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SPACE APPLICATIONS OF AUTOMATION, ROBOTICS AND MACHINE INTELLIGENCE SYSTEMS (ARAMIS)
VOLUME 4: APPLICATION OF ARAMIS CAPABILITIES TO SPACE PROJECT FUNCTIONAL ELEMENTS

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16. ABSTRACT

This study explores potential applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities, and to their related ground support functions, in the years 1985-2000, so that NASA may amke informed decisions on which aspects of ARAMIS to develop. The study first identifies the specific tasks which will be required by future space project tasks, and evaluates the relative merits of these options. Finally, the study identifies promising applications of ARAMIS, and recommends specific areas for further research.

The ARAMIS options defined and researched by the study group span the range from fully human to fully machine, including a number of intermediate options (e.g., humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

This is Volume IV of a four-volume set. Volume IV consists of two documents: NASA CR-162082 and an appendix, NASA CR-162083.

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VOLUME 4: APPLICATION OF ARAMIS CAPABILITIES TO SPACE PROJECT FUNCTIONAL ELEMENTS

4.1 INTRODUCTION

4.1.1 Contractual Background of Study

On June 10, 1981, NASA Marshall Space Flight Center (MSFC) awarded a twelve month contract (NAS8-34381) to the Space Systems Laboratory and the Artificial Intelligence Laboratory of the Massachusetts Intstitute of Technology, for a study entitled "Space Applications of Automation, Robotics, and Machine Intelligence Systems (ARAMIS)", Phase I. The Space Systems Laboratory is part of the M.I.T. Department of Aeronautics and Astronautics; the Artificial Intelligence Laboratory is one of M.I.T.'s interdepartmental laboratories. Work on the contract began on June 10, 1981, with a termination date for Phase I on June 9, 1982.

Following discussions between M.I.T. and NASA MSFC, the contract was expanded to include several additional tasks specifically concerned with structural assembly in space. This "structural assembly expansion" to the contract started on October 27, 1981, with a termination date also on June 9, 1982.

At NASA's request, separate progress reports were produced for the original contract tasks (called the "main study") and for the structural assembly expansion. Separate final reports were also prepared, though some sections are identical in both.

This document is the final report for Phase I of the ARAMIS main study. The final report for the structural assembly expansion of this study is entitled "Automated Techniques for Large Space Structures" (also contract number NAS8-34381).

The NASA MSFC Contracting Officer's Representative is Georg F. von Tiesenhausen (205-453-2789). The M.I.T. Principal Investigators are Professor Rene H. Miller (617-253-2263) and Professor Marvin L. Minsky (617-253-5864). The M.I.T. Study Manager is David B.S. Smith (617-253-2298).

4.1.2 Contributors to this Study

Work on this contract has been performed in the M.I.T. Space Systems Laboratory and in the M.I.T. Artificial Intelligence Laboratory. The members of the study team are listed in Table 4.1.

The main body of the final report was written by the Study Manager. The bulk of this report, however, consists of appendices presenting the study data; this information was produced by the team members.

The study group consulted a large number of people during the performance of this research. In addition to the consultations referenced in this report's data sheets, the study group also benefitted from general discussions with several groups and individuals. In particular, the research team acknowledges the contributions of: Dr. William B. Gevarter (National Bureau of Standards) on automation and robotics in general; Dr. Ewald Heer (Jet Propulsion Laboratory) on the classification of automation, robotics, and machine intelligence systems; Mr. Rodger A. Cliff (NASA Goddard Space Flight Center) on spacecraft computers;

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Four members of the study group visited Kennedy Space Center for two days of briefings and tours of the payload checkout, integration, and launch facilities, under the guidance of Mr. Thomas Feaster of the KSC Future Aerospace Projects Office. This visit was extremely useful to the team, as an introduction to the complex interactions in payload checkout and to the unusual time constraints of KSC's operations.

The Space Project Breakdowns (presented in Volume 2 of this report) were developed in consultation with MSFC Project Engineers: William T. Carey, for the Geostationary Platform; Carroll C. Dailey, for the Advanced X-ray Astrophysics Facility (AXAF); James R. Turner, for the Teleoperator Maneuvering System; Kenneth R. Taylor, Max E. Nein, and Claude C. Priest, for the Space Platform. The study group thanks them for their review and suggestions. The research team also thanks Dr. Thomas H. Markert (M.I.T. Center for Space Research), for discussions on X-ray astronomy observation procedures in the AXAF breakdown.

4.1.3 Organization of the Final Report

Volume 1 of the final report is the Executive Summary. Volumes 2, 3, and 4 are roughly chronological, in the sense that the data and results presented were developed in that order by the study.

Volume 2: Space Projects Overview describes the space project breakdowns, which are used to identify tasks ("functional elements") which will be required by future space projects.

Volume 3: ARAMIS Overview gathers together the information specifically related to automation, robotics, and machine intelligence systems (ARAMIS). The volume starts with a general discussion of ARAMIS and the organization of this field into "topics." It then presents general information forms on ARAMIS "capabilities" which are candidates to perform space project tasks.

Volume 4: Application of ARAMIS Capabilities to Space Project Functional Elements is the pivotal volume in the report, since it deals with the relationships between the space project tasks and the ARAMIS capabilities. Specifically, in Volume 4 the list of tasks generated in Volume 2 and the background knowledge on ARAMIS presented in Volume 3 are combined to define "candidate ARAMIS capabilities" for each task. Volume 4 then presents the evaluation of the relative merits of the various candidates to perform the space project tasks, and the selection of the promising options suggested for further study.

Thus Volumes 2 and 3 serve to some extent as preparatory material and appendices to Volume 4, which contains most of the complexities of the research effort. Therefore a complete description of the study's objectives and method is included in Volume 4, while partial synopses of the study method appear in Volumes 2 and 3, specifically explaining the production of the data in those volumes.

The study recipient who wishes to apply the results of this study to a new space project will principally use Volume 4, referring to Volume 2 to check further on the definition of a space project task, and referring to Volume 3 for descriptions of suqgested candidate ARAMIS capabilities. In addition, Volume 3 is intended as a general introduction to the field of ARAMIS and to its complex jargon.

4.2 STUDY OBJECTIVES AND GUIDELINES

4.2.1 NASA and ARAMIS: The Problem

To put this study in general context, the need for automation, robotics, and machine intelligence systems in NASA activities stems largely from considerations of cost effectiveness and safety. It is expected that the use of ARAMIS will reduce the cost of certain space activities and of related ground support functions. In addition, there are some applications of ARAMIS required by safety considerations (e.g. EVA functions during solar flares), and by non-interference requirements (e.g. zero-g materials processing). Also, the emerging larger scope of spacecraft and space activities suggests that ARAMIS will likely be desirable to deal with routine or repetitive operations (e.g. tribeam production for large space structures).

The cost of automating all space activities, however, would be prohibitive. Ultimately, the human being's extreme flexibility and ingenuity in dealing with partial information or novel situations can only be replaced by ARAMIS at unwarranted cost. In the opinion of the study group, there is an optimum mix of humans and machines to perform space activities, which will yield best performance at minimum program cost. This optimum mix is not yet known, for several reasons.

First, the scope and complexity of space projects is currently in rapid expansion, due in part to the availability of the Shuttle as a transportation system. Therefore the requirements of future space projects are not yet known in detail. In some cases, new projects may emerge from current experimental research, with unexpected ARAMIS requirements (e.g. the handling of dangerous biological experiments in a remote space facility).

Second, our knowledge of the potential abilities of humans and machines in the space environment is limited. The human activities performed to date in space by the U.S. have only started the learning process typical of human endeavor: techniques and tools have been tried only a few times, and there have not yet been the several iterations in procedure development and tool design to allow humans to reach their maximum productivity. Also, certain tasks (e.g. structural assembly) have only been tried in limited simulations on earth.

Third, on the ARAMIS side, our knowledge is limited mostly by the youth of the technology. Information on automation and robotics is not yet organized and classified, as in the more established engineering disciplines. There are no comprehensive directories of ARAMIS research, for example. The "ARAMIS community" is only beginning to communicate publicly between its many branches, and to educate potential customers. However, although the researchers in the field of ARAMIS are extending their expertise beyond their immediate specialties to cover more of the field, this process has not yet extended to aerospace applications. Very few ARAMIS experts are aware of the specific applications of automation and robotics to space activities, and of associated requirements such as space-rating, reliability, real-time trouble shooting, and documentation.

In an overall sense, the U.S. suffers from the lack of a national-level framework to develop and apply automation and robotics. The success stories of ARAMIS application in West Germany and Japan, for example, are due in large part to a governmental committment to develop these technologies and to transmit them rapidly to the users. In the U.S., this has been left largely to industrial management, which has been too slow to appreciate the potentials involved. Volume 3 of this report presents a general discussion of ARAMIS, and suggests some further sources of information.

Focusing on NASA's need for automation, robotics, and machine intelligence systems, several previous studies (refs. 4.1 through 4.9) have identified potential improvements from use of ARAMIS in a number of areas, including: design and test of space equipment; mission profile and schedule development; launch vehicle servicing and launch operations; in-space tasks and hardware, and associated ground support. A number of NASA studies, current, planned, or proposed, deal with aspects of ARAMIS applications in these areas. Some of these research efforts are listed in the ARAMIS bibliography in Appendix 3.3 (Volume 3); others are referenced throughout this report.

This study addresses in-space tasks and hardware, and associated ground support. It also considers some pre-launch operations, specifically the payload integration and checkout at KSC. This is a systems study, in that it defines and evaluates design alternatives; detailed design and development of ARAMIS hardware is left to later research efforts.

4.2.2 Research Objectives

The general objectives of the ARAMIS study are listed in Table 4.2. The overall objective of the ARAMIS study is to contribute to NASA's understanding of the potential of ARAMIS for space applications.

TABLE 4.2: GENERAL OBJECTIVES OF ARAMIS STUDY

OVERALL OBJECTIVE: To develop an understanding of the potential of automation, robotics, and machine intelligence systems for space applications, so that NASA may make informed decisions on which aspects of ARAMIS to develop.

PHASE I OBJECTIVES:

A) To develop a systematic method for analyzing the problem
B) To identify and describe ARAMIS candidates for the performance of specific tasks in space projects
C) To evaluate (qualitatively) the relative merits of ARAMIS candidates, and to define promising options for ARAMIS-enhancement of space projects

The first general objective in Phase I is to develop a systematic method to perform the overall study, based on the general method described in the Statement of Work and the Study Proposal. This systematic method should: a) include a fully traceable data base of outside inputs (which are expected to be numerous) on ARAMIS capabilities; b) allow the study recipients to retrace the method with other input data (such as different outside opinions on ARAMIS, or updated estimates from later R&D); c) be applicable to other space projects, beyond those specifically chosen for study, so that the scope of the analysis may be broadened.

The second Phase I general objective is to identify and describe ARAMIS candidates for the performance of specific tasks in space projects. This can be expanded into a series of more specific objectives:

1) Select four space projects, which collectively cover a wide spectrum of tasks, both in space and on the ground.

2) Break down the selected space projects (Geostationary Platform, Advanced X-ray Astrophysics Facility, Teleoperator Maneuvering System, and Space Platform) into successively finer levels (project, missions, sequences, activities, functional elements) to identify small tasks making up the space projects.

3) Produce a list of space project tasks, collecting all the tasks in the four space project breakdowns.

4) For each space project task, define appropriate candidate "ARAMIS capabilities". Each capability is defined to be a piece of ARAMIS capable of satisfying, <u>by itself</u>, a space project task.

5) Describe each ARAMIS capability, including current state-of-the-art and future projections. This step is one of the principal elements of the study, since it explores what ARAMIS is today and what it can become.

The third general objective in Phase I of the study is to evaluate qualitatively the relative merits of ARAMIS candidates, and to define promising options for ARAMIS-enhancement of space projects. This general objective can also be expanded into more specific objectives:

a) Evaluate the relative merits of the candidate ARAMIS capabilities for each space project task. This evaluation of the ARAMIS options is also a major element of the study, since it involves the technical details (present and future) of the various ARAMIS capabilities.

b) Identify any research and development enhancement of a capability from prior R&D of other capabilities (e.g. a dextrous manipulator benefits from prior R&D of tactile sensors and micro-actuators).

c) Based on (a) and (b), identify ARAMIS capabilities which significantly improve the performance of space project tasks, or significantly enhance the R&D of other useful ARAMIS capabilities. These are promising applications of ARAMIS to space projects.

4.2.3 Guidelines and Assumptions

The guidelines and assumptions originally set forth in the Statement of Work evolved as the study progressed. Those described below are therefore the updated guidelines actually applied during the study.

1) The study shall address selected space activities and related ground activities. These include payload integration and checkout after delivery to Kennedy Space Center, orbital deployment and checkout, nominal operations in space and on the ground, maintenance and repair, modification, and retrieval or disposal.

2) It is assumed that each space project task has an optimum in terms of ARAMIS and that different tasks will have different optima. These optima are defined as having a combined minimum of time, maintenance, nonrecurring and recurring costs, and technological risk, and a maximum of reliability and useful life.

3) The mission time span covered by this study shall be 1985-2000, i.e. the spacecraft are assumed to fly in the years 1985-2000. Assuming a technology cutoff date five years prior to launch, the technology covered by this study ranges from the present to the year 1995. Cost estimates are expressed in 1981 dollars.

4) The resulting technology application, advancement and demonstration requirements shall be objective oriented rather than evolutionary. This means that technology shall be applied and advanced to respond to specifically defined requirements from this study rather than advanced along a broad front in a general evolutionary way.

5) Full use shall be made of the present state-of-the-art, nationally and internationally, and its rapid progress which is documented in literature and published research documents. This

shall include present and planned teleoperator robot technology work. Careful projections shall be made into the time frame covered by this study.

6) All documentation shall be provided in a well organized and traceable manner using tabulation, matrices, and graphical presentations in addition to a clear and concise text. All results and conclusions shall be clearly related to the assumptions made so that, if later updating efforts are performed, their effect can be readily assessed.

7) Phase I of the study shall consider space project tasks in the generic sense, i.e. each task will be researched by itself rather than in the context of a specific project. The purpose of Phase I is to develop and transfer a catalog of information to the user, on ARAMIS options to perform generic space tasks. Therefore scenario-specific issues (e.g. launch dates, orbital constraints, integration of ARAMIS applications with each other, budget limits) are left for future research, and to the discretion of the study user.

4.3 SYNOPSIS OF STUDY METHOD

4.3.1 Overview of Study Method

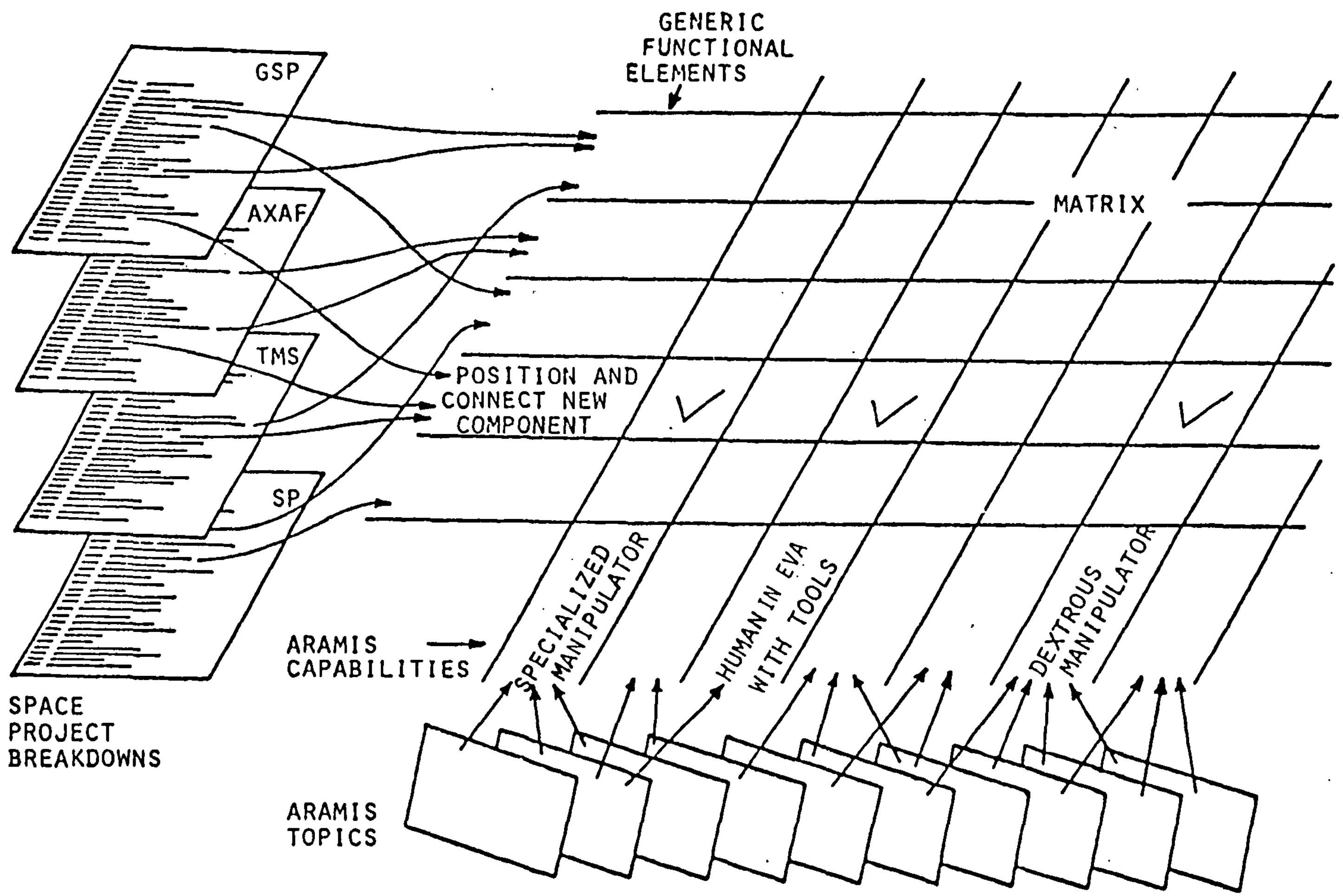
The overall ARAMIS study method is illustrated in schematic form in Figure 4.1. The method concentrates on the production of a matrix relating space project tasks (called "generic functional elements"; on the vertical axis in the figure) to pieces of ARAMIS (called "ARAMIS capabilities"; on the horizontal axis in the figure). The example in the figure shows that the generic functional element "Position and Connect New Component" can be satisfied by any of three ARAMIS capabilities: Specialized Manipulator, Human in EVA with Tools, or Dextrous Manipulator. Note that each ARAMIS capability by itself can satisfy the generic functional element.

