NASA-TM-108752

JSC-25453

Rendezvous, Proximity Operations and Capture Quality Function Deployment Report

Engineering Directorate
Navigation, Control & Aeronautics Division

December 1991

NASA
National Aeronautics and Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

(NASA-TM-108752) RENDEZVOUS, PROXIMITY OPERATIONS AND CAPTURE QUALITY FUNCTION DEPLOYMENT REPORT (NASA) 66 p

N93-25952

Unclas

G3/17 0163522

JSC-25458

Rendezvous, Proximity Operations and Capture Quality Function Deployment Report

December 1991

Edited By:

Stephen L. Lamkin

Approved by:

Gregory C. Hite
Chief, Navigation and Guidance Systems Branch
Navigation, Control and Aeronautics Division
Engineering Directorate

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

RPOC QFD REPORT

Table of Contents

List of Figures

List of Tables

Rendezvous, Proximity Operations and Capture Quality Function Deployment Report

1. Introduction

Rendezvous, Proximity Operations, and Capture (RPOC) is a missions operations area which is extremely important to present and future space initiatives and must be well planned and coordinated. To support this, a study team was formed to identify a specific plan of action using the Quality Function Deployment (QFD) process. This team was composed of members from a wide spectrum of engineering and operations organizations which are involved in the RPOC technology area.

2. Background

The key to this study's success is an understanding of the needs of potential programmatic customers and the technology base available for system implementation. To this end, the study team conducted interviews with a variety of near term and future programmatic customers and technology development sponsors. The QFD activity led to a thorough understanding of the needs of these customers in the RPOC area, as well as the relative importance of these needs.

3. Sponsor's Perspective

The sponsor of the RPOC QFD effort was Gregory C. Hite, Chief of the Navigation and Guidance Systems Branch in the Navigation, Control and Aeronautics Division at JSC. Benefits to be gained from the study are:

a. A defined, logical approach for establishing a RPOC center of excellence;
b. A plan to evaluate the state-of-the-art in hardware components and software algorithms necessary to implement automatic RPOC functions;
c. A plan to define an acceptable procedure for implementation of automatic RPOC functions on both manned and unmanned vehicles;
d. A plan for spending future advanced research and development funds to support the RPOC activity;
e. Confidence in the derived RPOC master plan for achieving the center of excellence such that management advocacy exists to implement the proposed plan and potential RPOC implementers will come to this group for expertise;
f. A means to establish agreed-upon action priorities;
g. A long-range planning base for RPOC activities to be implemented over an extended period of time;
h. Lasting RPOC team relationships.

4. Team Objectives

Specific objectives of the RPOC QFD activity were:

a. Collectively understand the elements, functions, and characteristics of RPOC, and the products delivered to customers;
b. Define and prioritize the FY 91-93 activities of the RPOC community to meet customer needs;
c. Define what the leadership could do, in addition to the RPOC community, to better meet the needs of customers.
d. Establish boundaries for the activity which extend from low earth orbit to interplanetary missions for both manned and unmanned missions; ascent guidance is considered only as it affects the rendezvous phase.

5. Team Membership and Technical Contribution

The RPOC QFD team included both civil service and contractor members, primarily from the JSC engineering and operations technical community, selected for their specific RPOC experience and expertise. The individuals involved are identified in Appendix A.

6. QFD Concept

Quality Function Deployment (QFD) is a formal technique for capturing a user's needs and mapping them into product and process parameters. It consists of techniques for creating and completing a series of matrices showing the association between specific features of a product and statements representing the "Voice of the Customer". In other words, it provides a structure for ensuring that customer's wants and needs are carefully considered, then directly transferred into an organization's internal requirements.

The QFD methodology is a structured process that uses the construction of the House of Quality matrix to lead the team members through the process. The House of Quality matrix is a tool that quantifies the results obtained by the QFD team, and allows analysis at each step in the process. The QFD process and methodology are further discussed in Section 15.

7. RPOC Term Definitions

Early in the RPOC QFD process it became evident that several of the key terms associated with Rendezvous, Proximity Operations and Capture, illustrated in Figure 1, needed to be defined to support a commonality of understanding and approach. The following definitions were agreed upon by all team members, and used throughout the RPOC QFD process.

7.1 Rendezvous

Rendezvous is the mission phase in which a series of scheduled maneuvers adjust the orbital elements to achieve desired offsets in position and velocity relative to another body, such that the two bodies are brought into close proximity to each other with small relative velocity.

7.2 Flyby

Flyby is the mission phase in which a series of scheduled maneuvers adjust the orbital elements to achieve desired offsets in position and velocity relative to another body, such that the two bodies are brought into proximity to each other with large relative velocity.

7.3 Proximity Operations

Proximity operations is the mission phase which requires precision control of the relative position, attitude, and velocity between two vehicles and which is characterized by frequent, small maneuvers. This phase includes flyarounds, approaches, departures, formation flying, stationkeeping, docking, berthing, tethering and other operations conducted at close range to another vehicle.

Distinguishing criteria often used to establish the range for the proximity operations zone include the following:

- Where knowledge of the other vehicle's attitude is required for proper system operation of each vehicle;
- Where loss of communications or inability to execute a translation maneuver unacceptably increases the risk of an imminent collision;
- Ranges at which manual operations occur to maintain one vehicle in proximity to the other;
- Ranges where plume impingement and contamination effects must be considered.

Typically the proximity operation zone begins at a range of 2 kilometers.

Note that the initiation of the proximity operations mission phase is not necessarily defined as the maximum range of the proximity operations sensor(s), since a given sensor may have long range as well as short range capabilities.

7.4 Stationkeeping

The procedure whereby a vehicle maintains a position relative to a second vehicle within a prescribed envelope, and during which the second vehicle does not execute translation maneuvers to maintain the desired relative position.

7.5 Formation Flying

The procedure whereby a vehicle maintains a position relative to another vehicle, or vehicles, within a prescribed envelope, and during which any of the vehicles may execute maneuvers.

7.6 Attachment/Capture Procedures

7.6.1 Docking

A procedure that results in an attached condition between two vehicles by mechanically coupling the two vehicles together in a rigid fashion. The procedure requires a positive closure rate to activate the docking mechanism.

7.6.2 Berthing
The procedure by which two vehicles are attached by means of a manipulator system on one of the vehicles. The procedure requires essentially zero relative rates between the two vehicles to effect capture.

7.6.3 Tethering
The procedure by which two vehicles are attached by means of a tether cable system. The tethered phase requires maneuvering by one or both vehicles to maintain stable conditions or conduct tethered operations.

7.7 Operating Modes

7.7.1 Autonomous
A mode in which a vehicle, or system, can evaluate and alter its operation to achieve its objective, without external supervision or control.

7.7.2 Automatic
A mode in which a vehicle, or system, can perform predefined operations without human intervention.

7.7.3 Manual
A mode in which a vehicle or system is operated by the vehicle crew.

7.7.4 Teleoperated
A mode in which a vehicle or system is operated remotely by a human.

7.8 Vehicle Types

7.8.1 Active Vehicle
The vehicle which performs translational maneuvers to effect a rendezvous. This vehicle is traditionally designated the "chaser" vehicle.

7.8.2 Passive Vehicle
The vehicle which does not perform translational maneuvers to effect a rendezvous, but may perform maneuvers to enable a rendezvous. This vehicle is traditionally designated the "target" vehicle.

7.8.3 Cooperative Vehicle
A vehicle which provides capabilities (e.g. command and control, sensor information or aid) for the enhancement or accomplishment of a rendezvous.

7.8.4 Uncooperative Vehicle
A vehicle which does not provide capabilities for the enhancement or accomplishment of a rendezvous.

8. RPOC Elements, Functions, and Characteristics

The QFD team defined a typical RPOC scenario (Figure 1), then identified the elements, functions, and characteristics of RPOC that are required to be accomplished in the normal course of any program. The list in Appendix B served as a mind jogger of the many aspects for RPOC QFD team members consideration

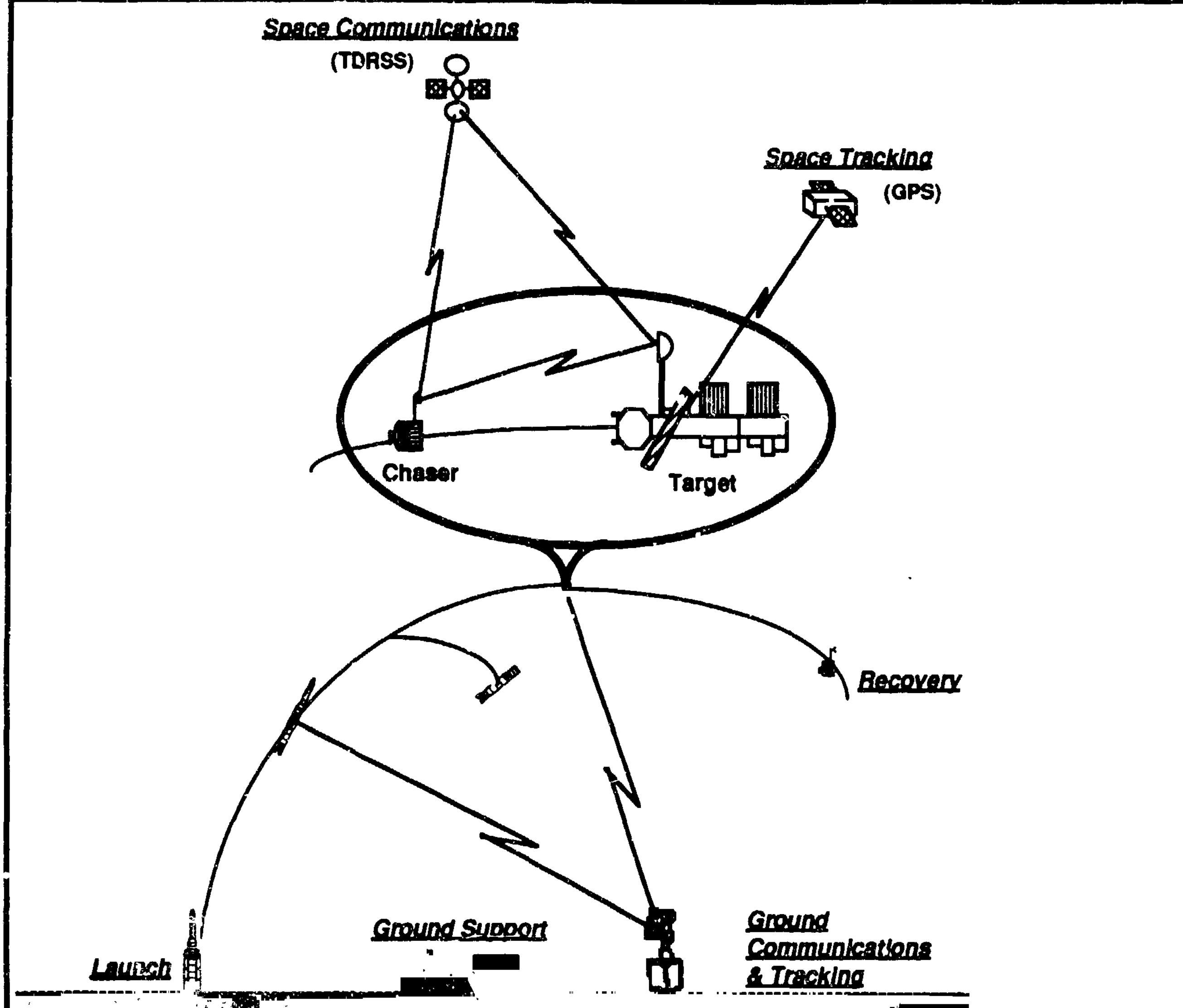

Figure 1. Typical Rendezvous, Proximity Operations, and Capture Scenario/Mission

9. Identification of Customers

Initially the QFD team identified potential customers of RPOC technology. The list included government agencies, private space groups, universities, foreign nationals and industry, and served to identify the kinds of customers needing RPOC technology. Once the customer base was defined, this list served as a catalyst to tailor the questions to be asked each of the customers selected for interviewing.

The list of RPOC customers (Appendix C) was developed to identify the breadth of the potential customers for interview; from this list interviewees were selected. The customer interview process is described in Appendix D. The interviews were conducted and reviewed to identify the needs of customers and prioritize these needs. The products to be delivered to the customers are in response to these needs, reflected in the list of general RPOC functions as covered in Appendix B. For example, a customer may desire new levels of reliability and fault tolerance in order to satisfy a mission requirement for an autonomous RPOC vehicle. Specifically, the need is for higher levels of reliability and fault tolerance for the RPOC vehicle and for the types of systems appropriate for autonomous operations. Generally, system (and vehicle) reliability and fault tolerance are included in the list of RPOC functions.

The definition of the term 'customer' and the subsequent identification of who are RPOC customers is central to this QFD. In the purest sense, a customer is one who seeks the products and services supplied by another, and expects to be satisfied. In this case, the supplier is the RPOC community and the RPOC customers are identified by their association with the members of the RPOC community. RPOC customers seek to satisfy their needs within the RPOC community. Programs or contractors may also seek to acquire an RPOC capability or, having the capability, may seek the services or products of other community members. In this sense most of the RPOC community are also RPOC customers; it should be no surprise that the total list of customers is comprised mainly of members of the RPOC community.

This understanding and definition of a customer is both practical and appropriate, since the RPOC community members are identifiable as an unstructured group of professional individuals or organizations which practices aerospace engineering or operations in the RPOC arena, or are known to have RPOC expertise. Alternatively, the RPOC community is defined as providers of the RPOC functions (See Appendix B). All organizations and levels are included if they have RPOC offices or contractors (who are tasked with RPOC functions) up to the program level. Also included are funding organizations if RPOC programs or research are supported by that organization.

Central to the theme (and to the objectives) of this study, is the definition of the term 'RPOC leadership'. The RPOC leadership are also members of community, but they are hard to distinguish. Formally, leadership seeks to manage and inspire a group to foster self improvement, attain identifiable goals, and produce. To the RPOC community, there appears to be no identifiable leadership, other than the program or contractor management. Although management seek goals (mostly programmatic) and productivity, this group does little to foster or inspire self improvement or goals which are community related. In these areas, the management seeks its guidance from the RPOC community itself and so RPOC community leadership is not within management. The responsibility for RPOC community leadership must rest on its most active members, especially in the areas of advanced RPOC capability development, new technology development, product or quality improvements, process efficiency, and the coordination of such efforts. Establishment of an identifiable RPOC community leadership is essential to further RPOC advocacy.

10. Individuals Interviewed

The team attempted to interview representative RPOC customers. Time constraints dictated that the number of interviews be limited to nine. Customers were selected who were expected to have RPOC needs, and were involved in a variety of programs. The customers chosen were:

Aldo Bordano, Deputy Chief, Navigation, Control and Aeronautics Division, Engineering Directorate, JSC. Mr Bordano is JSC point of contact for development of the NASA Code R Integrated Technology Plan which addresses how NASA will develop RPOC technologies.

Harry J. Buchanan, Manager, Cargo Transfer Vehicle (CTV) Project Office, MSFC. The CTV currently envisions a need for automated rendezvous and capture operational capability.

Kenneth J. Cox, Chief, Navigation, Control and Aeronautics Division, Engineering Directorate, JSC. Dr Cox's division is the lead NASA organization for the Exploration Technology Program for development of automated and autonomous rendezvous and capture technology. He is also chairman of the NASA Strategic Avionics Technology Working Group (SATWG) which is responsible for identifying guidance, navigation, and control priorities, including RPOC.

John D. DiBattista, Program Element Manager for Autonomous Rendezvous and Docking (AR&D), NASA Headquarters, Code RC. Mr. DiBattista is responsible for development of automated rendezvous and capture technology within NASA.

Allan L. Dupont and David B. Weaver, Lunar and Mars Exploration Program Office, JSC. Messrs Dupont and Weaver are responsible for mission development and operations in the Lunar and Mars Program Office. The current planning for flights to the Moon and Mars anticipate use of automated and autonomous rendezvous and capture technology.

Claude A. Graves, Jr. Chief, Systems Engineering Division, Engineering Directorate, JSC. Mr Graves is responsible for advanced systems concepts development and identifying technology requirements and issues.

Fred Huffaker, Space Exploration Initiative, MSFC. Mr. Huffaker, in the Program Development Office at MSFC, is responsible for analyses, concepts, and requirements of transportation systems supporting missions to Mars.

Mark B. Nolan, Manager, Technology and Commercial Projects Office, New Initiative Office, JSC. Mr. Nolan is responsible for coordination of technology development at JSC and the application of unique JSC expertise to engineering and operational problems in the RPOC area.

Robert C. Ried, Chief Engineer, Lunar/Mars Exploration, Engineering Directorate, JSC. Dr. Ried is responsible for coordinating engineering solutions to the problems of Lunar and Mars exploration across the many engineering disciplines at JSC. He also advises the Director of Engineering on application of JSC expertise to Lunar/Mars engineering problems involving RPOC.

11. Findings and Results

The Affinity/Tree Diagrams of the customer needs and technical solutions are shown in Tables 1 and 2. The results of the RPOC QFD process are shown in Tables 3 and 4 and Figures 2 and 3. The use of the House of Quality tool enabled the RPOC QFD team to focus upon the real drivers and identify which customer needs carried the highest ratings.

