spaceliner 100 IVHM technologies prioritization workshop conducted by an inter-Center NASA team in April 2000.

Chart 6.2-2 presents the relative prioritization data for the Margin Technologies category. The Air Breathing Main Propulsion technology area was ranked first, followed closely by the High Performance Subsystems technologies. The team scored the Lightweight Subsystems area third at 77% of the highest priority technology area.

Chart 6.2-3 shows the results for the Operations Technologies category. The distribution of priorities shows a cluster of three technologies having the highest priorities including the Elimination of Support Systems, Simplified Mating Operations, and the use of Single Main Propellants. These are followed in priority by a cluster of the Leak Free Joints and Passive Aero Solutions technologies. The remaining four technology areas are a third priority cluster as shown with priority ratios in the 68 to 76% range.

Chart 6.2-4 provides the collaborative data for the two Safety Technologies. The data show that the team considered these technology areas to be approximately equally important as safety technologies to advanced RLV systems design, development and

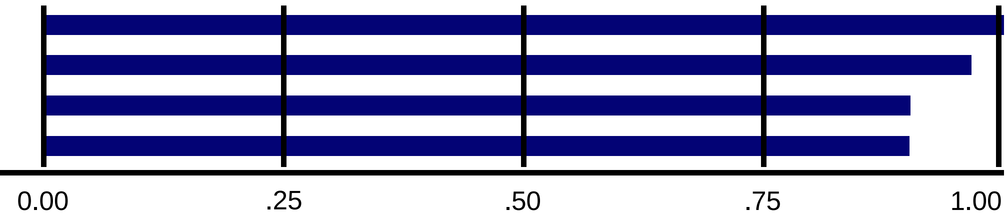
SPST Propulsion Technologies

6.2-1 Priorities by Technology Category

IVHM Technologies

Technical Criteria

Technology	Priority	Ratio
Critical Failures Identification	0.265	1.000
Automated Predictive Maintenance	0.256	0.966
Systems Health Verification	0.239	0.903
Preflight Checkout	0.239	0.902
	1.000	



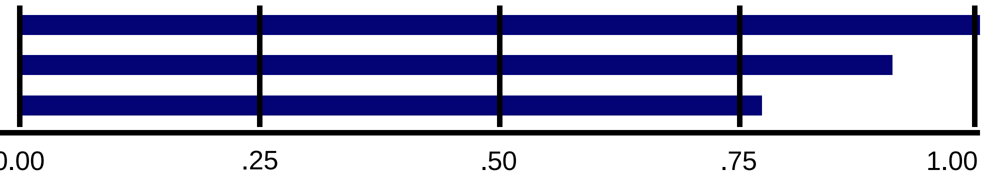
SPST Propulsion Technologies

6.2-2 Priorities by Technology Category

Margin Technologies

Technical Criteria

Technology	Priority	Ratio
Air Breathing Main Propulsion	0.373	1.000
High Performance Subsystems	0.339	0.909
Lightweight Subsystems	0.288	0.773
	1.000	



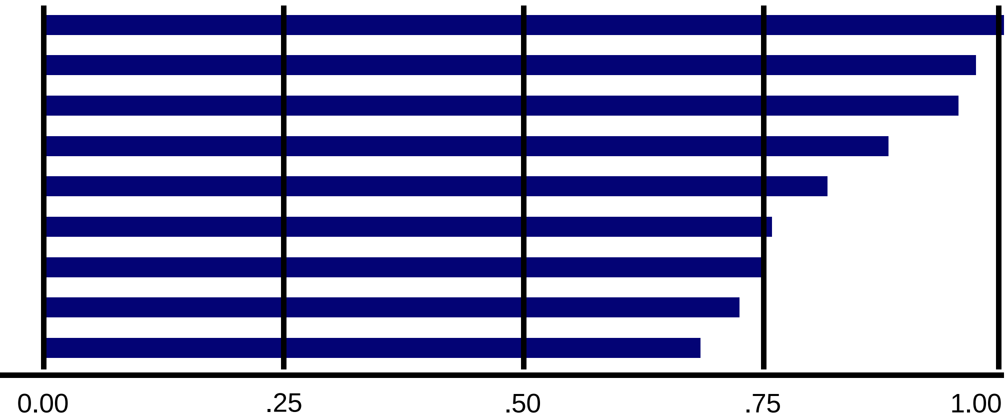
SPST Propulsion Technologies

6.2-3 Priorities by Technology Category

Operations Technologies

Technical Criteria

Technology	Priority	Ratio
Elimination of Support Systems	0.133	1.000
Simplified Mating Ops	0.129	0.971
Single Main Propellants	0.126	0.953
Leak Free Joints	0.117	0.880
Passive Aero Solutions	0.108	0.816
Elimination of Turnaround Ops	0.101	0.759
Cleaning Alternatives	0.099	0.747
Cryogenic Conditioning	0.096	0.725
Wireless Communication	0.091	0.684
	1.000	



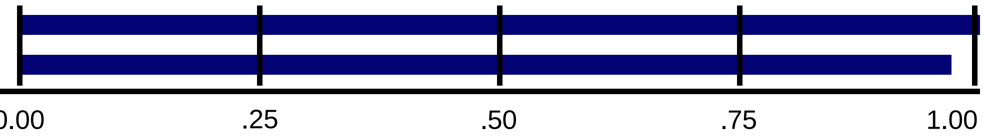
SPST Propulsion Technologies

6.2-4 Priorities by Technology Category

Safety Technologies

Technical Criteria

Technology	Priority	Ratio
Pyrotechnics Elimination	0.507	1.000
System Failures Tolerance	0.493	0.971
	1.000	



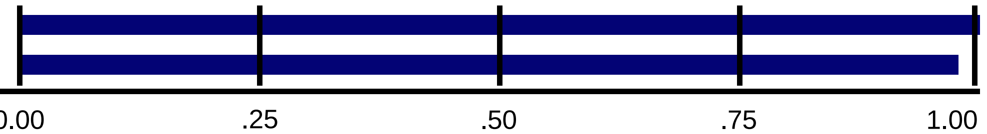
SPST Propulsion Technologies

6.2-5 Priorities by Technology Category

Thermal Control Technologies

Technical Criteria

Technology	Priority	Ratio
Active TPS Elimination	0.506	1.000
Active Thermal Control Elimination	0.494	0.977
	1.000	



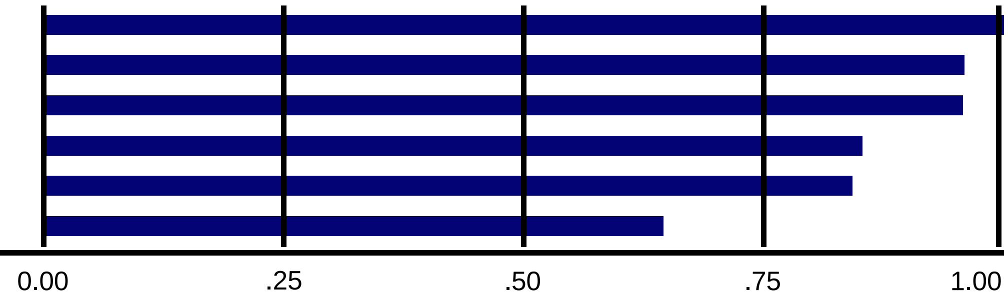
SPST Propulsion Technologies

6.2-6 Priorities by Technology Category

Number of Systems Reduction Technologies

Technical Criteria

Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.190	1.000
Integrated RCS/OMS/MPS	0.182	0.959
Integrated Prop/Thermal/Power	0.182	0.958
Integrated RCS/OMS	0.162	0.853
All Rocket Cycle	0.160	0.843
Residual Gases Utilization	0.123	0.645
	1.000	



operations. There is no significant separation in their priorities as scored by the evaluation team.

Chart 6.2-5 presents the data for the two Thermal Control technologies considered by the workshop. As in the case of the two Safety technologies, on balance the team scored these particular technologies equally against the technical criteria.

Chart 6.2-6 shows the data for the technologies to Reduce the Number of Systems in an advanced RLV system. The results indicate three distinct clusters of technology priorities. The team scored the MPS Low Thrust Mode for OMS, the Integrated RCS/OMS/MPS, and the Integrated Propulsion/Thermal/Power technologies with the highest priorities. Integrated RCS/OMS and All Rocket Cycle technologies were scored in a second priority cluster at about 85% of the highest priority technology. The Residual Gases Utilization technology was ranked lowest at 65% of the highest priority.

6.3 Integrated Programmatic Prioritization

Charts 6.3-1 through 6.3-6 present the integrated prioritization of the candidate technology areas by category across the 19 weighted programmatic evaluation criteria. The format is the same as for the technical priority charts.

Chart 6.3-1 provides the weighted programmatic prioritization results for the IVHM technologies category. Just as in the case of the technical assessments, the programmatic evaluators found the four candidate IVHM technology areas to be of about equal priority for purposes of IVHM technology investment planning.

Chart 6.3-2 shows the collaborative data for the Margin technologies. The priorities show somewhat more separation than the technical evaluations and the ranking of the candidate technologies are different. It is seen that instead of first priority as in the technical data, the Air Breathing Main Propulsion technology is assessed to be third priority at 64% of the first priority High Performance Subsystems technology. Lightweight Subsystems is found to have a relatively strong second priority at 83% of High Performance Subsystems.

Chart 6.3-3 presents the collaborative team results for Operations technologies. The programmatic criteria led to a different order of priorities among the candidate technologies compared to the technical prioritization results. Single Main Propellants and the Elimination of Support Systems have the highest priorities along with Wireless Communication technologies. Wireless Communication technologies is an example of a case where a candidate technology area was prioritized low on the technical criteria, but high on the programmatic criteria. The elimination of Turnaround Operations also was assessed at a high priority. The remaining technologies were assessed at a lower cluster of priorities ranging from 69 to 82% of the highest priority technology.

Chart 6.3-4 shows the data for the Safety technologies. While the two candidate technologies were equally prioritized technically, the data show that the Pyrotechnics Elimination technology was assessed by the Programmatic evaluators to be of

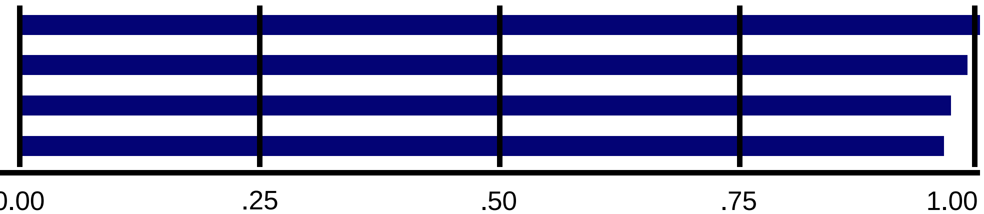
SPST Propulsion Technologies

6.3-1 Priorities by Technology Category

IVHM Technologies

Programmatic Criteria

Technology	Priority	Ratio
Critical Failures Identification	0.255	1.000
Systems Health Verification	0.252	0.987
Preflight Checkout	0.247	0.970
Automated Predictive Maintenance	0.246	0.963
	1.000	



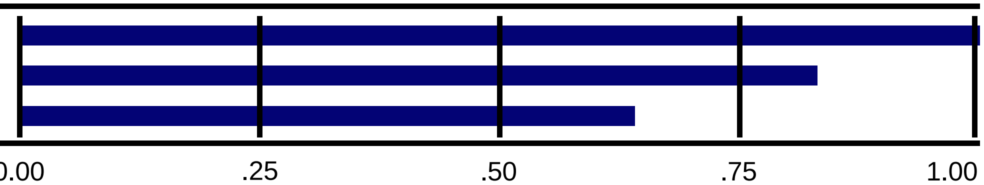
SPST Propulsion Technologies

6.3-2 Priorities by Technology Category

Margin Technologies

Programmatic Criteria

Technology	Priority	Ratio
High Performance Subsystems	0.405	1.000
Lightweight Subsystems	0.336	0.831
Air Breathing Main Propulsion	0.259	0.641
	1.000	