As illustrated in the figure, the generic functional elements (GFE's) are generated from the space project breakdowns. The breakdown procedure and the collection of the generic functional elements is described in Section 4.3.2, and in Volume 2: Space Projects Overview.

The ARAMIS capabilities are generated by considering each generic functional element in turn, and defining pieces of ARAMIS capable of satisfying the element. These definitions are based on the general background knowledge and organization of ARAMIS developed by this study. Section 4.3.3 and Volume 3: ARAMIS Overview describe the methods used to research and organize the field of ARAMIS.

The checkmarks on the matrix grid in the figure are for

FIGURE 4.1: ARAMIS STUDY METHOD: GENERIC FUNCTIONAL ELEMENT/ARAMIS CAPABILITY MATRIX



NOTE: EACH CHECKMARK ACTUALLY CONSISTS OF A SERIES OF DECISION CRITERIA VALUES, AND OF COMMENTS ON SPECIAL ASPECTS OF THAT ARAMIS APPLICATION schematic presentation only. In actuality, each checkmark consists of values of seven decision criteria, with commentary and data sources, on the potential application of that ARAMIS capability to that generic functional element. These criteria are defined and discussed in Section 4.6. It should also be noted that the matrix schematic shown here is for illustrative purposes. The actual study data is stored in computer files and printed out line by line, one generic functional element at a time. The details of these formats are presented in the following sections.

A more specific overview of the main study method is the flowchart of major tasks and results shown in Figure 4.2. The numbers next to the flowchart boxes refer to the study tasks listed in Table 4.3. These tasks are discussed in greater detail in the following sections.

As shown in Table 4.3, the ARAMIS study uses a specialized nomenclature, partly adopted from NASA and partly defined specifically for this study. Table 4.4 defines this nomenclature, as well as some acronyms.

Sections 4.3.2 and 4.3.3 (following) summarize the descriptions of study method from Volumes 2 and 3, respectively. Sections 4.4 through 4.7 then describe the remainder of the study method, introducing appended results as warranted.

Most of the data management functions required by the study method were implemented on a computer, for ease of access and display of the information. The use of the computer in the ARAMIS study is discussed in Appendix 4.F.

FIGURE 4.2: MAJOR TASKS AND RESULTS OF ARAMIS MAIN STUDY (PHASE I)

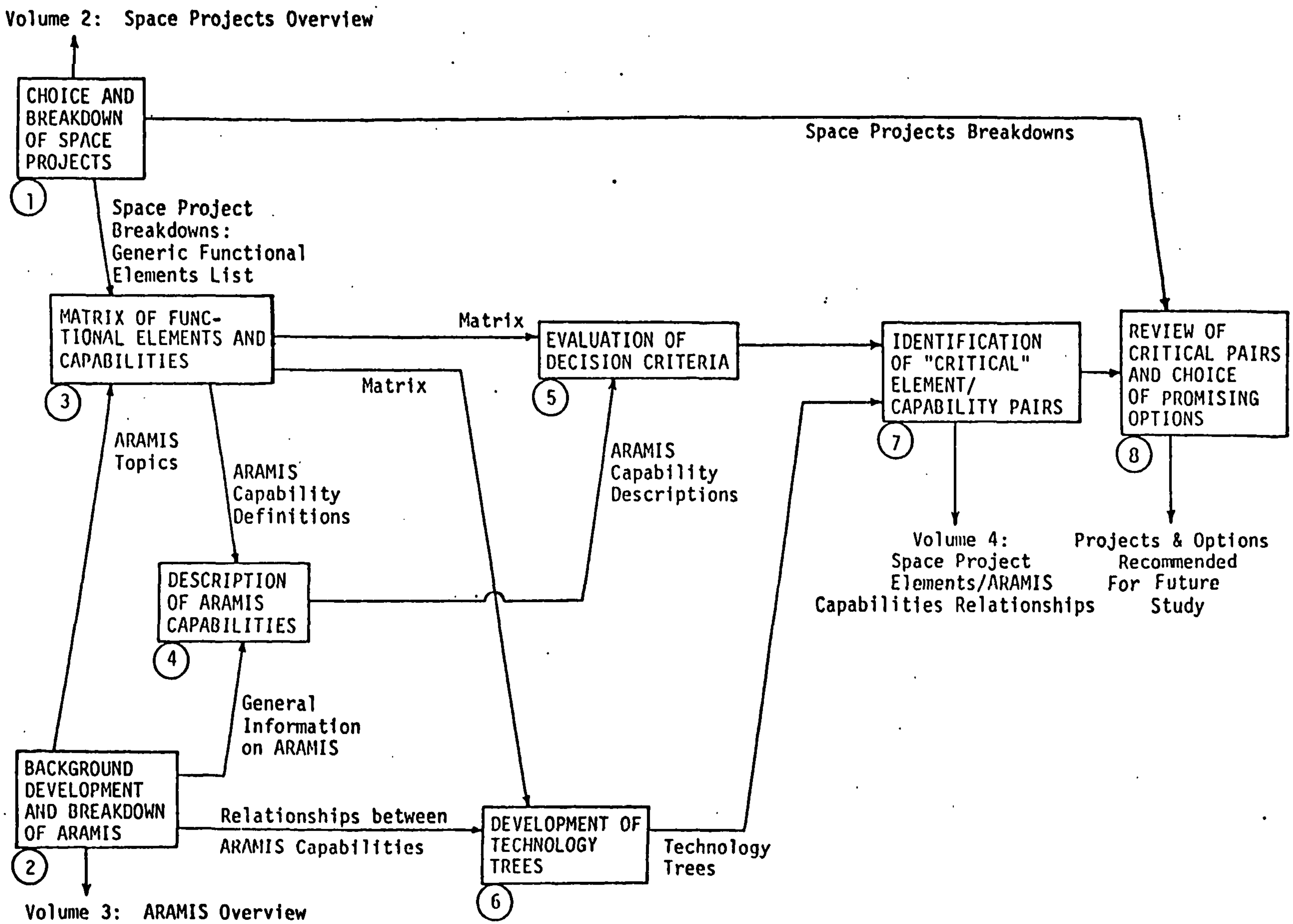


TABLE 4.3: MAJOR TASKS OF ARAMIS MAIN STUDY (PHASE I)

1) Select space projects for study, and break down space projects into "Functional Elements"; then collect "Generic Functional Elements List" from the breakdowns.

2) Develop background knowledge, and organize the field of ARAMIS into "Topics"

3) Define candidate "ARAMIS Capabilities" able to satisfy generic functional elements

4) Describe current state-of-the-art and future projections of ARAMIS capabilities

5) Evaluate "Decision Criteria" to judge relative merits of the ARAMIS capabilities in satisfying generic functional elements

6) Develop "Technology Trees" displaying how the R&D of some capabilities enhances the R&D of other capabilities

7) Identify "Critical Element/Capability Pairs", showing potentially valuable applications of ARAMIS capabilities

8) Define promising options for enhancement of space projects by inclusion of ARAMIS

TABLE 4.4: ARAMIS STUDY NOMENCLATURE

ARAMIS - Automation, Robotics, and Machine Intelligence Systems

FUNCTIONAL ELEMENT - A small piece of a space project (examples: Open Access Panel, Open Supply Valve), which can be satisfied by a single ARAMIS capability.

GENERIC FUNCTIONAL ELEMENT LIST (GFE LIST) - A list of all the functional elements in the four space project breakdowns; a functional element already collected from a previous breakdown is not listed again.

ARAMIS TOPIC - A part of the overall field of ARAMIS (e.g. Manipulators, Machine Vision Techniques, Computer Architecture); the study group identified 28 such topics (with considerable overlap between topics) which collectively cover ARAMIS.

ARAMIS CAPABILITY - A piece of ARAMIS (hardware and/or software) which can by itself satisfy a generic functional element; each capability only involves a small (manageable) part of the wide field of ARAMIS.

DECISION CRITERIA - Indices of the performance of an ARAMIS capability applied to a generic functional element; these indices are evaluated for each candidate ARAMIS capability applied to each generic functional element.

TECHNOLOGY TREES - Favorable sequences of ARAMIS development; i.e. early R&D of certain capabilities enhances later R&D of other capabilities (e.g. prior R&D of tactile sensors and microactuators benefits the development of a dextrous manipulator).

CRITICAL ELEMENT/CAPABILITY (E/C) PAIR - An application of an ARAMIS capability to a generic functional element, for which: the decision criteria values are favorable; and/or the capabilities are important in technology trees. This is therefore a promising application of ARAMIS.

GSP - Geostationary Platform

AXAF - Advanced Xray Astrophysics Facility

TMS - Teleoperator Maneuvering System

SP - Space Platform

4.3.2 Space Project Breakdowns

In consultation with NASA MSFC, four space projects were selected for study: the Geostationary Platform (GSP, a communications relay satellite); the Advanced X-ray Astrophysics Facility (AXAF, an X-ray telescope spacecraft); the Teleoperator Maneuvering System (TMS, a multipurpose free-flying satellite tender); and the Space Platform (SP, a versatile platform for scientific and space applications research). These projects were chosen to span the range of space activities expected in the years 1985-2000: communications, astronomy, satellite servicing and support, and science and applications development. Thus the four projects collectively include a wide spectrum of tasks, both in space and on the ground. Therefore if suitable candidate ARAMIS capabilities could be defined to perform these tasks, it was expected that these capabilities could perform the majority of the tasks required by NASA's projects in the next twenty years.

Each selected space project was then broken down into successively finer levels: project, missions, sequences, activities, functional elements. At the most detailed level, "functional elements" are small tasks (e.g. Track Nearby Objects, Compute Optimal Consumables Allocation, Position and Connect New Component) required by the space projects, sufficiently small that the same functional element may occur in several space projects, or several times in one space project.

The study group then produced a list of "generic functional elements", collecting all the functional elements in the four space project breakdowns. A functional element already collected from a previous breakdown was not listed again, (e.g. Compute Optimal Consumables Allocation occurs in all four breakdowns, but appears only once in the Generic Functional Element List.) This required awareness of commonalities of functional elements within and between the breakdowns.

The Generic Functional Element List compiled by this method is presented in Appendix 2.C (Volume 2). It contains 330 generic functional elements, from which all four space project breakdowns can be completely assembled. Since these projects span a broad spectrum, it is expected that this list should also contain most (or all) of the elements of a wide variety of space projects. Yet each generic functional element is sufficiently small in scope that any ARAMIS capability which can perform the element only involves a small part of the wide field of ARAMIS.

As mentioned in guideline (7)(Section 4.2.3), Phase I of the ARAMIS study considers space project tasks by themselves, outside the context of any specific space projects. Therefore this study concentrates on the Generic Functional Element List. The project breakdowns are only occasionally consulted, to clarify the definition of a generic functional element by checking its context in the source breakdown(s).

4.3.3 ARAMIS Classification

Concurrently with the breakdown of space projects, the study group researched and classified the field of ARAMIS, to develop the necessary background and the traceable data base needed to define and describe ARAMIS capabilities.

As discussed in Section 3.2.2 (Volume 3), the present-day field of ARAMIS lacks comprehensive directories or introductions to the interlocking technologies involved. Access to information can therefore be difficult (e.g. looking up "computers" in a library yields an unmanageable amount of information, most of it irrelevant).

Based on literature and consultation, the research team therefore developed a classification system for ARAMIS, organizing the field into 28 "topics". These are listed in Table 4.5, and defined in Volume 3, Appendix 3.A. There is considerable overlap between topics, a natural (and probably desirable) result of the active interaction of technologies in rapid development. Fortunately for clarity, these topics can be grouped into 6 general "areas", again with considerable overlap between areas.

The topics are useful in that looking up one topic yields a manageable amount of data, and experts on individual topics can be found for consultation. The ARAMIS bibliography in Appendix 3.B (Volume 3) is organized by topics. Volume 3 also includes a general discussion of ARAMIS, and a section on other useful sources of information.

TABLE 4.5: LIST OF ARAMIS "AREAS" AND "TOPICS"

(6 Areas, 28 Topics)

MACHINERY

1. Automatic Machines
2. Programmable Machines
3. Intelligent Machines
4. Manipulators
5. Self-Replication

SENSORS

6. Range & Relative Motion Sensors
7. Directional & Pointing Sensors
8. Tactile Sensors
9. Force & Torque Sensors
10. Imaging Sensors
11. Machine Vision Techniques
12. Other Sensors (Thermal, Chemical, Radiation, etc.)

HUMAN-MACHINE

13. Human-Machine Interfaces
14. Human Augmentation & Tools
15. Teleoperation Techniques
16. Computer-Aided Design

DATA HANDLING

17. Data Transmission Technology
18. Data Storage and Retrieval
19. Data & Command Coding
20. Data Manipulation

COMPUTER INTELLIGENCE

21. Scheduling & Planning
22. Automatic Programming
23. Expert Consulting Systems
24. Deductive Techniques (Theorem Proving)
25. Computer Architecture

FAULT DETECTION & HANDLING

26. Reliability & Fault Tolerance
27. Status Monitoring & Failure Diagnosis
28. Reconfiguration & Fault Recovery

4.4 SELECTION OF GENERIC FUNCTIONAL ELEMENTS FOR STUDY

4.4.1 Classification of GFE's

The Generic Functional Element List shown in Appendix 2.C (Volume 2) was collected from the space project breakdowns by a computer program. Therefore the generic functional elements appear in the order in which they appeared in the four space projects. For ease of access and clarity of presentation, the 330 generic functional elements were classified into 9 types: these types are listed in Table 4.6.

TABLE 4.6: TYPES OF GFE's

A.	Power Handling
B.	Checkout
C.	Mechanical Actuation
D.	Data Handling and Communication
E.	Monitoring and Control
F.	Computation
G.	Decision and Planning
H.	Fault Diagnosis and Handling
I.	Sensing

Each GFE was assigned to one (and only one) type, at the discretion of the study group. The result is presented in Appendix 4.A: Generic Functional Element List (Grouped by Types of GFE's).

As with most classification schemes used in this study, there is considerable overlap between types of GFE's. For example, most decision and planning GFE's involve some computation; and there are many commonalities between checkout functions and fault diagnosis. The GFE's were assigned to those types that seemed most representative, to make it easier for the user to locate any GFE's of interest. Due to the overlaps between types, however, the user may need to check more than one type before finding the desired GFE.

4.4.2 Reduction of GFE List

A detailed investigation of each of the 330 elements in the GFE List was beyond the scope of this study. Therefore, in consultation with MSFC, the research team reduced the list to those 69 GFE's most worthy of study. Six criteria were used in this selection:

1) Those GFE's which were adequately handled by current techniques (i.e. any proposed alternatives appear to degrade overall performance) were disregarded. For example, g21 Open Payload Bay Doors is unlikely to be improved over current practice.

2) Also disregarded were those GFE's considered too specific, i.e. they were so specific in nature that they would require a closely tailored piece of ARAMIS with no other useful applications. For example, g74 Adjust Component (part of a repair sequence) is too dependent on the actual nature of the component to be studied in the general sense of this study; similarly g217 Fine Focus Detector (part of the AXAF observation

sequence) depends too closely on the design of the detector. This criterion also extends to those GFE's that were clearly the responsibility of the user (e.g. payload-specific functions on the Space Platform).

3) In many cases several GFE's were similar from the ARAMIS point of view, in that each GFE suggested the same candidate ARAMIS capabilities, and the relative merits of those capabilities would be similar in each application. For example, g32 Deploy Radiators can be satisfied by the same candidate capabilities as g31 Deploy Solar Arrays; since the relative merits of the candidates are expected to be similar for both tasks, detailed further research on g31 alone was considered sufficient.

For those GFE's that were similar except that one GFE suggested more candidate capabilities (beyond those suggested by the other GFE's), the GFE with the widest selection of candidate capabilities was retained for further study, and the exceptions to the similarity were noted. Also, in some cases a GFE was labeled similar to two other GFE's, indicating that its candidate capabilities is a subset of the capabilities of both other GFE's.

4) Those GFE's which did not suggest any application of ARAMIS were disregarded. For example, g43 Separation Coast (from the deployment of the GSP) does not require any application of ARAMIS.

5) Those GFE's which were expected to occur very infrequently were disregarded, on the grounds that development of an ARAMIS capability to meet them would probably not be economical.

For example, g164 Jettison Debris (an occasional TMS function) was considered infrequent.

6) Conversely to (5), those GFE's which occurred frequently (i.e. in all four space project breakdowns, or often in some of the breakdowns) were considered desirable for further study and preferentially kept. For example, g73 Position and Connect New Component occurs in all four breakdowns, as can be checked in Appendix 2.B (Volume 2).

The reduction process and its result is presented in Appendix 4.B: Reduced Generic Functional Element List. This Appendix contains the full GFE List (grouped by types of GFE's), with annotations showing which GFE's were selected for further study, and what criteria were used in setting aside the others.