Although the top 3 customer needs were anticipated, the priority of some others was somewhat of a surprise to team members.

What was more of a surprise for the team members, were the priorities of the technical solutions, although given the customer's needs, the heavy emphasis upon demonstration of technology was not surprising. The real surprise is that customers' need for demonstrated technology is not currently being met within the RPOC community, and customers felt this was a critical item.

Good definitions of the customer needs and the technical solutions are critical for achieving a common understanding within the RPOC community. This results in clearer direction and mutually satisfactory agreements among the numerous individuals and organizations involved. Accurate trade-offs and prioritization are essential to success. These important definitions are provided in Appendix E for use in evaluating these results.

Table 1. Affinity/Tree Diagram of RPOC Customer Needs

Level 1 Customer Need	Level 2 Customer Need	Level 3 Customer Need
1.0 Systems Operability	1.1 Optimize Degree of Independence	1.1.1 Human Interaction
		1.1.2 System to System
	1.2 Ease of Use	
	1.3 Effective Functional Partitioning	1.3.1 Navigation Partitioning
2.0 Meet Mission/ Program Objectives	2.1 Unmanned Resupply	2.1.1 Upgradable to Man Rated
	2.2 Autonomous RPOC	
	2.3 Efficient Rendezvous Techniques	2.3.1 Elliptical Orbit Rendezvous
	2.4 Efficient Proximity Operations Techniques	2.4.1 Minimize Vehicle-to Vehicle Interaction
		2.4.1.1 Maintain Stable Conditions
		2.4.2 Minimize Plume Impingement
	2.5 Effective Space Traffic Control	2.5.1 Collision Avoidance
		2.5.2 Ability to Control 2 or More Vehicles
3.0 Low Program Risk	3.1 Reliable Systems	
	3.2 Demonstrated Systems & Technology	
	3.3 System Acceptability	
4.0 Low Programmatic Cost	4.1 Increase Design Process Efficiency	
	4.2 Accommodate Technology Growth & Insertion	
	4.3 Increase Operations Efficiency	4.3.1 Minimize Engineering Operations Maintenance Support
5.0 Knowledgeable Comprehensive Consultation		

Table 2. Affinity/Tree Diagram for RPOC Customer Technical Solutions

Level 1 Technical Solutions	Level 2 Technical Solutions	Level 3 Technical Solutions
1.0 Design Philosophy	1.1 Use Incremental Design Approach	
	1.2 Use Simple Systems	
	1.3 Use Redundant Components & Information	
	1.4 Use Conservative Margins	
	1.5 Use Standardized Interfaces	
	1.6 Use Friendly Interfaces	
	1.7 Define System Requirements for Minimum Training	
	1.8 Use Failure Resistant Components	
	1.9 Use Concurrent Engineering Process	
2.0 Collect & Exchange Knowledge	2.1 Perform Survey of State of the Art RPOC Capabilities	
	2.2 Build Databases	
	2.3 Develop Integrated Technology Plan	
3.0 Develop Advanced Technology	3.1 Develop Advanced Sensors	
	3.2 Develop Advanced Algorithms	
	3.3 Develop Improved Docking Mechanisms & Facilities	
4.0 Define Mission Architectures Requirements & Constraints	4.1 Define Resupply/Return Mission Requirements	
	4.2 Develop Traffic Control Strategy	
	4.3 Define Operating Zones	
	4.4 Define Operating Modes	
5.0 Define System Requirements	5.1 Early Definition & Maturity of Requirements	
	5.2 Improve System Requirements Traceability Process	
6.0 Define Operating Requirements	6.1 Provide Effective Telemetry/Command/ Navigation Infrastructure	

Level 1 Technical Solutions	Level 2 Technical Solutions	Level 3 Technical Solutions
	6.2 Reduce/Standardize Mission Dependent Reconfiguration	6.2.1 Reduce/Standardize Flight Software Reconfiguration
		6.2.2 Reduce/Standardize Flight Turnaround Reconfig
7.0 Design RPOC Systems	7.1 Perform Functional Analysis on all RPOC Systems	
	7.2 Develop Trajectory Approach Techniques	
	7.3 Apply Expert Systems to RPOC	
	7.4 Develop Algorithms for Rendezvous	
	7.5 Design Attitude & Translation Control Systems to Minimize Contamination & Plume Impingement	
8.0 Evaluate RPOC Systems & Technologies	8.1 Perform Systems & Technologies Trade Studies	8.1.1 Analyze Tether Applications to Reduce Plume Effects
		8.1.2 Navigation Infrastructure
	8.2 Perform Simulations	8.2.1 Non-Real Time
		8.2.2 Real Time
	8.3 Perform Hardware Evaluations	
	8.4 Perform Statistical Analyses	
	8.5 Perform Rapid Prototyping & Testing	
9.0 Develop & Maintain Common Tools & Facilities	9.1 Automate Design Process of RPOC Systems	
	9.2 Use Automatic Code Generation	
	9.3 Automate Mission Planning (Ground) & Replanning (On-Board)	
10.0 Demonstrate RPOC Systems & Capabilities	10.1 Perform Flight Demonstrations	10.1.1 Conduct Shuttle Flight Demonstrations
		10.1.2 Conduct Unmanned Vehicle Flight Demonstrations

Level 1 Technical Solutions	Level 2 Technical Solutions	Level 3 Technical Solutions
		10.1.3 Conduct Multi-Vehicle Flight Demonstrations
	10.2 Perform Ground Demonstrations	10.2.1 Conduct Prototype System Ground Tests
		10.2.2 Conduct Ground Tests with Flight Hardware

Table 3: Relative Weight of Importance of RPOC QFD Customer Needs

Customer Need	Rel. Wt.
3.2 Demonstrated Systems & Technology	22.4%
2.2 Autonomous RPOC	14.4%
2.1 Unmanned Resupply	9.5%
2.3 Efficient Rendezvous Techniques	7.0%
3.1 Reliable Systems	6.7%
5.0 Knowledgeable Comprehensive Consultation	6.5%
4.3 Increase Operations Efficiency	6.5%
3.3 System Acceptability	5.3%
2.4 Efficient Proximity Operations Techniques	5.1%
4.1 Increase Design Process Efficiency	4.7%
4.2 Accommodate Technology Growth & Insertion	4.6%
1.1 Optimize Degree of Independence	3.0%
1.3 Effective Functional Partitioning	2.0%
1.2 Ease of Use	1.5%
2.5 Effective Space Traffic Control	0.8%

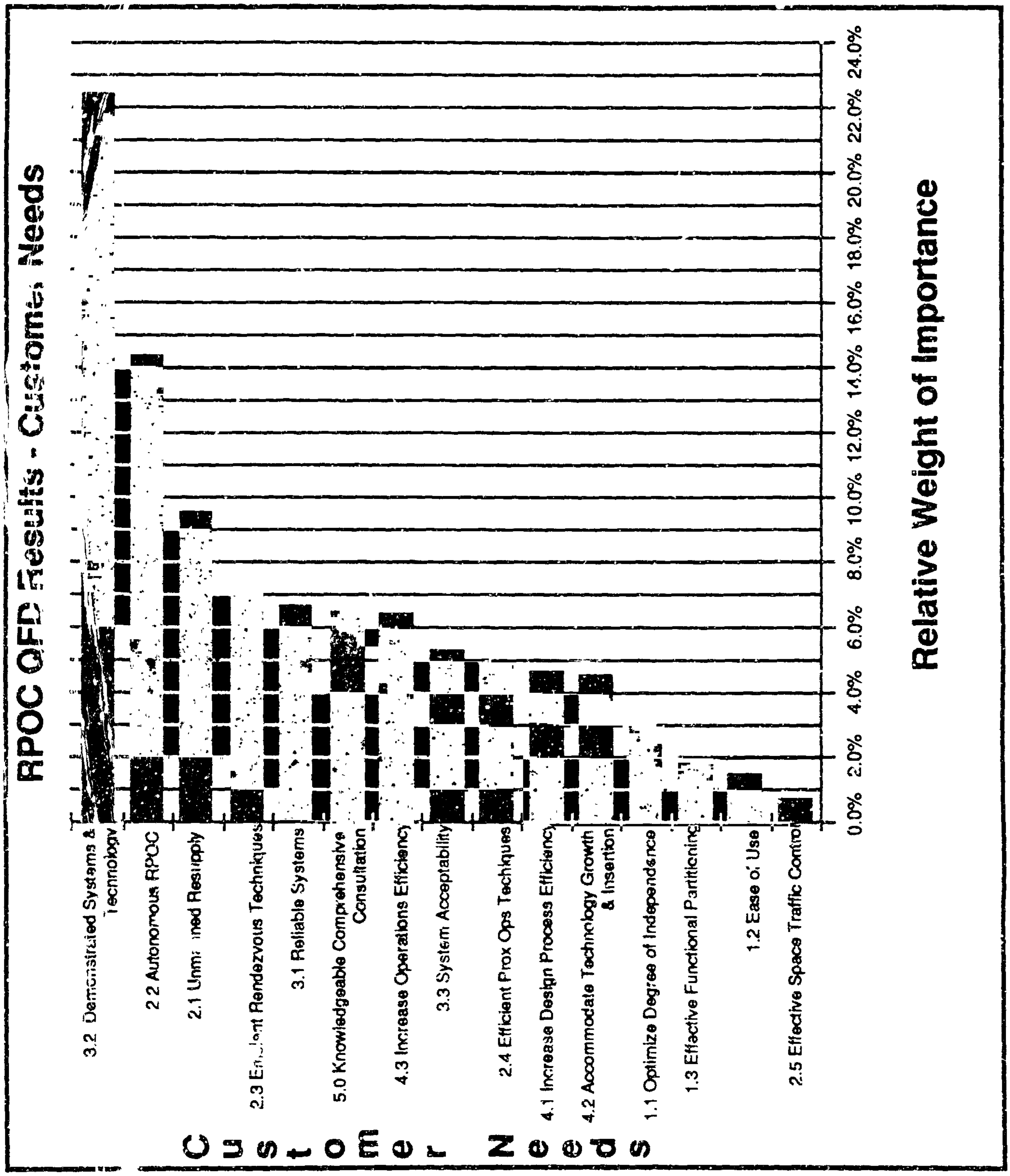

Figure 2. Ranking of Customer Needs

Table 4. Technical Solutions to Customer Needs

Technical Solution to Customer Needs	Rel. Wt
8.1 Perform Systems & Technologies Trade Studies	5.9%
10.1.3 Conduct Multi-Vehicle Flight Demonstrations	4.8%
10.1.2 Conduct Unmanned Vehicle Flight Demonstrations	4.8%
8.4 Perform Statistical Analyses	4.5%
8.2.1 Perform Simulations - Non-Real Time	4.5%
8.2.2 Perform Simulations - Real Time	4.5%
8.3 Perform Hardware Evaluations	3.6%
10.2.2 Conduct Ground Tests with Flight Hardware	3.6%
10.2.1 Conduct Prototype System Ground Tests	3.5%
1.1 Use Incremental Design Approach	3.4%
10.1.1 Conduct Shuttle Flight Demonstrations	3.2%
8.5 Perform Rapid Prototyping & Testing	3.2%
3.2 Develop Advanced Algorithms	3.0%
3.1 Develop Advanced Sensors	3.0%
3.3 Develop Improved Docking Mechanisms & Facilities	2.8%
1.9 Use Concurrent Engineering Process	2.7%
9.3 Automate Mission Planning(Gnd) & Replanning(On-board)	2.5%
6.1 Provide Effective Telemetry/Command/Navigation Infrastructure	2.1%
6.2 Reduce/Standardize Mission Dependent Reconfiguration	2.0%
2.3 Develop Integrated Technology Plan	2.0%
2.1 Perform Survey of SOA RPOC Capabilities	1.9%
2.2 Build Databases	1.9%
9.1 Automate Design Process of RPOC Systems	1.9%
6.2.1 Reduce/Standardize Flight Software Reconfiguration	1.7%
7.3 Apply Expert Systems to RPOC	1.7%
6.2.2 Reduce/Standardize Flight Turnaround Reconfiguration	1.7%
7.5 Develop Attitude/Translation Control Systems to Minimize Contamination & Plume Impingement	1.6%
7.2 Develop Trajectory Approach Techniques	1.5%
1.5 Use Standardized Interfaces	1.5%
4.2 Develop Traffic Control Strategy	1.5%
.4 Develop Algorithms for Rendezvous	1.4%
5.1 Early Definition & Maturity of Requirements	1.3%
4.1 Define Resupply/Return Mission Requirements	1.2%
1.2 Use Simple Systems	1.1%
1.3 Use Redundant Components & Information	1.0%
1.8 Use Failure Resistant Components	1.0%
5.2 Improve System Requirements Traceability Process	1.0%
7.1 Perform Functional Analysis on All RPOC Systems	0.9%
1.6 Use Friendly Interfaces	0.9%
1.4 Use Conservative Margins	0.8%
4.4 Define Operating Modes	0.8%
4.3 Define Operating Zones	0.8%
1.7 Define System Requirements for Minimum Training	0.6%
9.2 Use Automatic Code Generation	0.6%