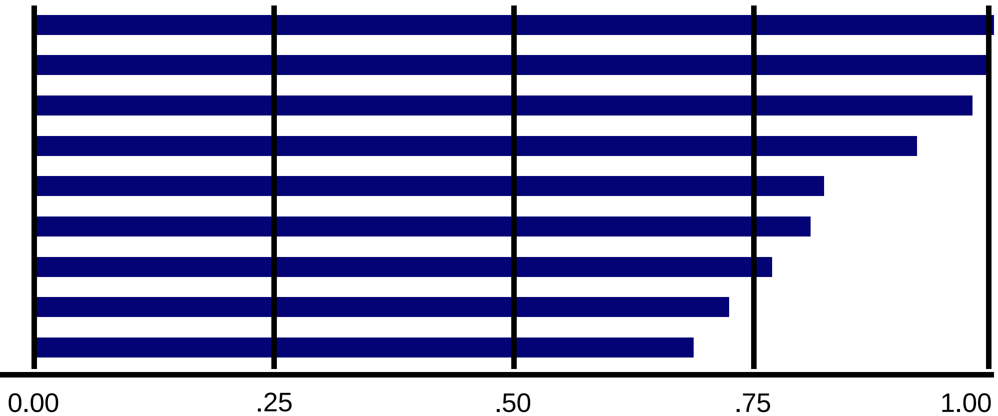
SPST Propulsion Technologies

6.3-3 Priorities by Technology Category

Operations Technologies

Programmatic Criteria

Technology	Priority	Ratio
Single Main Propellants	0.130	1.000
Elimination of Support Systems	0.129	0.996
Wireless Communication	0.127	0.978
Elimination of Turnaround Ops	0.119	0.920
Cleaning Alternatives	0.107	0.823
Passive Aero Solutions	0.105	0.809
Simplified Mating Ops	0.100	0.769
Cryogenic Conditioning	0.094	0.724
Leak Free Joints	0.089	0.687
	1.000	



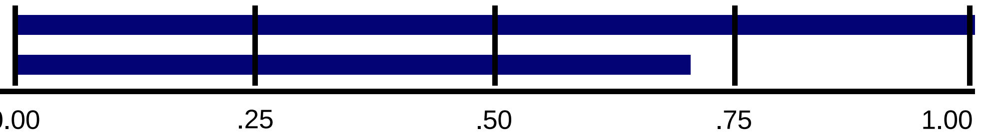
SPST Propulsion Technologies

6.3-4 Priorities by Technology Category

Safety Technologies

Programmatic Criteria

Technology	Priority	Ratio
Pyrotechnics Elimination	0.587	1.000
System Failures Tolerance	0.413	0.704
	1.000	



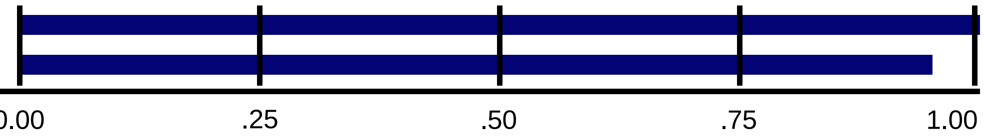
SPST Propulsion Technologies

6.3-5 Priorities by Technology Category

Thermal Control Technologies

Programmatic Criteria

Technology	Priority	Ratio
Active Thermal Control Elimination	0.513	1.000
Active TPS Elimination	0.487	0.951
	1.000	



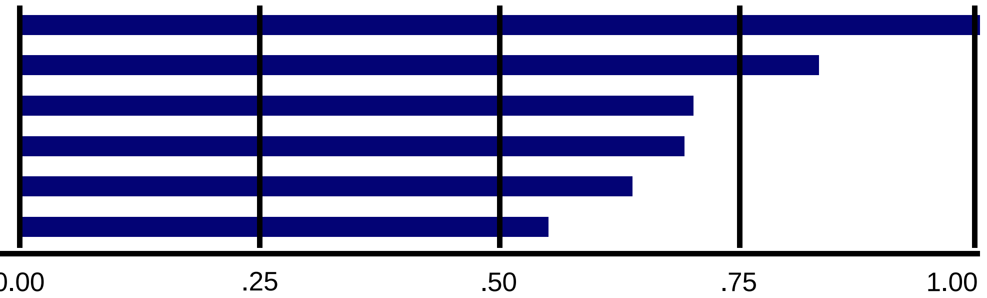
SPST Propulsion Technologies

6.3-6 Priorities by Technology Category

Number of Systems Reduction Technologies

Programmatic Criteria

Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.226	1.000
Integrated RCS/OMS	0.189	0.833
Integrated RCS/OMS/MPS	0.159	0.702
All Rocket Cycle	0.157	0.692
Integrated Prop/Thermal/Power	0.145	0.638
Residual Gases Utilization	0.125	0.551
	1.000	



significantly higher priority (30% higher) than the Systems Failures Tolerance technology.

Chart 6.3-5 presents the data for the two Thermal Control technologies. Like the Technical evaluators, the Programmatic evaluators did not find any significant difference between the priorities of these technologies within the Thermal Control category.

Chart 6.3-6 provides data results for the Reduction in Number of Systems category of technologies. Overall there is approximately a 2 to 1 spread in the priorities with the MPS Low Thrust Mode for OMS technology having the highest priority and the Residual Gases Utilization technology having the lowest priority. The Integrated RCS/OMS technology is ranked at a relatively strong second priority (83%), followed by a cluster of the other three candidate technologies ranging from 64 to 70% of the highest priority. Comparison of these data with Chart 6.2-6 shows interesting but logically consistent differences in the results compared to the technical assessments.

6.4 Combined Technical and Programmatic Prioritization

Charts 6.4-1 through 6.4-6 present the combined technical and programmatic prioritization of the candidate technology areas by category across all technical and programmatic evaluation criteria. The overall sets of technical and programmatic criteria are weighted equally (50% - 50%) in these results.

Chart 6.4-2 provides an example of the effects of combining the technical and programmatic prioritization results. The technical priorities for these three technology areas showed Air Breathing Propulsion as the first priority followed by High Performance Subsystems technologies. Programmatically Air Breathing Propulsion was assessed to be third priority with High Performance Subsystems technologies first priority. However, on balance with an equal emphasis on technical and programmatic criteria, High performance Subsystems technologies were found to be first priority, followed by Air Breathing Propulsion and Lightweight Subsystems very closely clustered in second priority. The higher the emphasis on technical criteria, the stronger Air Breathing Propulsion ranks in priority. Conversely, the higher the emphasis on the programmatic criteria the lower Air Breathing Propulsion ranks. This will be shown in the next set of prioritization data charts.

In order to provide data to assess the sensitivity of technology priorities with respect to the relative emphasis or weighting placed on technical versus programmatic evaluation criteria, Charts 6.4-7 through 6.4-12 provide combined technical and programmatic prioritization results for a 70% - 30% weighting between the technical and programmatic criteria for each of the six technology area categories. These data can be compared to the baseline Charts 6.4-1 through 6.4-6 to study the potential impact of placing heavier emphasis on the technical criteria.

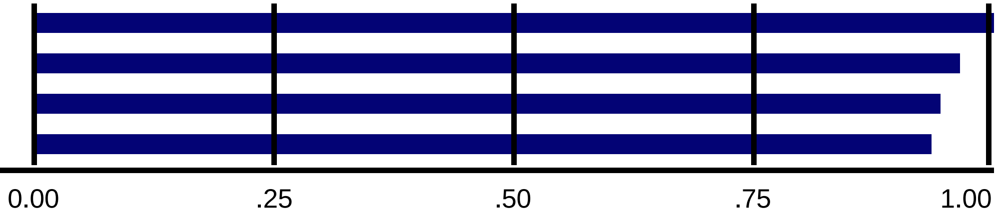
Charts 6.4-13 through 6.4-18 show combined technical and programmatic prioritization data for a 30% - 70% weighting of the technical and programmatic criteria.

SPST Propulsion Technologies

6.4-1 Priorities by Technology Category (Technical 50%, Programmatic 50%)

IVHM Technologies

Technology	Priority	Ratio
Critical Failures Identification	0.260	1.000
Automated Predictive Maintenance	0.251	0.965
Systems Health Verification	0.246	0.944
Preflight Checkout	0.243	0.935
	1.000	

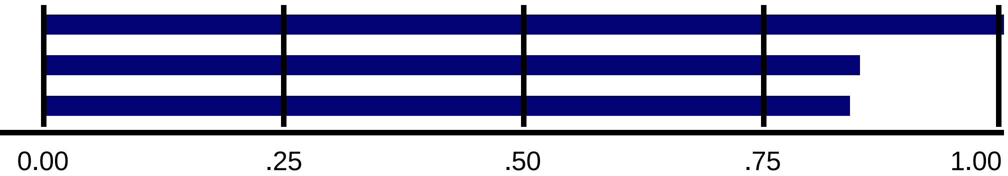


SPST Propulsion Technologies

6.4-2 Priorities by Technology Category (Technical 50%, Programmatic 50%)

Margin Technologies

Technology	Priority	Ratio
High Performance Subsystems	0.372	1.000
Air Breathing Main Propulsion	0.316	0.850
Lightweight Subsystems	0.312	0.840
	1.000	

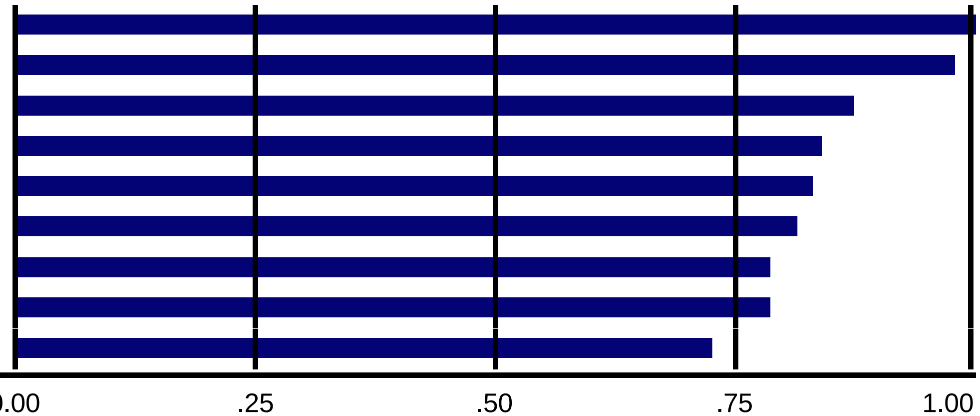


SPST Propulsion Technologies

6.4-3 Priorities by Technology Category (Technical 50%, Programmatic 50%)

Operations Technologies

Technology	Priority	Ratio
Elimination of Support Systems	0.131	1.000
Single Main Propellants	0.128	0.978
Simplified Mating Ops	0.114	0.873
Elimination of Turnaround Ops	0.110	0.840
Wireless Communication	0.109	0.831
Passive Aero Solutions	0.107	0.814
Leak Free Joints	0.103	0.786
Cleaning Alternatives	0.103	0.786
Cryogenic Conditioning	0.095	0.726
	1.000	

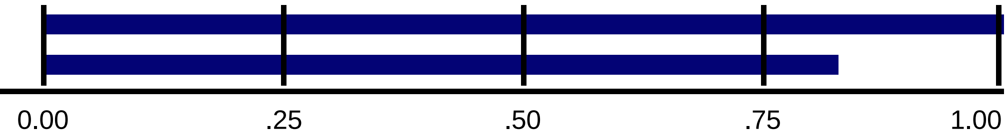


SPST Propulsion Technologies

6.4-4 Priorities by Technology Category (Technical 50%, Programmatic 50%)

Safety Technologies

Technology	Priority	Ratio
Pyrotechnics Elimination	0.547	1.000
System Failures Tolerance	0.453	0.827
	1.000	