4.4.3 Definitions of GFE's

For clarity of presentation, definitions of those 69 GFE's selected for further study are listed in Appendix 4.C: Definitions of GFE's Selected for Further Study. In most cases, the definitions are those of the original functional elements in the space project breakdowns. In some cases the definitions have been expanded somewhat beyond the specific context of the source breakdowns, to make the GFE slightly more general in scope. For example, g184 Monitor Telemetry is originally a fairly specific AXAF function, part of the initial operational checkout; as a GFE, it is more broadly defined to include the monitoring of telemetry from any spacecraft, so that its evaluation by the study will have useful information for a wider range of study recipients. In some cases, the GFE definitions are specifically broadened to include similarities to other GFE's not selected for detailed study.

4.5 DEFINITION OF CANDIDATE ARAMIS CAPABILITIES

4.5.1 Issues in Definition of Capabilities

As discussed in Section 4.3.1 above, one of the principal tasks of this study is the production of a matrix relating generic functional elements to ARAMIS capabilities. ARAMIS capabilities are defined to be small pieces of automation, robotics, or machine intelligence systems, suitable for application to space project tasks. They can be hardware, software, or both together.

The study group first attempted to generate ARAMIS capabilities by considering only the field of ARAMIS, without reference to the generic functional elements. The team tried a "branching-tree" type of classification on the whole of ARAMIS. The intention was to break down ARAMIS into successively finer levels, until the lowest level would contain all the desired capabilities. For example, ARAMIS could be first broken down into the general areas of sensing, computation, actuation, and communication; then each area could be further broken down, and so on.

After some work on the concept, however, the study group concluded that the branching-tree type of breakdown tended to confuse the organization of ARAMIS rather than clarify it. ARAMIS can be broken down in a variety of ways, each of which contains information useful to the reader; a too-specific breakdown method obscures instructive relationships between pieces of ARAMIS. For example, a useful classification for sensors distinguishes between proprioceptive sensors (which sense only within the device, e.g.

joint position sensors in a manipulator) and exteroceptive sensors (which sense the outside environment, e.g. laser ranging systems); but too much attention to this distinction obscures the fact that some sensors can serve as both simultaneously, e.g. a camera watching the position of a manipulator (proprioceptive) and the target being reached for (exteroceptive).

For these reasons, the study group chose a more versatile classification scheme for ARAMIS, breaking the field down into 6 general areas and 28 topics, with considerable overlaps between areas and between topics. These areas and topics are listed in Table 4.5 above, and the ARAMIS topics are discussed and defined in Volume 3. Thus the process of <u>classification</u> of ARAMIS was separated from the process of <u>definition</u> of ARAMIS capabilities.

4.5.2 Method of Definition Used in Study

The study group used a simple and pragmatic approach to define ARAMIS capabilities. In team brainstorm sessions, the generic functional elements were considered one at a time. For each GFE, based on the background knowledge and the ARAMIS topics developed by the study, the research team defined candidate ARAMIS capabilities. Additional literature search, consultation, and conceptual design were done, as needed, to ensure that all potential candidate capabilities to perform each GFE were identified. Each ARAMIS capability was assigned to two team members for detailed study.

As an example of this process, Table 4.7 shows the candidate ARAMIS capabilities defined for GFE g73 Position and Connect New Component. Eight capabilities were defined as candidates for this GFE.

This example illustrates several aspects of the definition process. Each candidate capability in the example can satisfy, by itself, the generic functional element. This locks together the levels of detail of GFE's and ARAMIS capabilities, thus keeping the production and presentation of the study matrix straightforward.

TABLE 4.7: CANDIDATE ARAMIS CAPABILITIES DEFINED FOR ONE GENERIC FUNCTIONAL ELEMENT

g73 POSITION AND CONNECT NEW COMPONENT	
2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
4.1	COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
14.3	HUMAN IN EVA WITH TOOLS
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

Another issue is the possible interpolation or hybridization between capabilities. In the example above, one could define a combination of the Human in EVA with Tools and the Specialized Manipulator under Human Control (the Shuttle RMS) to perform the GFE. In general, one could form intermediate capabilities or partnerships between many pairs of capabilities in the matrix. The study group decided to limit the candidates to those capabilities significantly different from each other, leaving interpolations between capabilities to the study recipient. This kept the number of candidate capabilities manageable. Also, such interpolations are usually suggested by circumstances specific to a space project, and thus beyond the scope of this more general study.

In a number of instances, the research team considered the issue of the time dependence of capabilities. For example, it is expected that a machine vision system in 1995 will be substantially better than in 1985; therefore the applicability of such a capability would depend on the date of use. Since Phase I of this study does not concern itself with space mission launch dates, the study group dealt with this issue in two ways. In most cases, if a capability could be brought online in 1985 at the earliest (following an orderly development program), then it was defined as it would appear in 1985. For those cases where significant time variations in capabilities were expected, near-term and far-term versions were presented as separate capabilities. In the example in Table 4.7 above, the Computer-Controlled Dextrous Manipulator with Force Feedback is a far-term descendant of the current industrial Dedicated Manipulator under

Computer Control.

The example also illustrates the human-to-machine span considered by this study, since the candidate capabilities range from a human in a pressure suit to a fully autonomous manipulator. This wide range is in keeping with the study guideline (and the study group's philosophy) that the human-to-machine range is one of the variables to be studied: the optimum mix of humans and machines will fall somewhere in this range (including, possibly, at one of the endpoints).

The study matrix, listing the candidate ARAMIS capabilities defined for each of the 69 GFE's selected for detailed study, is presented in Appendix 4.D: Matrix: Generic Functional Elements and Candidate ARAMIS Capabilities.

4.5.3 Classification of Capabilities by Topics

Altogether, 78 ARAMIS capabilities were defined. Many of these capabilities are potentially very versatile, in that they are candidates for many GFE's. The most extreme example of this is Human on Ground with Computer Assistance, a candidate to satisfy 30 GFE's - though not necessarily the best choice for any particular GFE. The number of candidate capabilities associated with a GFE ranges from 3 (e.g. for g105 Project Desired Functions from Mission Profile) to 13 (for g490 Structure Subsystem Checkout).

To simplify access to, and presentation of, the ARAMIS capabilities, they were grouped by ARAMIS topics and assigned numbers accordingly. These assignments were necessarily arbitrary, since many capabilities could be associated with several topics (e.g. Dextrous Manipulator under Human Control, which could be classified under Manipulators, Human-Machine Interfaces, or Teleoperation Techniques). The study group assigned each capability to the topic which seemed to describe the technical challenge in the capability most accurately (e.g. the Dextrous Manipulator under Human Control was classified under Teleoperation Techniques, because of the difficulties in closing the multi-media sensory-motor loop).

The ARAMIS capability code numbers were assigned by taking the ARAMIS topic numbers (as listed in Table 4.5 above) and adding sequential numbers to them. Thus 14.2 Dextrous Manipulator under Human Control is the second capability listed under topic 14, Teleoperation Techniques. The code numbers appear in the matrix listing in Appendix 4.D.

The study group wishes to emphasize the distinction between ARAMIS topics and ARAMIS capabilities. The topics were broken down from the overall field of ARAMIS, and have a considerable amount of overlap between each other. The capabilities are specific pieces of ARAMIS, defined as candidates to fulfill specific generic functional elements. After their definition, the capabilities were arbitrarily associated with topics, for the convenience of the study researchers and recipients.

4.5.4 Descriptions of ARAMIS Capabilities

A substantial part of the study effort was devoted to the further description of the defined ARAMIS capabilities. This information is presented through the medium of ARAMIS Capability General Information Forms (one per capability). These forms are described in Section 3.4.2, and presented in Appendix 3.C (both in Volume 3). These forms were included in Volume 3 to collect together all the information specifically on ARAMIS, and to keep the size of Volume 4 manageable. Each of these forms contains: a definition of the capability; identification of individuals and organizations working on the concept; current technology level (using the 7-level scale from the NASA OAST Space Systems Technology Model); time and cost estimates to reach higher technology levels; remarks on special aspects; identification of which other capabilities should be developed prior to this one, to enhance its R&D; and a list of the code numbers of GFE's to which the capability applies. This information was developed through literature search, consultation, and conceptual design.

4.5.5 Development of Technology Trees

"Technology trees" are favorable sequences of development of ARAMIS capabilities, such that early R&D of certain capabilities enhances the later R&D of other capabilities. For example, the early development of a Specialized Manipulator under Human Control paves the way for the later R&D of a Dextrous Manipulator under Human Control.

Based on the general information developed on ARAMIS capabilities, the study group generated technology trees by identifying which capabilities should logically be developed prior to each capability. This information appears in the ARAMIS Capability General Information Forms in Appendix 3.C (Volume 3). The technology trees are further discussed in Section 3.4.3, and are presented in graphical form in Appendix 3.D.

4.6 EVALUATION OF CANDIDATE CAPABILITIES

4.6.1 Decision Criteria

As mentioned in the Overview of Study Method (Section 4.3.1), the study does not only identify candidate applications of ARAMIS to space project tasks. It also evaluates the candidate ARAMIS capabilities, according to seven decision criteria, listed in Table 4.8. These decision criteria are indices of the performance of an ARAMIS capability in fulfilling a generic functional element.

TABLE 4.8: DECISION CRITERIA

1) Time to Complete Functional Element
2) Maintenance
3) Nonrecurring Cost
4) Recurring Cost
5) Failure-Proneness
6) Useful Life
7) Developmental Risk

The values of the decision criteria were estimated on a 1-to-5 scale. At the level of detail of this study, a finer resolution (e.g. 1-to-10) would have been inappropriate. The value "1" was considered most favorable performance, with "5" least desirable. This choice matches physical meaning to the numbers (e.g. short time is a 1, long time is a 5). The exception is "useful life", which does not seem to have an antonym; therefore long life is a 1, short life is a 5, for numerical consistency. Thus an ARAMIS capability showing ones and twos in its decision criteria is preferable to one showing fours and fives.

The estimation of decision criteria values was done by the study team in brainstorm sessions, following literature search, consultation, and conceptual design. The basic estimation procedure was refined through two iterations: an internal example of study tasks to develop task procedures, and an example of study output done at the request of NASA OAST. The study group eventually settled on a straightforward method to assign decision criteria values: for each generic functional element, the study group considered the list of candidate ARAMIS capabilities and selected one capability as "current technology"; this capability then received defined baseline criteria values (discussed below). The other capabilities were then rated relative to this current technology capability.

In most cases, the present-day method of performing a generic functional element was chosen as the "current technology" capability. For example, Human on Ground with Computer Assistance was defined as the current technology candidate to perform the GFE Compute Optimal Consumables Allocation. In some cases, the current technology option was not apparent, either because several methods are currently in use, or because the GFE in question is not yet part of current space projects. In those instances the study group arbitrarily selected one of the candidate capabilities as "current technology", to maintain the consistency of the procedure.

For most of the decision criteria, the current technology capability is given a value of "3". Therefore a rating of 1 or 2 for another capability indicates that it is superior to the current technology capability in that criterion. Conversely, a

4 or 5 indicates performance worse than the current technology capability (e.g. a machine vision system might be slower than the current-technology human eye, or an automated diagnostic system more costly in R&D than current-technology telemetry). For some decision criteria, current technology is not likely to correspond to the middle of the 1-to-5 range, and is therefore set equal to another number. These exceptions are detailed in the criteria definitions below.

1) Time: the time required for the ARAMIS capability to perform the functional element. Current technology (e.g. EVA repair) is defined as "3".

2) Maintenance: a composite of: the number of maintenance missions required, the maintenance time, the down-ratio (of maintenance time to total time), the maintenance cost. The latter element is a function of the others, and involves a tradeoff between higher R&D cost of a low-maintenance system and higher operations cost of a high-maintenance system. Because these various elements have different relative importance depending on the situation (e.g. a maintenance mission to GEO is likely to be more costly and difficult than one to LEO), this is a subjective evaluation requiring engineering judgement. One specific issue the study group tackled was the maintenance requirement of humans and human-including capabilities: the research team decided that for humans in space, maintenance includes consumables, down time for sleep, and the requirement for

crew rotation; these factors are not relevant for humans on the ground. Current technology (e.g. maintenance by Shuttle) = "3".

3) Nonrecurring cost: includes RDT&E costs, and possibly procurement and deployment costs (depending on how many units are procured and deployed). This cost can be conceptually split into two subcosts: the cost of basic R&D to develop the technology, and the cost to adapt the technology to the requirements of the space environment and the specific application desired. This distinction is evident in technology developed by industry and transferred to NASA: the basic R&D cost may be written off to industry.

In initial discussion, the study group intended to rate current technology as "1", on the grounds that current technology would have its R&D already paid for. Later discussions, however, recognized that although its basic R&D could be written off, the technology would still require adaptation costs for specific applications. And therefore some more advanced technology might have lower nonrecurring costs because of its lower adaptation costs. An example of this is integrated circuitry, a current technology that still carries a nonrecurring cost of application to a functional element. However, the more advanced technology of very large scale integrated circuitry (VLSI), though costly in basic R&D, may be considerably cheaper in application to certain problems than current IC's. If the basic R&D cost can be written off to other programs, or spread across several projects, the nonrecurring cost of VLSI capabilities might well be lower than IC capabilities in some applications. Therefore current technology is defined as "2" in this criterion.

4) Recurring cost: includes logistics, maintenance, repair, nominal operations, and (where appropriate) procurement and deployment. As in "maintenance" above, the study group includes consumables and crew rotation as part of nonrecurring costs for humans in space. Current technology = "3".

5) Failure-proneness: a composite of: mean time between failures, mean time between repairs, redundancy in design, severity of failures. Can include errors in judgement by (supposedly) intelligent machines. There is a one-way relationship between this criterion and maintenance: a failure-prone system will probably require considerable maintenance and repair; however, a reliable system may still require considerable maintenance. Current technology = "3".

6) Useful life: the total life of the device or system. This criterion can be difficult to interpret, because many devices can be designed and built with very long lifetimes, assuming occasional maintenance (e.g. if a repair TMS is launched many times, with repairs and retrofits between missions, does it have an infinite useful life?). As a result, in many cases the study group found it more useful to define useful life as technical obsolescence; this situation is common in aerospace systems, which are kept on-line by maintenance and

repair until technically obsolete. Thus the relative values for this criterion indicate which capabilities are likely to replace other obsolete designs (e.g. a capability with a value of 3 would eventually be replaced by a more versatile competitor with a value of 2 or 1). Current technology = "3".

7) Developmental risk: a subjective judgement of the difficulty in successfully bringing a capability online. A capability requiring a significant technological advance (e.g. a Learning Expert System) would have a high developmental risk. In the opinion of the study group, current technology has the lowest developmental risk, and is therefore defined as "1".

4.6.2 Decision Criteria Comparison Charts and ARAMIS Capability Application Forms

As mentioned above, decision criteria values were assigned in team brainstorm sessions. These sessions had two principal outputs: Decision Criteria Comparison Charts and ARAMIS Capability Application Forms.

An example of a Comparison Chart is presented in Table 4.9. The chart shows the decision criteria values estimated for the eight candidate ARAMIS capabilities which apply to GFE g73 Position and Connect New Component. Such charts were produced on a blackboard in the team sessions: for each GFE in turn, the candidate capabilities were listed; one capability was selected as "current technology" (Human in EVA with Tools in the example);

TABLE 4.9: DECISION CRITERIA COMPARISON CHART

GFE: g73 POSITION AND CONNECT NEW COMPONENT

GFE TYPE: C. Mechanical Actuation

The movement, alignment, insertion, and fastening of a component to (or into) a spacecraft. This includes the fastening of mechanical, electrical, and fluid interfaces. The inverse of this task covers the disconnection and removal of components from a spacecraft. Since the task includes alignment of the component, it requires either a close-tolerance actuator in a close-tolerance worksite geometry, or compliance in actuator or worksite, or feedback to the actuator control.

DECISION CRITERIA

CANDIDATE ARAMIS CAPABILITIES:

	TIME	MAINTENANCE	NONRECURRING COST	RECURRING COST	FAILURE PRONENESS	USEFUL LIFE	DEVELOPMENTAL RISK	
2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL	1	1	3	2	5	4	2	
4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR	2	2	4	2	3	3	3	
4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK	2	2	4	2	4	2	4	
4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK	1	2	5	2	3	1	5	
14.3 HUMAN IN EVA WITH TOOLS	3	3	2	3	3	3	1	C.T.
15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL	3	2	3	3	4	2	2	
15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL	3	2	4	3	3	2	3	
15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT	3	3	3	3	4	2	2	

then those team members responsible for the detailed study of the capabilities estimated their decision criteria values; discussions between the researchers and comparisons to the current technology baseline then adjusted the criteria values to reflect the relative merits of the candidates (for example, in the table above, the Specialized Manipulator under Human Control was considered roughly as fast as the Human in EVA with Tools, but the Computer-Controlled Dextrous Manipulator with Force Feedback was expected to be faster).

Thus the Comparison Charts serve as quick-reference displays of the relative merits of candidate capabilities, as estimated by the study group. One such chart was produced for each of the 69 GFE's under detailed study. They are presented in Appendix 4.E: Candidate ARAMIS Capabilities: Comparison Charts and Application Forms.

The ARAMIS Capability Application Forms include the decision criteria values developed in the team sessions. However, they also include details and remarks on these numbers, and data sources where applicable. Some of these comments were generated during the team discussions on criteria values. Other commentary comes from additional literature review and consultations with experts. Each Application Form also includes a section for remarks on special aspects of the capability's application to the GFE (e.g. versatility of capability, operator safety, special logistics requirements, contingency preparedness, reliance on other technologies).