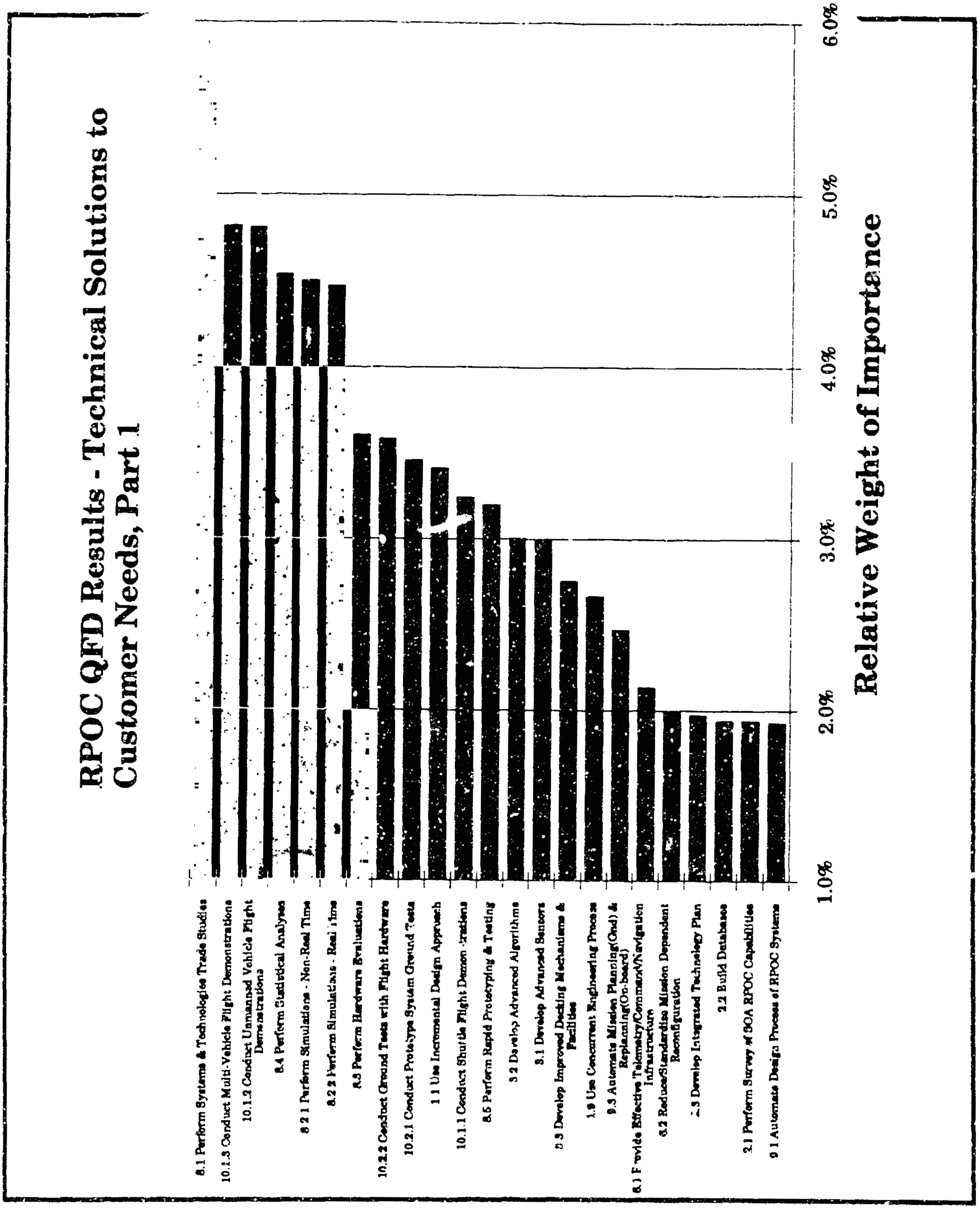

Figure 3A. Ranking of Technical Solutions to Customer Needs, Part 1

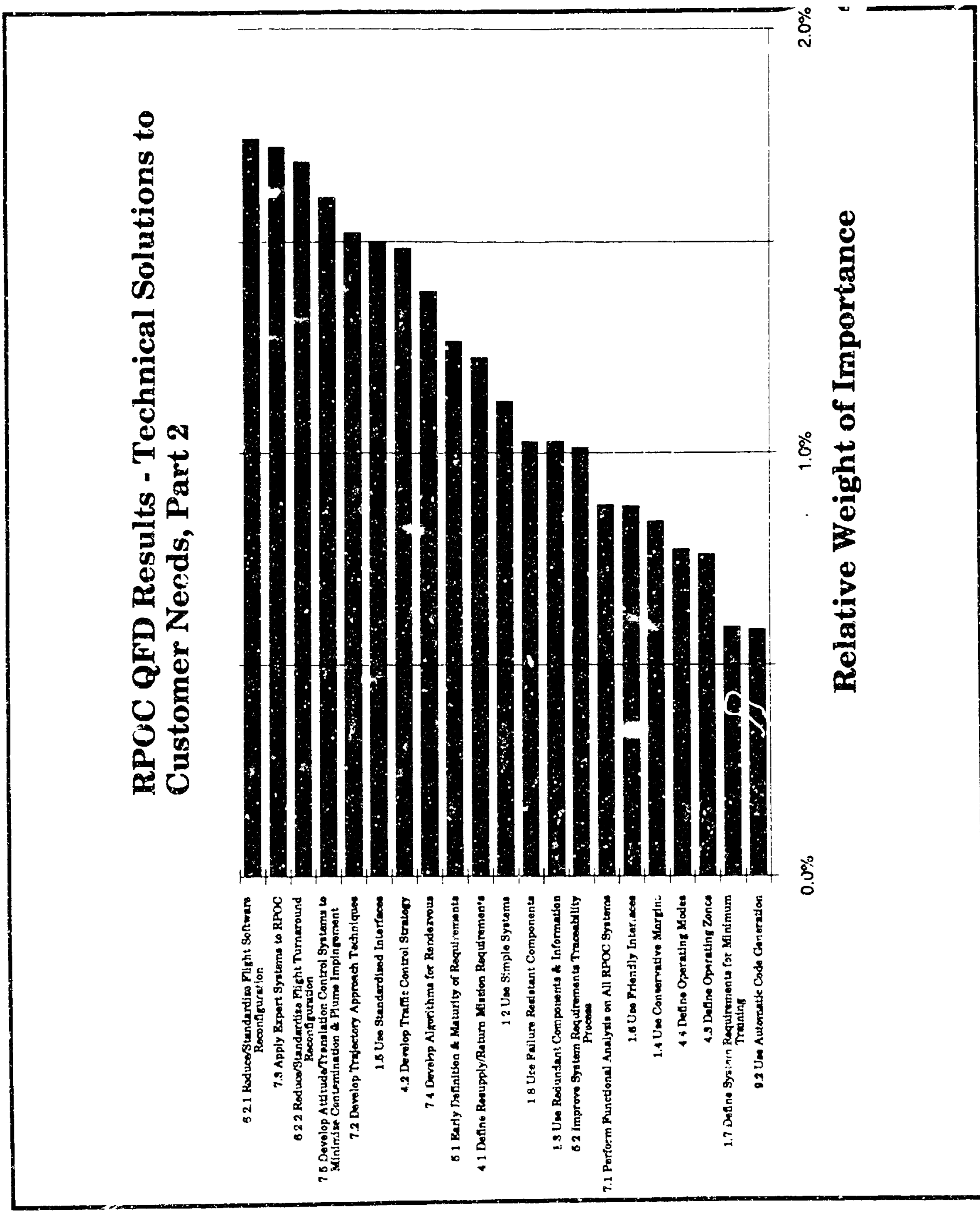

Figure 3B. Ranking of Technical Solutions to Customer Needs, Part 2

12. Recommended FY 91-93 Activities to Meet Customer Needs

The time interval of FY91-93 is short compared to the time needed to design, build and accomplish a project in space. However, the activities of the RPOC community in this interval should be focused on initiating efforts that can produce large results in the years following FY93. The major areas recommended for activity are identified in Sections 12.1 and 12.2. They are inter-related and should be performed in parallel.

The activities recommended here can be done only with management awareness, concurrence, approval, and support. These activities will require man-hours from specific personnel and some expenditure of resources that require cost accounting by the participating organization. Management approval is required if the effort is to continue.

A logical start for approval is with the management of the organizations that supported this RPOC QFD. They have the resources to support their activities and outside contacts to influence management in other needed organizations. Their support is crucial to the accomplishment of the tasks that follow.

12.1 RPOC Community Formation

Until now, the RPOC community has been divided and segmented by organization (e.g. NASA center, commercial company) and/or by program over how to equitably distribute and share the limited funding, manpower skills, and facilities needed for RPOC activities. After listening to customers from different programs and organizations say essentially the same things, and realizing that each does not have the total resources necessary to accomplish their needs and goals, it is apparent that the organizations involved in RPOC need the strength available from a cooperative forum. Therefore, it is recommended that the customers and implementers of RPOC establish such a forum. The goal of this organization is to:

> Provide technical interchange and support among members, share resources, and advance the development of RPOC capabilities for future space endeavors.

The formation activities should include the following:

a. Establish contacts and lines of communication. Identify who the RPOC players are in government, industry, academia, and internationally. Where are they located? Who are the points of contact for each RPOC discipline?

b. Identify resources. What are our capabilities and resources? What are our strengths and weaknesses? Establish mutual RPOC strategic plans consistent with NASA direction (i.e., funding, manpower, skills, data, equipment, facilities).

c. Compile a list of activities. What are we doing in RPOC? What are the immediate needs? What are the long term needs? Identify and understand our customers, suppliers, and products.

d. Begin to organize. How do we organize and structure our community to take advantage of collective strengths and effectively minimize redundancy and overlap? Will the organization be vague in the formal sense because of the many participants and organizational agendas? How do we maintain an active and cooperative environment at the working level?

e. Establish regular technical exchange meetings through existing forums (e.g. SATWG - Strategic Avionics Technology Working Group).

12.2 Addressing Customer Needs.

Based on the current schedules for programs needing RPOC capabilities, it is essential that the immediate efforts in the RPOC community address the long-term customer needs. Based on the interviews with customers and discussions within the RPOC QFD team, there is one effort that seems to address the multiple needs of the RPOC customers: demonstrating RPOC capability in space with a level of independence beyond that of the manual modes currently used in the U.S. Space Program. An appropriate level of independence, considering both the needs of impending programs and the level of technology maturity, is a demonstration of automated (not autonomous) RPOC between two space vehicles. Such a demonstration would address the customer needs of unmanned resupply, system acceptability, and demonstrated systems and technology. It would partially address other needs: optimized degree of independence; effective functional partitioning; autonomous RPOC; efficient rendezvous and proximity operations techniques; and increased operational efficiency.

It is reasonable for this demonstration to use supervised automation (man-tending or monitoring with override capability), both to protect the investment in the mission and as a possible standard way of doing automated RPOC in low earth orbit in the future.

Ways to conduct a reasonably priced flight experiment to demonstrate the concepts involved need to be explored. Conducting a Space Shuttle Detailed Test Objective (DTO), with free-flyers, is one option that was mentioned within the RPOC QFD team.

To satisfy RPOC customer needs, the following are recommended for FY91-93:

a. Further define, understand, and reach consensus on approaches for satisfying customer needs;

b. Collect and analyze pertinent technology data and information;

c. Examine options to demonstrate supervised RPOC automation in low earth orbit;

d. Develop each option considering high level mission planning, vehicle choices, RPOC performance requirements, RPOC instrumentation choices, and initial cost estimates;

e. Select and advocate the most appropriate and feasible option;

f. Establish the options and/or coalitions available to fund such a demonstration;

g. Aggressively seek funding.

13. What the RPOC Leadership Could Do to Better Satisfy Customer Needs

The RPOC QFD team spent considerable time and effort to define and prioritize RPOC activities necessary to meet customers needs. The next task is to define, create, and execute the mechanisms required to meet the needs of the customers. Oversight of RPOC technology development should be more centralized, and placed in a small and knowledgeable steering group. The steering group, specifically responsible for RPOC technology, should be established to guide all RPOC technology activities. This multi-organization group should be formed within the RPOC technical development community. Ultimate responsibility for development and operation would not rest with the group; rather, the group would be the advocate for RPOC. It would know where the expertise resides, and be aware of current and future activities. It would maintain a database of reference information about RPOC technologies. Leadership of the group should rotate annually among its members. In short, it should be the focal point for all RPOC activities.

It is not difficult to identify program managers who support the need for RPOC development. What is difficult, however, is to find program managers who are willing and/or able to support RPOC development with funding and personnel. RPOC technology is easily transferred between programs, thus preventing duplication of effort. However a non-programmatic sponsor for the technology is needed during Phases A & B, with specific program application and customization in Phases C & D. This is a difficult situation which must be addressed. Customers have a need for RPOC capability, yet RPOC capability will be slow in developing if funding and personnel support are not forthcoming. This, then, is the dichotomy. Customers need demonstrated RPOC capability. Yet, without adequate funding and personnel, the demonstrated capability will not occur in a timely fashion to meet the customers' needs.

14. Recommended Future Activities

The RPOC Quality Function Deployment process was effective in identifying customer needs and in defining promising approaches to satisfying those needs.

The top three customer needs - demonstrated systems and technologies, autonomous rendezvous proximity operations and capture, and unmanned resupply - are interrelated. The top potential technical solutions - trade studies, unmanned flight demonstrations, multi-vehicle flight demonstrations, statistical analyses, and Shuttle flight demonstrations - indicate a strong desire to augment analysis and ground demonstrations with flight demonstrations of hardware under actual conditions, and a need to reduce the development risk placed on new programs.

The use of demonstrated systems and technologies is one way to reduce risk and minimize development costs for new programs. The development of unmanned resupply capability is an excellent method of developing and demonstrating RPOC technology systems and technology. The development of an unmanned resupply capability also reduces both resupply risk and cost via the use of expendable launch vehicles. The risk to human lives is removed, the risk of launching low-value items with a high-value national asset (the Space Shuttle) is removed, and the cost of delivering the items can be reduced by using a lower cost vehicle with potentially smaller ground operations requirements. It has the added benefit of being demonstrable in low-earth orbit using technology that is largely available.

The development of an autonomous RPOC capability can reduce operational costs even further by reducing or eliminating dependence on ground command and control operations, or by eliminating the need for expensive command and control infrastructures. This capability can build on the success of an unmanned resupply capability in low-earth orbit. Autonomy is an essential capability for unmanned planetary missions requiring multiple vehicles, and may be required for manned missions as well.

The challenge is to provide a focus for the efforts of the RPOC community which will enable NASA to:

- advance RPOC technology in a number of technically challenging areas;
- establish intercenter and government/industry/academia working relationships;
- build momentum and enthusiasm;
- provide tangible evidence of progress;
- provide flight performance data for use by current and future programs;
- remove traditional impediments to rapid development of new systems;
- use limited funds most effectively.

The Exploration Technology Program has planned technology development of autonomous rendezvous and docking capability, emphasizing requirements development and ground demonstrations. A logical extension of that plan is flight demonstration aimed at proving concepts and components. The DOD Delta Star project demonstrates that, given a clear set of objectives, reasonable funding, and a maximum amount of delegated responsibility, concepts can be turned into missions in a relatively short period of time.

A plan for a Shuttle flight demonstration should attempt to use a maximum amount of off-the-shelf components in progressively more sophisticated Detailed Test Objectives (DTOs). These missions could use low-cost, functional test vehicles which exist only to provide platforms for the systems to be tested. An existing vehicle such as SPAS (Shuttle Pallet Satellite) could be modified to provide a target vehicle. These vehicles could be launched and retrieved by the Space Shuttle, and could be combined with other missions for effective Shuttle utilization and reduced cost. The flight demonstrations could be structured in the following sequence:

- Flight 1 - demonstrate automatic proximity operations and capture with a passive target;
- Flight 2 - demonstrate completion of automatic near-field rendezvous maneuvers with a passive target PLUS automatic proximity operations and capture;
- Flight 3 - demonstrate completion of automatic far-field rendezvous maneuvers (orbit insertion on) with a passive target PLUS completion of a automatic near-field rendezvous maneuvers with a passive target PLUS automatic proximity operations and capture.

This flight program would demonstrate all ground and onboard functional aspects of rendezvous, proximity operations, and capture required for unmanned resupply. The program would clearly establish a focus for RPOC technology development, and would satisfy the objectives mentioned above. An autonomous capability would come later.

Other, more modest future activities of high value include:

- Close joint JSC, MSFC, and NASA HQ involvement in additional QFD efforts that either modify or build upon this report.

- Expansion of the customers interviewed to include pertinent DoD, NASA HQ Code M, and industry organizations involved in RPOC activities. Their needs could then be folded into the existing RPOC QFD House of Quality to see if the hierarchy of needs is significantly affected.

- Establish a periodic forum for RPOC related technical interchange, and invite all members of the government, industry, and academia RPOC community to participate.

- Establish a focal point for the collection and dissemination of RPOC related requirements and performance data to maximize the use of scarce resources and decrease duplication of effort.

- Undertake a RPOC community-wide survey of simulation and analysis capabilities to catalog the capabilities and ensure consistency of simulation and analysis results within the RPOC community.

- Periodically review what are the RPOC needs with the customer community and update the QFD together with appropriate adjustments in the technical solutions as to how we satisfy customer needs.

15. RPOC QFD Process and Methodology

First application of the QFD process was in the Kobe Shipyard of Mitsubishi Heavy Industries in 1972. It was introduced to the US in 1983. The QFD process offers many benefits. It promotes effective communication, reduces changes as design enters production, and decreases time for design and production phases. It also allows for prioritization of product and process parameters along with early identification of hardware design features. Additional QFD benefits include identifying targets for cost reduction, reliability, flexibility for individual tailoring, and provisions for engineering breakthroughs.

However, the QFD process is not without its challenges. Although it is perceived as being complex, the process has an exact "cookbook" form. The process requires minimum training, but the QFD team must adhere to the procedures. The process requires the full attention of the QFD team for the duration of the task. Because of this, management support for the project is essential. Team members must be given time away from their other duties to do a credible QFD job.

There are two generally accepted QFD techniques. They are the Four Phased approach and the Matrices of Matrices approach, both having common goals and elements. Both methods drive towards specific means to develop technical requirements, and put emphasis on setting priorities at each stage of development. Both provide for the consideration of cost, reliability, new concepts or technology, and for the use of additional tools and techniques as appropriate.

As with any process there are requirements for success. First, and foremost, is a strong commitment by management to the effort. The QFD process requires dedicated participation by individuals who represent all applicable engineering and operations functions. To be successful, the QFD group needs to be of controllable size, usually 10 or less individuals, and every member of the QFD needs to have good listening skills. In addition the QFD facilitator needs a broad understanding of the project and excellent communication skills. It is critical to get the right team members who possess appropriate knowledge, and allow adequate time for preparation and for team members to overcome a sense of vulnerability.

The QFD process starts with the QFD team identifying who the customers are and preparing a plan for gathering and analyzing information about the customers. The customers are interviewed to identify their needs. Following the interviews, the interview teams prepare write-ups that identify the customer's needs and separate them from customer identified solutions. The write-ups are reviewed and agreement received from the customer. The needs are then listed without evaluation of their merits. The QFD team conducts a brainstorming session to establish the Affinity and Tree Diagrams for the customer needs. The Affinity Diagram is a grouping of customer needs that are similar to each other and have a common title. (See Tables 1 & 2 for the Affinity/Tree Diagrams for customer needs and technical solutions.) The Tree Diagram, sometimes referred to as an Affinity/Tree Diagram, is the hierarchical organization applied to the Affinity Diagram. Once a hierarchy is established for the Affinity/Tree Diagrams, the key customer needs are identified, and definitions for each of the key customer needs developed. These definitions, discussed in Appendix E, help to ensure consistency when evaluating the customer needs later. The key customer needs are now transferred to the House of Quality (Appendix F).

Next step in the QFD process is to identify the relative degree of importance of each key customer need, based upon the QFD team members knowledge and their perception of how a customer would rate his identified needs. Not every customer need will be rated for each customer, only those mentioned in the interview with a specific customer.

Next is an evaluation of how well customer needs are currently being met, and the relative degree of planned improvement in the future. The team must define how far into the future they will be evaluating the customer needs. When evaluating the relative degree of improvement, the plans and resources needed to implement the improvements should be realistic. (i.e. don't plan on a 200% improvement, but only have funding to get 25%.)

Within the list of customer needs, there are probably several needs which, if solved, would create excitement within the customer base. These specific needs are urgently sought by a single customer, or by several customers; solving these needs would generate significant amounts of business for an organization. These are called sales points and should be identified from among the existing customer needs. Generally, there are only 2-3 major sales points, and an equal number of minor ones. With the completion of these determinations, a relative weight of importance of the customer needs can be calculated. These weights are used as a guide for selecting the key customer requirements on which to concentrate time and resources.