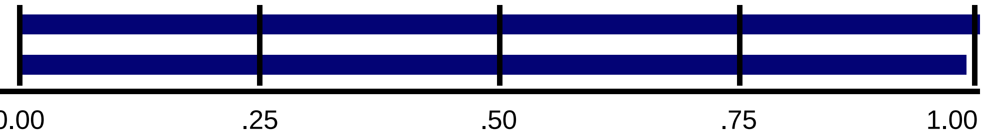


SPST Propulsion Technologies

6.4-5 Priorities by Technology Category (Technical 50%, Programmatic 50%)

Thermal Control Technologies

Technology	Priority	Ratio
Active Thermal Control Elimination	0.503	1.000
Active TPS Elimination	0.497	0.986
	1.000	

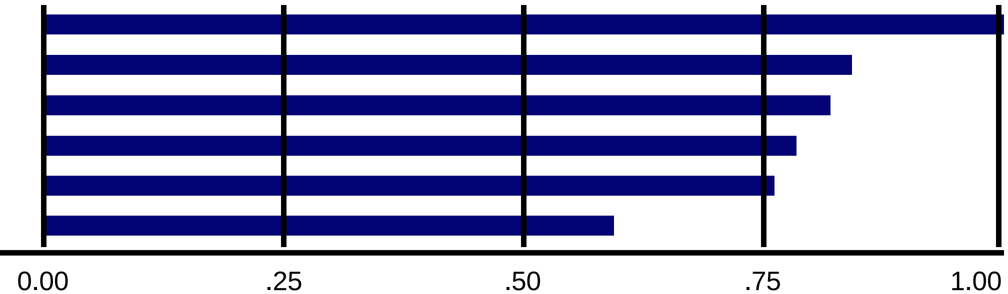


SPST Propulsion Technologies

6.4-6 Priorities by Technology Category (Technical 50%, Programmatic 50%)

Number of Systems Reduction Technologies

Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.208	1.000
Integrated RCS/OMS	0.175	0.842
Integrated RCS/OMS/MPS	0.171	0.819
Integrated Prop/Thermal/Power	0.163	0.784
All Rocket Cycle	0.159	0.761
Residual Gases Utilization	0.124	0.594
	1.000	



6.5 Prioritization of Technology Area Categories

Chart 6.5-1 presents the collaborative results of the workshop team's prioritization of the six technology area categories themselves. The highest prioritized category is the IVHM technologies, followed relatively closely by a cluster of the Margin, Number of Systems Reduction, and Operations categories. The Thermal Control and Safety technologies categories are clustered last with priority ratios of 62 and 55%, respectively. The overall spread in these relative priorities across the categories is about 2 to 1.

6.6 Global Prioritization of All Technology Areas

Chart 6.6-1 shows the results of the workshop team's prioritization of the 26 candidate technology areas expressed in global format across both technical and programmatic evaluation criteria with 50% (technical) and 50% (programmatic) weighting. This is possible because a common pivot technology (Space Shuttle) was used across each of the six categories of candidate technology areas. The data show that the MPS Low Thrust Mode for OMS (Number of Systems Reduction technology) and High Performance Subsystems (Margin technology) technologies are found to have the highest priorities, followed by a closely prioritized cluster of seven technologies from across the categories, including Integrated RCS/OMS, Integrated RCS/OMS/MPS, Integrated Propulsion/Thermal/Power, Air Breathing Main Propulsion, Active Thermal Control Elimination, Active TPS Elimination, and Lightweight Subsystems technologies.

The remaining candidate technologies across the categories are uniformly prioritized from 71% (Elimination of Support Systems) down to 49% (Systems Failures Tolerance). The overall priority spread is approximately 2 to 1.

Charts 6.6-2 and 6.6-3 provide global prioritization data for a 70% - 30% weighting of the technical and programmatic criteria, and a 30% - 70% weighting, respectively.

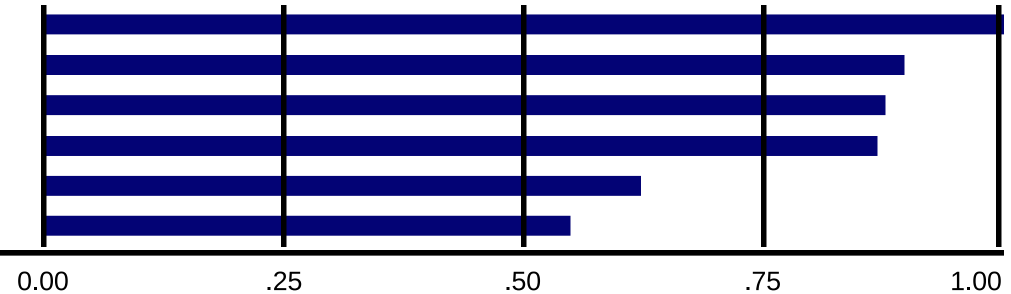
The results of the global processing of the evaluation team's baseline data across all the technical and programmatic criteria indicate that the highest leverage propulsion and propulsion-related technologies are those that (1) reduce the number of RLV systems to be designed, developed, tested, and operated; (2) increase system margins; and (3) simplify thermal control of the flight vehicle. IVHM and Operations technologies are important but rank lower that those technology areas based on the SPST evaluation criteria. The particular Safety technology areas considered in this workshop were found to be of relatively low priority with respect to the other identified technology areas based on all the technical and programmatic criteria.

6.7 Separate Global Prioritization Against Safety and Cost Criteria

The collaborative prioritization of the full set of 26 candidate technology areas based on the separate workshop assessments of the potential to increase system safety and reduce cost are summarized on Charts 6.7-1 and 6.7-2, respectively. The combined priorities across the safety and cost criteria, equally weighted, are shown on Chart 6.7-

6.5-1 Prioritization of Technology Categories

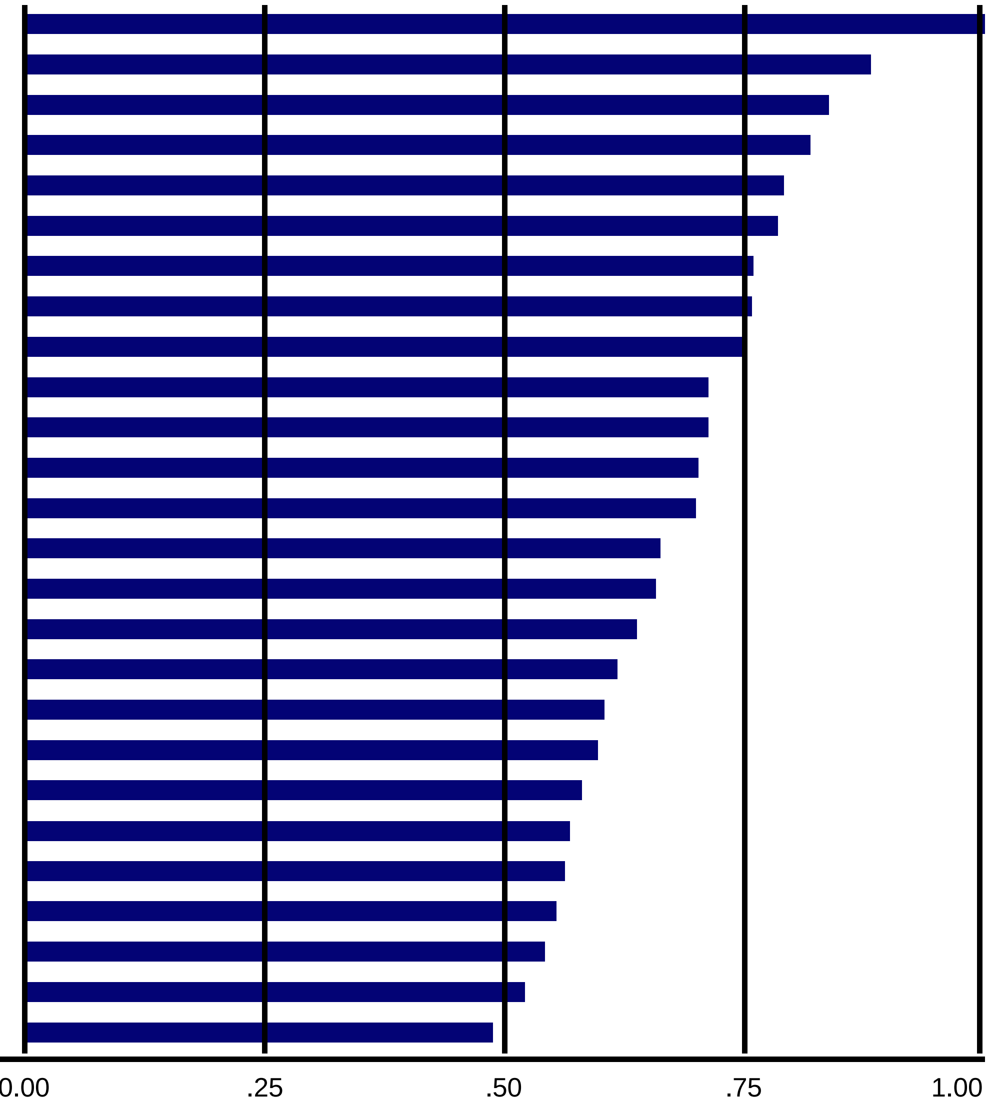
Technology Category	Priority	Ratio
IVHM Technologies	0.208	1.000
Margin Technologies	0.186	0.897
Number of Systems Reduction T	0.182	0.877
Operations Technologies	0.180	0.868
Thermal Control Technologies	0.129	0.622
Safety Technologies	0.114	0.549
	1.000	



SPST Propulsion Technologies

6.6-1 Global Prioritization (Technical 50%, Programmatic 50 %)

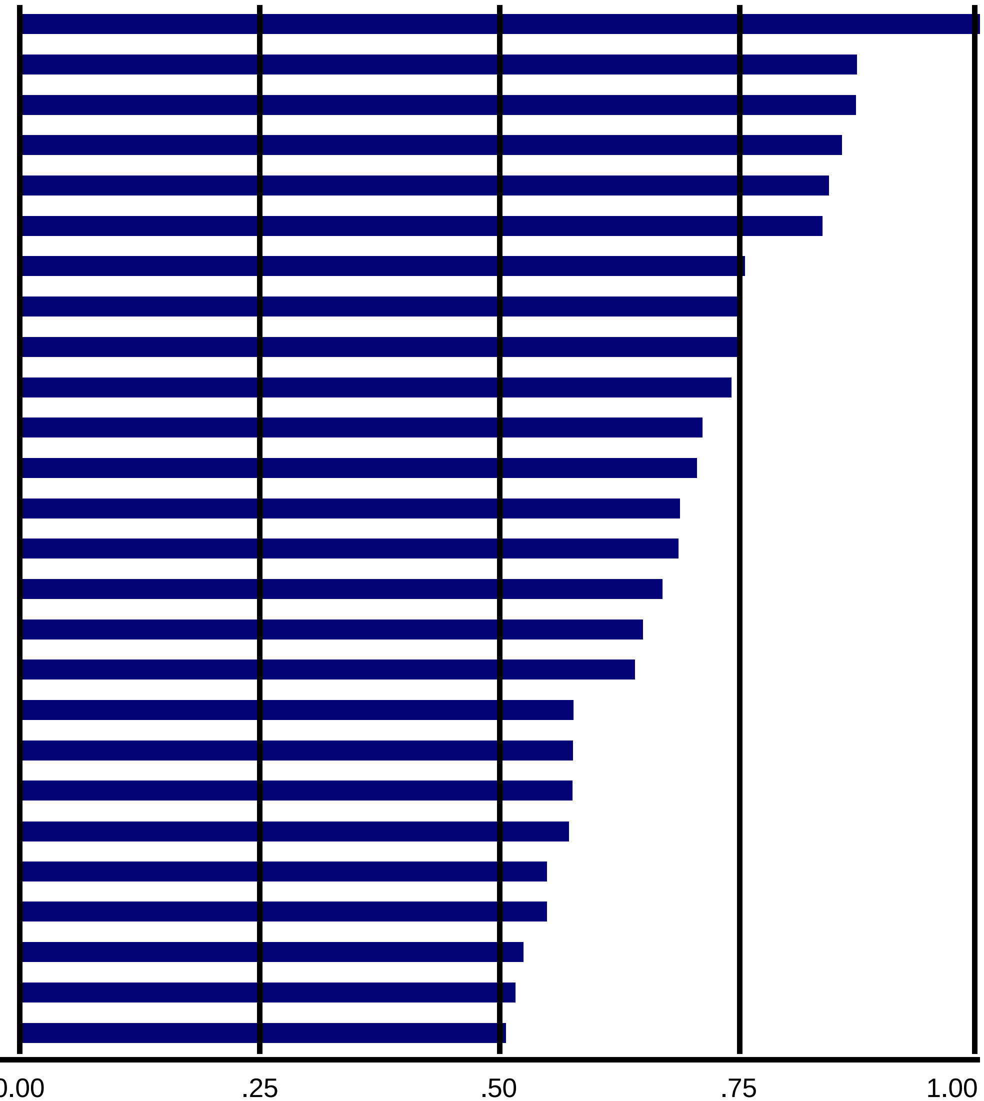
Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.056	1.000
High Performance Subsystems	0.050	0.881
Integrated RCS/OMS	0.047	0.837
Integrated RCS/OMS/MPS	0.046	0.819
Integrated Prop/Thermal/Power	0.044	0.791
Active Thermal Control Elimination	0.044	0.784
Air Breathing Main Propulsion	0.043	0.759
Active TPS Elimination	0.043	0.757
Lightweight Subsystems	0.042	0.748
Elimination of Support Systems	0.040	0.712
Critical Failures Identification	0.040	0.712
All Rocket Cycle	0.039	0.702
Single Main Propellants	0.039	0.699
Automated Predictive Maintenance	0.037	0.662
Systems Health Verification	0.037	0.657
Preflight Checkout	0.036	0.638
Simplified Mating Ops	0.035	0.617
Elimination of Turnaround Ops	0.034	0.604
Wireless Communication	0.034	0.597
Passive Aero Solutions	0.033	0.581
Cleaning Alternatives	0.032	0.568
Residual Gases Utilization	0.032	0.563
Leak Free Joints	0.031	0.554
Pyrotechnics Elimination	0.030	0.542
Cryogenic Conditioning	0.029	0.521
System Failures Tolerance	0.027	0.488
	1.000	