An example of an ARAMIS Capability Application Form is shown on Table 4.10. Following the example in Table 4.9, this is the form which details the decision criteria values estimated for the capability Computer-Controlled Dextrous Manipulator with Force Feedback, as applied to the GFE g73 Position and Connect New Component. The form presents each criterion value, followed by remarks and data sources where applicable. In addition, the form includes a section for remarks on special aspects of this specific application of the capability. Such remarks might indicate what capability is considered "current Technology" for this GFE; they might describe specific adaptations or support functions desirable for this application; and they might identify advantages or disadvantages not specifically covered by the decision criteria (e.g. operator safety, versatility).

The ARAMIS Capability Application Forms are also presented in Appendix 4.E. This appendix is organized for accession from the point of view of the generic functional elements. For each of the 69 GFE's under detailed study, the appendix presents a package of information, including: the Decision Criteria Comparison Chart listing the GFE, its definition, its candidate ARAMIS capabilities, and the relative criteria values of the candidate capabilities; and, for each candidate capability, an ARAMIS Capability Application Form, presenting the commentary on the estimated criteria values.

TABLE 4.10: ARAMIS CAPABILITY APPLICATION FORM

CAPABILITY NAME: Computer Controlled Dextrous Manipulator With Force Feedback
CODE NUMBER: 4.2 DATE: 6/15/82 NAMES: Paige/Ferreira/Kurtzman
GENERIC FUNCTIONAL ELEMENT NUMBER AND NAME: g73 Position and Connect New Component

DECISION CRITERIA (1 TO 5 SCALES; CURRENT TECH.=3 UNLESS NOTED)

TIME TO COMPLETE FUNCTIONAL ELEMENT (1 SHORT, 5 LONG): 2
REMARKS AND DATA SOURCES: The dextrous manipulator requires less time than a Human in EVA with Tools since it doesn't involve human safety, does not require suiting time, and can optimize motions to the mechanical limit of the hardware.

MAINTENANCE (1 LITTLE, 5 LOTS): 2
REMARKS AND DATA SOURCES: Maintenance would be low since the only parts likely to need service are the mechanical parts. The software and sensors would be very reliable (Minsky).

NONRECURRING COST (1 LOW, 5 HIGH; CURRENT TECH.=2): 4
REMARKS AND DATA SOURCES: This cost is high since no system has yet been developed which incorporates the abilities of this manipulator. Some of the R&D will probably be done commercially.

RECURRING COST (1 LOW, 5 HIGH): 2
REMARKS AND DATA SOURCES: This capability was judged below current technology in recurring costs as it does not necessitate the support of a human. This capability may cost slightly more than a dedicated manipulator since the end-effector would require more maintenance.

FAILURE-PRONENESS (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: The failure-proneness is higher than that of a human (who can correct problems after they occur) since the programming is neither adaptive or intelligent.

USEFUL LIFE (1 LONG, 5 SHORT): 2
REMARKS AND DATA SOURCES: The dextrous manipulator has a useful life which is longer than the more obsolescent dedicated manipulator. Eventually it should be replaced by manipulators with vision. Its useful life is judged longer than current technology as it is deemed more desirable to have an autonomous system than use valuable human-in-space time.

DEVELOPMENTAL RISK (1 LOW, 5 HIGH; CURRENT TECH.=1): 4
REMARKS AND DATA SOURCES: This is high since there is currently no manipulator that can be called dextrous, and to advance to computer control would also be a large step.

OTHER REMARKS AND SPECIAL ASPECTS: This manipulator has the advantage of being adaptable to a number of tasks. The system could probably be built with a modular design, so that a vision capability could easily be added as it comes online. The current technology capability is Human in EVA with Tools.

Thus, for the study recipient who has particular space project tasks in mind, and who wishes to know what ARAMIS options are available for each of those tasks, Appendix 4.E presents that information, GFE by GFE. It is expected that most study users will be using the data in this fashion. Section 4.8 describes a suggested procedure for this kind of accession to the study output.

For those study users interested in specific ARAMIS capabilities (rather than GFE's) and their applications to space project tasks in general, this report includes Appendix 4.G: Transpose Matrix: ARAMIS Capabilities and their Applications to GFE's. In this appendix information is presented capability by capability. For each ARAMIS capability, the GFE's for which it is a candidate are listed; this is therefore the transpose of the matrix presented in Appendix 4.D. In addition, for each capability, Appendix 4.G also presents the decision criteria values for its applications to GFE's (repeating rows of numbers from the Comparison Charts in Appendix 4.E). Thus the reader can compare the criteria values for a particular capability's applications to GFE's. However, commentary on the criteria values is not included, since it appears in the Application Forms in Appendix 4.E (accessible through the GFE's).

As a general comment, the evaluation and documentation of decision criteria values was the most time-consuming task in the study, in terms of people-hours (although the background research hours also contributed to the filling out of the ARAMIS

Capability General Information Forms in Appendix 3.C, Volume 3). Because the various capabilities were assigned to different people for detailed study, the study members naturally tended to defend their capabilities in the team sessions. This improved the process, as the discussions rapidly pointed to lacks in the team's knowledge, suggested sources of further information, and generated some of the commentary on the Application Forms. For these reasons, the study group found the time spent on this task valuable, and essential to the completion of the study objectives.

4.6.3 Limitations of Evaluation Method

This study's systematic method of evaluation of candidate ARAMIS capabilities has certain limitations. In general, the use of ARAMIS in space activities is a varied and complex problem, and the estimation of specific numbers for specific decision criteria tends to oversimplify the issue. The study group therefore requests that users keep in mind the following points.

There are overlaps and tradeoffs between the decision criteria. For example, maintenance and failure-proneness contribute to recurring costs, and developmental risk tends to drive nonrecurring costs. Examples of tradeoffs include level of R&D (nonrecurring costs) versus useful life, versus failure-proneness, or versus maintenance; the latter three criteria can usually be improved by increasing nonrecurring costs. When the criteria values were estimated, the research team tried to balance these relationships by engineering judgement, assuming that the capabilities would result from an orderly development program. Should a particular capability be developed with emphasis on reliability, this would be reflected by a lower criteria value for failure-proneness and maintenance (and possibly recurring cost, if it depends heavily on maintenance) and a higher value for non-recurring cost (due to the extra R&D required). Thus the study group's criteria values describe baseline capabilities, from which the user can extrapolate variations.

Because Phase I of this study deals with generic functional elements rather than actual space projects, scenario-specific issues are purposely left out of the analysis. For instance, in the example in Table 4.9 above, the eight candidate capabilities to perform GFE g73 Position and Connect New Component are rated for that task in general, without regard to the space project in which the GFE might occur. For instance, the merits of Human in EVA with Tools depend on how easily available the human is: at a manned space platform, the time and cost required for EVA could be significantly lower than current practice. Similarly, the performance of the manipulators under human control depends on what sensors are used (direct eyesight, video, force-feedback, etc.), what communication bandwidth is available for remote operations, and what time delays are imposed. In many instances, it is possible to imagine two different space projects in which the relative merits of two capabilities would be reversed, i.e.

one would be preferable for the GFE in one scenario while the second would be best in the other.

Thus it would be overly simplistic to choose between candidate capabilities by adding their criteria values and comparing the totals (though easy to do in Table 4.9). The ratings should first be weighted according to specific project constraints or requirements. For example, the recurring cost to complete a functional element may be almost irrelevant if the element occurs in a once-every-three-years maintenance task, but critical if it occurs in a frequently performed task in routine operations. Therefore the recurring cost criterion values should be weighted (down in the first case, up in the second) in the evaluation of the candidate capabilities. These weightings may lead to selection of different capabilities for the GFE in the two cases: a high-recurring-cost capability (presumably with other compensating advantages) for the occasional task, and a low-recurring-cost capability for the frequent routine operation.

A related issue is the significance of GFE's in overall project scenarios. It is possible to identify, from the decision criteria values, an ARAMIS capability which significantly improves the performance of a GFE relative to current techniques. However, if the GFE turns out to be insignificant in a space project of interest (e.g. a task performed only once, during deployment by the Shuttle) then the development of the capability is not warranted for that project, no matter how impressive its criteria values.

Some care should also be used in comparing the criteria values of a particular capability in its applications to various GFE's. Such comparisons are presented in Appendix 4.G, showing, for example, the 30 sets of criteria values that the capability Human on Ground with Computer Assistance received in its 30 potential applications to GFE's. In 20 of those cases, the capability was chosen as current technology, and its criteria values therefore set. In the other ten cases, the criteria values vary, relative to whatever other capabilities were identified as current technology. Thus the necessities of the method can obscure differences or similarities: for example, Human on Ground with Computer Assistance could be significantly faster in performing one GFE than another, but if it is the current technology capability for both GFE's, the time criterion will be rated at "3" in both cases; conversely, the capability may be just as fast as applied to two GFE's, but the time criterion might be rated "3" in one case (as fast as the current technology capability) and "2" in the other (faster than another, slower current technology capability).

As a final caveat, returning to the reduction of the GFE List discussed in Section 4.4.2, those GFE's set aside because of similarity to other GFE's also deserve special attention. While it is expected that the candidate capabilities for a GFE under detailed study (e.g. g73 Position and Connect new Component) would show similar performance for a "similar" GFE set aside in the reduction (e.g. g160 Install New Tank), there may be some differences that would suggest slightly different criteria values. Therefore, if the study recipient is interested in g160, the decision criteria values for g73 should be reviewed with the specific space project task in mind.

The study mitigates the above-described limitations in three ways. First, the criteria are estimated on a 1-to-5 scale, so that each number on the scale covers a spread of performance. At the level of detail of this study, a 1-to-10 scale would have been inappropriate, since such resolution is not available. Thus two capabilities close to each other in a particular criterion, or whose relative merits could reverse depending on the space project scenario, could be given the same value for that criterion.

Second, all the criteria values are accompanied by commentary describing the reasons for the evaluation, and by data sources where applicable. The Decision Criteria Comparison Charts (in Appendix 4.E; example shown in Table 4.9 above) have very limited usefulness in themselves. In most cases, the commentary in the associated ARAMIS capability Application Forms (immediately following each Comparison Chart in Appendix 4.E) is more instructive than the numbers themselves.

Third, the Application Forms include an entry for "Other Remarks on Special Aspects", including identification of the current technology capability for that GFE, and advantages and disadvantages not covered directly by the decision criteria (e.g. operator safety, versatility).

In summary, the recipient of the Phase I output would use the matrix of GFE's and candidate ARAMIS capabilities (presented in Appendix 4.D) and the ARAMIS Capability General Information Forms (in Appendix 3.C) to spread out the options to perform the GFE's of interest, and to find some information on the capabilities, including available data sources for further information. The Comparison Charts and Applications Forms (in Appendix 4.E) would then display the study group's opinion on the relative merits of the options. The final decision on the most appropriate capability for each task, however, rests with the study user, since this decision involves constraints and requirements specific to the user's particular space project. The study output makes available information to support that decision process, and suggests a systematic approach to the choice; the input data can be refined and updated, the evaluations reviewed one at a time, and various weightings tried on the criteria values, to improve the decision.

4.7 PROMISING APPLICATIONS OF ARAMIS

4.7.1 Selection Method

Keeping in mind the limitations described in the previous section, the study group developed a straightforward, general method to identify those ARAMIS capabilities which showed favorable decision criteria values in their application to GFE's.

First, the study matrix was separated into 9 sub-matrices, by types of GFE's. As described in Appendix 4.F (section 4.F.3), the study matrix data is stored as an array in an APL computer program. Therefore it was not difficult to write simple APL programs that applied algorithms selectively to sections of the overall matrix, by identifying which type each GFE belongs to.

For example, the Power Handling submatrix contains the 5 power handling GFE's selected for detailed study, together with their candidate ARAMIS capabilities and associated decision criteria values. Table 4.11 presents this data. Thus each of the 9 submatrices is a separate subset of the full study matrix (which contains 69 GFE's).

The reason for this separation was to identify promising applications of ARAMIS for each <u>type</u> of task (e.g. the capabilities which significantly improved power handling functions). Since each submatrix contains a manageable fraction of the overall matrix data, tracing the justifications for selection of promising capabilities is relatively simple. Also, for those capabilities which are candidates for GFE's of several different types, this separation identifies any specific types of task

TABLE 4.11: SUBMATRIX OF POWER HANDLING GFE's

g1 VERIFY POWER SYSTEM FUNCTION

		TM	MT	NC	RC	FP	UL	DR	
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	3	3	2	3	3	3	1	C.T.
14.6	MANUAL TESTING ON GROUND	4	1	1	2	4	4	1	
16.1	COMPUTER MODELING AND SIMULATION	2	3	4	2	2	1	2	
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	1	3	4	3	2	1	2	
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	3	2	2	2	3	2	2	

g23 POWER SUBSYSTEM CHECKOUT

		TM	MT	NC	RC	FP	UL	DR	
14.3	HUMAN IN EVA WITH TOOLS	4	5	3	5	3	4	1	
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	3	5	3	4	2	3	2	
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	2	3	3	2	3	1	2	
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	3	4	3	4	2	3	2	
27.3	EQUIPMENT FUNCTION TEST VIA TELEMETRY	3	3	2	3	3	3	1	C.T.
27.4	EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER	1	3	2	2	4	1	2	
27.5	EQUIPMENT DATA CHECKS BY ONSITE HUMAN	3	4	2	4	3	3	2	
27.6	EQUIPMENT DATA CHECKS VIA TELEMETRY	2	3	1	3	4	3	1	

g87 ADJUST CURRENTS AND VOLTAGES

		TM	MT	NC	RC	FP	UL	DR	
1.6	AUTOMATIC SWITCHING SYSTEMS	1	3	2	1	3	3	1	
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	3	3	2	3	3	3	1	C.T.
14.4	HUMAN WITH CHECKLIST	4	2	2	4	4	5	1	
21.1	ONBOARD SEQUENCER	1	2	2	1	5	4	1	
21.2	OPERATIONS OPTIMIZATION PROGRAM	3	3	3	2	1	2	2	
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	2	4	5	2	1	1	4	
25.1	ONBOARD DEDICATED MICROPROCESSOR	2	4	3	2	2	2	2	
25.2	ONBOARD MICROPROCESSOR HIERARCHY	2	3	4	2	1	1	3	
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	2	4	3	2	2	2	2	
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	3	3	2	2	2	3	1	
25.5	ONBOARD ADAPTIVE CONTROL SYSTEM	2	2	4	2	1	1	3	

(TABLE CONTINUED)

TABLE 4.11: SUBMATRIX OF POWER HANDLING GFE'S (CONTINUED)

g88 ADJUST BATTERY CHARGING CYCLE

	TIME	MAINTENANCE	NONRECURRING COST	RECURRING COST	FAILURE PRONENESS	USEFUL LIFE	DEVELOPMENTAL RISK	
14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE	3	3	2	3	3	3	1	C.T.
25.1 ONBOARD DEDICATED MICROPROCESSOR	1	4	3	1	2	2	2	
25.2 ONBOARD MICROPROCESSOR HIERARCHY	1	3	4	1	1	1	3	
25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM	1	4	3	1	2	2	2	
25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND	2	3	2	1	2	3	1	
25.5 ONBOARD ADAPTIVE CONTROL SYSTEM	1	2	4	2	1	1	3	

g240 MAINTAIN SAFE BATTERY CHARGE LEVELS

	TIME	MAINTENANCE	NONRECURRING COST	RECURRING COST	FAILURE PRONENESS	USEFUL LIFE	DEVELOPMENTAL RISK	
1.8 AUTOMATIC SWITCHING SYSTEMS	3	3	2	3	3	3	1	C.T.
25.1 ONBOARD DEDICATED MICROPROCESSOR	2	3	3	3	3	1	2	
25.2 ONBOARD MICROPROCESSOR HIERARCHY	2	2	4	3	2	1	3	
25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM	2	3	2	3	3	2	2	
25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND	4	2	2	3	3	4	1	
25.5 ONBOARD ADAPTIVE CONTROL SYSTEM	2	1	4	3	2	1	3	

C.T.= Current technology

for which a capability is particularly suited.

An APL computer program was used on each submatrix in turn, to apply a simple algorithm to the data. An example of the program's output (as calculated from the power handling submatrix) appears in Table 4.12. First, the program identified which capabilities were candidates for the 5 power handling GFE's, and counted the number of their occurences. For example, Table 4.12 shows that the Onboard Adaptive Control System appeared as a candidate for 3 (right-handmost column) of the 5 GFE's, as can be checked in Table 4.11.

Second, for each of the capabilities, the program summed all of its decision criteria values and divided the total by its number of occurences. In other words, the number in the first column of Table 4.12 is the average sum of decision criteria values for that capability. For example, as can be seen in Table 4.11, the Onboard Adaptive Control System has criteria value sums of 15 (for g87), 14 (for g88), and 16 (for g240), for an average sum of 15 (shown in Table 4.12).