The next major step in the QFD process is to identify technical solutions to the customers needs. This list is developed within the QFD team using existing data, combined experience from team members, and technical interchanges with the customers. Brainstorming is used to identify additional technical solutions that may not have been previously noted. In addition, customer ideas for technical solutions are also noted. The information is then organized using the Affinity/Tree Diagram process to identify any gaps. Identifying gaps permits the team to make sure that every customer need has at least one technical solution associated with it. Once the technical solutions have been identified, clearly understood definitions for the technical solutions (see Appendix E) are developed so that all team members understand what the technical solutions mean.

Following identification of the technical solutions, a relationship matrix is developed which indicates the relative strength of a technical solution to satisfy a customer need. The technical solutions are evaluated by the QFD Team on the basis of strong, moderate, weak, or no relationship between the technical solution and the customer need. For a large matrix, QFD team members can be divided into groups to complete segments. Once each group has completed their segment, the completed chart can be reviewed by the entire QFD team. The team should not expect relationships between each pair. Also, a technical solution which does not address any of the customer needs is suspect; it indicates that a customer need may not have been identified, or the technical solution may be unnecessary.

The importance weight of the technical solutions is computed for each technical solution that has a relationship with a customer need, by taking the sum of a strength of association value (9,3,1,or 0) assigned to the relationship determined in the relationship matrix times the relative weight of the customer needs that correlate to that technical solution. This importance weight is then normalized to determined the relative weight of the technical solutions. These relative weights indicate the potential priority of technical solutions, which then must be balanced against available resources, the difficulty of providing the technical solution, the potential for a breakthrough, or the need for improvement in a particular technical area.

Next a technical comparison is conducted, identifying how well the RPOC community is capable of satisfying each technical solution. Specific target values are assigned to as many of the technical solutions as possible to define specific goals/ranges for designers, and establish targets for later trade studies and analysis (See Appendix J). Each target value must be agreed upon by the Team, and be measurable.

The last procedure is to conduct a comparison of the technical solutions against each other. This comparison, known as a correlation matrix, assists in identifying trade-offs and interactions. The completion of this step puts the top on the House of Quality and completes the development of the House of Quality tool. The tool is then analyzed to identify the priorities that are indicated. These conclusions can be presented as Pareto Diagrams, or bar or pie charts to indicate the relative priorities of the customer needs and the technical solutions. Strategic and tactical plans can now be developed to implement the conclusions indicated by the QFD process.

The House of Quality chart is described in detail in Appendix F. The actual composite House of Quality for the RPOC QFD process is in Appendix G. A chronological listing of the activities and the QFD process actually followed by the team is presented for reference in Appendix H. A list of QFD team observations is provided in Appendix I for consideration in similar future efforts.

Appendix A. RPOC QFD Team Membership

J. Yeo/JSC Navigation, Control, & Aeronautics Division (EG): Jody served as the facilitator. He is currently the Guidance, Navigation and Control (GN&C) System Development Manager (SDM) for the Space Station Freedom (SSF) Program.

S. Lamkin/JSC Navigation, Control, & Aeronautics Division (EG): Steve served as the assistant facilitator as well as the recorder and editor of the documentation. He is the NASA Technical Manager for the NASA Headquarters Code R sponsored Autonomous Rendezvous and Docking (AR&D) project.

W. Culpepper/JSC Tracking & Communications Division (EE): Bill provided expertise in the areas of sensor technology and hardware development. He supports multiple NASA programs.

F. Elam/JSC Navigation, Control, & Aeronautics Division (EG): Frank provided expertise in the areas of systems integration and advanced test bed concepts. He is manager of the Advanced Avionics Laboratory, a derivative of the SSF GN&C Emulator Test Bed.

P. Kachmar & S. Solis/C. S. Draper Labs: Peter and Sonny jointly represent CSDL in providing Integrated GN&C System expertise to the team. They've supported various NASA projects since Apollo, and currently support the Space Shuttle (SS), Space Station Freedom (SSF) and the Space Exploration Initiative (SEI) Programs, as well as the AR&D project.

B. Wissinger/ McDonnell Douglas Space System Company (MDSSC): Brad is the manager of the Application and Analysis Support Contract (AASC) rendezvous, proximity operations and tether group supporting the SS and SSF programs. He is also the lead for a task to develop an automated rendezvous mission planning tool.

F. Clark/Lockheed Engineering & Sciences Company (LESC): Fred is the lead engineer for the Engineering Support Contract (ESC) group which is currently supporting the AR&D task. He has provided tool development and analysis support to JSC for SS, SSF and advanced programs.

R. Eick/TRW: Dick provides project management and systems engineering and integration support to the AR&D project.

R. Merriam/JSC Systems Engineering Division (ET): Bob is involved with tool development and analysis associated with the Mars rendezvous phase of the Space Exploration Initiative (SEI). He also supports rendezvous analyses for various NASA programs.

R. Schaf/JSC Flight Design & Dynamics Division (DM): Bob represented the Mission Operations technical community. He is currently performing analyses and trades associated with SS/SSF rendezvous activities.

W. Jackson/JSC Navigation, Control, & Aeronautics Division (EG): Bill has supported rendezvous analyses for all NASA programs. He is currently the Head of the On-orbit Guidance and Prox Ops Section.

Individuals providing expertise to the QFD team on a part time basis were:

E. Jones/General Dynamics: RPOC
N. Smith/Martin Marietta: RPOC
B. Bicknell/Martin Marietta: QFD process consultant

Appendix B. RPOC Elements, Functions, and Characteristics

The following is the RPOC QFD team compilation of significant elements and functions that characterize rendezvous, proximity operations, and capture, or are necessary to effectively understand and work in this area.

1. World-Wide RPOC Design Knowledge Capture
1.1. World-wide RPOC Data Collection
1.2. RPOC Community Directory
1.3. ...a Base Building
1.4. Synthesis & Analysis
1.5. Capture as Applicable from each Organization/Program
2. Advanced Technology Development
2.1. Technology Requirements Definition
2.2. RPOC Technology Readiness Level
3. Program Description & Planning
3.1. Establish Need For RPOC
3.2. Define Goals
3.3. Safety
3.4. Servicing
3.5. Reliability
3.6. Maintainability
3.7. Cost
3.8. RPOC Benefits Definition
4. Mission/Program Architecture Definition Studies
4.1. Mission Design
4.2. Mission Constraints
    4.2.1. Plume Impingement
    4.2.2. Collision Avoidance
    4.2.3. Out-of-plane Requirements
    4.2.4. Target Vehicle Characteristics
        4.2.4.1. Cooperative
        4.2.4.2. Uncooperative
4.3. Conceptual Design
4.4. Planning Methodology
4.5. Profile Planning
    4.5.1. Attachment Planning
        4.5.1.1. Tethering
        4.5.1.2. Berthing
        4.5.1.3. Docking
    4.5.2. Separation (Undocking)
    4.5.3. Rendezvous Profile
        4.5.3.1. Long Range
        4.5.3.2. Short Range
        4.5.3.3. Orbit Characteristics
    4.5 Launch Windows
    4.5.5. Proximity Operations
    4.5.6. Formation Flying
    4.5.7. Stationkeeping
4.6. Mission Design Products
    4.6.1. Design Reference Missions
    4.6.2. Error Budgets (Requirements)
5. Operations
5.1. Pre-Mission Preparation
    5.1.1. Dispersions (Trajectory)

- 5.1.2. Contingency Definition
- 5.1.3. Training
- 5.1.4. Procedures Development
- 5.1.5. Rules Development (Systems Operating)
- 5.1.6. Safety

5.2. Real-Time Operations
- 5.2.1. Ground Support
- 5.2.2. Mission Control
- 5.2.3. Sustaining Engineering

5.3 Post-Mission Analysis/Documentation

6 RPOC Analysis and Evaluation

6.1. Methods/Tools
- 6.1.1. Prototyping
- 6.1.2. Simulation
  - 6.1.2.1. Man-in-the-Loop Simulations
  - 6.1.2.2. Non-Real Time Simulation
- 6.1.3. Statistical
  - 6.1.3.1. Monte Carlo Simulations
- 6.1.4. Trajectory Dispersions
- 6.1.5. Analytical Methods
- 6.1.6. Test Beds

6.2. RPOC Product Types

6.2.1. Performance Analysis
- 6.2.1.1. IGN&C Performance
  - 6.2.1.1.1. Sensor Evaluation

6.2.2. Trade Studies
- 6.2.2.1. Command & Control Partitioning

7 RPOC Operation

7.1. Modes
- 7.1.1. Autonomous
- 7.1.2. Automatic
- 7.1.3. Manual
- 7.1.4. Teleoperated

7.2. Proximity Operations

7.3. Stationkeeping

7.4. Formation Flying

7.5. Rendezvous

7.6. Attachments
- 7.6.1. Berthing
- 7.6.2. Docking
- 7.6.3. Tethering

8 System Engineering & Integration (SE&I) (Integrated Systems)

8.1. Overall System Integration
- 8.1.1. Performance Analysis
- 8.1.2. Performance Envelope

8.2. Integrated Test & Verification
- 8.2.1. Ground Demonstration
- 8.2.2. Flight Demonstration

8.3. Configuration Control

8.4. Test Facilities Requirements Definition

9 Manufacturing

10 Project Management

11 Marketing

12 Cost Control

13 Documentation

14 RPOC Integrated System Definition & Development

14.1. Integrated System Functional Requirements
14.2. System Design, Development, Test & Evaluation (DDT&E)
- 14.2.1. Data Management System
- 14.2.2. Power
- 14.2.3. Propulsion
- 14.2.4. Integrated GN&C System Definition
  - 14.2.4.1. Guidance/Targeting
  - 14.2.4.2. Control
  - 14.2.4.3. Navigation
- 14.2.5. Communications & Tracking
  - 14.2.5.1. Tracking Sensors
- 14.2.6. FDIR/FDA (Fault Detection Isolation & Recovery/Fault Detection & Annunciation)
  - 14.2.6.1. Redundancy Management
- 14.2.7. Mechanical

14.3. System Architecture
- 14.3.1. Distributed System
- 14.3.2. Centralized System

14.4. Crew/Operator Interface
14.5. System & Subsystem Integration
14.6. Vehicle Considerations
- 14.6.1. Vehicle Under Consideration
- 14.6.2. Other Vehicles
  - 14.6.2.1. Consumables Constraints
  - 14.6.2.2. Sensors
  - 14.6.2.3. Propellant Capabilities
  - 14.6.2.4. Out-of-plane Capabilities
  - 14.6.2.5. Rotation-Translation Effector Capability
  - 14.6.2.6. Structural Characteristics
  - 14.6.2.7. Docking Contact Conditions
  - 14.6.2.8. Structural Constraints

14.7. Hardware
- 14.7.1. Sensors
- 14.7.2. Docking Mechanisms
- 14.7.3. Robotics
- 14.7.4. Component Design

14.8. Software
- 14.8.1. Fuzzy Logic
- 14.8.2. Artificial Intelligence
- 14.8.3. Neural Networks
- 14.8.4. Algorithms

14.8.5. Hardware Interface Programs (HIPs)

Appendix C. List of Potential Customers

Space Groups or Organizations
- National Space Council
- Space Studies Institute
- National Space Society
- L5 Society

Department Of Defense
- National Aerospace Plane (NASP)
- US Space Command
  - On-Orbit Refueler
- Strategic Defense Initiative Office
- Defense Advanced Research Project Agency
- Naval Research Lab
- Space Systems Div (USAF/AFSC)
  - Shuttle Pallet Satellite (SPAS)

NASA
- Headquarters
  - Code M - George Levin/Mike Card
  - Code R - John DiBattista
- Strategic Avionics Technology Working Group - Ken Cox, Chairman
- Goddard Space Flight Center- Technology
- Johnson Space Center "
- Ames Research Center "
- Langley Research Center "
- Kennedy Space Center "
- Lewis Research Center "
- Jet Propulsion Lab "
- Marshall Space Flight Center "
- Stennis Space Center "

Universities
- U of Alabama
- U of North Dakota
- U of Texas - Austin
- Cal Tech
- MIT
- Johns Hopkins U

Foreign
- USSR
- Japan
  - Orbital Servicing Vehicle (OSV)
  - H-II Orbiting Plane (HOPE)
- European Space Agency (ESA)
  - Hermes
  - Man Tended Free-Flyer (MTFF)

Space Exploration Initiative (SEI)
- JSC New Initiatives Office
  - Technology & Commercial Projects Office
    - Solar System Planet Rendezvous
  - Lunar & Mars Exploration Projects Office
    - Mars Rover/Sample Return (MRSR)
    - Mars Observer
    - Mars Transfer Vehicle
    - Lunar Transfer Vehicle
    - Comet & Asteroid Rendezvous/Flyby
    - Planetary Surface Systems (PSS)
    - Personnel Launch System (PLS)
- Lunar & Mars Exploration Program Office
  - System Engineering & Integration Office
  - Mission Development & Operations

Space Shuttle
- Shuttle Deputy Director - L. Nicholson
- Engineering Integration Office - L. Williams
- Integration & Operations Office - H. Lambert
- Flight Design - J.Harpold, M.Collins, E.Smith
- Laser Docking Sensor Flight Experiment - J. Prather
- Assembly Integration Panel
- Assembly Operations Engineering Assessment Panel

Space Station Freedom
- Level 3 - JSC Mission Operations Directorate
- Assured Crew Return Vehicle Project Office
- Heavy Lift Launch Vehicle/Cargo Transfer Vehicle - MSFC Program Office
- Polar Orbiting Platform

Orbital Maneuvering Vehicle (OMV)

Satellite Servicing System

GEO Repair, Service & Retrieval

Artificial Satellites

Deployable Stages
- Deployable 3rd Stage - IUS, PAM, Centaur, TranStage, Delta Star, Delta Zenith

Tethers
- Tether Applications in Space W.G. - Code M
- Tether Satellite System Program Office

Advanced Manned Launch System (AMLS)

Contractors
- Honeywell International
- Litton
- Aerospace Corp.
- Hughes
- IBM
- COMSAT
- GE/RCA Aerospace
- Loral Corp
- McDonnell Douglas Space Systems Co.
- TRW
- Rockwell International
- Martin Marietta
- General Dynamics
- Lockheed Missiles & Space
- Boeing Aerospace
- Southwest Research Institute
- C.S.Draper Labs
- Orbital Sciences
- Environmental Research Institute of Michigan (ERIM)

Appendix D. The Customer Interview Process

Interviewing customers to determine their needs is a key element of the QFD process. The team attempted to anticipate these needs, and get smart, in brainstorming sessions before the interviews began. The team prepared a question structure, based upon the RPOC characteristics and elements described in Appendix B, with specific questions to ask the customers. Before each interview, each interview team selected the questions that were most appropriate for the particular customer. Actually interviewing the customers and carefully noting their needs was critical to developing the House of Quality. Trying to rate the importance of various needs without input from the customers would be virtually impossible. The interview teams found this an easy task after hearing the customer's concerns.

To conduct the interviews, the RPOC QFD team was divided into teams of three persons each. (Additionally, a separate team went to Marshall Space Flight Center.) One individual in each team was selected as the primary interviewer, and one was selected as primary recorder. (Two teams also used a tape recorder.) All three members participated in the interview to varying degrees, but the primary interviewer was charged with asking the prepared questions, and keeping the interview on track if tangential issues arose.

After the interviews were completed, each group made Affinity/Trees of individual customer's needs, and ranked these in importance on a scale from 1 to 5 (5 being the most important). Any items mentioned by the customer that the team decided were not fundamental needs ("whats") but rather technical solutions ("hows") to other basic needs were carefully noted. Each group prepared a narrative of the interview. Any "whats" or "hows" mentioned in the interview were annotated in the narrative. This served two useful purposes: first, by carefully examining and understanding the narrative, the interview groups could double-check their work to make sure that no needs identified by the customer were missed; second, these narratives were returned to customers for review and clarification, and to show how their comments were used in development of the RPOC QFD House of Quality. Traceability between the RPOC QFD House of Quality and the narratives was maintained, and proved useful to both the customers and the team.

Appendix E. Definitions of Customer Needs and Technical Solutions

The following definitions of customer needs and technical solutions were developed within the RPOC QFD team for consistency and to establish a common base of understanding. They do not necessarily represent "official" or even complete definitions; instead they represent a level of completeness necessary for the RPOC QFD team members and customers to achieve a common understanding.

E-1 RPOC QFD Definitions of Customer Needs

E-1.1 System Operability

E-1.1.1 Optimize Degree of Independence

Optimizing the degree to which a system is free from external supervision or control enta choosing the level of independence most suitable for achieving mission goals consistent w constraints. Examples of these levels are autonomous, automatic, supervised and manual.

E-1.1.2 Ease of Use

A system is said to have ease of use if it has intuitive displays and controls. Ideally, an easy-to-use system requires minimal training because its functions and modes are intuitive. Controls behave in predictable ways, and displays present information in a consistent manner.

E-1.1.3 Effective Functional Partitioning

A design optimization process by which the functions required to perform an objective are analyzed and allocated for efficient resource utilization and maximum performance. The functions may be divided among hardware, software, onboard, earth based, other surfaces in space and systems.

E-1.2 Meet Mission/Program Objectives

E-1.2.1 Unmanned Resupply

The use of unmanned spacecraft to deliver to or retrieve from another spacecraft items such as consumables, waste products, replacement equipment, and maintenance supplies.