SPST Propulsion Technologies

6.6-2 Global Prioritization (Technical 70%, Programmatic 30 %)

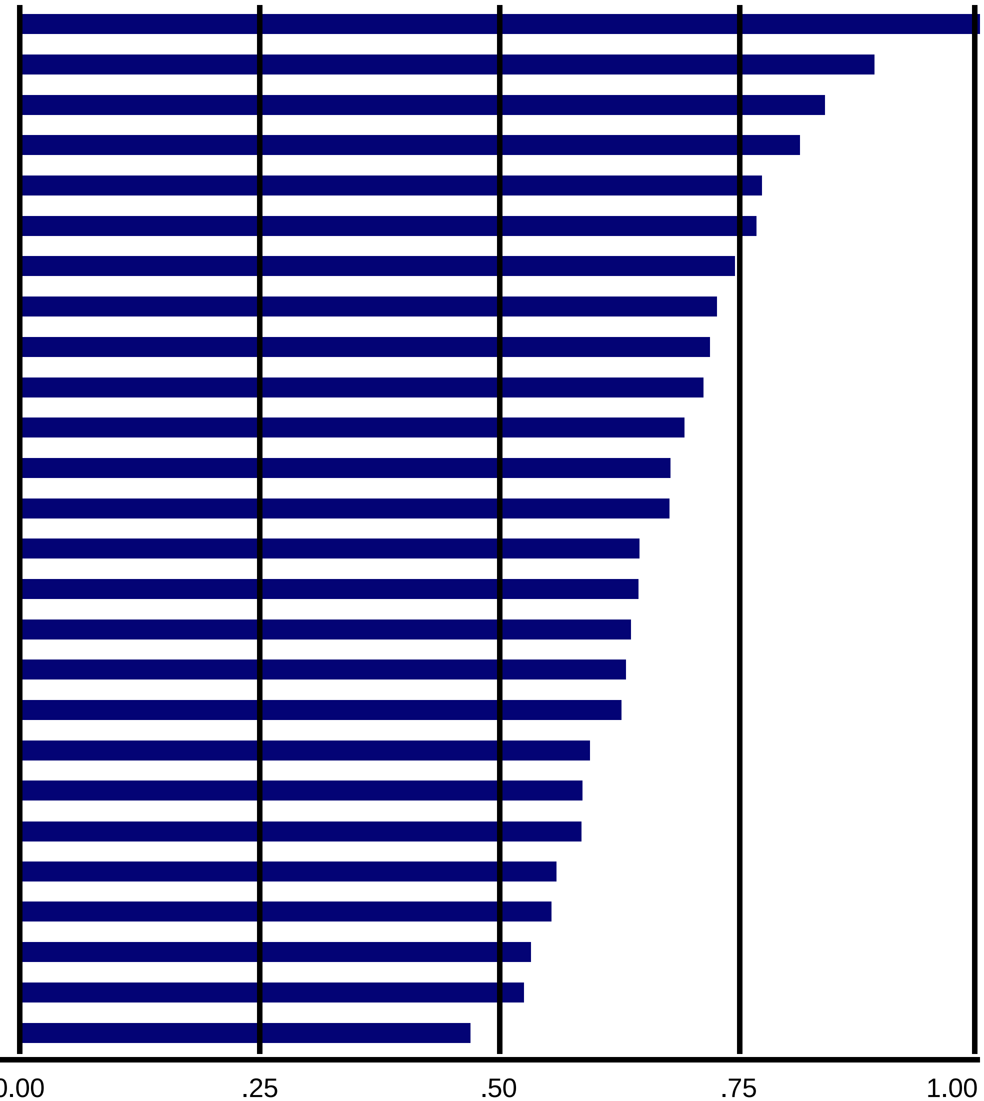
Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.056	1.000
High Performance Subsystems	0.049	0.872
Integrated RCS/OMS/MPS	0.048	0.871
Integrated Prop/Thermal/Power	0.048	0.856
Air Breathing Main Propulsion	0.047	0.843
Integrated RCS/OMS	0.047	0.836
Active Thermal Control Elimination	0.042	0.755
Lightweight Subsystems	0.042	0.751
Critical Failures Identification	0.042	0.747
Active TPS Elimination	0.041	0.742
All Rocket Cycle	0.040	0.711
Elimination of Support Systems	0.039	0.705
Automated Predictive Maintenance	0.038	0.688
Single Main Propellants	0.038	0.686
Systems Health Verification	0.037	0.669
Preflight Checkout	0.036	0.649
Simplified Mating Ops	0.036	0.641
Passive Aero Solutions	0.032	0.577
Elimination of Turnaround Ops	0.032	0.576
Leak Free Joints	0.032	0.576
Residual Gases Utilization	0.032	0.572
Cleaning Alternatives	0.031	0.549
Wireless Communication	0.031	0.549
Pyrotechnics Elimination	0.029	0.525
Cryogenic Conditioning	0.029	0.517
System Failures Tolerance	0.028	0.506
	1.000	



SPST Propulsion Technologies

6.6-3 Global Prioritization (Technical 30%, Programmatic 70 %)

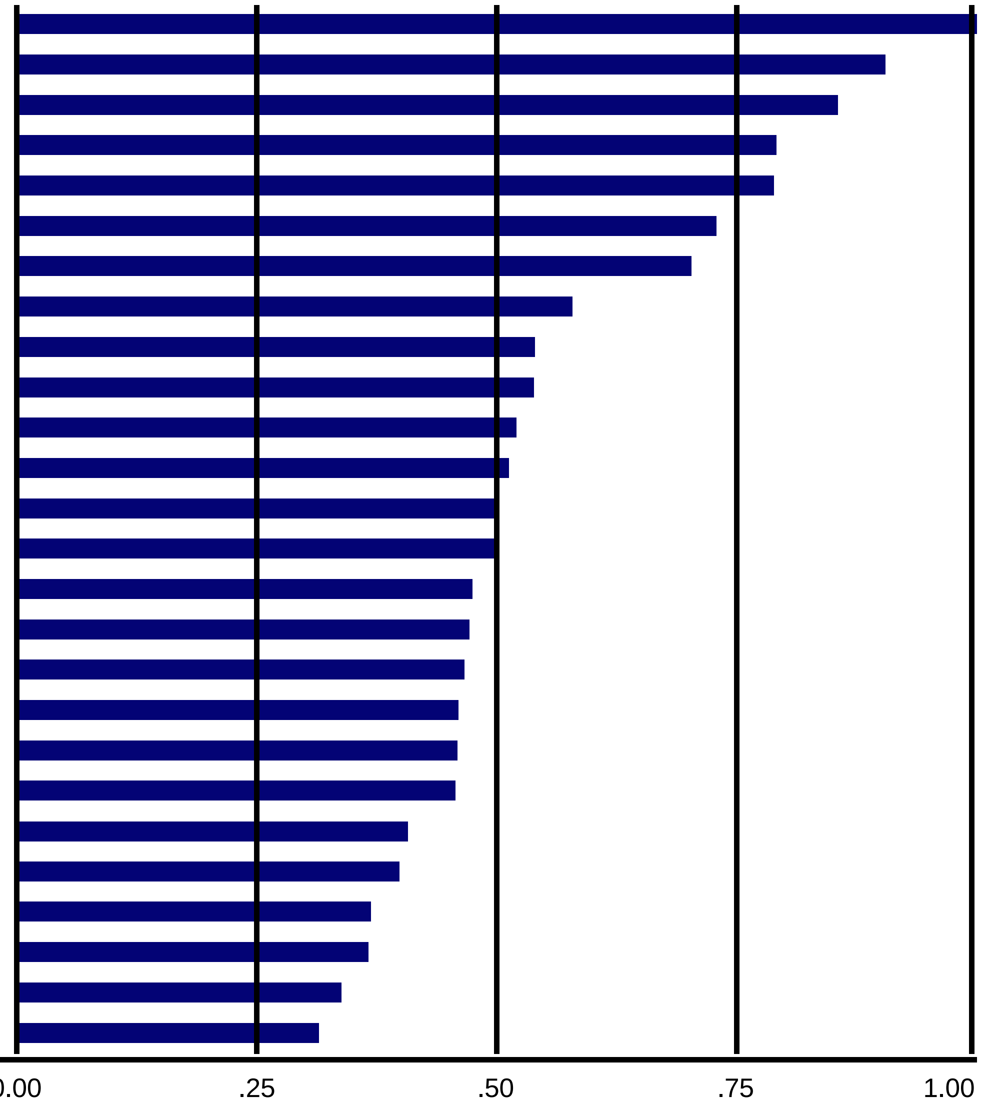
Technology	Priority	Ratio
MPS Low Thrust Mode for OMS	0.057	1.000
High Performance Subsystems	0.051	0.890
Integrated RCS/OMS	0.048	0.839
Active Thermal Control Elimination	0.046	0.813
Active TPS Elimination	0.044	0.773
Integrated RCS/OMS/MPS	0.044	0.768
Lightweight Subsystems	0.042	0.745
Integrated Prop/Thermal/Power	0.041	0.726
Elimination of Support Systems	0.041	0.719
Single Main Propellants	0.040	0.712
All Rocket Cycle	0.039	0.692
Critical Failures Identification	0.038	0.677
Air Breathing Main Propulsion	0.038	0.676
Systems Health Verification	0.037	0.646
Wireless Communication	0.037	0.644
Automated Predictive Maintenance	0.036	0.637
Elimination of Turnaround Ops	0.036	0.631
Preflight Checkout	0.036	0.627
Simplified Mating Ops	0.034	0.594
Cleaning Alternatives	0.033	0.586
Passive Aero Solutions	0.033	0.585
Pyrotechnics Elimination	0.032	0.559
Residual Gases Utilization	0.031	0.554
Leak Free Joints	0.030	0.532
Cryogenic Conditioning	0.030	0.525
System Failures Tolerance	0.027	0.469
	1.000	