Third, the program ranks the capabilities according to their average sums and prints them out in that order. Since the lower numbers represent favorable ratings, the Onboard Adaptive Control System's average sum of 15 makes it one of the most favorable applications of ARAMIS in power handling. In comparison, the Human on Ground with Computer Assistance appears as a candidate for 3 GFE's, and is defined as the "current technology" capability in each of those cases. Therefore it receives set decision

TABLE 4.12: AVERAGE SUMS OF DECISION CRITERIA VALUES: POWER HANDLING

ARAMIS CAPABILITIES:		AVERAGE SUMS: ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
25.5	ONBOARD ADAPTIVE CONTROL SYSTEM	15	13.33	13.33	11	12.67	13.67	14	12	3
27.4	EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER	15	14	12	13	13	11	14	13	1
25.2	ONBOARD MICROPROCESSOR HIERARCHY	15.67	14	13	11.67	13.67	14.33	14.67	12.67	3
1.6	AUTOMATIC SWITCHING SYSTEMS	16	14	13	14	14	13	13	15	2
16.1	COMPUTER MODELING AND SIMULATION	16	14	13	12	14	14	15	14	1
21.1	ONBOARD SEQUENCER	16	15	14	14	15	11	12	15	1
21.2	OPERATIONS OPTIMIZATION PROGRAM	16	13	13	13	14	15	14	14	1
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	16	14.5	13	12.5	13.5	13.5	15	14	2
25.1	ONBOARD DEDICATED MICROPROCESSOR	16.33	14.67	12.67	13.33	14.33	14	14.67	14.33	3
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	16.33	14.67	12.67	13.67	14.33	14	14.33	14.33	3
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	16.33	13.33	13.67	14.33	14.33	14	13	15.33	3
14.6	MANUAL TESTING ON GROUND	17	13	16	16	15	13	13	16	1
27.6	EQUIPMENT DATA CHECKS VIA TELEMETRY	17	15	14	16	14	13	14	16	1
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	18	15	15	16	15	15	15	17	3
27.3	EQUIPMENT FUNCTION TEST VIA TELEMETRY	18	15	15	16	15	15	15	17	1
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	18.5	15.5	15.5	16	15.5	16	16	16.5	2
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	19	17	15	14	17	18	18	15	1
27.5	EQUIPMENT DATA CHECKS BY ONSITE HUMAN	21	18	17	19	17	18	18	19	1
14.4	HUMAN WITH CHECKLIST	22	18	20	20	18	18	17	21	1
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	22	19	17	19	18	20	19	20	1
14.3	HUMAN IN EVA WITH TOOLS	25	21	20	22	20	22	21	24	1

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

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criteria values each time, with individual sums (and an average sum) of 18. Thus capabilities with numbers around 18 in the first column of Table 4.12 are roughly comparable in overall performance to current technology.

Fourth, the program identifies the sensitivity of each capability's average sum to each of the seven decision criteria. This is done by recomputing the average sum, disregarding one of the decision criteria each time. The resulting 7 numbers are presented in columns 2 through 8 in Table 4.12. For example, the Onboard Adaptive Control System has decision criteria value sums of 13 (for g87), 13 (for g88), and 14 (for g240), if the time criterion is neglected each time. Therefore, its average sum without the time criterion is 13.33, as listed in column 2 in Table 4.12; similarly for columns 3 through 8, omitting each decision criterion in turn. The resulting numbers indicate that the overall rating of this capability is particularly sensitive to non-recurring cost and to developmental risk: if either nonrecurring cost (column 4) or developmental risk (column 8) is not included, the average sum shows a substantial improvement (i.e. a sizably lower number).

Several comments on this procedure should be noted. First, one advantage of the separation of the study matrix into submatrices is that the poor performance of a capability in one type of task does not affect its rating in others. For example, the Human in EVA with Tools has an unfavorable average sum in power handling tasks (see Table 4.12), which is not a surprising result. However, this low score will not affect the average sum for this capability in other types of GFE's (e.g. mechanical actuation tasks). In general, applying these algorithms to the entire study matrix at once would not do justice to many capabilities, whose favorable ratings in some types of applications would be nullified by their performance in others. If a capability is indeed good in a variety of applications, then it will appear near the top of several submatrices.

Second, the average sum rating is the simplest, most general algorithm which the study group could devise. Specifically, it applies no weightings of any kind to the decision criteria, thus giving equal importance to time, maintenance, nonrecurring cost, recurring cost, failure-proneness, useful life, and developmental risk. The appropriate weightings of the various criteria depend strongly on space project scenarios (e.g. a spacecraft in GEO is more difficult to service, suggesting an increased input from the maintenance criterion). However, since Phase I of this study considers the GFE's outside the context of space projects, the study group did not apply any weightings, leaving those either to specific case design studies in Phase II or to the discretion of the study recipient.

Third, since such weightings could add or subtract one or two points from an average sum, the ranking in Table 4.12 is not intended to be definitive. For example, both the Onboard Adaptive Control System (average sum 15) and the Operations Optimization Program (average sum 16) are candidates for power management functions; weighting their criteria values according to specific project constraints could reverse the order of their ranking. However, their unweighted criteria values (listed in Table 4.11) were assigned by comparing their <u>relative</u> merits; therefore the ranking of their average sums indicates that the study group found the Onboard Adaptive Control System slightly more favorable <u>in comparison</u> to the Operations Optimization Program, rather than in an absolute sense. Thus a study recipient who wishes to apply weightings to these values should check the appropriate ARAMIS Capability Application Forms (in Appendix 4.E) to find the study group's qualitative reasons for the relative estimates of decision criteria values, since these reasons may be relevant to the weighted values also.

Fourth, the number of occurences of each capability (righthandmost column in Table 4.12) indicates the statistical base for the average sum. If the capability occurs only once (e.g. Equipment Data Checks by Onboard Computer, which receives a favorable average sum of 15 in its application to g23 Power Subsystem Checkout), then the capability is specifically appropriate to that task. Then it will probably be more useful to consult the Comparison Chart and Application Forms for that GFE in Appendix 4.E, to obtain information on options for that task. If the capability occurs a number of times, (e.g. the Onboard Adaptive Control System, and the Onboard Microprocessor Hierarchy, both candidates for 3 of the 5 power handling GFE's) then its average sum reflects more closely its merit in various applications. Its ranking is statistically more significant, and the capability possibly more desirable.

In addition to the average sum ranking, the study group also considered technology trees in the evaluation of capabilities. Technology trees (described in Section 3.4.3, presented in Appendix 3.D, in Volume 3) are representations of favorable sequences of development, such that early R&D of some capabilities enhances the later R&D of others. If a capability's development improves the development of other promising options, this increases that capability's overall desirability, in the opinion of the study group. Capabilities which either had favorable average sum rankings, or which were significant in technology trees, or both, were called "critical element/capability pairs" (indicating a favorable match of GFE and capability) or, more simply, "promising applications of ARAMIS".

4.7.2 Promising Applications of ARAMIS

Power Handling: Based on the average sum rankings presented in Table 4.12, the decision criteria values in Table 4.11, and the Technology Trees in Appendix 3.D, the study group selected the following capabilities as promising applications of ARAMIS for power handling functions.

For overall power system control, the Onboard Adaptive Control System, implemented on an Onboard Microprocessor Hierarchy, offers the advantages of speed, resistance to failure, and ease of modification. The Onboard Microprocessor Hierarchy for spacecraft power management is the approach used in two NASA studies (Refs. 4.11, 4.12) and in the US Air Force's Teal Ruby satellite. The development of the Onboard Adaptive Control System also benefits later R&D of sophisticated manipulators, and of a fully autonomous Learning Expert System. The R&D of the Onboard Microprocessor Hierarchy supports later R&D of manipulators, imaging sensors with computer processing of data, failure diagnosis by onboard systems, and the Teleoperator Maneuvering System. Note also that the Onboard Microprocessor Hierarchy benefits from prior development of the Onboard Dedicated Microprocessor.

For checkout and monitoring of power systems, Equipment Function Test by Onboard Computer and Equipment Data Checks by Onboard Computer appear favorable, since they can routinely handle large amounts of data without the costs of telemetry or human supervision. The Equipment Function Test by Onboard Computer enhances later development of Fault Tolerant Software.

If the power system to be managed is simple, then the traditional Automatic Switching Systems are favored because of low costs. They should also be considered as a backup mode to the more sophisticated options. Automatic Switching Systems is one of the technologies which contribute to manipulator development.

In general, the emphasis in power handling should be on onboard and automated systems. As power systems technology becomes more complex, the costs of telemetry and human supervision will become excessive.

Checkout: The average sum rankings of capabilities for checkout tasks are presented in Table 4.13. The decision criteria values can be found in the Comparison Charts for checkout GFE's, in Appendix 4.E. The 9 checkout GFE's include tasks in space

TABLE 4.13: AVERAGE SUMS OF DECISION CRITERIA VALUES: CHECKOUT

ARAMIS CAPABILITIES:		AVERAGE SUMS:								
		ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
25.1	ONBOARD DEDICATED MICROPROCESSOR	12	11	10	9	11	10	11	10	1
25.2	ONBOARD MICROPROCESSOR HIERARCHY	12	11	11	9	11	10	11	9	1
16.1	COMPUTER MODELING AND SIMULATION	14	13	11	11	13	12	12	12	1
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	15	13	12	13	13	13	13	13	1
27.7	INTERNAL ACOUSTIC SCANNING	16	14	13	13	14	14	14	14	1
27.4	EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER	16.2	14.2	13.4	13.6	14.2	13.2	14.4	14.2	5
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	16.29	14.29	13.43	12.86	14.29	14	14.86	14	7
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	17	16	14	12	16	16	16	12	1
27.3	EQUIPMENT FUNCTION TEST VIA TELEMETRY	17.5	14.5	14.67	15.17	14.67	14.83	14.83	16.33	6
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	18	15	15	16	15	15	15	17	2
27.6	EQUIPMENT DATA CHECKS VIA TELEMETRY	18.25	15.25	15.25	16.5	15.25	15	15	17.25	4
6.1	OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)	19.5	17.5	16.5	16.5	17.5	15.5	16	17.5	2
11.3	THERMAL IMAGING SENSOR WITH MACHINE PROCESSING	20	18	17	15	17	18	18	17	1
14.6	MANUAL TESTING ON GROUND	20	15	18	19	17	16	16	19	2
14.1	DIRECT HUMAN EYESIGHT	20.5	16.5	16.5	19.5	16.5	17	17.5	19.5	2
13.1	HUMAN EYESIGHT VIA VIDEO	21	17	17	20	17	17	18	20	2
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	21.43	17.71	17.43	18.14	17.71	19.43	18.71	19.43	7
10.1	THERMAL IMAGING SENSOR WITH HUMAN PROCESSING	22	18	19	18	18	20	19	20	1
14.3	HUMAN IN EVA WITH TOOLS	22	17.5	17.5	20.5	17.5	19	19	21	2
27.5	EQUIPMENT DATA CHECKS BY ONSITE HUMAN	22	18.75	17.25	19.25	18	19.75	19	20	4
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	22.71	19	18.14	19.57	19.14	20	19.57	20.86	7
11.1	IMAGING (STEREO) WITH MACHINE PROCESSING	27	22	23	22	24	23.5	24.5	23	2
11.2	IMAGING (NON-STEREO) WITH MACHINE PROCESSING	27	22	23	22	24	23.5	24.5	23	2

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

and tasks on the ground prior to launch.

The Equipment Data Checks by Onboard Computer and Equipment Function Test by Onboard Computer are promising options for 5 and 7 GFE's, respectively, due to their low recurring costs and autonomous abilities. The Equipment Function Test by Onboard Computer also enhances the development of Fault Tolerant Software. One interesting note is that these two capabilities were favored both for checkout in space and for payload checkout on the ground, prior to launch. There are advantages to having the same checkout system in both places, so that data prior to and after launch can be compared.

There are also several checkout GFE's that are particularly well handled by specific capabilities. For the checkout of the Space Platform/payload interfaces, the Onboard Dedicated Microprocessor and Onboard Microprocessor Hierarchy are favorable options. As shown in the technology tree in Appendix 3.D, these capabilities enhance the development of a wide variety of other capabilities, including manipulators, human-machine interfaces, sensors, failure detection and diagnosis systems, and the TMS.

For mission sequence simulation, either prior to launch, as part of spacecraft verification, or after launch, to support mission decisions or failure diagnosis, Computer Modeling and Simulation was preferred. The study group felt that this capability would be particularly useful if implemented end-to-end, i.e. from the original misstion definition, through spacecraft design, manufacture, test, integration, launch, on-orbit checkout, nominal operations, spacecraft modifications, and fault diagnosis and handling. Having such a capability would also improve communication between mission supervisors, and reduce documentation requirements. This capability also enhances the development of manipulators (and the training of their operators) and the development of expert systems.

The Deterministic Computer Program on Ground received an average sum of 15 for g10 Check Electrical Interfaces. For that same GFE, however, Equipment data Checks by Onboard Computer received a 13.

For g49 Structure Subsystem Checkout, Internal Acoustic Scanning has a favorable average sum of 16, but Equipment Function Test by Onboard Computer is close, with an average sum of 17.

Mechanical Actuation: The average sum rankings of capabilities for mechanical actuation tasks are presented in Table 4.14. The decision criteria values can be found in the Comparison Charts for the 8 mechanical actuation GFE's, in Appendix 4.E.

For the specific task of docking, the Automated Docking Mechanism seemed more promising than other options, due to its low maintenance and recurring cost. Such a system is apparently in use by the Soviet Union. It should be noted, however, that this capability benefits from prior development of the other docking options.

For 5 simple mechanical actuations (deployments, component motions), the traditional Onboard Deployment/Retraction Actuator was favored, due to its low maintenance, costs, and developmental

TABLE 4.14: AVERAGE SUMS OF DECISION CRITERIA VALUES: MECHANICAL ACTUATION

ARAMIS CAPABILITIES:		AVERAGE SUMS: ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
3.1	AUTOMATED DOCKING MECHANISM	15	13	14	12	14	11	13	13	1
2.1	ONBOARD DEPLOYMENT/RETRACTION ACTUATOR	17.8	15	14.8	15.4	15	14.4	14.4	16.8	5
13.3	DOCKING UNDER ONSITE HUMAN CONTROL	18	15	15	16	15	15	15	17	1
15.4	TELEOPERATED DOCKING MECHANISM	18	14	16	16	16	14	15	17	1
1.1	STORED ENERGY DEPLOYMENT DEVICE	20	17	17	18	17.5	16.5	15	19	2
14.3	HUMAN IN EVA WITH TOOLS	20.38	16	16	18.5	16.13	18.38	17.88	19.38	8
2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL	20.43	17.71	17.57	17.43	17.57	16.43	17.43	18.43	7
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL	21	17.14	17.43	17.86	17.43	18.14	18.71	19.29	7
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT	21.14	17.57	17.29	18	17.43	17.86	19.43	19.29	7
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL	21.86	18	18.43	18.29	18.29	19.14	19.71	19.29	7
4.1	COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR	22.83	19.5	19.5	19.17	19.5	19.17	20.33	19.83	6
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK	22.86	19.86	19.43	17.86	19.71	20.57	21.57	18.14	7
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK	23.43	20.14	20.14	19.43	20.29	19.57	21.29	19.71	7
1.2	SHAPE MEMORY ALLOYS	26	23	23	22	22	23	21	22	1
1.3	INFLATABLE STRUCTURE	26	23	21	22	22	22	22	24	1

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

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risk. In addition, this capability benefits the development of manipulators. However, if the task is complex (e.g. deployment of large surfaces, delicate motions of components), these actuators are impractical.

For many mechanical actuation functions, the average sums of five capabilities (each of which applies to 7 or 8 GFE's) were within 2 points of each other: Human in EVA with Tools, Dedicated Manipulator under Computer Control, Specialized Manipulator under Human Control, Teleoperator Maneuvering System with Manipulator Kit, and Dextrous Manipulator under Human Control. This indicates that, without weightings on the decision criteria values, these mechanical actuation options are comparable in overall merits. It is the constraints and figures of merit of specific space projects which will make one or the other of these five candidates most favorable. Since these capabilities span the range of telepresence, Phase II of this study will clarify these issues, through case studies of the application of telepresence to space projects. See Section 4.9 for a description of the Phase II objectives.

As shown in the technology trees in Appendix 3.D, the R&D of simple automatic manipulators and human-controlled manipulators supports the development of more dextrous human-controlled manipulators, culminating in the TMS with Manipulator Kit (which also benefits from a variety of other technologies). These manipulators also enhance the development of sophisticated autonomous manipulators (e.g. Computer-Controlled Specialized Compliant Manipulator). Overall, such complex computer-controlled options were less favored, due to high nonrecurring costs to develop their control software.

Data Handling and Communications: The average sum rankings of capabilities for data handling and communications tasks are presented in Table 4.15. The decision criteria values can be found in the Comparison Charts for the 9 data handling and communications GFE's, in Appendix 4.E.

As can be seen in the right-handmost column of Table 4.15, most of the capabilities that apply to data handling and communications GFE's are candidates only for one or two of those tasks. Of those with three or four potential applications, the Onboard Microprocessor Hierarchy and the Onboard Dedicated Microprocessor are promising options for data-taking and data-processing functions. The Onboard Deterministic Computer Program, with four potential applications and a rating close to the microprocessors, would probably be implemented on a microprocessor or microprocessor hierarchy. As shown in the technology trees in Appendix 4.D, the R&D of microprocessors benefits the development of a wide variety of capabilities, including sensors, human/machine interfaces, failure diagnosis systems, manipulators, and the Teleoperator Maneuvering System.

The other promising options have single applications. For long-term data storage on the ground, Microform on Ground (i.e. microfiche or microfilm) is favored because of its low nonrecurring and recurring costs (virtually no maintenance is required).