E-1.2.2 Autonomous RPOC

The capability of a vehicle's systems to evaluate and alter its operation to achieve rendezvous, perform proximity operations and effect a capture with another vehicle (cooperative or uncooperative) without external supervision or control.

E-1.2.3 Efficient Rendezvous Techniques

The design of rendezvous profiles. This includes determination of targeting offsets (aimpoints) to minimize propellant usage subject to operational and guidance, navigation and control constraints. Consideration must be given to appropriate use of onboard navigation, and its effect on controlling trajectory dispersions. Techniques must also contend with lighting constraints, timelines, and phasing. Appropriate targeting must be used. Techniques may include the capability to handle rendezvous in highly elliptical and hyperbolic orbits, multiple rendezvous, and rendezvous to a libration point in the earth-moon system.

E-1.2.4 Efficient Proximity Operations Techniques

The development of control techniques used during proximity operations (see definition) which take into account sensor performance and result in efficient propellant usage, acceptable piloting/control workloads, minimum plume impingement and contamination effects, and efficient time usage while meeting required safety and consumables constraints. The development applies to techniques used during approach, stationkeeping, or departure activities between two or more spacecraft.

E-1.2.5 Effective Space Traffic Control

This function involves the concurrent ctive control of space vehicles (usually two or more) relative to a common reference. This reference may be an active vehicle or a non-active space base. This function is characterized by procedures such as formation flying, stationkeeping and collision avoidance. Key initiatives to meet this need include: (1) development of advanced sensors and algorithms; (2) definition of control strategy and operating zones; (3) simulations and (4) flight demonstrations.

E-1.3 Low Program Risk

E-1.3.1 Reliable Systems

Reliable systems assure that critical functions are supported with a high probability of success over the required lifetime by utilizing various system design techniques. These techniques may include using: simple, inherently reliable hardware (i.e. hardware with high Mean Time Between Failure); or redundant hardware components with the appropriate failure detection, isolation and reconfiguration schemes implemented; or redundant information derived from dissimilar sources; or use of conservative design margins which allow higher levels of sensor or effector error (thus reducing the likelihood of a critical hardware failure). Reliable systems support low program risk.

E-1.3.2 Demonstrated Systems & Technology

Having demonstrated systems and technology implies that a given technology has actually been demonstrated before it has to be used by a particular program. This approach lowers program risk, because a program manager does not have to develop unproven technology. The word "demonstrated" in this definition is essentially a synonym for "proven". Note that the terminology "demonstrated" technology is in past tense. The program manager does not want to be responsible for carrying out the demonstration.

E-1.3.3 System Acceptability

Ideally, system acceptability is the process by which a system is compared to an accepted standard and deemed functionally equal to or superior to that standard. In this process, the standard is defined by the appropriate members of the RPOC community. The baseline system becomes certified when it meets the standard. Then, an additional system would be acceptable if it meets or exceeds the standards of the certified system.

In practice, such an absolute standard may be impossible to define, a priori. More likely, the standard will evolve over time. Given this, system acceptability is somewhat subjective. However, it certainly is enhanced by using demonstrated technology, reliable systems, and a conservative design philosophy; in other words, anything that would make a system more acceptable in the common sense of the word.

E-1.4 Low Programmatic Cost

E-1.4.1 Increase Design Process Efficiency

This function increases the productivity of engineers defining and designing new onboard or ground systems. The design process includes requirements definition and validation, system engineering and integration, requirements integration, and product hardware and software design. Examples of improvements include using engineering work stations with advanced three-dimensional graphics, improved data bases, automatic software code generation, and the use of interactive design groups in a concurrent engineering process.

E-1.4.2 Accommodate Technology Growth & Insertion

Accommodate technology growth and insertion means to do those things, both during the original design and manufacture, and during the operational phase, which will facilitate subsequent technology advancement of onboard and ground hardware and software. Examples include the use of system modularity, effective hardware/software partitioning, standard interfaces, and hooks for increased automation.

E-1.4.3 Increase Operations Efficiency

This refers to efforts to reduce the overall resources required (or cost) to accomplish the mission objectives of the program during the Operations Phase (or Phase D). It includes as subheadings:

a. Creating a Mission & Operations Concept which is most cost effective: Laying out a scheme for conduct of missions which trades off cost (or resources required) against setting up an operations organization which is required to perform the mission(s) envisioned by the program.

b. Reduce cost controllable items in the operations effort: This is an effort to streamline the operations effort without reducing the real-time operations. This includes reducing the replanning and mission preparation required between missions, post flight reconfiguration for the next flight, facilities costs between missions and the man hours used in these functions.

c. Include operations consideration in the definition and design phases of the program.

E-1.5. Knowledgeable Comprehensive Consultation

This refers to the need that the customer has for consultation concerning all phases of RPOC. The consulting organization should possess, or have ready access to, information on hardware and software; functions of guidance, navigation, control, sensors, structures, propulsion, power, vehicle health monitoring, and expert systems; pertinent work being accomplished in government and industry; facilities and support capabilities available; interrelationship and application of Code R focused technology, Code M advanced development, and specific vehicle needs with consideration of multi-programs. Particular customer needs include:

a. Support for funding advocacy: The data and information would be provided to program and project managers, advanced activity planners and budgetary officials to assist them with determining needs, direction, rationale, relative importance of past, present and future tasks and capabilities in the rendezvous, proximity operations and capture community.

b. Timeline of Programmatic needs: Refers to the need for program and technology funding organizations and managers to lay out funding levels and schedules for each fiscal year so that projections for future programs can be constructed.

c. Technical Advice: Refers to the wide area of expert advice needed by customers for direction and decision making.

d. Trades/Simulations/Studies: Refers to the customer need for trade studies, simulations and/or testing during the development of programs or systems, and where to go to contract for such services.

E-2 RPOC QFD Definitions of Technical Solutions

E-2.1 DESIGN PHILOSOPHY

E-2.1.1 Use Incremental Design Approach

The philosophy of increasing in conservative intervals from a basic design toward an enhanced design that meets the system's total objective(s). It implies verification of the current design level before proceeding to the next increment and tends to phase in the utilization of new systems designs and concepts to lessen the chances of failure. It is also concerned with delaying the incorporation of new technology into designs until that technology is sufficiently mature and demonstrated to limit the level of risk.

E-2.1.2 Use Simple Systems

The concept of utilizing systems and designs that have been developed at the lowest level of complexity necessary to accomplish a task. The multiple use of identical components within a subsystem, subsystem elements within a system, or software modules within a software system can also contribute to the sense of having a simple system.

E-2.1.3 Use Failure Resistant Components

The philosophy of using the most reliable components and parts available and/or affordable to increase the reliability of the entire system.

E-2.1.4 Use Redundant Components & Information

The application of the same component or subsystem in parallel one or more times in an effort to offset the impact of failure of a single component or subsystem. Redundant information can be derived from dissimilar sources and used in the same manner. The use of redundancy implies the need for a managing criteria to handle failures by selecting an alternate path within the parallel environment in the event of a failure.

E-2.1.5 Use Conservative Margins

A system design is usually based on a set of nominal parameters. The design is expected to continue to function should any one or more of the parameters be somewhat off nominal. The ability to function with this off-nominal condition means that the system has margin. If the system can be designed to remain functional even if some (not necessarily all) parameters or sets of parameters take on values beyond what might be expected, that system can be said to have been designed with conservative margins. Alternatively, the system might be said to be robust.

E-2.1.6 Use Standardized Interfaces

An interface is a process that allows system building blocks (hardware and software) to be connected. A standard interface means that all building blocks (of a certain category) have the same interface and hence their interconnections are uniformly defined. The use of standardized interfaces within a system design is a positive influence in areas such as ease of design, cost of design, time to complete fabrication, cost of procurement, and ease of test and checkout. Standardized interfaces also provide a simple, predictable means of inserting technology at a later date. As examples, standard interfaces can apply to electrical power, signal, mechanical, thermal connections and software modules.

E-2.1.7 Use Friendly Interfaces

The employment of connections (visual, audible and tactile) between the system and humans that are comfortable, consistent, easy to use and intuitive to the human. This approach enhances operation of the system.

E-2.1.8 Define Systems Requirements for Minimum Training

The process, generally early in a program's development, where the system partitioning and degrees of autonomy are established with emphasis given to diminish the amount of human intervention and participation required in the operations phase of the task.

E-2.1.9 Use Concurrent Engineering Process

Concurrent Engineering refers to the simultaneous application of three elements (management processes, quality function deployment processes, and quality engineering for "robust" design) to reduce product development costs, increase customer satisfaction with the products, and reduce the product development time.

Management processes include four points to develop a better "game plan" and three points to effect closer cooperation:

Better "game plan"

a) Concurrent processes (production capability, field support capability, and robust quality)
b) Focus activities on quality, cost, and delivery
c) Emphasize satisfaction as perceived by the customer
d) Emphasize competitive benchmarking

Closer Cooperation

a) Integration of the organization
b) Employee involvement and participative management
c) Strategic relationship with suppliers

Quality function deployment (QFD) processes ensure that the "voice of the customer" is present from the very start of the product development process.

Quality engineering for "robust" design refers to the ability of the product to keep performance close to ideal customer satisfaction under actual use conditions. It reduces rework of the design due to operating conditions or production methods, because "quality is developed concurrently with the product design and the development of production and field support capability".

[Ref: Clausing, D., Concurrent Engineering, Design and Productivity International Conference, Honolulu, Hawaii, 6 February 1991.]

E-2.2 Collect & Exchange Knowledge

E-2.2.1 Perform Survey of State-of-the-Art RPOC Capabilities

The act of performing a survey (literature searches, government and industry surveys, etc.) to define the state of the art of hardware, software, systems and facilities associated with the RPOC functions and the compilation of collected data.

E-2.2.2 Build Databases

The process of defining and implementing database structures to effectively capture and track the characteristics, capabilities and level of maturity of RPOC related technology (hardware, software, systems and facilities) and the subsequent data entry and database maintenance.

E-2.2.3 Develop Integrated Technology Plan

Identify requirements (needs and timeframe) for technology/advanced development activities. Develop and advocate a plan to develop and demonstrate the technology required to meet the identified system needs within the desired timeframe. Review and update the plan annually.

E-2.3 Develop Advanced Technology

E-2.3.1 Develop Advanced Sensors

Develop the advanced technology required in the sensors area to meet identified system needs by a specified date. The technology development should be evolutionary and applicable to multiple programs, if possible. The development should provide for the highest possible technology readiness level prior to system incorporation.

E-2.3.2 Develop Advanced Algorithms

Develop the advanced technology required in the area of software algorithms to meet identified system needs by a specified date. The technology development should be evolutionary and applicable to multiple programs, if possible. The development should provide for the highest possible technology readiness level prior to system incorporation.

E-2.3.3 Develop Improved Docking Mechanisms & Facilities

Develop the advanced technology required in the area of docking mechanisms to meet identified system needs (e.g., reliability) by a specified date. The technology development should be evolutionary and applicable to multiple programs, if possible. The development should provide for the highest possible technology readiness level prior to system incorporation. Hardware evaluation facilities should contain new docking mechanism concepts. Hardware evaluations should include malfunctions such as damage, degradation and debris fouling (e.g., insulation).

E-2.4 Define Mission Architectures, Requirements & Constraints

E-2.4.1 Develop Resupply / Return Mission Requirements

Define the factors affecting the rendezvous, proximity operations, and capture (RPOC) - related design of resupply missions to an orbiting vehicle or scientific facility, such as types/amounts/characteristics of transported items, resupply frequency, characteristics of the vehicle being resupplied, and trajectory data.

E-2.4.2 Develop Traffic Control Strategy

Define the methods and techniques required to control the orderly and safe movement of spacecraft within a predefined volume around an orbiting vehicle. The strategy should minimize the operational complexity and probability of collisions.

E-2.4.3 Define Operating Zones

Based on mission objectives, vehicle constraints, and the traffic control strategy, define the regions of space in which a vehicle may or must operate relative to a base vehicle. The zones are delineated by the allowable operations within the zone.

E-2.4.4 Define Operating Modes

Establish the methods by which a spacecraft will accomplish its functions during specific phases in its mission with respect to the level of autonomy. Basic modes are autonomous, automatic, supervised, and manual.

E-2.5 Define System Requirements

E-2.5.1 Early Definition & Maturity of Requirements

Apply adequate resources and effort at the very beginning of a project to thoroughly perform the trade studies and simulations to yield realistic program and system requirements that minimize later revision. A requirement is a specification of some aspect of a deliverable end-item. The term requirement connotes that which is a must, the irreducible minimum of acceptability, an imperative, as contrasted to the merely desirable or merely an objective.

A requirement at the more general level defines a function to be performed, not how to do it. Such requirements are used at Level I as broad program objectives, and in Level II for system functions. Level II also contains environment, reliability, lifetime, verification, and project timelines. Level III contains detailed systems requirements, including functional decomposition, performance specifications, and interfaces.

Early definition and maturity of requirements will greatly increase the design process efficiency and thus lower the programmatic costs.

E-2.5.2 Improve System Requirements Traceability Process

There are two purposes for requirements traceability. One is to maintain a bidirectional bookkeeping process that shows the documentation source of a detailed requirement based on a more general requirement. This is a dry, bare-bones numerical cross-referencing system without explaining the rational or derivation of the more detailed requirement. The second aspect of requirements traceability, equally important, is to document the rationale of the derived requirement as contained in a trade study, analysis, simulation, or other report.

Without two-way traceability, a requirement may be overlooked (going from the general to the specific), or a detailed requirement may not be updated when a change is made to the parent requirement. Without documentation of the rationale or analysis of a numerical specification, it will be unknown and unchallengeable as to what degree of confidence the original author of the performance specification intended to convey, whether the analysis has become obsolete, or whether it contains errors.

E-2.6 Define Operating Requirements

E-2.6.1 Provide Effective Telemetry/Command/Navigation Infrastructure

This infrastructure consists of the collection of telemetry, command and navigation links and the facilities which control, generate or receive them. The support it provides to an operational RPOC vehicle is effective if the RPOC mission objectives are satisfied while providing adequate capability for command, control and monitoring at the same time. The infrastructure may have to (for example) support various levels of independence, require minimum/acceptable vehicle reconfiguration and provide adequate communications coverage and reliability.

E-2.6.2 Reduce/Standardize Mission Dependent Reconfiguration

This item refers to the efforts to minimize the reconfiguration of reusable vehicles and systems to meet the mission peculiar requirements of the next flight. Such reconfiguration is a necessary cost burden but can be controlled and/or standardized where possible. Also included in this item is reconfiguration of facilities (Mission Control Center (MCC), communications & tracking network, etc.) if called for in the mission requirements. Considerations of reconfiguration costs should be embedded in the design process for future RPOC vehicles. The acceptability, reliability and ease of use of reusable RPOC systems/vehicles will be enhanced by diligence in this area which, in a wider sense, is aimed at reducing or controlling the cost of operations.

List of Mission Dependent Reconfiguration Items:

Mission Planning:
- Payload Rules Development & Publication
- Timeline Development & Publication
- Procedures Development & Publication
- Flight Design Development & Publication
- All mission verification

Reconfiguration of Mission Dependent Hardware Interfaces
Reconfiguration of Mission Dependent Software
MCC/LCC Mission Dependent Reconfiguration
Team/Crew Training (includes facilities time)
Interface Testing
Payload Mounting/Servicing Pre-launch

E-2.6.3 Reduce/Standardize Flight Software Reconfiguration

This item refers to the efforts to minimize the periodic software reconfiguration for reusable vehicles and systems to satisfy the changed requirements which normally burden flight software loads. This is a necessary configuration control task. However, measures are needed to accommodate the upgrading and redesign of flight software so as to reduce the manpower and facility time required. This will be especially important as vehicle, system, and ground software increases in volume and complexity with the advent of expert systems, autonomous systems and more capable on-board algorithms. In such an environment, an inefficient and expensive reconfiguration process will reflect on system acceptability, reliability and ease of use. Accommodation of software reconfiguration should be considered early in the system design and continue throughout the design process. Although the primary aim of this effort is to control the overall cost of operations, a wider impact is realized.

E-2.6.4 Reduce/Standardize Flight Turnaround Reconfiguration

This item refers to the effort to minimize the non-mission dependent reconfiguration which is required to prepare a reusable vehicle or system for the next flight. Such reconfiguration or turnaround activities include inspection, testing, repair, transport, re-outfitting and refueling of the reusable RPOC vehicle or system. Also included are any ground facilities which require turnaround reconfiguration. Complex and costly turnaround requirements will affect the acceptability, reliability and ease of use of the vehicle/system. Turnaround considerations should enter into the early design process and continue during mission scheduling and launch processing. The aim is to reduce the cost of operations, but impacts in many other areas are evident.