SPST Propulsion Technologies

6.7-1 Increased Safety

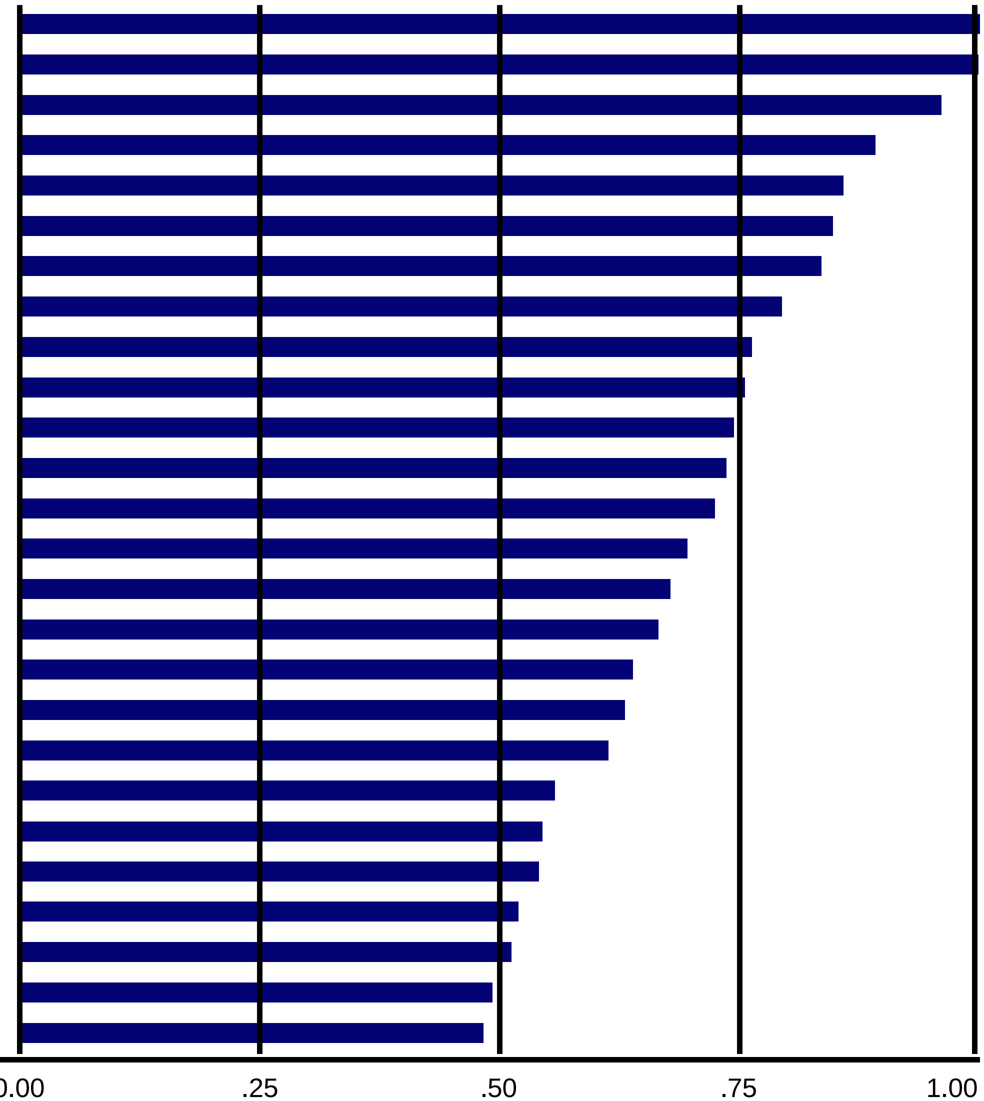
Technology	Priority	Ratio
Automated Predictive Maintenance	0.069	1.000
Critical Failures Identification	0.063	0.905
Systems Health Verification	0.059	0.855
Pyrotechnics Elimination	0.055	0.792
Leak Free Joints	0.055	0.789
Preflight Checkout	0.050	0.729
System Failures Tolerance	0.049	0.703
Simplified Mating Ops	0.040	0.579
Elimination of Turnaround Ops	0.037	0.540
Cleaning Alternatives	0.037	0.539
Air Breathing Main Propulsion	0.036	0.520
Elimination of Support Systems	0.035	0.513
Active TPS Elimination	0.035	0.502
Single Main Propellants	0.035	0.501
Integrated RCS/OMS	0.033	0.474
Integrated RCS/OMS/MPS	0.033	0.472
MPS Low Thrust Mode for OMS	0.032	0.466
Active Thermal Control Elimination	0.032	0.460
Passive Aero Solutions	0.032	0.459
Integrated Prop/Thermal/Power	0.032	0.457
Cryogenic Conditioning	0.028	0.408
All Rocket Cycle	0.028	0.399
High Performance Subsystems	0.026	0.369
Lightweight Subsystems	0.025	0.366
Wireless Communication	0.023	0.338
Residual Gases Utilization	0.022	0.314
	1.000	



SPST Propulsion Technologies

6.7-2 Decreased Cost

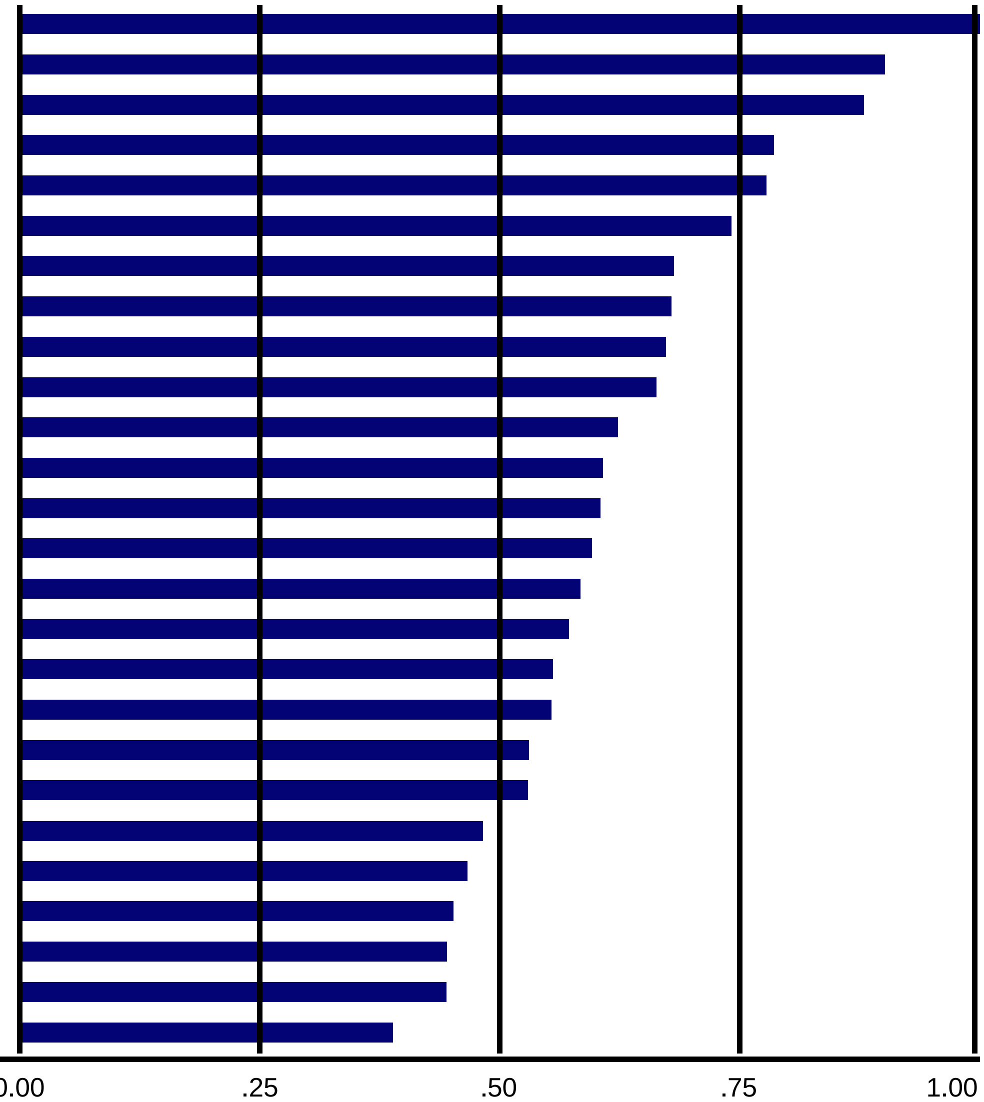
Technology	Priority	Ratio
Automated Predictive Maintenance	0.054	1.000
Elimination of Turnaround Ops	0.054	0.999
Systems Health Verification	0.052	0.960
Elimination of Support Systems	0.048	0.891
Preflight Checkout	0.046	0.858
Critical Failures Identification	0.046	0.847
Integrated Prop/Thermal/Power	0.045	0.835
Simplified Mating Ops	0.043	0.794
Leak Free Joints	0.041	0.763
Integrated RCS/OMS/MPS	0.041	0.755
Single Main Propellants	0.040	0.744
Active TPS Elimination	0.040	0.736
Integrated RCS/OMS	0.039	0.724
All Rocket Cycle	0.038	0.696
Active Thermal Control Elimination	0.037	0.678
MPS Low Thrust Mode for OMS	0.036	0.665
Air Breathing Main Propulsion	0.035	0.639
Wireless Communication	0.034	0.630
System Failures Tolerance	0.033	0.613
High Performance Subsystems	0.030	0.557
Lightweight Subsystems	0.029	0.544
Pyrotechnics Elimination	0.029	0.541
Cleaning Alternatives	0.028	0.519
Passive Aero Solutions	0.028	0.512
Cryogenic Conditioning	0.027	0.492
Residual Gases Utilization	0.026	0.483
	1.000	