TABLE 4.15: AVERAGE SUMS OF DECISION CRITERIA VALUES: DATA HANDLING AND COMMUNICATIONS

ARAMIS CAPABILITIES:		AVERAGE SUMS:								
		ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
18.9	MICROFORM ON GROUND	13	8	12	12	11	12	11	12	1
17.1	TRACKING AND DATA RELAY SATELLITE SYSTEM	14	11	12	11	13	12	13	12	1
17.4	DIRECT COMMUNICATION TO/FROM ORBITER VIA CABLE	14	12	11	13	12	13	10	13	1
18.10	ELECTRICALLY ALTERABLE READ ONLY MEMORY	14	13	13	12	12	12	10	12	1
26.1	FAULT TOLERANT SOFTWARE	14	12	13	10	12	13	13	11	1
18.6	OPTICAL DISC	15	13	13	12	14	13	13	12	1
25.2	ONBOARD MICROPROCESSOR HIERARCHY	15.33	13.67	13	11.67	13	14	14.33	12.33	3
25.1	ONBOARD DEDICATED MICROPROCESSOR	15.75	13.5	12.5	13.25	13.5	13.75	14.25	13.75	4
13.5	COMPUTER-GENERATED AUDIO	16	12	14	14	15	12	14	15	1
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	16	12.5	13	14	14	14	14	14.5	2
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	16	14	13	13	14	13	15	14	1
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	16.25	14	13	13.25	14	14.25	14.75	14.25	4
17.3	DIRECT TRANSMISSION TO/FROM ORBITER	17	15	14	15	14	14	14	16	1
1.6	AUTOMATIC SWITCHING SYSTEMS	18	15	15	16	15	15	15	17	1
13.2	HUMAN EYESIGHT VIA GRAPHIC DISPLAY	18	15	15	16	15	15	15	17	2
17.2	DIRECT TRANSMISSION TO/FROM GROUND	18	15	15	16	15	15	15	17	1
18.1	ONBOARD DATA RECORDER	18	15	15	16	15	15	15	17	1
18.2	RANDOM ACCESS MEMORY	18	15	15	16	15	15	15	17	1
18.4	MAGNETIC BUBBLE MEMORY	18	15.5	16	14.5	16.5	14.5	15.5	15.5	2
19.1	ANALOG/DIGITAL CONVERTER	18	15	15	16	15	15	15	17	1
27.3	EQUIPMENT FUNCTION TEST VIA TELEMETRY	18	15	15	16	15	15	15	17	1
18.8	HOLOGRAPHIC STORAGE	20	17	17	15.5	19	18	17.5	16	2
18.13	CHARGE-COUPLED DEVICE MEMORY	20	16	17	17	18	17	17	18	1
18.5	MAGNETIC DISC MEMORY	20.5	17.5	17.5	17	18.5	17.5	17	18	2
13.4	COMPUTER PRINTOUT	21	17	18	19	18	18	16	20	1
13.6	STEREOPTIC VIDEO	21	19	17	18	17	18	18	19	1
18.7	ERASABLE OPTICAL DISC	21	18	18	16.5	20	18.5	18	17	2
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	21	17	17	18	17	19	19	19	1
18.11	CRYOELECTRONIC MEMORY	22	21	18	17	20	18	21	17	1
18.3	MAGNETIC TAPE	22.5	18.5	18.5	20.5	19	18.5	18.5	21.5	2
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	24	20	19	20	20	22	21	22	1
13.7	3-D DISPLAY	25	23	20	20	21	21	23	22	1
18.12	ELECTRON BEAM MEMORY	26.5	24.5	23.5	21.5	22.5	23	21.5	22.5	2

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

For long-term data storage in space, Electrically Alterable Read-Only Memory and Optical Disc are promising options, because of low maintenance (hence low recurring cost) and high reliability.

For short-term data storage in space, Random Access Memory and Magnetic Bubble Memory are favored, due to low maintenance, R&D cost, and developmental risk.

In general, computer memory development enhances the R&D of Computer Modeling and Simulation, which in turn supports development of manipulators and expert systems. Computer memory development also supports the R&D of the Onboard Dedicated Microprocessor, the Onboard Microprocessor Hierarchy, imaging sensors with computer processing, and human/machine interfaces (e.g. graphic displays and computer-generated audio).

For communications during spacecraft checkout (either on-orbit or during payload integration), Direct Communication to/from Orbiter via Cable is a favorable option, with low R&D costs and high reliability. This is currently in use for ground checkout and for on-orbit checkout in the payload bay; however, this also suggests the possibility of letting a satellite drift near the orbiter during on-orbit checkout (e.g. during solar array deployment), still tethered by a long communication cable. The cable would be released from the spacecraft once the tests were complete, and reeled in by the orbiter.

For the interface between humans and computers, the promising options are Computer-Generated Audio and Human Eyesight via Graphic Display, particularly in those situations when more traditional methods are cumbersome(e.g. during EVA, docking, or manipulator control). In general, the development of human/machine interfaces is an important prerequisite to successful telepresence applications.

To maintain communications links, Fault Tolerant Software is promising, due to low maintenance and high reliability. Its R&D also enhances the eventual development of the Learning Expert System with Internal Simulation.

Monitoring and Control: Table 4.16 presents the average sum rankings of capabilities for monitoring and control tasks (i.e. the routine functions of spacecraft operations). The decision criteria values can be found in the Comparison Charts for the 9 monitoring and control GFE's, in Appendix 4.E.

For monitoring of spacecraft components and procedures in general, a promising option is Equipment Data Checks by Onboard Computer, because it doesn't incur the costs of telemetry or human supervision. The onboard computer in this capability might be an Onboard Dedicated Microprocessor or an Onboard Microprocessor Hierarchy, both of which also receive favorable average ratings, less than two points behind the Equipment Data Checks. The development of microprocessors enhances the R&D of many capabilities, including manipulators, human/machine interfaces, sensors, failure detection and diagnosis systems, and the TMS, as shown in the technology trees in Appendix 3.D.

For thermal subsystem control, the promising options are the Operations Optimization Program (average sum 15) and the Onboard Adaptive Control System (average sum 16). These two capabilities

TABLE 4.16: AVERAGE SUMS OF DECISION CRITERIA VALUES: MONITORING AND CONTROL

ARAMIS CAPABILITIES:		ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
21.2	OPERATIONS OPTIMIZATION PROGRAM	15	12	13	12	12	14	14	13	1
27.4	EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER	15.5	13	14	12.5	14	12.5	13.5	13.5	2
25.5	ONBOARD ADAPTIVE CONTROL SYSTEM	16	13	14.5	12	13.5	15	15	13	2
1.6	AUTOMATIC SWITCHING SYSTEMS	17	14.33	14.67	15	14.33	13.67	14	16	3
25.1	ONBOARD DEDICATED MICROPROCESSOR	17.13	14.88	14.5	14.5	14.88	14.13	14.75	15.13	8
25.2	ONBOARD MICROPROCESSOR HIERARCHY	17.25	15.25	14.75	13.25	14.75	15.5	15.75	14.25	4
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	17.83	15.67	14.67	15.17	15.17	14.83	15.33	16.17	6
14.8	ONSITE HUMAN JUDGMENT	18	15	13	16	14	16	17	17	1
18.1	ONBOARD DATA RECORDER	18	15	15	16	15	15	15	17	1
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	18	17	14.5	13	16.5	16.5	17	13.5	2
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	18	15.29	15.57	15.43	15.43	14.71	15	16.57	7
27.5	EQUIPMENT DATA CHECKS BY ONSITE HUMAN	18	15	15	16	15	15	15	17	1
27.6	EQUIPMENT DATA CHECKS VIA TELEMETRY	18	14.5	16	16	16	15	14	16.5	2
21.1	ONBOARD SEQUENCER	18.5	16.5	15.5	17	16.5	14.5	13.5	17.5	2
23.1	EXPERT SYSTEM WITH HUMAN SUPERVISION	18.5	17	14	15	15.5	16.5	17	16	2
14.4	HUMAN WITH CHECKLIST	18.67	14.33	17	17.67	15	15.33	15	17.67	3
14.5	HUMAN JUDGMENT ON GROUND	19	15	18	18	15	15	15	18	1
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	19.4	16	16.8	17.2	15.8	16.4	15.8	18.4	5
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	20.8	17.4	16.6	18	17	18	18	19.8	5

AVERAGE SUMS:

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

showed comparable promise in their application to the related power handling task g87 Adjust Currents and Voltages. Both capabilities are low-maintenance options, not prone to failures. In addition, the Onboard Adaptive Control System enhances the R&D of dextrous manipulators, and both contribute to the development of expert systems.

If the monitoring and control tasks are simple, then the traditional Automatic Switching Systems are favored due to low costs. They should also be considered as a backup mode for the more sophisticated options. Automatic Switching Systems contribute to manipulator development.

In general, the more favorable options are automated, since the large volumes of routine monitoring and control data in complex spacecraft will make human evaluation too expensive.

Computation: The average sum rankings of the capabilities for computation tasks are presented in Table 4.17. The decision criteria values can be found in the Comparison Charts for the 6 computation GFE's, in Appendix 4.E. Computation tasks include numerical processing, logical operations, computer checkout and operation, and calculation of control profiles for actuators.

For 5 of the computation GFE's, the Onboard Microprocessor Hierarchy is a promising option, due to its reliability, versatility, and low recurring cost. The development of this capability also enhances the R&D of sophisticated manipulators, imaging sensors with computer processing, failure diagnosis systems, and the TMS.

TABLE 4.17: AVERAGE SUMS OF DECISION CRITERIA VALUES: COMPUTATION

ARAMIS CAPABILITIES:		AVERAGE SUMS: ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
25.5	ONBOARD ADAPTIVE CONTROL SYSTEM	15	13	13	11	13	14	14	12	1
25.2	ONBOARD MICROPROCESSOR HIERARCHY	16.6	14.8	13.6	12.6	14.8	14.6	15.6	13.6	5
21.2	OPERATIONS OPTIMIZATION PROGRAM	17	15	13	14	15	15	15	15	1
25.1	ONBOARD DEDICATED MICROPROCESSOR	17.2	15.6	13.2	14.2	15.8	14.2	14.8	15.4	5
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	17.4	14.8	14.4	15	15.2	14.4	14.6	16	5
23.1	EXPERT SYSTEM WITH HUMAN SUPERVISION	17.67	15	13.33	14.67	15.67	15.67	16	15.67	3
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	17.67	16	13.67	12.67	16.67	16.67	16.67	13.67	3
13.2	HUMAN EYESIGHT VIA GRAPHIC DISPLAY	18	15	16	16	15	15	14	17	1
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	18.33	14.83	15.33	16.33	14.83	15.83	15.5	17.33	6
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	18.33	16.67	14.33	15.33	16	15.5	15.83	16.33	6
14.4	HUMAN WITH CHECKLIST	19	14.67	18	18	15	15.33	15	18	3
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	23	19	18	20	18.5	21	20	21.5	2
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	23	20	19	21	18	20	19	21	1

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

Also promising are the Onboard Dedicated Microprocessor and Deterministic Computer Program on Ground, with average sums less than a point behind the microprocessor hierarchy. The development of space-qualified microprocessors enhances the R&D of a variety of capabilities, including the Onboard Microprocessor Hierarchy, manipulators, sensors, human/machine interfaces, and checkout systems, as shown in the technology trees in Appendix 3.D. The Deterministic Computer Program on Ground has the advantage of low recurring cost, since it does not require in-space maintenance of hardware.

For logical operations and evaluations, the Expert System with Human Supervision and the Learning Expert System with Internal Simulation show some promise. These systems can handle multi-variable decision tasks rapidly and reliably. As satellites become more complex, expert systems may become a necessity, to sift through all of the interrelated status data from a spacecraft, and to formulate appropriate responses to spacecraft conditions. As shown in the technology trees in Appendix 3.D, the Expert System with Human Supervision benefits from prior R&D of Computer Modeling and Simulation, the Theorem Proving Program, and the Operations Optimization Program; in turn, it enhances the Automatic Programmer and Program Tester and the Learning Expert System with Internal Simulation.

For the single task g94 Computer Load Scheduling, the Operations Optimization Program is comparable to the Onboard Microprocessor Hierarchy (both with average sums of 17). The Operations Optimization Program uses operations research techniques (e.g. linear programming, dynamic programming, or variations of these); therefore its development benefits the R&D of expert systems.

For the single task g103 Apply Compensating Forces (e.g. for spacecraft structure control), the Onboard Adaptive Control System is a promising option, due to its low maintenance, high reliability, and versatility. The development of this capability benefits the R&D of dextrous manipulators and of learning expert systems.

Decision and Planning: Table 4.18 presents the average sum rankings of capabilities for decision and planning tasks. The decision criteria values can be found in the Comparison Charts for the 12 decision and planning GFE's, in Appendix 4.E. Decision and planning tasks include definition and modification of mission objectives, projections of desired functions, constraints, figures of merit, and consumables requirements, optimal consumables allocation, spacecraft status modeling, system evaluation, hazard avoidance, and choice between procedural options.

For optimal scheduling and consumables allocation, the Operations Optimization Program (using linear programming, dynamic programming, or variations of these) is a promising option, because of its low cost and developmental risk, and high reliability. This capability also supports the development of expert systems.

TABLE 4.18: AVERAGE SUMS OF DECISION CRITERIA VALUES: DECISION AND PLANNING

	ARAMIS CAPABILITIES:	ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
21.2	OPERATIONS OPTIMIZATION PROGRAM	14.5	12.5	11	11.5	13.5	12:5	13.5	12.5	2
16.1	COMPUTER MODELING AND SIMULATION	17.33	15.67	14.33	13.33	15.33	15.33	15.67	14.33	3
14.8	ONSITE HUMAN JUDGMENT	17.5	15	14.5	16	14	14	15	16.5	2
25.3	ONBOARD DETERMINISTIC COMPUTER PROGRAM	17.86	16	13.86	14.86	15.86	14.57	16	16	7
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	17.86	15.57	14.86	15.29	15.86	14.43	15.14	16	7
14.5	HUMAN JUDGMENT ON GROUND	18	14.33	16.33	16.67	15.67	14	14	17	3
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	18.1	16.8	14.2	13.3	16.7	16.8	17.1	13.7	10
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	18.11	15	15.22	16.22	15.22	15	14.89	17.11	9
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	18.5	16	14.5	16	15	16	16	17.5	2
23.1	EXPERT SYSTEM WITH HUMAN SUPERVISION	18.8	17	14.8	15	16.2	16.6	17	16.2	5
14.4	HUMAN WITH CHECKLIST	19.38	15.63	17.25	17.38	16.38	15.63	15.63	18.38	8

AVERAGE SUMS:

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

To support decisions on mission status and procedures, Computer Modeling and Simulation is useful, particularly if implemented end-to-end, i.e. from the original mission definition, through spacecraft design, manufacture, test, integration, launch, on-orbit checkout, nominal operations, spacecraft modifications, and fault diagnosis and handling. Having such a capability would also improve communication between mission supervisors, and reduce documentation requirements. This capability also enhances the development of manipulators (and the training of their operators) and the development of expert systems.

For many of the simpler decision and planning functions, the Onboard Deterministic Computer Program and the Deterministic Computer Program on Ground are adequate, with the advantage of low recurring costs (no direct human supervision is required). Although limited to situations that can be strictly modeled with numerical criteria or if-then relationships, these options can handle many routine decision functions for spacecraft. More abstract decisions requiring qualitative evaluations are left to more sophisticated software or humans.

The use of Onsite Human Judgment is favorable in two tasks: for the evaluation of system performance, because of the human's versatility and low failure-proneness; and for the piloting of spacecraft around objects, because of the human's rapid evaluation of three-dimensional data and rapid definition of responses to trouble. The development of Onsite Human Jugement, by training, simulation, and experience, benefits onsite human functions, including EVA, docking under human control, and the human control of manipulators.

The versatility of the Learning Expert System with Internal Simulation (10 applications) and of the Human on Ground with Computer Assistance (9 applications) should also be noted. Any decision and planning task that can be handled computationally can also be done by the Learning Expert System, which incorporates the abilities of the other computational options. In addition, its learning and simulation abilities allow it to predict outcomes of procedures, in order to make qualitative decisions. When it makes such decisions, it will be faster and more thorough than a human; however, its developmental risk and nonrecurring cost are high. The human, on the other hand, is current technology; but the recurring costs for salary and for updates of computer aids bring down its overall rating.

Fault Diagnosis and Handling: The average sum rankings of capabilities for fault diagnosis and handling tasks are presented in Table 4.19. The decision criteria values can be found in the Comparison Charts for the 7 fault diagnosis and handling GFE's, in Appendix 4.E.

To identify problems, Equipment Data Checks by Onboard Computer, Equipment Function Test by Onboard Computer, and Equipment Data Checks via Telemetry are promising options. The development of the Equipment Function Test by Onboard Computer also contributes to the development of Fault Tolerant Software. Also useful is the Deterministic Computer Program on Ground,

TABLE 4.19: AVERAGE SUMS OF DECISION CRITERIA VALUES: FAULT DIAGNOSIS AND HANDLING

ARAMIS CAPABILITIES:		AVERAGE SUMS: ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
27.4	EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER	15	14	12	12	13	13	13	13	1
26.1	FAULT TOLERANT SOFTWARE	15.67	14.33	13.67	11.67	14	14	14.67	11.67	3
27.1	EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER	16	14.5	12	13.5	14.5	13.5	14	14	2
27.6	EQUIPMENT DATA CHECKS VIA TELEMETRY	16	13	13	14	14	14	13	15	1
23.1	EXPERT SYSTEM WITH HUMAN SUPERVISION	16.33	14.67	11.33	13.33	14.33	15	15	14.33	3
25.4	DETERMINISTIC COMPUTER PROGRAM ON GROUND	16.33	14.33	13	13.67	14.33	13.67	13.67	15.33	3
22.1	AUTOMATIC PROGRAMMER AND PROGRAM TESTER	17	15	13	14	16	15	15	14	1
16.1	COMPUTER MODELING AND SIMULATION	17.5	15	14	15	15	15	15	16	2
14.2	HUMAN ON GROUND WITH COMPUTER ASSISTANCE	17.6	15.4	13.8	14.8	14.6	15.4	15	16.6	5
14.5	HUMAN JUDGMENT ON GROUND	18	14.67	15.83	16.17	15.17	14.33	14.83	17	6
14.4	HUMAN WITH CHECKLIST	18.5	15	15.75	16.75	15.75	15.25	15	17.5	4
23.2	LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION	18.6	17.4	14.6	13.6	17	17.6	17.6	13.8	5
24.1	THEOREM PROVING PROGRAM	19	17	15.25	14.75	16.75	17.25	17.75	15.25	4
27.3	EQUIPMENT FUNCTION TEST VIA TELEMETRY	19	16	15.5	16.5	16	16	16	18	2
14.7	ONSITE HUMAN WITH COMPUTER ASSISTANCE	21.17	18.67	16.17	17.83	17.17	18.83	18.67	19.67	6
14.8	ONSITE HUMAN JUDGMENT	21.4	18	17.4	19.4	17.4	17.6	18.2	20.4	5
27.2	EQUIPMENT FUNCTION TEST BY ONSITE HUMAN	22	18.5	17	19	18	20	19.5	20	2
27.5	EQUIPMENT DATA CHECKS BY ONSITE HUMAN	23	20	18	20	19	20	20	21	1

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

which in this application is an on-ground equivalent to the data checks and function test by onboard computer.