List of Turnaround Reconfiguration Items:

Generic Mission Planning:
- Generic Rules Maintenance
- Generic Procedures Maintenance
- Generic Flight Design
- Generic Timeline Maintenance
- All Reverification

Repair/Outfitting/Upgrades Processing at Landing Site/Launch Site
Transportation to Launch Site
Facilities Maintenance
MCC/LCC/Landing/Abort Site Turnaround

All Generic Training

E-2.7 Design RPOC Systems

E-2.7.1 Perform Functional Analysis on all RPOC Systems

An iterative process by which system functions and sub-functions are progressively identified and analyzed as a basis for defining alternatives for meeting system performance and design requirements. Performance requirements are established for each function and sub-function identified. System functions include mission, production, test and support functions. All modes of operational usage and support are considered in the analysis. (See MIL-STD-499A)

E-2.7.2 Develop Trajectory Approach Techniques

As used here, "approach" is regarded as the final approach to a target. Approach generally corresponds to the region in which proximity operations occurs. Considerations include: propellant consumption, plume impingement and contamination, lighting, relative attitude, and safety.

E-2.7.3 Apply Expert Systems to RPOC

The development of rule-based software technology applications to support the system functions required to perform the Rendezvous, Proximity Operations and Capture mission phases.

E-2.7.4 Develop Algorithms for Rendezvous

These algorithms include any guidance and targeting that are needed for rendezvous. Different algorithms are needed for rendezvous in low earth orbit, rendezvous in elliptic, or hyperbolic orbits, or rendezvous to a libration point. Other critical algorithms include various types of estimation needed for state determination. Expert systems are not considered to be a part of this category.

E-2.7.5 Develop Attitude & Translational Control Systems to Minimize Plume Impingement & Contamination

This may include propulsion systems that use inert gases. In this case, plume may still be a problem in terms of loads, but contamination problems are greatly ameliorated. Systems for attitude control include momentum wheels, control moment gyros, and other non-propulsive systems. Minimizing plume impingement and contamination is of major concern only during proximity operations.

E-2.8 Evaluate RPOC Systems & Technologies

E-2.8.1 Perform Systems & Technologies Trade Studies

This item uses the term "trade study" in a limited sense, as defined below:

An analysis of competing alternatives performed to support decision making is called a "trade study" (or simply "trade"). The criterion for choosing the best alternative is often cost or performance or a set of quantities which support a comparison. (Although analysis is not the only method of producing a quantifiable scale for comparison of alternatives, for the purposes of this QFD, only those trades supported by analysis are included in this definition. Trades supported by other means are included along with the other types of evaluations classed by the tool used, such as "simulations", "hardware test" or "prototyping".)

E-2.8.2 Perform Simulations - Non-Real Time

A simulation is an analysis tool conducted with a computer (or computers), containing math models of part or all of a flight system, together with math models of related systems, the flight vehicle (or vehicles), the appropriate vehicle dynamics and operating environments. Typically, time histories of variables are computed. As used in this report, a simulation does not contain actual system hardware, except for hand controllers or displays necessary for the man/machine interface. A simulation study often compares alternatives, whose results can be used for comparison.

A non-real time simulation is one where the simulated time in the math model does not coincide with time in the real world. This type of simulation does not contain a man "in-the-loop".

E-2.8.3 Perform Simulations - Real Time

A real time simulation is one in which the simulated time coincides with real time. This type of simulation can have a man "in-the-loop" to judge human factors related to man-machine interfaces. Typical simulation configurations may contain realistic controls and displays, out-the -window scene generators, and cockpit mockups. As stated above, as used in this report, a simulation does not contain other system hardware. (See Section E-2.8.4)

E-2.8.4 Perform Hardware Evaluations

A hardware evaluation is a test of part or all of the RPOC and related systems' hardware. It includes tests where the remainder of the system is modeled by a computer (or computers) similar to a "real-time simulation" as defined above. Hardware evaluation can be a limited physical test of a device or component, or combinations thereof. The hardware can be at any stage of development, such as engineering models, prototype hardware, flight quality hardware, or merely similar hardware.

A hardware evaluation differs from a prototype or flight hardware demonstration in that the former is done in the earlier design stages of a project for the purpose of evaluation, and the latter is done later in the project, with the final design, as proof of satisfying the specifications. A hardware evaluation is designed to prove that the hardware meets the performance specifications, while a hardware demonstration merely shows that it works, somewhere within limit specifications.

E-2.8.5 Perform Statistical Analyses

These analyses utilize statistical distributions to represent vehicle or system performance. Performance is determined by various acceptable methods for sampling, averaging or calculating means and deviations at the times data are desired. Other methods (e.g. Monte Carlo, Covariance) interpret the statistical performance distribution as an envelope for vehicle performance, and the statistical means and variances to forecast utilization figures, lifetimes, mean time between failures or other desired quantities.

E-2.8.6 Perform Rapid Prototyping & Testing

Rapid prototyping is a process for quickly developing and testing designs satisfying a portion of the system requirements. It provides a basis for requirements verification, design concept validation, and the final design specifications. Rapid prototyping is characterized by quick implementation and testing, frequent revisions, math modeling, and simulations.

E-2.9 Develop & Maintain Common Tools & Facilities

E-2.9.1 Automate Design Process of RPOC Systems

Develop an efficient process to accomplish system design and validation (requirements, concept, development). The process should be characterized by: (1) effective, efficient tools (i.e., user friendly, graphics workstations which support multiple programs/functions and use a common database); (2) design knowledge capture (to maintain cognizance of state of art, technology/advanced development activities and sources); and (3) improved study methodology (i.e., hands-on, quick turnaround, initially low fidelity with generic modeling, then higher fidelity as programs mature and data becomes available).

E-2.9.2 Use Automatic Code Generation

Use a tool which will accept the definition of software requirements in the form of logic flows, mathematical expressions, module delimiters, data flow diagrams, etc. and will produce executable software code in a form understandable by the developers of the requirements. It should include automatic documentation as a feature.

E-2.9.3 Automate Mission Planning (Ground) & Replanning (On-board)

Develop a tool which will accept mission constraints (lighting, phasing, sensor capability, fuel/time optimality, expected dispersions/uncertainties, etc.) and will generate candidate mission plans (trajectory, timeline, resource requirements, maneuver placement, etc.). The plans should be presented in a "user-friendly" manner such that quick assessment and modification can be made and the process repeated if required. The tool should be "end-to-end" such that multiple tools and data exchanges are not required.

E-2.10 Demonstrate RPOC Systems & Capabilities

E-2.10.1 Conduct Shuttle Fight Demonstrations

Use the Shuttle as an orbiting test bed for evaluation of RPOC related software, hardware, procedures, or techniques. Such demonstrations are needed to accommodate new RPOC technology or to prove new components or concepts necessary for ongoing or new programs.

E-2.10.2 Conduct Unmanned Vehicle Flight Demonstrations

Use an unmanned spacecraft as an orbiting test bed for evaluation of RPOC related software, hardware, procedures, or techniques. Such demonstrations may be needed to accommodate new RPOC technology or to prove new components or concepts necessary for ongoing or new programs.

E-2.10.3 Conduct Multi-vehicle Flight Demonstrations

Use of multiple spacecraft simultaneously in orbit as testbeds for evaluation of RPOC related software, hardware, procedures, or techniques. Such demonstrations may be needed to accommodate new RPOC technology or to prove new components or concepts necessary for ongoing or new programs.

E-2.10.4 Conduct Prototype System Ground Tests

Conduct tests on the ground (as contrasted to in-flight test) of the complete RPOC system, using system hardware which is an early version of flight-quality hardware. Related systems (especially avionics) may also be included in the test, as either simulated or real hardware. The term includes both open loop and closed loop tests, The system is typically connected to computers providing appropriate interfaces, and math models similar to the simulations described above. System stimuli, environment, and output may be provided or measured by physical test equipment intended to closely approximate in-flight conditions.

E-2.10.5 Conduct Ground Tests With Flight Hardware

Means the same as the preceding definition, except that flight-quality hardware is used. Usually extreme measures are taken to control and certify precisely the test conditions, test data, anomalies, and other occurrences. These tests include functional tests, performance tests, acceptance tests, and official qualification test for the hardware and system.

Solutions to Customers Needs ("Hows")

1.0 Design Philoscphy
- 1.1 Use Incremental Design Approach
- 1.2 Use Simple Systems
- 1.3 Use Redundant Components & Information
- 1.4 Use Conservative Margins
- 1.5 Use Standardized Interfaces
- 1.6 Use Friendly Interfaces
- 1.7 Define System Requirements for Minimum Training
- 1.8 Use Failure Resistant Components
- 1.9 Use Concurrent Engineering Process

2.0 Collect & Exchange Knowledge
- 2.1 Perform Survey of SOA RPOC Capabilities
- 2.2 Build Databases
- 2.3 Develop Integrated Technology Plan

3.0 Develop Advanced Technology
- 3.1 Develop Advanced Sensors
- 3.2 Develop Advanced Algorithms
- 3.3 Develop Improved Docking Mechanisms & Facilities

4.0 Define Mission Architectures, Requirements & Constraints
- 4.1 Define Resupply/Return Mission irements
- 4.2 Dev.lop Traffic Control S agy
- 4.3 Define Operating Zones
- 4.4 Define Operating Modes

5.0 Define System Requirements
- 5.1 Early Definition & Ma
- 5.2 Improve Syst

6.0 Define Operating Requirements
- 6.1 P. ovid
- 6.'

7.0 Design RPOC System

8.0 Evaluate RPOC Systems & Technologies

9.0 Develop & Maintain Common Tools & Facilities

10.0 Demonstrate RPOC Systems & Capabilities

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	4.4	5.1	5.2	6.1	6.'
1.0 Design Philoscphy: 1.2																							
1.3		o																					
1.4			Δ																				
1.5		Δ																					
1.6					□																		
1.7		□			Δ	Δ																	
1.8			X	Δ																			
1.9	□	□	□	□	□	□	□																
2.0 Collect & Exchange Knowledge: 2.1	□				□		□																
2.2				□	□		□	□		Δ													
2.3	Δ				□	□	□	□		Δ	Δ												
3.0 Develop Advanced Technology: 3.1	□	X	□	□				□	□	□	□	Δ											
3.2	□	X	□	□						□	□	Δ	Δ										
3.3	□	□	□	Δ	□			Δ		□	□	Δ	Δ										
4.0 Define Mission Architectures, Requirements & Constraints: 4.1				□	□			□	□	□	□												
4.2		□	□	□	□	□	□		□	□	□	□	□	□									
4.3							□		□	□	□						Δ						
4.4			□			Δ	Δ	□	□	□	□		Δ	□	□		Δ	Δ					
5.0 Define System Requirements: 5.1	Δ	□				□	Δ		Δ	□	□		□	□		Δ	□	Δ	Δ				
5.2							□									Δ	□	□	□	Δ			
6.0 Define Operating Requirements: 6.1	□		□	□	Δ	□	□	□	□				□	□			Δ	Δ	Δ	Δ			
6.'		Δ	o	□			□	Δ	□											Δ			
		Δ	o		□				□				o							Δ			
		Δ	o	□	Δ			Δ	□							□				Δ		□	
7.0 Design RPOC System	Δ	□	Δ			□	□		Δ	□	□			□			□	Δ	Δ	□		Δ	
			□	□	Δ	□	□		□	□	□		Δ	Δ			Δ	Δ	Δ	□		□	
	□	o	□	□	Δ	Δ	Δ		□	□	□	□	Δ	Δ			Δ		Δ			□	
			Δ	□		□	□		□	□	□	□	Δ	Δ			Δ	Δ	Δ	□		□	
		o		□			Δ	□	□	□	□	□				□	□	Δ	□	□			
8.0 Evaluate RPOC Systems & Technologies	□	□	□	Δ			□	□	Δ	Δ	Δ		Δ			Δ	Δ	Δ	Δ	Δ		Δ	
			□	□					□				Δ	Δ		Δ	Δ	Δ	Δ			□	
			□			Δ	Δ						Δ	Δ			Δ	Δ	Δ			Δ	
	□	□	Δ	Δ	□			□		□	□		Δ	□	Δ	□	Δ	Δ	□				
			□	Δ					□					□		Δ	Δ	Δ	□				
													Δ	Δ	□		Δ	Δ	Δ	□			
9.0 Develop & Maintain Common Tools & Facilities	Δ	X			□											Δ	□	□		Δ	□		
		X												□									
		X				□	□							Δ		Δ		□	Δ				
10.0 Demonstrate RPOC Systems & Capabilities	□		□			Δ							Δ	Δ	Δ			Δ	Δ				
	□		□										Δ	Δ	Δ			□	Δ				
	□		□			□							Δ	Δ	Δ		□	□	Δ				
						Δ		□		□	□		Δ	□	Δ				Δ				
			□	□		□		□		□	□		Δ	□	Δ				Δ				

Customer Demands ("What's")	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	4.4	5.1	5.2	6.1	6.'
1.1 Optimize Degree of Independence									9				3	3	1		1		9	3		9	
1.2 Ease of Use	1	3				9	3		3				1	1	1		1		3			3	
1.3 Effective Functional Partitioning					3				9	3	3	1		3		:	9	3	3	3	1	9	
2.1 Unmanned Resupply	3	1	1	1		1		1	3			1	3	3	3	9	3	1				3	
2.2 A tonomous RPOC	3	1	1	1				1	3			3	9	9	9	1						1	
2.3 E icient Rendezvous Techniques			1			1		1	3	3	3		3	3			3	3	1			3	
2.4 Efficient Prox Ops Techniques			1			1		1	3	1	1		1	9	3		3	3	1			3	
2.5 Effective Space Traffic Control	3	1				3			3	1	1	1	9	9		1	9	9	1	1		9	
3.1 Reliable Systems	9	9	9	3	3			9	3	1	1		3	1	3					1	3		
3.2 Demonstrated Sys ms & Technology	9				3					3	3	3	3	3	3								
3.3 System Acceptability	3	3	3	1	1	1	1	3	3	1	1	:	1	1	1	1	1	1	1	9	9	9	
4.1 Increase Design Process Efficiency		1			3				9	9	9		1							9	9		
4.2 Accommodate Technology Growth & Insertion	9			9	9				1	1	1	9	9	3	9	3	3	1	3	3	1	1	
4.3 Increase Operations Efficiency		3	1	1	3	9	9	1	9	1	1		1	1	1	3	9	3	3	3		9	
5.0 Knowledgeable Comprehensive Consultation									1	9	9	9											
Importance Weight of Technical Requirements	3.9	1.3	1.2	1.0	1.7	1.0	0.7	1.2	3.1	2.2	2.2	2.3	3.5	3.5	3.2	1.4	1.7	0.9	0.9	1.5	1.2	2.5	:
Relative Weight of Technical Requirements	3.4%	1.1%	1.0%	0.8%	1.5%	0.9%	0.6%	1.0%	2.7%	1.9%	1.9%	2.0%	3.0%	3.0%	2.8%	1.2%	1.5%	0.8%	0.8%	1.3%	1 0%	2.1%	2.