SPST Propulsion Technologies

6.7-3 Increased Safety & Decreased Cost

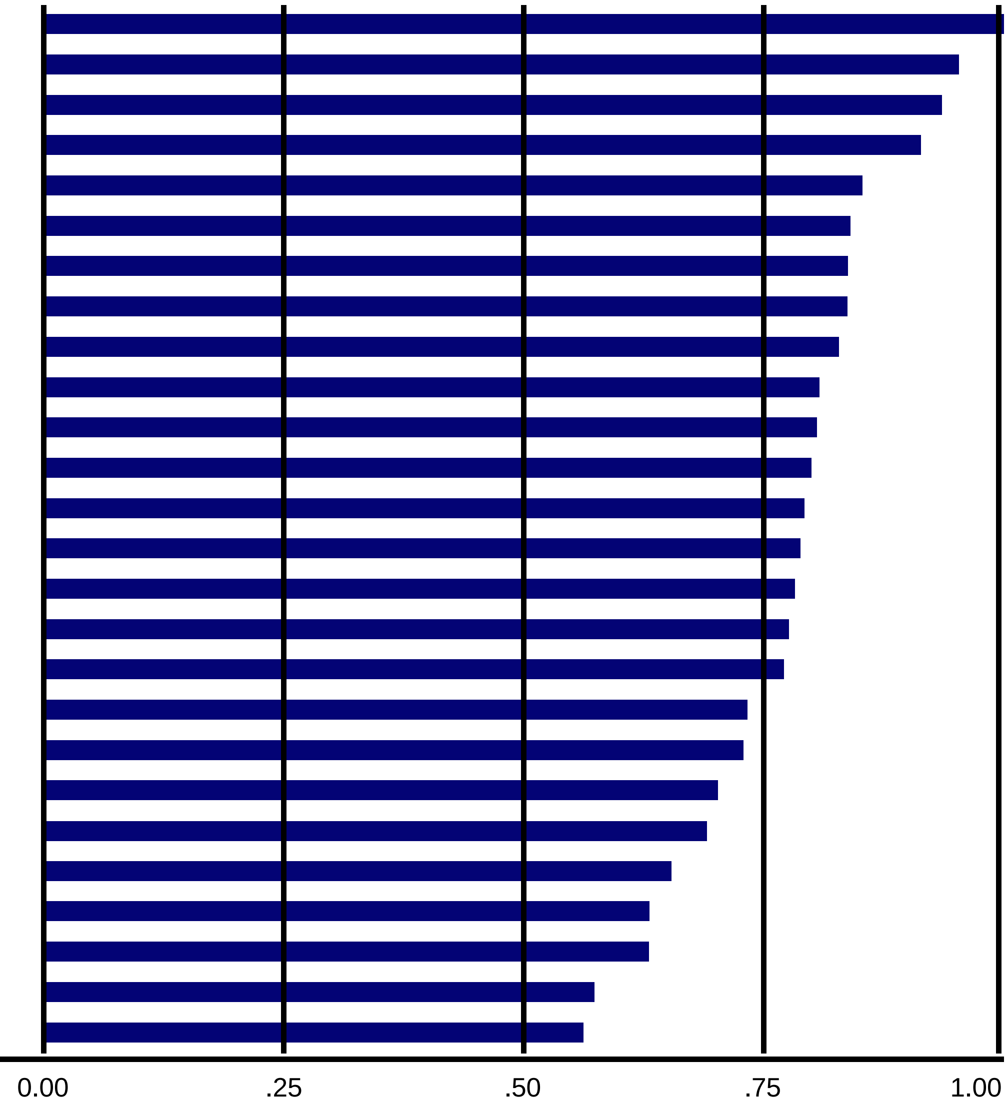
Technology	Priority	Ratio
Automated Predictive Maintenance	0.062	1.000
Systems Health Verification	0.056	0.901
Critical Failures Identification	0.054	0.880
Preflight Checkout	0.048	0.786
Leak Free Joints	0.048	0.777
Elimination of Turnaround Ops	0.046	0.741
Pyrotechnics Elimination	0.042	0.682
Elimination of Support Systems	0.042	0.679
Simplified Mating Ops	0.042	0.673
System Failures Tolerance	0.041	0.663
Integrated Prop/Thermal/Power	0.038	0.623
Single Main Propellants	0.037	0.608
Active TPS Elimination	0.037	0.605
Integrated RCS/OMS/MPS	0.037	0.596
Integrated RCS/OMS	0.036	0.584
Air Breathing Main Propulsion	0.035	0.572
Active Thermal Control Elimination	0.034	0.556
MPS Low Thrust Mode for OMS	0.034	0.554
Cleaning Alternatives	0.033	0.530
All Rocket Cycle	0.033	0.529
Passive Aero Solutions	0.030	0.482
Wireless Communication	0.029	0.466
High Performance Subsystems	0.028	0.452
Cryogenic Conditioning	0.027	0.445
Lightweight Subsystems	0.027	0.444
Residual Gases Utilization	0.024	0.388
	1.000	



SPST Propulsion Technologies

6.7-4 Technical, Programmatic, Increased Safety & Decreased Cost

Technology	Priority	Ratio
Automated Predictive Maintenance	0.049	1.000
Critical Failures Identification	0.047	0.953
Systems Health Verification	0.046	0.936
MPS Low Thrust Mode for OMS	0.045	0.914
Preflight Checkout	0.042	0.853
Integrated RCS/OMS	0.042	0.840
Integrated Prop/Thermal/Power	0.041	0.838
Integrated RCS/OMS/MPS	0.041	0.837
Elimination of Support Systems	0.041	0.828
Active TPS Elimination	0.040	0.808
Elimination of Turnaround Ops	0.040	0.806
Leak Free Joints	0.040	0.800
Active Thermal Control Elimination	0.039	0.792
Air Breathing Main Propulsion	0.039	0.788
High Performance Subsystems	0.039	0.783
Single Main Propellants	0.038	0.776
Simplified Mating Ops	0.038	0.771
Pyrotechnics Elimination	0.036	0.733
All Rocket Cycle	0.036	0.729
Lightweight Subsystems	0.035	0.702
System Failures Tolerance	0.034	0.691
Cleaning Alternatives	0.032	0.653
Passive Aero Solutions	0.031	0.631
Wireless Communication	0.031	0.630
Cryogenic Conditioning	0.028	0.574
Residual Gases Utilization	0.028	0.562
	1.000	



3. Chart 6.7-4 shows the combined prioritization when these data are combined with the baseline data for the technical and programmatic criteria. The technical, programmatic, cost, and safety prioritizations are each weighted equally at 25% each to examine the effects of consolidation of all the workshop data.

Chart 6.7-1 shows a 3 to 1 spread in priorities across all the 26 technology areas based on their potential to increase system safety. These data indicate the strong assessed importance of the IVHM technologies in achieving safe RLV operations. These are followed in priority by Pyrotechnics Elimination and Leak Free Joints technologies. Preflight Checkout and System Failures Tolerance were also found to be strong priorities.

Chart 6.7-2 shows that relative to the potential to reduce cost, Automated Predictive Maintenance, the Elimination of Turnaround Operations, and Systems Health Verification are high priority technology areas. These are followed in priority by a number of other IVHM, Operations, and technologies that reduce the number of systems to be developed and operated.

Chart 6.7-3 shows the importance of the IVHM technologies in these assessments when the results for safety and cost are combined with equal weightings. Leak Free Joints and the Elimination of Turnaround Operations are included in the second cluster of priorities. The third cluster includes Pyrotechnics Elimination, Elimination of Support Systems, Simplified Mating Operations, and System Failures Tolerance technology areas.

Chart 6.7-4 shows the data when the separate technical, programmatic, safety, and cost global results are combined with 25%/25%/25%/25% weightings. Again the IVHM technologies are high priority, but the data indicate the technical and programmatic influence in placing strong priority on reducing the number of systems, improving operations, and increasing system margins.

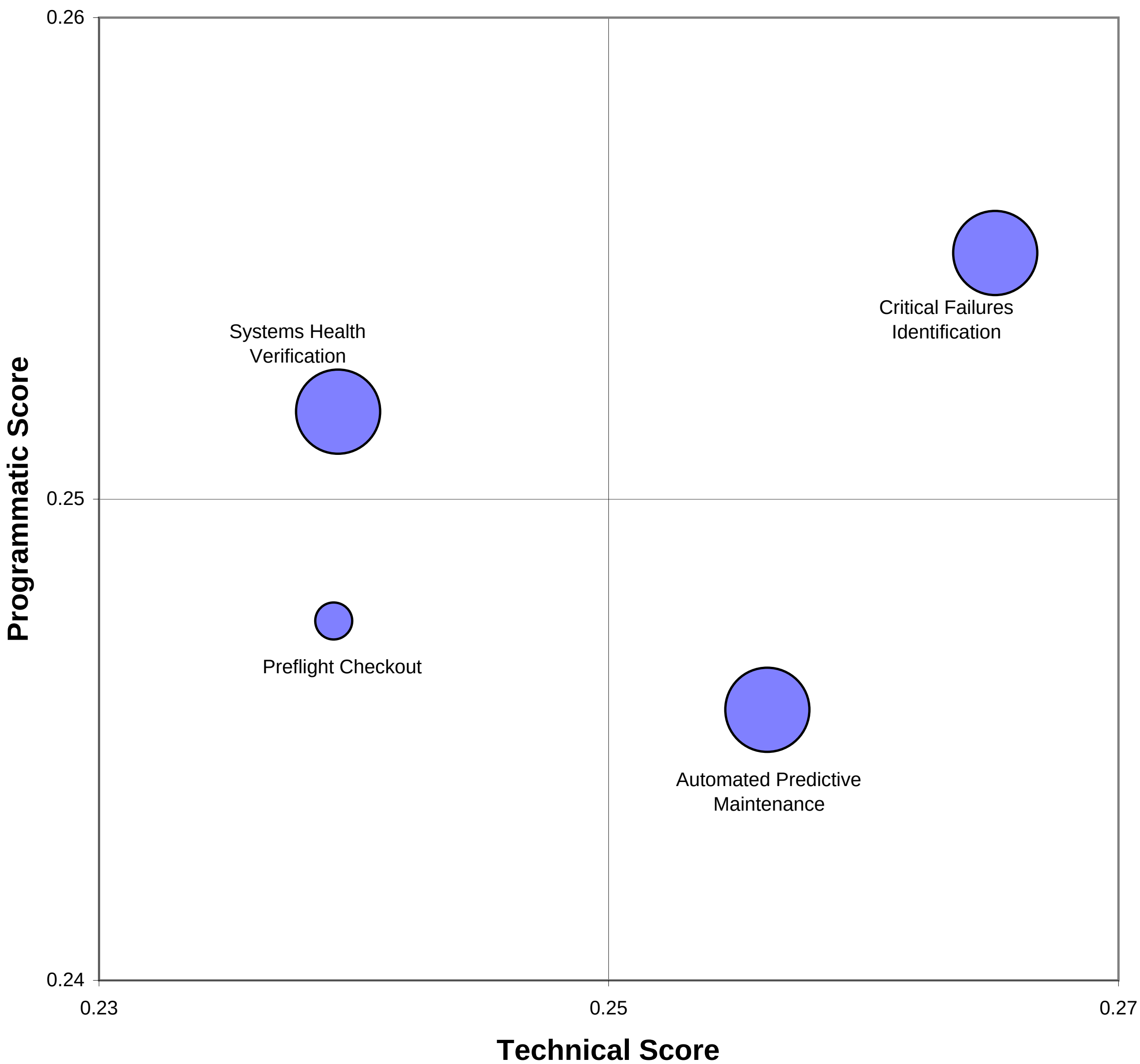
6.8 Technical Versus Programmatic Graphic Data

Charts 6.8-1 through 6.8-6 present technical priorities (or scores) plotted as a function of programmatic priorities (or scores) for each of the six technology area categories. The bubble size in each graphic represents the relative magnitude of the midpoint of the estimated investment required to mature the technology area to a TRL 6 level. It should be noted that the bubble size in each individual graphic is scaled to indicate the required investment level for candidate technology areas within the technology category represented by that chart.

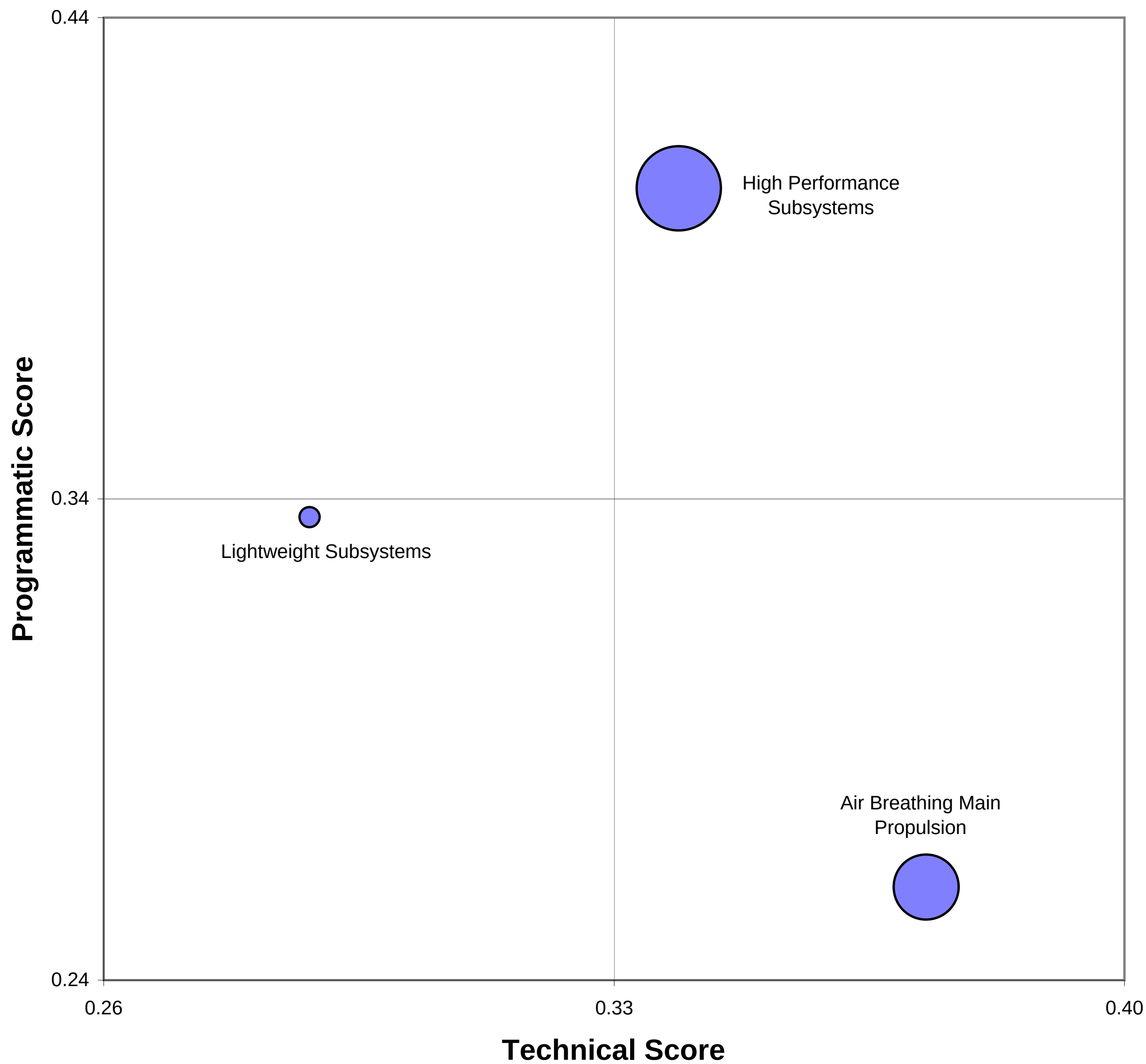
These data provide a graphic display of both the technical and programmatic prioritization results, and the relative level of investment required for each of the six categories of technology areas derived by the SPST bottom-up process. For example, Chart 6.8-3 shows that the highest priorities among the Operations technology areas were found to be the Elimination of Support Systems and the use of Single Main