To recover from failures, Fault Tolerant Software is favored, because it operates rapidly and autonomously, with low recurring costs. (Fault Tolerant Software was also recommended for g241 Maintain Communications Links, a similar function in Data Handling and Communication). The use of this capability is limited to those problems that can be modeled in software, and whose solutions can be programmed in advance. The development of Fault Tolerant Software contributes to the R&D of a Learning Expert System with Internal Simulation.

For diagnosis of more complex problems and development of solutions, the Expert System with Human Supervision is a promising option (Refs. 4.13, 4.14). In this application the expert system is similar to the medical diagnosis systems currently in development. The human updates the data base, inputs the symptoms of the problem, and suggests potential solutions to be evaluated by the expert system. These functions of the human could be replaced by a Learning Expert System with Internal Simulation, but at considerable nonrecurring cost and developmental risk. A related potential application of the expert system is to support the launch protocol during countdown at KSC; the expert system would do continuous diagnosis on the large amounts of data received by launch control, trace and display problems, and suggest solutions in real time. The Expert System with Human Supervision also enhances the development of the Automatic

Programmer and Program Tester.

The study group feels that expert systems may become not only desirable but necessary in future spacecraft missions. The traditional philosophy is to anticipate all possible one-point and two-point failure modes during the design process, and to design either safeguards or recovery systems to deal with possible problems. However, as spacecraft complexity increases, the prediction of all such failure modes and effects becomes combinatorially enormous. At the same time, on-orbit repair systems are becoming available, such as the Shuttle, the Teleoperator Maneuvering System, or repair teleoperators onboard the spacecraft itself. This suggests an alternative to the total-failure-prediction criterion: it may be sufficient to load a detailed functional representation of the spacecraft, including the relationships between components (particularly the effects of component failures on other components) into the relational data base of an expert system. Then the expert system can perform two services: during design it can systematically search for severe failure combinations, to be designed out of the spacecraft; after launch, it can help in (or perform) failure diagnosis, suggest potential solutions, and verify that the proposed solutions will cure the problems. The repair systems can then implement those solutions. When the spacecraft designers become confident that the failure diagnosis expert system has a sufficient data base to perform the services described above, then the spacecraft can be cleared for manufacture.

The Human on Ground with Computer Assistance shows some versatility: it applies to 5 GFE's. For the definition of a software correction algorithm, the human can be favorably aided by an Automatic Programmer and Program Tester, which accepts high-level (e.g. english-language) descriptions of what the program is supposed to do, then writes the computer code and checks it in a simulation of the spacecraft software. For the identification of faulty software and the definition of correction algorithms, Computer Modeling and Simulation is another favorable option to aid the human.

Sensing: Table 4.20 presents the average sum rankings of capabilities for sensing tasks. The decision criteria values can be found in the Comparison Charts for the 4 sensing GFE's, in Appendix 4.E.

For all four sensing functions, the Optical Scanner (Passive Cooperative Target) had an average sum rating nearly three points better than its nearest competitor, and nearly five points better than the next-nearest. In addition, the development of the optical scanner enhances the R&D of the Automated Docking Mechanism and of the TMS. The optical scanner requires that the target cooperate by displaying passive laser reflectors in known locations. The system scans the reflectors with a laser beam and computes their positions, thus deducing the location and orientation of the components to which the reflectors are attached. The high speed, reliability, and low cost of such a system (e.g. the PATS military version) make it a promising

TABLE 4.20: AVERAGE SUMS OF DECISION CRITERIA VALUES: SENSING

ARAMIS CAPABILITIES: AVERAGE SUMS:

		ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
6.1	OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)	13.25	11.5	11.75	10.5	11.75	11.25	11.25	11.5	4
6.4	RADAR (ACTIVE TARGET)	16	14	14	13.33	13.33	13.33	13.67	14.33	3
7.1	DEAD RECKONING FROM STORED MODEL	18	17	16	16	17	13	13	16	1
6.3	RADAR (PASSIVE TARGET)	18.33	16.33	16.67	15.33	16	14.67	14.67	16.33	3
6.5	ONBOARD NAVIGATION AND TELEMETRY	19	17	15	15	16	17	17	17	1
8.1	TACTILE SENSORS	19	15	18	16	18	15	15	17	1
13.2	HUMAN EYESIGHT VIA GRAPHIC DISPLAY	19.75	16.5	16.25	16.75	16.5	17.5	17.5	17.5	4
6.2	PROXIMITY SENSORS	20	15	19	17	19	16	15	19	1
13.1	HUMAN EYESIGHT VIA VIDEO	20.5	17	17	18.5	17	17	17	19.5	4
11.1	IMAGING (STEREO) WITH MACHINE PROCESSING	21.75	18.5	19.25	16.75	19.5	19	20	17.5	4
14.1	DIRECT HUMAN EYESIGHT	21.75	18.5	17.5	19.75	17.5	19	17.5	20.75	4
11.2	IMAGING (NON-STEREO) WITH MACHINE PROCESSING	22.25	19	19.75	17.25	20	19	20.5	18	4

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

option. The laser reflectors can also carry identification codes (such as the bar codes read by similar laser scanners in supermarkets). This suggests that all spacecraft components could be tagged with identifying reflectors in known locations, so that an optical scanner could locate and recognize them. The position information would then be used either directly by a computer, or by a human through the medium of a computer-generated graphic display.

The closest competitor to the Optical Scanner is Radar (Active Target), which has advantages in power consumption and range (at long ranges, the laser power required by the Optical Scanner can pose a safety hazard), but which requires an active transponder on the target. This capability also supports the development of the Automated Docking Mechanism and of the TMS.

Other sensing options (e.g. Dead Reckoning from Stored Model, Onboard Navigation and Telemetry, Tactile Sensors, various human eyesight options) have specialized uses, and their respective merits depend strongly on the specific details of the applications. The weighting factors from actual space projects will significantly affect the choices between these options. It should be noted that the human eyesight options are versatile, and are likely to be more reliable in unexpected situations. They can sometimes be coupled with Optical Scanners, or serve as backup modes.

4.8 USE OF THIS REPORT BY THE STUDY RECIPIENT

4.8.1 Suggested Procedure

The ARAMIS study group anticipates two types of users of this Phase I final report. The first is the Project Engineer (PE), who has either a full space project or a set of space project tasks in mind, and is interested in the ARAMIS options to perform these tasks. The second is the ARAMIS design engineer, who is interested in developing useful and versatile capabilities to meet space project needs. The information in this final report is organized and presented principally for the first type of user, the Project Engineer. The method of use suggested in this section and demonstrated in the next is therefore aimed at the PE.

The second type of user, the ARAMIS design engineer, may be specifically interested in the general discussion of ARAMIS, the listing and definitions of ARAMIS topics, the ARAMIS bibliography, and the ARAMIS Capability General Information Forms, all in Volume 3. In addition, Appendix 4.G presents the 78 ARAMIS capabilities defined by the study; each of these is followed by a listing of the GFE's to which the capability applies, and of the decision criteria values estimated for each application. The commentary on those criteria values is available from the ARAMIS Capability Application Forms in Appendix 4.E.

The suggested method for use of this report by the PE is summarized in Table 4.21 . The first step is the examination

TABLE 4.21: SUGGESTED METHOD FOR USE OF THE ARAMIS STUDY PHASE I INFORMATION

1) EXAMINE GENERIC FUNCTIONAL ELEMENT LIST, TO ASSIMILATE STUDY NOMENCLATURE AND LEVEL OF DETAIL OF GFE'S.
2) BREAK DOWN NEW SPACE PROJECT, USING SAME NOMENCLATURE AS GFE LIST WHENEVER POSSIBLE.
3) FOR EACH FUNCTIONAL ELEMENT IN THE NEW PROJECT WHICH MATCHES AN ELEMENT IN THE STUDY'S GFE LIST, CHECK REDUCED GFE LIST. IDENTIFY THE RELEVANT GFE'S FROM THE 69 STUDIED IN DETAIL.
4) USE STUDY MATRIX TO IDENTIFY CANDIDATE ARAMIS CAPABILITIES FOR EACH FUNCTIONAL ELEMENT. CHECK ARAMIS CAPABILITY GENERAL INFORMATION FORMS FOR DESCRIPTIONS OF CANDIDATE CAPABILITIES.
5) USE DECISION CRITERIA COMPARISON CHARTS AND ARAMIS CAPABILITY APPLICATION FORMS FOR STUDY'S EVALUATION OF CANDIDATE CAPABILITIES.
6) BASED ON STUDY DATA ON CANDIDATE ARAMIS CAPABILITIES, AND ON THE CONSTRAINTS OF THE NEW SPACE PROJECT, SELECT THE APPROPRIATE ARAMIS CAPABILITIES FOR THE SPACE PROJECT TASKS.

of the 330-element Generic Functional Element list in Appendix 4.A. This allows the PE to become familiar with the study nomenclature and the level of detail of the GFE's. The GFE List with breakdown code numbers and the space project breakdowns are available in Appendices 2.B and 2.A of Volume 2, if the user wants further clarification of the meaning and context of the GFE's.

The second step is the breakdown of the PE's new project, along the lines used by the study group (the breakdown procedure is discussed in Section 2.3, Volume 2). In particular, the user should use the study's GFE's in the breakdown whenever appropriate, since it is those common GFE's which the study data will cover.

Third, for each of the functional elements in the new project breadkdown which is the same as one of the 330 GFE's defined by this study, the PE should check the Reduced GFE List in Appendix 4.B. Case 1: the GFE of interest is one of the 69 GFE's selected for detailed study. The PE will then look for information on that GFE, as described below. Case 2: the GFE of interest is labeled "similar to" one (or more) of the 69 GFE's. Then the PE should focus on that selected GFE to find information in this study, keeping in mind the limitations of the similarity between the GFE's (discussed in Section 4.6.3). Case 3: the GFE of interest is either adequately handled by "current technology", or "too specific", or "infrequent". Then this study did not cover this GFE in detail, for reasons described in the notes to Appendix 4.B. For cases 1 and 2, Appendix 4.C presents definitions of the 69 GFE's selected for further study, so that

C-2

the PE can verify the similarity of the functional elements in the new project to the relevant GFE's.

Fourth, the PE should use the study matrix presented in Appendix 4.D to identify the ARAMIS capabilities which the study group defined as candidates for each GFE of interest. Descriptions and information on the candidate capabilities are presented in the ARAMIS Capability General Information Forms in Appendix 3.C (Volume 3). In looking over these descriptions, the PE may find some candidates unacceptable because of constraints specific to the new project (e.g. a launch data well before expected availability of the capability).

Fifth, the PE should consult the Decision Criteria Comparison Charts and ARAMIS Capability Application Forms in Appendix 4.E, to find the study group's evaluation of the relative merits of candidate capabilities applied to each GFE of interest. The study group urges that the limitations to this evaluation method, discussed in Section 4.6.3, be kept in mind during examination of the estimated decision criteria values.

Finally, based on the study's presentation of candidate ARAMIS capabilities and their evaluations, and on the specific constraints of the new project, the PE can select the appropriate ARAMIS capabilities for the space project tasks. The PE can support this decision process further by consulting data sources listed in the various data forms, or the more general sources in the ARAMIS bibliography (Appendix 3.B in Volume 3). It is anticipated that project-specific constraints will have a significant effect on the final choices. For example, if the PE commits to the use a particular ARAMIS capability for a project task, then that capability would probably be applied to as many other tasks as possible, even if those applications were less than optimal, to minimize spacecraft complexity.

In general, the study group emphasizes that no overall method, such as this study's, can replace the engineering judgement of the Project Engineer. It is not possible to develop a general cut-and-dry system to select ARAMIS Capabilities for the tasks in any space project. What this study can do is to spread out the ARAMIS options for the PE's to review, to present background information and data sources on the options, and to display the study group's opinion on the potential advantages, disadvantages and relative merits of the options. The final decision on the most appropriate capability for each task, however, rests with the PE, since this decision involves constraints and requirements specific to the particular space project. The study output presents information to support that decision process, and suggests a systematic approach to the choice; the input data can be refined and updated, the evaluations reviewed one at a time, and various weightings tried on the criteria values, to improve the decision.

4.8.2 Example of Procedure

This example considers the case of a PE interested in ARAMIS options for a radio telescope spacecraft, and particularly in the deployment of the numerous structural components and instrument packages in the antenna array. First, the PE would examine the Generic Functional Element List in Appendix 4.A, with emphasis on the Mechanical Actuation GFE's to look at deployment tasks.

A relevant section of this GFE List is shown in Table 4.22. This would acquaint the PE with the GFE's defined by this study.

TABLE 4.22: SECTION OF GFE LIST
(FROM APPENDIX 4.A)

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C. MECHANICAL ACTUATION

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g22: ROTATE OTV/GSP PACKAGE OUT OF ORBITER
g25: RAISE CENTRAL MAST
g26: LEPLOY MAIN REFLECTORS
g27: DEPLOY ANTENNA RECEIVER ARRAYS
g28: DEPLOY ANTENNA TRANSMIT ARRAYS
g29: DEPLOY SUBREFLECTOR
g30: DEPLOY INTERFEROMETER
g31: DEPLOY SOLAR ARRAYS
g32: DEPLOY RADIATORS
g34: RETRACT SOLAR PANELS
g42: SEPARATE OTV FROM GSP
g45: DEPLOY SOLAR PANELS
g46: DEPLOY INTER-PLATFORM LINK ANTENNAS
g67: TRANSFER REPAIR EQUIPMENT TO REPAIR SITE
g68: OPEN ACCESS PANEL

o
o
o

Second, the PE would break down the new project into functional elements, using the study's GFE's as much as possible. For the deployment tasks of particular interest, the likely choices are GFE's g25, g26, g27, g28, g29, g30, g31, g32, g45, g46. For this example, let us suppose that g25 Raise Central Mast, g27 Deploy Antenna Receiver Arrays, g28 Deploy Antenna Transmit Arrays, g29 Deploy Subreflector, and g30 Deploy Interferometer are specifically appropriate and thus end up in the PE's breakdown.

Third, for each of the functional elements in the new project breakdown which is the same as one of this study's GFE's, the PE checks the Reduced GFE List in Appendix 4.B. For the deployment tasks, the relevant section of this list is shown in Table 4.23. Of the five GFE's in the PE's breakdown, g27 is one of the GFE's focused on by this study; g28 and g30 are similar to g27; and g25 and g29 are similar to g27 and g31 Deploy Solar Arrays. Therefore g27 and g31 appear to be the relevant GFE's, whose candidate capabilities would probably also apply to the PE's needs. To verify this, the PE can look up the definitions of g27 and g31 in Appendix 4.C, repeated here in Table 4.24.

Fourth, the PE uses the study matrix in Appendix 4.D to identify the ARAMIS capabilities defined by the study group as candidates for the GFE's of interest. For g27 and g31, the appropriate section of this matrix is shown in Table 4.25 . The PE should keep in mind the specific constraints of the radio telescope spacecraft (e.g. technology cutoff date, orbital parameters, availability of maintenance) in reviewing these candidate

TABLE 4.23: SECTION OF REDUCED GFE LIST
(FROM APPENDIX 4.B)

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g25: RAISE CENTRAL MAST
Similar to g27 and g31.

g26: DEPLOY MAIN REFLECTORS
Similar to g27 and g31.

\+ g27: DEPLOY ANTENNA RECEIVER ARRAYS

g28: DEPLOY ANTENNA TRANSMIT ARRAYS
Similar to g27.

g29: DEPLOY SUBREFLECTOR
Similar to g27 and g31.

g30: DEPLOY INTERFEROMETER
Similar to g27.

\+ g31: DEPLOY SOLAR ARRAYS

g32: DEPLOY RADIATORS
Similar to g31.

g34: RETRACT SOLAR PANELS
Current technology or inverse of g31.

g42: SEPARATE OTV FROM GSP
Current technology.

g45: DEPLOY SOLAR PANELS
Current technology or similar to g31.

g46: DEPLOY INTER-PLATFORM LINK ANTENNAS
Similar to g27 and g31.

\+ g67: TRANSFER REPAIR EQUIPMENT TO REPAIR SITE

g68: OPEN ACCESS PANEL
Current technology.

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TABLE 4.24: SECTION OF APPENDIX 4.C:
DEFINITIONS OF GFE's SELECTED FOR DETAILED STUDY

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g27: DEPLOY ANTENNA RECEIVER ARRAYS

The on-orbit deployment of the GSP antenna receiver arrays and, more generally, of any spacecraft components which are not extremely fragile (fragile components are deployed under g31 Deploy Solar Arrays). Most of these deployments happen once, at the beginning of spacecraft on-orbit life; some components are later retracted and redeployed, usually as part of servicing and repair sequences.

Also covers:	g25	Raise Central Mast
	g26	Deploy Main Reflectors
	g28	Deploy Antenna Transmit Arrays
	g29	Deploy Subreflector
	g30	Deploy Interferometer

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o
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g31: DEPLOY SOLAR ARRAYS

The on-orbit deployment of solar arrays and, more generally, of spacecraft components. This includes fragile components (e.g. solar panels, radiators) that require safe geometries and minimal stresses during deployment. Most of these components require retractions and redeployment during spacecraft life.