FOLDOUT FRAME

Technical Solutions Correlations

- Δ Strong Positive
- □ Positive
- X Negative
- o Strong Negative

…Maturity of Requirements
…stem Requirements Traceability Process
…vide Effective Telemetry/Command/Navigation Infrastructure
6.2 Reduce/Standardize Mission Dependent Reconfiguration
6.2.1 Reduce/Standardiz Flight Software Reconfiguration
6.2.2 Reduce/Standardize Flight Turnaround Reconfiguration
7.1 Perform Functional Analysis on All RPOC Systems
7.2 Develop Trajectory Approach Techniques
7.3 Apply Expert Systems to RPOC
7.4 Develop Algorithms for Rendezvous
7.5 Develop Attitude/Translation Control Systems to Minimize Contamination & Plume Impingement
8.1 Perform Systems & Technologies Trade Studies
8.2.1 Perform Simulations - Non-Real Time
8.2.2 Perform Simulations - Real Time
8.3 Perform Hardware Evaluations
8.4 Perform Statistical Analyses
8.5 Perform Rapid Prototyping & Testing
9.1 Automate Design Process of RPOC Systems
9.2 Use Automatic Code Generation
9.3 Automate Mission Planning(Gnd) & Replanning(On-board)
10.1.1 Conduct Shuttle Flight Demonstrations
10.1.2 Conduct Unmanned Vehicle Flight Demonstrations
10.1.3 Conduct Multi-Vehicle Flight Demonstrations
10.2.1 Conduct Prototype System Ground Tests
10.2.2 Conduct Ground Tests with Flight Hardware

	6.2	6.2.1	6.2.2	7.1	7.2	7.3	7.4	7.5	8.1	8.2.1	8.2.2	8.3	8.4	8.5	9.1	9.2	9.3	10.1.1	10.1.2	10.1.3	10.2.1
6.2.1																					
6.2.2																					
7.1	□	□	□																		
7.2	X	X	X																		
7.3	X	o			Δ																
7.4	X	o			□																
7.5			X		Δ																
8.1			□	Δ	□	□	□	□													
8.2.1	□			□	Δ	□	Δ	Δ													
8.2.2	□				Δ	□	Δ	Δ		Δ											
8.3	□								□	Δ	Δ										
8.4	□				Δ		Δ	□		Δ	Δ	Δ									
8.5									□	Δ	Δ	Δ	Δ								
9.1				□					Δ	Δ	Δ		□	Δ							
9.2	Δ	Δ					□			□	□			Δ	Δ						
9.3	Δ		Δ		□	□	□		□	Δ	Δ		Δ		□						
10.1.1					Δ	□	□	Δ		Δ	Δ	Δ	Δ	□		□	□				
10.1.2					Δ	Δ	□	Δ		Δ	Δ	Δ	Δ	□		□	□	Δ			
10.1.3					Δ	□	□	Δ		Δ	Δ	Δ	Δ	□		□	□	Δ	Δ		
10.2.1				□	□			□		Δ	Δ	Δ	Δ	□	□	□		Δ	Δ	Δ	
10.2.2										Δ	Δ	Δ	Δ	□	□	□		Δ	Δ	Δ	Δ

6.2	6.2.1	6.2.2	7.1	7.2	7.3	7.4	7.5	8.1	8.2.1	8.2.2	8.3	8.4	8.5	9.1	9.2	9.3	10.1.1	10.1.2	10.1.3	10.2.1	10.2.2	Rate of Importance (	Rate of Importan	Rate of Impo	Rate of	Rat
			3		3			9	3	3			3	1		3		3	1			1	3	4		
3	3	3			3			1		3	1		9			1	3	3	3	9	9		4			
			9		3			9	1	3	1		3	1		3	1	1	1	3	3	4		4		
1	1	1		3	1	3	3	9	9	9	9	9	3	3		1		9	9	3	3	2		3		
1	1	1	1	3	9	3	3	9	9	9	9	9	1	3		9	3	9	9	3	3	5	4	3	5	
3	3		1	3	1	9		9	9	9	3	9	1	1		1	3	3	3	3	3	3		1	5	
3	3		1	9	1		9	9	3	9	3	9	1	1			3	3	3	3	3	3	1	4	2	
	3		3	3	3	1	1	9	9	3	3	9	3	1		1			9	3	3	1		2		
9	9	9	3		1			3	3	1	1	3	3	1			3	3	3	3	9	3	5	3	2	
								3	1	1	3	1	3				9	9	9	9	9	4	5	4	4	5
9	3	9	3	3		1	9	3	1	3	3	3	9	1	1	1	9	9	9	3	3		2			
			1					9	9	1		3	9	9	9					3				4		
			1					9	9	1	1	1	9	3						3				5		5
9	9	9		3	3	3	3	9	3	9	1	9	1	1		9	3	3	3		1	1	2	3	3	
								9	9	9	9	9	9	9	3	9										5
2.3	2.0	1.9	1.0	1.8	2.0	1.6	1.9	6.8	5.2	5.2	4.2	5.2	3.7	2.2	0.7	2.9	3.7	5.6	5.6	4.0	4.1					
2.0%	1.7%	1.7%	0.9%	1.5%	1.7%	1.4%	1.6%	5.9%	4.5%	4.5%	3.6%	4.5%	3.2%	1.9%	0.6%	2.5%	3.2%	4.8%	4.8%	3.5%	3.6%					

H-Total= 115.5

FOLDOUT FRAME 2

A1	Rate of Importance (Customer #1) - Technical
A2	Rate of Importance (Customer #2) - Program
A3	Rate of Importance (Customer #3) - Technical
A4	Rate of Importance (Customer #4) - Program
A5	Rate of Importance (Customer #5) - Technical
A6	Rate of Importance (Customer #6) - Technical
A7	Rate of Importance (Customer #7) - Program
A8	Rate of Importance (Customer #8) - Program
A9	Rate of Importance (Customer #9) - Technical
A	Weighted Rate of Importance (All Customers)
B	NASA/Industry Now (Mid-FY 1991)
C	NASA/Industry Plan (End of FY 1995)
D	Ratio of Improvement
E	Sales Point
F	Importance Wt of Customer Needs
G	Relative Wt of Customer Needs

A1	A2	A3	A4	A5	A6	A7	A8	A9	A	B	C	D	E	F	G
1	3	4							0.9	2	3	1.5	1.0	1	3.0%
	4								0.4	2	3	1.5	1.0	1	1.5%
4		4							0.9	3	3	1.0	1.0	1	2.0%
2		3						5	1.2	1	3	3.0	1.2	4	9.5%
5	4	3	5		5		4	5	3.5	2	3	1.5	1.2	6	14.4%
3		1	5		2	2	2	3	2.0	2	3	1.5	1.0	3	7.0%
3	1	4	2					3	1.5	2	3	1.5	1.0	2	5.1%
1		2							0.3	1	1	1.0	1.0	0	0.8%
3	5	3	2		5		4		2.4	3	3	1.0	1.2	3	6.7%
4	5	4	4	5	5	4	5	3	4.3	2	3	1.5	1.5	10	22.4%
	2					5			0.8	1	3	3.0	1.0	2	5.3%
		4			4			4	1.4	2	3	1.5	1.0	2	4.7%
		5		5	5		3		2.0	2	2	1.0	1.0	2	4.6%
1	2	3	3		3	3	2		1.9	2	3	1.5	1.0	3	6.5%
				5			5	5	1.7	3	5	1.7	1.0	3	6.5%

Cust#1 Wt (W1)=	11.0%
Cust#2 Wt (W2)=	11.0%
Cust#3 Wt (W3)=	11.0%
Cust#4 Wt (W4)=	11.0%
Cust#5 Wt (W5)=	11.0%
Cust#6 Wt (W6)=	11.0%
Cust#7 Wt (W7)=	11.0%
Cust#8 Wt (W8)=	11.0%
Cust#9 Wt (W9)=	12.0%

A=A1*W1+A2*W2+A3*W3...
D=C/B
F=A*D*E
G=F/(F-Total)

F-Total= 43.36

G-Total= 1.00

FOLDOUT FRAME 3

Appendix F. House of Quality Chart

The House of Quality Chart, Figure E-1, is a working spreadsheet which shows the relationships between customer needs and the technical solutions resulting from the Quality Function Deployment process. The elements of the House of Quality, labeled on the referenced figure, are described as follows:

1 **Customer Needs** This is a list of the customer needs, also called "Whats", demands, or needs. These customer needs are presented at a high level because this was a first phase QFD. The QFD identified fourteen level 2 and one level one customer needs. These reflect the expressed desires of the customers, as recorded in the customer interviews.

2 **Technical Solutions** This is a list of the technical solutions, also called "Hows", which identify how the customer needs are to be satisfied. The Hows were taken from the second level of the tree diagram of technical solutions. There were forty-four Hows identified in this study. These were generally identified by the QFD team, not the customers. However, if a customer's response contained a How, it was included, and if no corresponding What was stated, a suitable customer need was inferred by the QFD team, and added to the list.

3 **Relationship Matrix Between Whats and Hows** A score was recorded on the House of Quality matrix, indicating the degree to which each How would satisfy a customer's Need. Some of the Hows satisfy more that one What, and each What was supported by more than one How. The scores are a judgement by the QFD team, based upon their experience and knowledge. To distinguish the most important relationships, the scores were Strong satisfaction (9 points), Moderate satisfaction (3 points), Weak satisfaction (1 point), and No satisfaction (0 points).

4 **Correlation Matrix for Each Pair of Hows** This matrix resembles the Roof of a house, which gives rise to the name of the House of Quality. Since many of the technical solutions are interdependent, each How supports or negates each of the other Hows to some degree. For example, redundancy tends to negate simplicity. The grades corresponded to two levels of positive and two levels of negative correlation, as well as no correlation. These relationships were evaluated and determined by the QFD team members, not the customers.

5 **Customer Names** This element is a listing of the names of those customers who were interviewed. To preserve customer confidentiality, names are not specifically associated with the study results.

6 **Matrix of Priorities** Each What is given a priority rating for each customer, from 1 to 5, with 5 being the highest. The Hows are not ranked by priority at this stage; their priorities are derived subsequently from a formula which includes the What priorities. These priorities were concerned not with importance *per se*, but with which What should be worked in the future, due to a present deficiency. For example, most customers would rank reliability as tops in importance; but if reliability were perceived as presently being adequate, it might rate a low ranking as to priority of future effort. The priorities are not exclusive; several Whats could be given the same priority rating.

7 **Weighted Rate of Importance** This is the weighted average for each customer need for all customers. This rating is used in the later formula as the symbol "A".

8 NASA/Industry Achievement Ratings On a scale of 1 to 5, NASA and industry are rated by the QFD team on their combined degree of achieving each What, with 5 being the highest rating. One rating is given for the present, or "now", and one rating for the target achievement at the end of a period of time. The numerical ratio of the two ratings is a measure of the degree of improvement targeted during the project term. This ratio, designated as "D", was used subsequently in one of the formulae.

9 Sales Point This item makes a What more important if, in addition to its own function for the RPOC product, its technology can be used in other products or systems. This rating was a judgement by the QFD team based upon their own experience, and not based upon the customer interviews. The allowable ratings were 1, 1.2 and 1.5. This rating is symbolized as "E" in the formulae.

10 Importance Weight of Customer Needs The absolute weight for each What was obtained by the formula shown in Figure F-1 (F = A x D x E), where the variables have been defined above.

11 Relative Weight of Customer Needs The relative weight is the absolute weight, divided by the sum of the weights, expressed as a percentage. This is the final, significant rating of importance for each What, weighted by the several considerations

12 Importance Weight of Technical Solutions The matrix ranking of each How with each What was adjusted, by multiplying each element in the matrix by the final importance weight of the related What. The resultant column for each How was then summed to obtain the importance weight for that How.

13 Relative Weight of Technical Solutions The relative weight of each technical solution, or How, was divided by the total weight of all Hows, and converted to a percentage, to obtain the relative importance rating for each How.

14 Quantitative Target of Each Technical Solution Improvement is difficult to measure unless it can be done quantitatively. For each How, a numerical method of measuring the accomplishment of a How was determined. The House of Quality shows the unit of measurement, and the numerical target of each How for the project time period. The RPOC House of Quality in Appendix G does not show this information because of the numerous targets possible with the RPOC technical solutions; the list was too extensive to fit onto the chart. However, the RPOC QFD team did identify possible quantitative values of the technical solutions by identifying the methods, measurements, and values, where known. The results of this exercise are shown in Appendix J.

15 RPOC QFD House of Quality The actual composite House of Quality for the RPOC QFD process is in Appendix G. The chart reflects the details of the highly structured analysis approach that is the heart of the QFD process, and the results of the team's activities.

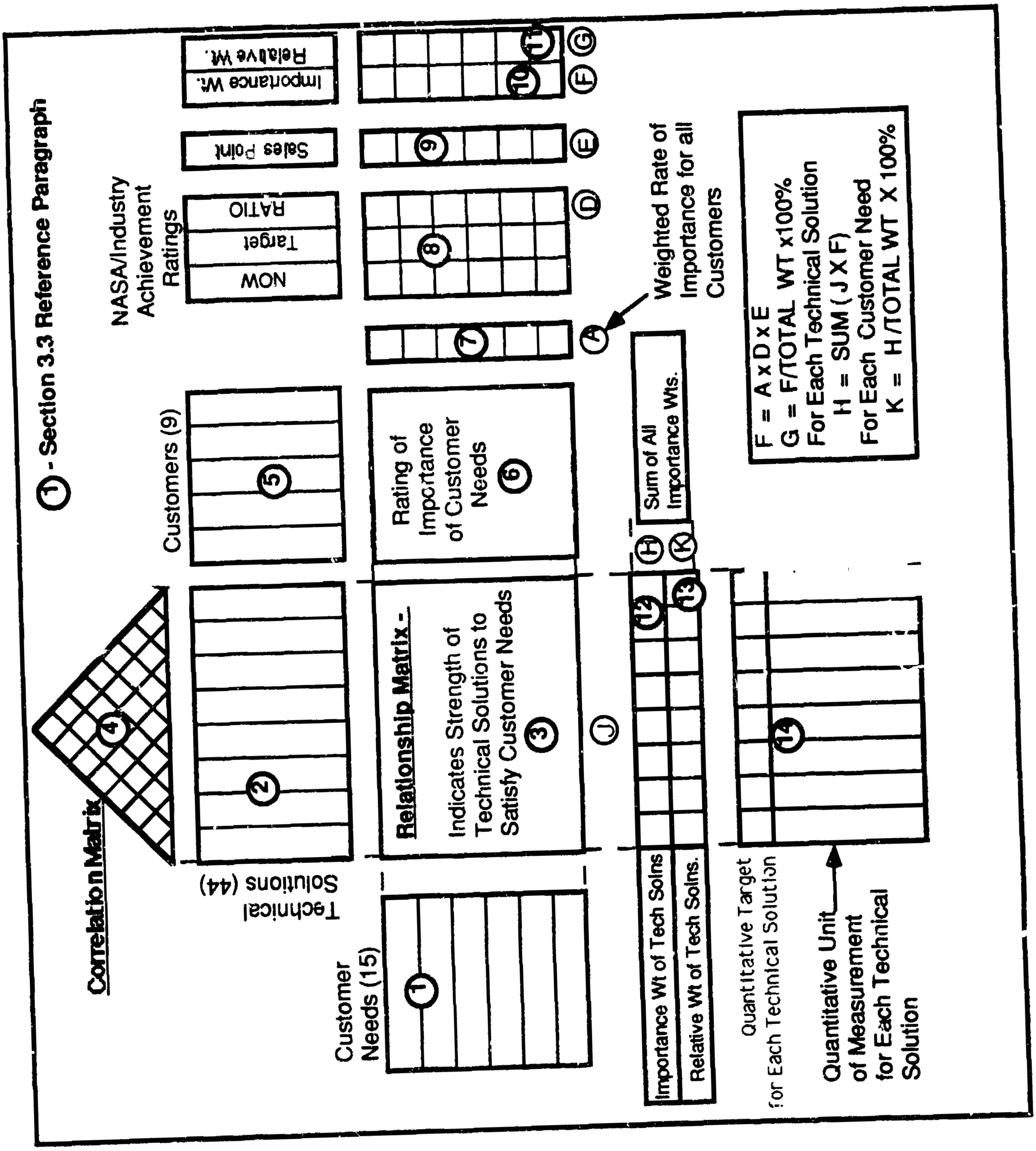

Figure F-1. Quality Function Deployment House of Quality

Appendix G. The RPOC QFD House of Quality

Appendix H. QFD Process Path Actually Followed

The sequence of events for the RPOC QFD was as follows:

3/5/91 • Defined the general objectives for this QFD process.
- Obtained authorization and assurance of support from a suitable management sponsor.
- Made arrangements for a consultant to provide QFD training and periodic support.
- Made arrangements for team support from industry representatives involved the RPOC arena.
- Selected the organizations needed to be represented.
- Wrote sponsors letter to supporting organizations.
- Assigned a facilitator and assistant facilitator.
- Obtained organizational assignments of team members.
- Made arrangements for a dedicated area to conduct the QFD for the planned period.
- Established a tentative schedule and defined a statement of benefits.

3/21/91 • Had a kick-off meeting of the team members with an introduction by the management sponsor.
- Initiated the QFD training and used the consultant to help with the first few steps in the process.

3/25/91 • Worked out a definitive QFD objective that everyone bought into.

3/25/91 • Brainstormed to define a list of potential customers.
- Worked with management sponsor to pare the customer list to a manageable size of customers to be interviewed.
- Define a potential product list off-line.
- Brainstormed to define the RPOC functions and elements which are and need to be accomplished in the normal course of a program.
- Developed a list of RPOC related terms which must be defined.
- Worked as a total team to establish these definitions. This turned out to be very tedious and time consuming.

4/4/91 • Brainstormed to define a What Tree based on speculation about what the potential customer needed. This proved to be very difficult to accomplish because we were unsure about what the customer really needed. We were also in a quandary about how to handle the wide disparity among potential customers and how to satisfy them all.

4/5/91 • Brainstormed to define a complete list of questions to be asked of the customers.
- Divided into sub-teams and made customer assignments to those sub-teams.

4/8/91 • The individual sub-teams defined the specific questions to be pursued with each assigned customer.
- A letter was written to the customers and sent by the management sponsor which defined in general the information being sought.
- The sponsoring management staff set up the customer interview appointments.

4/9/91 • Used in-house "Practice Customers" with some insight into the real customer needs to start the interview process.
- Established a standard interview product package to be generated by the sub-teams. This consisted of the following:
  - Customer What Tree with ratings
  - Customer interview narrative report which was reviewed by the customer and verified with major areas highlighted
  - Annotation of the customer narrative to show traceability of the needs to the resulting Whats and Hows in the House of Quality Matrix.

4/29/91 • Brainstormed with the whole group to define a final What Affinity/Tree which meets the needs of all the customers. In some cases, we decided that what the customer stated as a need (What) was determined by the team to be a How and was assigned as such.

4/16/91 • Brainstormed to define a How Affinity/Tree so that each What had one or more Hows which addressed it.

• Made another round of sub-team customer interview assignments with a schedule established.

4/22/91 • Conducted the second round of customer interviews, some of which required travel.

4/29/91 • Revisited the What and How Trees to insure that the needs of all our customer were reflected.

5/2/91 • Assigned sub-team responsibility for the definition of each What and How in the House of Quality Matrix. These sub-teams produced a definition for each one and presented it to the total group for discussion and modification. Finally individuals within these sub-teams were assigned continuing ownership responsibility so that any further amplification or modification of these definitions would be documented.