Propellants, at levels of investment greater that most of the other candidate technology areas.

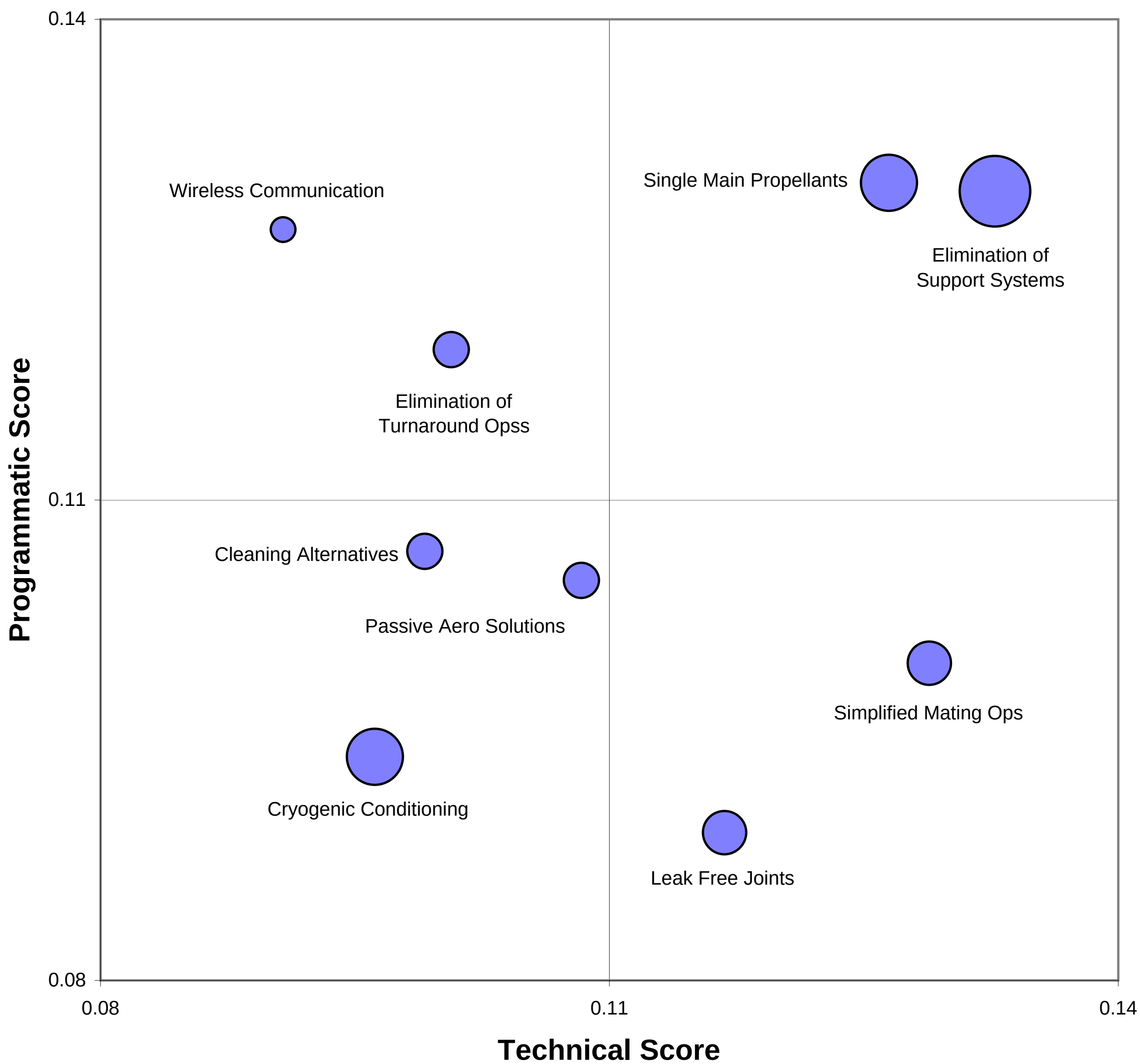
6.8-1 IVHM Technologies



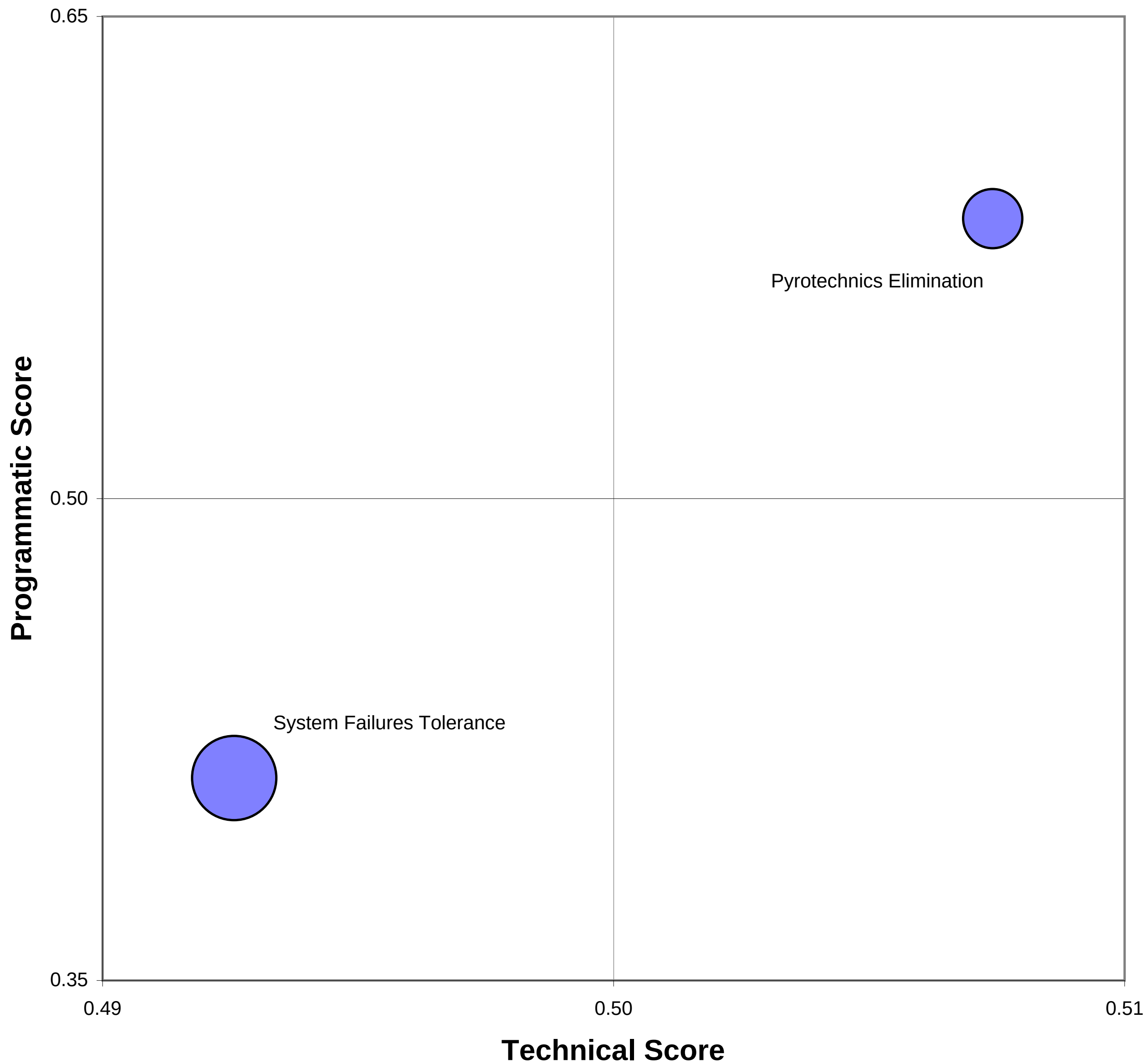
6.8-2 Margin Technologies



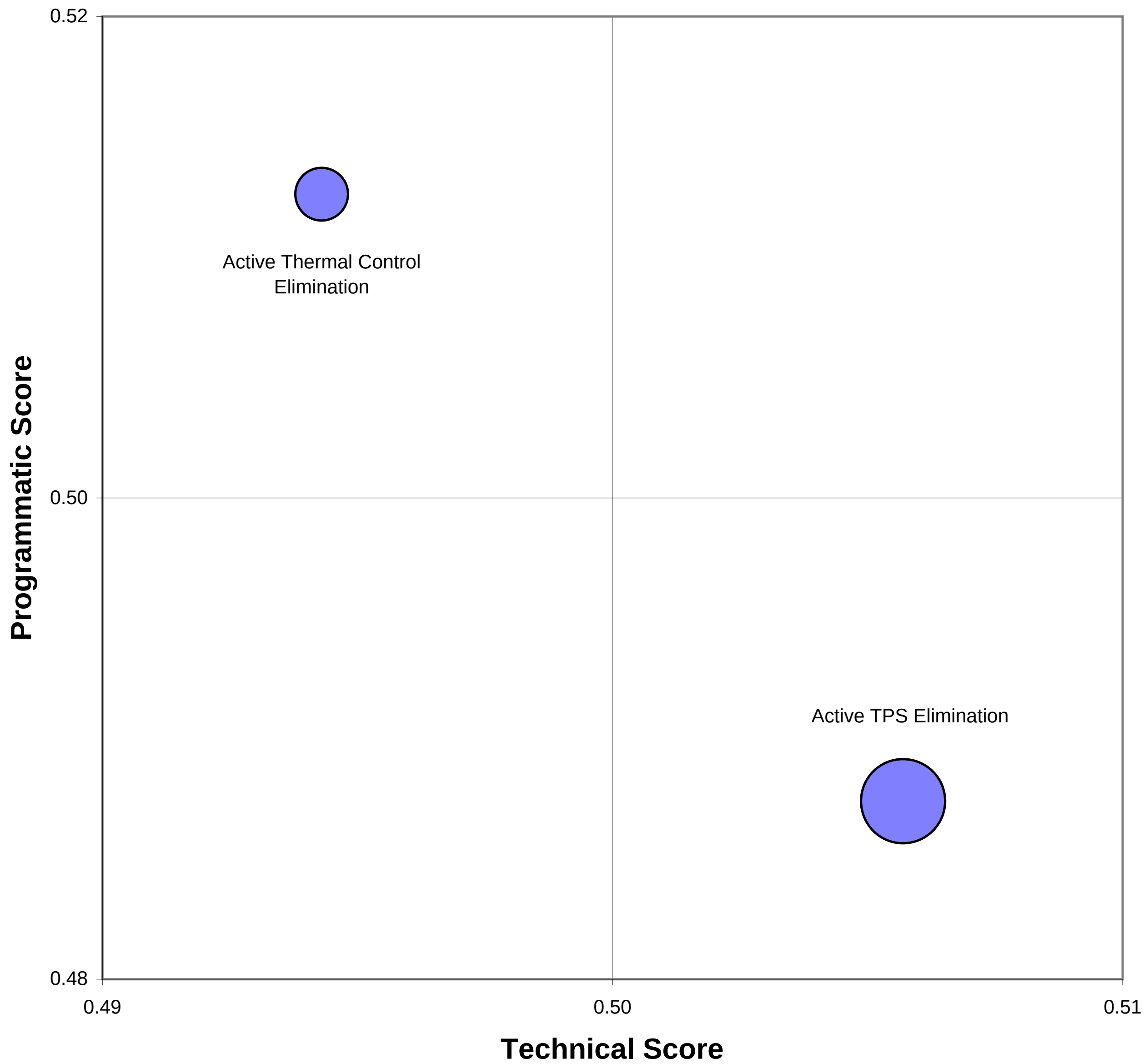
6.8-3 Operations Technologies



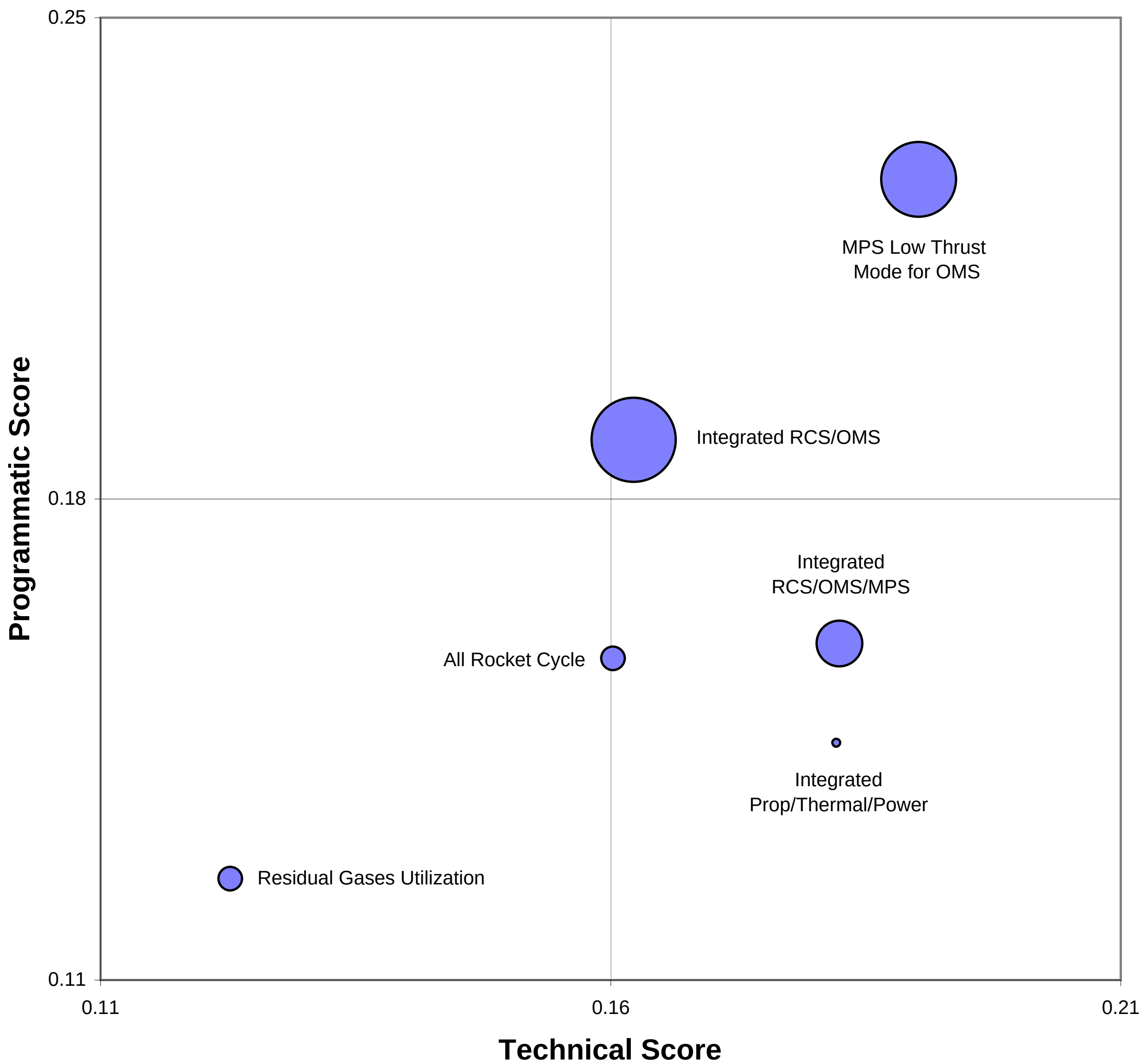
6.8-4 Safety Technologies



6.8-5 Thermal Control Technologies



6.8-6 Number of Systems Reduction Technologies



7. SUMMARY AND CONCLUSIONS

The two-day April 2001 SPST Technologies Prioritization Workshop provided roughly 10,000 data inputs into the facilitation central database software for processing into the forms and formats presented in this report. The NASA, DoD, industry, and academia team of evaluators did an excellent job of working through the assessment of the 26 candidate technology areas against the predefined SPST prioritization criteria using the current Space Shuttle system and its operation as a reference or pivot technology set.

A very valuable part of the overall workshop was the presentation and discussion of each of the 26 candidate technology areas. The set of briefings contained in Reference 2 represents a valuable resource in understanding and assessing the potential merits of the technology areas derived from the SPST bottom-up process. The briefings are posted on the Space Propulsion Synergy Team wing of the Virtual Research Center (VRC) web site hosted at the NASA Marshall Space Flight Center. The web address is http://voyager1.msfc.nasa.gov . Access can be established by going to the site and requesting a badge.

During the discussions at the workshop, the evaluation team, members of the SPST Functional Requirements (and Criteria Definition) team, Bottom-Up Integrated Technology Team, and the Technologies Definition and Documentation Team, all recognized that some of the candidate technologies could probably have scored higher had certain additional technical criteria been considered. The Functional Requirements team had selected 25 out of a total of 81 originally identified technical criteria, based on their relevance and the relative weightings of the QFD process. Also the team had decided to use these same technical and programmatic evaluation criteria because they were used in the April 2000 SPST workshop to prioritize candidate propulsion technologies derived from the top-down process of assessing candidate architectures for third generation RLV systems. Use of the same criteria enables a degree of consistency between the top-down and the bottom-up assessments.

Given the above considerations, it was decided that the assessments of the candidate bottom-up technologies would be done using the originally selected 25 technical criteria, and that the results should be interpreted accordingly.

The overall workshop results provide a significant decision support input into the prioritization of potential investments in the technology areas identified and defined in the SPST bottom-up assessment process. The technical and programmatic priorities documented in Section 6 can be compared by technology categories, and the combined technical and programmatic data are useful both at the technology category level and at the global level. Also the extra exercise by the workshop evaluators to prioritize the complete set of 26 technology areas according to their potential for (1) decreasing costs, and (2) increasing safety proved to be very interesting and useful as a separate decision support input to technology investment planning.

Conclusions Summary Based on the Global Prioritization Results

1. The results of the global processing of the evaluation team's baseline data (across all 25 technical and 19 programmatic criteria) for equal emphasis on the technical and programmatic criteria, indicate that the highest leverage propulsion and propulsion-related technologies are those that (1) reduce the number of RLV systems to be designed, developed, tested, and operated; (2) increase system margins; and (3) simplify thermal control of the flight vehicle. IVHM and Operations technologies are important but rank lower than those technology areas based on the complete set of SPST criteria. The particular Safety technology areas considered in this workshop were found to be of relatively low integrated priority based on all the criteria.