4/17/91 • Brainstormed with the whole group to score the relationship of the Whats and Hows. We did this in some cases with the whole team and in some cases with sub-teams which brought them back to the whole team for review

4/25/91 • Decided to use a single composite weight of the customer needs for use in the House of Quality Matrix. This composite need weight was an average of the weights based on individual customer interviews.

5/13/91 • Brainstormed to define how well we were currently meeting the customers needs.

5/13/91 • Brainstormed to define how well we should meet the customer needs by end of FY95.

5/14/91 • Brainstormed to define which of the Whats were major and minor Sales Points.

• Calculated the importance weights, relative weights of the Whats and resultant importance weights of the Hows.

5/16/91 • Barbara Bicknell and Nick Smith of Martin Marietta developed some examples of how to quantify and arrive at target values for the Hows. Nick returned and discussed this process with us. We then assigned the responsibilities for this to the owner's of the How definitions. After completion, these items were presented, discussed and modified as necessary. It was decided that the quantification parameters were more significant than the actual target values because actual measurement of the parameters may be difficult and expensive to implement.

5/17/91 • Defined the correlation between Hows by assigning columns of the matrix to teams of two or three people to be worked in an afternoon. These values were later checked for agreement by another team. Any disagreement was brought before the total group for discussion and consensus.

• We attempted to address the first objective for a near-term plan in a brainstorming session. We looked at the highest priority Hows from the Pareto diagram (Figure 3) and noted that flight demonstrations of the hardware and a total system were very important Hows. We agreed that this was an area that had a good potential for successful near-term activities. We formed an Affinity/Tree of possible flight (or even ground) experiments which would meet the customers needs.

5/21/91 • In a group discussion, we listed a number of RPOC Issues (which in some cases may simply become actions to be worked) which we felt were particularly significant. We also listed a few trade studies which needed to be conducted very early for a particular program.

5/22/91 • Management worked up an outline of the necessary documentation to complete the QFD task. This outline was then broken into pieces and assigned to various members of the team, so that each of the full time members had a part to be written. This was done to establish a strong sense of ownership in the final product.

Appendix I. QFD Team Observations

1. The right team membership is extremely important!
   - Team members need to have a vested interest in the outcome of the process.
   - Team membership should span the community of supporting organizations required for the end product.
   - Individual members should have experience in the technical and political realities of their organizations.
   - Individual members must be able to assume an assertive role in the process and not be wallflowers.
   - The member's home organization must be supportive of the process and allow him to devote the necessary time to the process.

2. Management must be willing to invest the time necessary for the QFD team to reach a logical conclusion of its work. As a general guideline, plan on the team needing twice what is planned for.

3. Management support and assurance of the usefulness and actual use of the resulting product is absolutely necessary.

4. The use of "Practice Customers" to start the interview and What tree formulation process was helpful in working out the process and interviewing skills.

5. We struggled to define the What Affinity/Tree before we talked to customers. The use of "Practice Customers" to prime the pump was a great help.

6. The use of sub-teams to make a first cut at the scoring of the relationship of Whats and Hows speeds up the process.

7. The use of Definition owners for each of the Whats and Hows worked well. We generally solicited volunteers so that people with the most familiarity with a particular area were used when possible.

8. Brainstorming discussions sometimes become very frustrating, especially late in the afternoon. It was usually better to break off these activities for the day when this problem became obvious.

9. Assignments were not always completed on schedule, and additional time was needed to complete the actions.

10. Obtaining agreement on definitions is very tedious and time consuming, but individual ownership helped speed the process.

11. There was considerable struggle to decide which customers were most important, and should be interviewed. The team decided to concentrate on near term NASA program offices and the technology development offices.

12. Whats and Hows should be defined as early as possible to properly score the relationships. Delaying this caused a great deal of confusion and misunderstanding.

13. Our team received a two day QFD training course immediately before beginning the QFD project. It is recommended, instead, that a five day course be taught about two weeks prior to the QFD project.

14. The What list can vary according to the QFD purpose. Our What list contained only those derived from customer interviews. A complete What list would contain all the higher level functions of a deliverable end item.

15. The Definitions created by the team for Whats, Hows, and the subject terminology, were among the most valuable products of the study. They clarified thinking, were educational, and resolved ambiguities. An example was the distinction between "automatic" and "autonomous".

16. Prior to customer interviews, the team made a very complete functional decomposition of RPOC functions. This tree identified the procedural steps normally taken in defining RPOC functional requirements. It also contained the functional requirements and related hardware or software. The functional requirement section included reliability, environment, life of product, and testing requirements. Making this list clarified the thinking of the team and gave them confidence in the completeness of the RPOC subject matter. Future QFD projects may want to follow this practice. For future space vehicle programs, this preliminary functional decomposition could serve as a checklist of things to be done during the design effort, and as an outline of a procurement specification.

17. Isolation from team members normal duties is essential. The work area for the QFD meetings was isolated from the team members' regular offices by being in an off-site NASA building. This isolation avoided interruptions and distractions. The QFD meeting area had two conference rooms, a computer room, and a work table. This spacious work area permitted breaking up into smaller teams upon occasion.

18. Computer equipment support is very helpful in conducting team discussions. Our equipment included four desktop computers, a viewgraph projector and screen, and an LCD overlay projector that attached to a computer and used the viewgraph projector to display the computer on a screen. This permitted real time discussions of changes and consensus faster because <u>all</u> team members could see what was under discussion. Most team members returned to their offices to do word processing.

19. The team was relieved of their other duties by their supervisors, except that one day per week was allocated to non-QFD tasks.

20. At first the team was puzzled about whether to categorize a RPOC feature as a What or a How. By definition, a How is a solution for a What. But in a certain sense, every How was itself a customer need; that is, a What. It was finally realized that Whats and Hows are a relationship between two features. Each How is also a What, at the next level, with its own set of subordinate Hows, and so on, level by level. Thus, there is a branching of What-How relationships, similar to a decomposition of functional requirements. In the QFD study guides, this concept is represented by a chain of House of Quality diagrams, in which the Hows of a preceding House become the Whats of the next House.

21. Customer interviews should be recorded on audio tape. Tape would have verified that no information was lost or overlooked.

22. In a similar manner, the team discussions were outstanding commentaries, vigorous and innovative. It is regretted that these discussions were not recorded by audio or video; useful and well reasoned material was not captured.

23. The names of the customers interviewed, the transcriptions of the interviews, and the Whats and Hows derived from a particular customer, should not be published. This preserves the confidentiality of the customers, and allows them to freely and openly express their opinions.

24. Each customer should be provided a summary of his interview. He then can provide corrections where needed.

Appendix J. Quantitative Values of Technical Solutions

Technical Solution	Method	Measurement	Target Value
Use Incremental Design Approach	Planned design growth	# interim design steps	Draper method
		# hooks & scars	Review STS/SSF
	Maturity of technology	OAET technology level	9
	Step-wise verification	% requirements met	to reach 100
Use Simple Systems	Degree of complexity	# of moving parts	Current RPOC
		# steps in operation	Current RPOC
	Multi-use of elements	# of different elements	Numeric might be a ratio of multi-use events to number of different elements. Object is to maximize ratio.
	Estimated reliability	Calculated MTBF	numeric
Use Failure Resistant Components	High reliability	MTBF or P(failure)	Breakdown target goals by component or at least element to answer reliability, schedule and cost questions.
	Available parts	Procurement lead time	Time in Days or Weeks
	Affordable	Cost to increase reliability vs. redundancy	????
	Use certified sources	# of questionable suppliers for parts	????
Use Redundant Components/Information	Efficient use of redundancy	# redundant components	ratio
		# redundant paths(minimize)	Probability of success
	Efficient use of functional	# of ways to derive	numeric
		redundancy	required information
	Failure modes & effects analysis (FMEA)	????	????
Use Conservative Margins	Ability to function when off-nominal	# of parameters off-nom	numeric
		# of std dev off-nom	numeric
	Component usage	% derating	numeric
Use Standardized Interfaces	Properties	# different interfaces	numeric
		ratio of standard to total number of interfaces	ratio
		# of interface requirements documents	numeric
Use friendly Interfaces	Comfortable, consistent, easy to use, intuitive	# training hours req	numeric
	User survey for feedback	# of changes requested	numeric
	Operability of controls	# of changes requested	numeric
Define System Requirements for Minimum Training	Ease of use	# training hours req	numeric
	Operability of controls	# of Operations reviews	numeric
	Concurrent Ops/Sys reqmts definition	# of meetings	numeric
Use Concurrent Engineering Processes	Maximize the number of multifunctional interdisciplinary teams formed	Number of teams	Maximum
	Minimize the number of required design changes	Number of design changes	Minimum
	Minimize quality loss	% quality loss	Minimum
	Maximize customer satisfaction	Number of complaints	Minimum

Technical Solution	Method	Measurement	Target Value
	Minimize product development time	Months to develop product	Minimum
	Maximize number of competitive benchmark studies	Number of st[illegible]es	Maximum
	Minimize product cost per unit	Cost per unit	Minimum
Perform Survey of State-of-the-Art RPOC Capabilities	Level of Participation	% of Surveyed responses	95%
		% of Questions Answered	99%
	Quality of Data Obtained	% of Responses Providing the requested Details	85%
Build Databases	Number of Contributors	% Increase in Contributors	20%/Yr (5 Yrs)
	Number of Users	% Increase in Users	25%/Yr (5 Yrs)
Develop Integrated Technology Plan			
Develop Advanced Sensors			
Develop Advanced Algorithms			
Develop Improved Docking Mechanisms & Facilities			
Define Resupply/Return Requirements	Minimize the number of requirements changes at program phases	Number of requirements changed	Minimum
	Develop resupply/return requirements analysis programs	Number of programs	>1
Develop Traffic Control Strategy	Prepare concept document	Document	1
	Minimize average contamination per vehicle per unit of time	Average angstroms contamination per vehicle per unit of time	TBD
	Minimize the amount of propellant per vehicle per unit of time required for traffic management	Mass of propellant per vehicle per unit of time	TBD
	Maintain the required mean separation required per vehicle	Mean range between vehicles	TBD
	Maximize the number of vehicles controlled	Number of vehicles controlled	Maximum
	Minimize the number of required interactions per unit of time	Number of interactions	Minimum
Define Operating Modes	Document defining guidelines for mode selection	Document	1
	Traceability to mission requirements	Number of satisfied requirements	Maximum
	Minimize training requirements	Training hours required	Minimum
Define Operating Zones	Prepare zone definition document	Document	1
	Minimize the number of zones	Number of zones	Minimum
	Maximize the number of operations allowed in each zone	Operations/zone	Maximum

Technical Solution	Method	Measurement	Target Value
	Maximize the number of vehicles allowed per zone	Vehicles/zone	Maximum
Early Definition & Maturity of Requirements			
Improve System Requirements Traceability Process			
Provide Effective Telemetry/Command/ Navigation Infrastructure	Calculate percentage of up and down link requirements (or total requirements) satisfied by current infrastructure	Percentage of Total Requirements (kbps/total kbps x 100)	100%
Reduce/Standardize Mission Dependent Reconfiguration	Minimize the total man-hours spent on Mission Dependent Reconfiguration for a flight	Man-Hours per Flight Hours for a Flight	Minimize
	Minimize the total man-hours spent on Mission Dependent Reconfiguration for a Fiscal Year	Man-Hours per Flight Hours per Year	Minimize
Reduce/Standardize Flight Software Reconfiguration	Minimize the total man-hours spent on Software Reconfiguration for a Fiscal Year	Man-Hours per Flight Hours per Year	Minimize
Reduce/Standardize Flight Turnaround Reconfiguration	Minimize the total man-hours spent on Turnaround Reconfiguration for a flight	Man-Hours per Flight Hours for a Flight	Minimize
	Minimize the total man-hours spent on Turnaround Reconfiguration for a Fiscal Year	Man-Hours per Flight Hours per Year	Minimize
Perform Functional Analysis of All RPOC Systems	Number of requirements, Systems, Functions, and Sub-functions	Change Traffic	Decrease Change Traffic
Develop Trajectory Approach Techniques	Minimize fuel usage	ΔV used	$\le (1 + x)100\%$ of nominal where ($x \ge 0$; x is TBD)
	Minimize contamination	Deposit at TBD m	≤TBD angstroms/cm^2
	Keep structural loads at an acceptable level	Peak load at TBD m	≤TBD
	Keep software costs low	Source lines of code	≤TBD
Apply Expert Systems to RPOC	Number of Systems & Functions Applied to	% of Total Functions	80%
	Requirements Satisfied	% of Total Requirements	80%
	Workload	Decreasing Workload	50% Reduction in Workload (on-board and ground)
Develop Algorithms for Rendezvous	Minimize fuel usage	ΔV used	$\le (1 + x)100\%$ of nominal where ($x \ge 0$; x is TBD)
	Control dispersions	Dispersions	≤TBD m at range TBD m
	Maximize nav accuracy	Navigation errors	≤TBD m at range TBD m
	Minimize computation	Execution time	≤TBD sec
	Keep software costs low	Source lines of code	≤TBD

Technical Solution	Method	Measurement	Target Value
Develop Attitude and Translational Control Systems to Minimize Plume Impingement and Contamination	Minimize contamination	Deposit at TBD m	≤TBD angstroms/cm^2
	Keep structural loads at an acceptable level	Peak load at TBD m	≤TBD
Perform Systems & Technology Trade Studies	Maximize Total Man-Hours & Facility Hours Available to Perform Trade Studies	Total of Man-Hours & Facility Hours	Maximize
Perform Simulations - Non-Real Time			
Perform Simulation - Real Time			
Perform Hardware Evaluations			
Perform Statistical Analyses	Maximize Total Man-Hours & Facility Hours Available to Perform Statistical Analyses	Total of Man-Hours & Facility Hours	Maximize
Automate Design Process of RPOC Systems			
Use Automatic Code Generation			
Automate Mission Planning			
Conduct Shuttle Flight Demonstrations	Document defining criteria for selection of STS flight demonstrations	Document	1
	Maximize number of scheduled, approved detailed test objectives (DTOs) per time period	Number of scheduled DTOs	Maximum
	Maximize the number of DTOs completed per time period	Number of DTOs completed	Maximum
	Maximize number of technology areas demonstrated per time period	Number of technology areas	Maximum
Conduct Unmanned Vehicle Flight Demonstrations	Document defining criteria for selection of unmanned flight demonstrations	Document	1
	Maximize number of scheduled, approved unmanned detailed test objectives (DTOs) per time period which support validation not otherwise possible	Number of scheduled DTOs	Maximum
	Maximize the number of approved unmanned DTOs completed per time period	Number of DTOs completed	Maximum
	Maximize number of technology areas demonstrated per time period	Number of technology areas	Maximum
Conduct Multi-Vehicle Flight Demonstrations	Document defining criteria for selection of multi-vehicle flight demonstrations	Document	1

Technical Solution	Method	Measurement	Target Value
	Maximize number of scheduled, approved multi-vehicle detailed test objectives (DTOs) per time period which support validation not otherwise possible	Number of scheduled DTOs	Maximum
	Maximize the number of approved multi-vehicle DTOs completed per time period	Number of DTOs completed	Maximum
	Maximize number of technology areas demonstrated per time period	Number of technology areas	Maximum
Conduct Prototype System Ground Tests	Quick Implementation	Meet Milestones	???
	Model Fidelity	% of Required Models	???
	Redesign	% of Rework Required for New Applications	???
	Testing	% of Final Testing Achieved	???
Conduct Ground Tests of Flight Hardware			

National Aeronautics and Space Administration

REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
JSC-25458		

4. Title and Subtitle
Rendezvous, Proximity Operations, and Capture Quality Function Deployment Report

5. Report Date
December 1991

6. Performing Organization Code
EG

7. Author(s)
Stephen Lamkin, Editor

8. Performing Organization Report No.

9. Performing Organization Name and Address
Navigation, Control and Aeronautics Division
Engineering Directorate
NASA Johnson Space Center
Houston, Texas 77058

10. Work Unit No.
593-14

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Navigation, Control and Aeronautics Division
Engineering Directorate
NASA Johnson Space Center
Houston, Texas 77058

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
Rendezvous, Proximity Operations, and Capture (RPOC) is a functional area which is extremely important to present and future space initiatives and must be well planned and coordinated. To support this, a study team was formed to identify a specific plan of action using the Quality Function Deployment (QFD) process. This team was composed of members from a wide spectrum of organizations which are involved in the RPOC technology area. The key to this study's success is an understanding of the needs of potential programmatic customers and the technology base available for system implementation. To this end, the study team conducted interviews with a variety of near term and future programmatic customers and technology development sponsors throughout NASA. The QFD activity led to a thorough understanding of the needs of these customers in the RPOC area, in addition to the relative importance of these needs. This document details the background and QFD process used by the team, and presents the results of their efforts.

17. Key Words (Suggested by Author(s))
Requirements, Automation, Controls, Guidance, Customer Needs, Total Quality, Quality Function Deploy, Navigation, House of Quality

18. Distribution Statement
Unclassified
Subject Category 01

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	60	

For sale by the National Technical Information Service, Springfield, VA 22161-2171
JSC Form 1424 (Rev Aug 89) (SWSFORMS Dec 89)