2. The results of the team's two extra assessments of the 26 candidate technology areas for their potential to specifically (1) decrease costs and (2) increase safety showed that the IVHM technologies (particularly Automated Predictive Maintenance and Systems Health Verification) are of high priority in achieving both of these advanced RLV system goals. These data showed that also several operations technology areas are important to reduce costs, including particularly the Elimination of Turnaround Operations, Elimination of Support Systems, Simplified Mating Operations, and use of Single Main Propellants. In addition, the reduction of the number of systems will be important, particularly the use of Integrated Propulsion/Thermal/Power systems and integrated RCS/OMS/MPS designs.

3. The extra assessments data showed that, in addition to the IVHM technologies (particularly Automated Predictive Maintenance, Critical Failures Identification, and Systems Health Verification), the two safety technology areas, Pyrotechnics Elimination and Systems Failure Tolerance, are high priorities as assessed specifically against the potential for increasing RLV system safety. The data also indicated the importance of Leak Free Joints and Simplified Mating Operations technologies to increase safety. Air Breathing Propulsion is important among the Margin technologies for its potential to increase system safety.

4. Combining the results of the baseline technical and programmatic priorities with the separate cost and safety assessments shows that overall the IVHM technologies are highest priority for investment in terms of overcoming some of the key impediments to achieving program success. Also technologies and design approaches that reduce the number of systems are importance to balanced investment planning. The technologies to improve operations and increase system margins are important including the development of Air Breathing Propulsion.

5. Overall, most of the technology solution areas identified by the SPST that address the impediments or barriers to achieving advanced RLV system goals tend not to be very exciting or exotic technologies. However, they address areas where large technological improvements are required. Also these technologies tend to be

crosscutting and required by most all envisioned system concepts. It is believed that detailed studies would show strong benefit-to-investment cost ratios for most of the identified high priority / high leverage technology areas.

6. The prioritization results of the April 2001 SPST Technologies Prioritization Workshop should apply to second generation as well as third generation RLV systems. It is believed that the SPST bottom-up process of identifying design and operations impediments to the achievement of advanced RLV system and program goals, and the identification and prioritization of potential technology solutions, provide a useful database for space transportation technologies investment planning at NASA. In the spirit of that belief, this document is provided by the Space Propulsion Synergy Team as a decision support package to the Agency.

8. REFERENCES

1. Integrated Technology Team (ITT) Status Briefing, Jay Penn, Presented to the National SPST Meeting, Huntsville, AL, April 12, 2001.

2. White Paper Briefings for the 2001 SPST Technologies Prioritization Workshop, Dan Levack, Marshall Space Flight Center, April 10-11, 2001.

3. Space Propulsion Synergy Team Technology Evaluation Criteria Definitions Book, Russel Rhodes, Final Release Copy, March 9, 2000.

APPENDIX A

PRIORITIZATION DATA AT THE INDIVIDUAL CRITERION LEVEL

Pages	**Technology Area Category**	**Evaluation Criteria**
A-1 thru A-25	IVHM Technologies	Technical
A-26 thru A-50	Margin Technologies	Technical
A-51 thru A-75	Operations Technologies	Technical
A-76 thru A-100	Safety Technologies	Technical
A-101 thru A-125	Thermal Control Technologies	Technical
A-126 thru A-150	Number of Systems Reduction	Technical
A-151 thru A-169	IVHM Technologies	Programmatic
A-170 thru A-188	Margin Technologies	Programmatic
A-189 thru A-207	Operations Technologies	Programmatic
A-208 thru A-226	Safety Technologies	Programmatic
A-227 thru A-245	Thermal Control Technologies	Programmatic
A-246 thru A-264	Number of Systems Reduction	Programmatic