Also covers:	g25	Raise Central Mast
	g26	Deploy Main Reflectors
	g29	Deploy Subreflector
	g32	Deploy Radiators
	g34	Retract Solar Panels
	g45	Deploy Solar Panels
	g46	Deploy Inter-Platform Link Antennas

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TABLE 4.25: SECTION OF STUDY MATRIX

(FROM APPENDIX 4.D)

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g27 DEPLOY ANTENNA RECEIVER ARRAYS

1.1 STORED ENERGY DEPLOYMENT DEVICE

1.2 SHAPE MEMORY ALLOYS

1.3 INFLATABLE STRUCTURE

2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR

2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL

4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR

4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK

4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK

14.3 HUMAN IN EVA WITH TOOLS

15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL

15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL

15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g31 DEPLOY SOLAR ARRAYS

1.1 STORED ENERGY DEPLOYMENT DEVICE

2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR

2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL

4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR

4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK

4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK

14.3 HUMAN IN EVA WITH TOOLS

15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL

15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL

15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

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capabilities, to assess their suitability to the actual project tasks. In this example, most or all of the candidates for g27 should be suitable, since it was a GFE originally selected in the new project breakdown. However, g31 should be reviewed more closely, since it entered into consideration through similarity to other GFE's. In this case all of g31's capabilities also appear under g27, so they are likely to be kept in consideration. To get a clearer understanding of the capabilities, the PE would read the ARAMIS Capability General Information Forms in Appendix 3.C (Volume 3). As a specific example, Table 4.26 repeats the form for capability 4.2 Computer-Controlled Dextrous Manipulator with Force Feedback, a candidate for both GFE's g27 and g31.

Fifth, for the GFE's of interest, the PE would consult the Decision Criteria Comparison Charts in Appendix 4.E. Following the example, Table 4.27 repeats the Comparison Chart for GFE g27 Deploy Antenna Receiver Arrays (the PE would also consult the chart for g31). In reviewing the numbers on such charts, the PE should keep in mind the limitations of the evaluation method, discussed in Section 4.6.3, particularly the specific requirements of the radio telescope spacecraft project, which may suggest weighting certain decision criteria more than others. To support this review process, the PE would consult the ARAMIS Capability Application Forms following each Comparison Chart in Appendix 4.E, to find the commentary associated with each of the estimated decision criteria values. For example, Table 4.28 repeats one of twelve Application Forms which

TABLE 4.26: ARAMIS CAPABILITY GENERAL INFORMATION FORM (FROM APP. 3.C)

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator with Force Feedback

CODE NUMBER: 4.2 DATE: 6/28/82 NAME(S): Kurtzman/Paige/Ferreira

DESCRIPTION OF CAPABILITY: A multipurpose multifingered manipulator, under computer control, and capable of operating under various geometries. The system would be reprogrammable and would use input from force-feedback sensors for final guidance and motion control.

WHO IS WORKING ON IT AND WHERE: Ewald Heer and Antal Bejczy (JPL); Marvin Minsky (MIT AI Lab); Dan Whitney (Draper Labs); Victor Sheinman (Automatix, Burlington, MA); Tom Williams (DEC, Maynard, MA).

TECHNOLOGY LEVELS:	LEVEL1: Now	LEVEL2: Now	LEVEL3: Now
LEVEL4: Now	LEVEL5: 1986	LEVEL6: 1986	LEVEL7: 1989

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Present and future levels were provided by Marvin Minsky. The intermediate levels were computed by interpolation based on the background of the study group.

R&D COST ESTIMATES BETWEEN LEVELS:		1-2: N/A	2-3: N/A
3-4: N/A	4-5: $10-20 Million	5-6: N/A	6-7: $2.5 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: Dan Whitney suggested a figure of $10-20 million to develop the whole system to level 6. Cost to go from level 6 to level 7 was estimated at $2.5 million by extrapolating from a figure of $1 million to space rate a dedicated manipulator under computer control (Robert F. Goeke, MIT Center for Space Research).

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 4.1 Computer-Controlled Specialized Compliant Manipulator; 15.2 Dextrous Manipulator under Human Control; 19.1 A/D Converter.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

TABLE 4.27: DECISION CRITERIA COMPARISON CHART (FROM APPENDIX 4.E)

GFE: g27 DEPLOY ANTENNA RECEIVER ARRAYS

GFE TYPE: C. Mechanical Actuation

The on-orbit deployment of the GSP antenna receiver arrays and, more generally, of any spacecraft components which are not extremely fragile (fragile components are deployed under g31 Deploy Solar Arrays). Most of these deployments happen once, at the beginning of spacecraft on-orbit life; some components are later retracted and redeployed, usually as part of servicing and repair sequences.

DECISION CRITERIA

CANDIDATE ARAMIS CAPABILITIES:

		TIME	MAINTENANCE	NONRECURRING COST	RECURRING COST	FAILURE PRONENESS	USEFUL LIFE	DEVELOPMENTAL RISK	
1.1	STORED ENERGY DEPLOYMENT DEVICE	3	3	2	2	3	5	1	
1.2	SHAPE MEMORY ALLOYS	3	3	4	4	3	5	4	
1.3	INFLATABLE STRUCTURE	3	5	4	4	4	4	2	
2.1	ONBOARD DEPLOYMENT/RETRACTION ACTUATOR	3	3	2	3	3	3	1	C.T.
2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL	4	4	3	4	4	2	2	
4.1	COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR	4	4	4	4	4	2	3	
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK	4	4	4	4	4	2	4	
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK	4	4	5	4	2	1	5	
14.3	HUMAN IN EVA WITH TOOLS	5	5	2	5	1	1	1	
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL	5	5	4	4	2	2	2	
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL	5	5	3	4	2	2	2	
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT	5	5	4	5	3	1	2	

TABLE 4.28: ARAMIS CAPABILITY APPLICATION FORM

(FROM APPENDIX 4.E)

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator With Force Feedback
CODE NUMBER: 4.2 DATE: 6/21/82 NAMES: Kurtzman/Paige/Ferreira
GENERIC FUNCTIONAL ELEMENT NUMBER AND NAME: g27 Deploy Antenna Receiver Arrays

DECISION CRITERIA (1 TO 5 SCALES; CURRENT TECH.=3 UNLESS NOTED)

TIME TO COMPLETE FUNCTIONAL ELEMENT (1 SHORT, 5 LONG): 4
REMARKS AND DATA SOURCES: The dextrous manipulator requires more time than an Onboard Deployment/Retraction Actuator as the actuator does not need to be transported to the payload as a manipulator would.

MAINTENANCE (1 LITTLE, 5 LOTS): 4
REMARKS AND DATA SOURCES: Maintenance would be low since the only parts likely to need service are the mechanical parts. The software and sensors would be very reliable (Minsky). The current technology capability, however, requires no maintenance.

NONRECURRING COST (1 LOW, 5 HIGH; CURRENT TECH.=2): 4
REMARKS AND DATA SOURCES: This cost is high since no system has yet been developed which incorporates the abilities of this manipulator. Some of the R&D will probably be done commercially.

RECURRING COST (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: This capability was judged greater than current technology in recurring costs as the Onboard Deployment/Retraction Actuator costs very little to procure and operate. This capability may cost slightly more than a dedicated manipulator since the end-effector would require more maintenance.

FAILURE-PRONENESS (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: The failure-proneness is higher than that of a human (who can correct problems after they occur) since the programming is neither adaptive or intelligent. The dedicated Onboard Deployment/Retraction Actuator is less likely to fail, although it is also more failure-prone than a human.

USEFUL LIFE (1 LONG, 5 SHORT): 2
REMARKS AND DATA SOURCES: The dextrous manipulator has a useful life which is longer than the more obsolescent dedicated manipulator. Eventually it should be replaced by manipulators with vision. Its useful life is judged longer than the single use current technology as it is capable of performing many tasks. For this functional element, the number of potential uses of the capability rather than when obsolescence will occur was the primary criterion for evaluating useful life.

DEVELOPMENTAL RISK (1 LOW, 5 HIGH; CURRENT TECH.=1): 4
REMARKS AND DATA SOURCES: This is high since there is currently no manipulator that can be called dextrous, and to advance to computer control would also be a large step.

OTHER REMARKS AND SPECIAL ASPECTS: This manipulator has the advantage of being adaptable to a number of tasks. The system could probably be built with a modular design, so that a vision capability could easily be added as it comes online. The current technology capability for performing this functional element is an Onboard Deployment/Retraction Actuator.

follow the Comparison Chart for GFE g27, specifically the form which describes the application of 4.2 Computer-Controlled Dextrous Manipulator with Force Feedback to this GFE.

Sixth, based on the study information described above, and on the specific constraints and requirements of the radio telescope project, the PE would select the ARAMIS capabilities appropriate to the project tasks. In the specific example, the decision criteria values, if merely added together, favor either 2.1 Onboard Deployment/Retraction Actuator (the "current technology" capability), or 1.1 Stored Energy Deployment Device, or 14.3 Human in EVA with Tools. However, some project-specific constraints may influence the choice: if the deployed components must also be retracted, the Stored Energy Deployment Device is inadequate; if the deployment takes place in a high orbit, difficult to reach by humans or dangerous due to high radiation levels, the Human in EVA with Tools may not be as favorable; an early technology cutoff date would exclude some of the advanced manipulator concepts; a strong need for reliability in deployment would weight the criteria values, improving the chances of those capabilities with low failure-proneness estimates; a desire to apply the deployment capability to other tasks as well would influence the decision towards the more versatile options. Thus the study output provides basic information to the user, outlining candidate capabilities, identifying further sources of data, and suggesting a systematic method to assess relative advantages and drawbacks to ARAMIS options; but the final selection requires engineering judgement by the Project Engineer.

4.9 PREVIEW OF PHASE II OF THIS STUDY: TELEPRESENCE

4.9.1 Definitions and Promising Applications

At the request of NASA OAST, the second phase of this study concentrates on the more specific subject of telepresence and its potential uses in space activities. Telepresence is defined by the character and degree of communication between the operator and the remote worksite: at the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions; at the control station, the operator receives sensory feedback to provide a feeling of actual presence at the worksite.

In other words, telepresence starts with the ingredients of current master-slave manipulators: a control station with one or two master arms; a remote worksite with one or two slave arms, geometrically similar to the master arms; and feedback (usually video, sometimes also force) to let the operator perceive what is happening at the worksite. However, telepresence requires a greater degree of dexterity and feedback than current teleoperators. The systems in use today (e.g. in the nuclear power industry) usually have two-finger claw grabbers as end-effectors, and therefore do not give the operator a feeling of natural manipulation, even in simple tasks. Similarly, the usual video feedback (from one or two cameras) does not provide depth or parallax perception, or peripheral vision; some do not have enough bandwidth to show sharp details in the workscene. To achieve telepresence, current systems may need to be upgraded to include stereovision, movable points of view, high-resolution zones of focus and low-resolution peripheral vision, sense of touch, force, and thermal and audio feedbacks. Which types and degrees of feedback are required depends on the specific task to be done; it is therefore easier to achieve telepresence in a simple, low-tolerance task than in a complex, delicate one. The defining criteria is that the interaction between operator and worksite must give the operator a comfortable impression of being there.

Phase II of this study will begin with a review of NASA program plans involving development or use of telepresence, such as remote spacecraft servicing and space structure construction. Also included will be an analysis of present state-of-the-art of technologies contributing to telepresence, to identify technologies and facilities available within NASA, within MIT, and in the U.S. in general. The future potential of these technologies and facilities will also be assessed.

This task will use a substantial part of the data developed in Phase I. This study defined 28 ARAMIS topics, including Manipulators, Tactile Sensors, Force and Torque Sensors, Imaging Sensors, Human-Machine Interfaces, Human Augmentation and Tools, Teleoperation Techniques, and Data Transmission Technology. All of these are also topics in telepresence. More specifically, Table 4.29 lists the ARAMIS capabilities defined in Phase I which may either contribute to or involve telepresence. The body of data on these capabilities, including sources of further information, is available to Phase II.

TABLE 4.29: ARAMIS CAPABILITIES POTENTIALLY CONTRIBUTING TO, OR INVOLVING TELEPRESENCE

6.1	Optical Scanner (Passive Cooperative Target)
6.2	Proximity Sensors
10.1	Thermal Imaging Sensor with Human Processing
13.1	Human Eyesight via Video
13.2	Human Eyesight via Graphic Display
13.5	Computer-Generated Audio
13.6	Stereoptic Video
13.7	3-D Display
14.1	Direct Human Eyesight
14.3	Human in EVA with Tools
14.5	Human Judgment on Ground
14.7	Onsite Human with Computer Assistance
14.8	Onsite Human Judgment
15.1	Specialized Manipulator under Human Control
15.2	Dextrous Manipulator under Human Control
15.3	Teleoperator Maneuvering System with Manipulator Kit
15.4	Teleoperated Docking Mechanism
16.1	Computer Modeling and Simulation
17.1	Tracking and Data Relay Satellite System
17.2	Direct Transmission to/from Ground
17.3	Direct Transmission to/from Orbiter
17.4	Direct Communication to/from Orbiter via Cable
25.1	Onboard Dedicated Microprocessor
25.2	Onboard Microprocessor Hierarchy
25.3	Onboard Deterministic Computer Program
25.5	Onboard Adaptive Control System
27.2	Equipment Function Test by Onsite Human
27.3	Equipment Function Test via Telemetry
27.5	Equipment Data Checks by Onsite Human
27.6	Equipment Data Checks via Telemetry

The study group will then select some representative projects for detailed case design studies of the application of telepresence in space. Candidates for study are the Advanced X-ray Astrophysics Facility (which would be studied as a telepresence counterpart to the EVA-serviced Space Telescope), the Teleoperator Maneuvering System, and the Space Platform.

It is anticipated that telepresence can provide a variety of services in space projects, either operating alone (e.g. a telepresence-equipped TMS inspecting and servicing satellites) or in partnership with astronauts (e.g. a construction team of two astronauts in EVA and three or four telepresence-equipped construction devices). Telepresence can operate in unhealthy environments (e.g. high-radiation orbits), or on delicate hardware (e.g. a vapor deposition factory which would be contaminated by oxygen leakage from pressure suits). Since telepresence does not require onsite life-support, it can perform tasks in locations expensive for humans to reach (e.g. geostationary or polar orbits). While the potential advantages of telepresence are not in question, the specific cases in which telepresence is warranted, and the degree of sophistication adequate to these tasks, are not yet clear. Section 4.7.2 of this report identified a number of promising applications of ARAMIS to mechanical actuation tasks: these capabilities span the whole range of telepresence. However, the relative merits of these options depend on specific details of their applications. Therefore Phase II will explore these options in specific case studies.

4.9.2 Issues in Telepresence

Some of the fundamental issues in telepresence, to be addressed by Phase II, are listed in Table 4.30, in the form of currently unresolved questions.

TABLE 4.30: SOME ISSUES IN TELEPRESENCE DEVELOPMENT

End-Effector Design:

1) Are non-anthropomorphic end-effectors (e.g. interchangeable end-effectors including specialized tools) sufficient for some tasks?

2) For those tasks which are best done by hands, should the hands have five, four, or fewer fingers?

3) Should fingers include force feedback, tactile feedback (imaging, force, or slip), thermal feedback?

Teleoperator Design:

1) Should telepresence devices be free-flying or fixed-base?

2) What loads will a telepresence manipulator encounter, and what strength will it require?

3) What is the tradeoff between teleoperator capability (e.g. its degree of telepresence) and cost?

4) To what extent can a computer in the control loop (supervisory control) help achieve telepresence?

Human Factors:

1) If the worksite manipulators are larger than human arms, how will the operator adapt to the unusual dynamics and scale effects?

2) In dealing with transmission time delays between operator and worksite, what are the limitations and alternatives to predictive displays?

3) What cues does the operator need to determine the orientations and velocities of objects (including the telepresence devices) in space?

4) What are the "presence" requirements (visual field, tactile fidelity) to make the operator feel comfortably onsite?

5) To what extent can ground-based simulations be used to validate telepresence concepts for use in space?

4.10 PHASE I CONCLUSIONS AND RECOMMENDATIONS

4.10.1 Conclusions

At the end of Phase I of the ARAMIS study, the research team draws the following conclusions:

1) Automation, Robotics, and Machine Intelligence Systems can be applied to a wide variety of NASA activities, both in space and on the ground.

2) In most cases, ARAMIS will not replace humans; it is more likely to be used to make the existing workforce more productive. This increase in productivity will be required to meet the higher workloads projected for the next fifteen years (e.g. Shuttle launch rates of 25 to 40 per year).

3) The ARAMIS study method provides an orderly display of ARAMIS options for space project tasks. It presents a traceable data base to the study recipient, and suggests a systematic method to select appropriate ARAMIS options. The input data can be refined and updated, and various weightings applied to the decision criteria values, as an aid to the decision making process.

4) Promising applications of ARAMIS to space and ground activities, selected on the basis of equal weightings of the seven decision criteria, are described in Section 4.7.2 of this report.

5) Case design studies and experimental work are needed to focus on the study information in the context of specific space projects. This is particularly true for telepresence applications, because the optimum mix of the human operators and of the several technologies involved is not yet clear.

6) Potential applications of ARAMIS to payload handling and launch vehicle operations at Kennedy Space Center require more specific study, for two reasons:

   a) KSC requires many parallel, interrelated functions under strict timelines. Therefore application of ARAMIS to one task may affect many others. Such relationships were beyond the scope of our more general study.

   b) Payload handling at KSC is one of the principal interfaces between NASA and the spacecraft builder. The division of functions between NASA and the spacecraft builder is not yet clear, particularly in the context of the new Space Transportation System.

7) Space-qualified microprocessors will play a critical role in ARAMIS applications to spacecraft functions. Low weight, low power consumption, and large computational capability make current microprocessor chips a fundamental enabling technology for a wide variety of space activities.

8) There is considerable ARAMIS expertise throughout NASA. However, information on individual contributions to this expertise is not widely distributed.

9) Industry is doing a considerable amount of R&D on ARAMIS for manufacturing applications. Much of this research can be used by NASA, but in-house work will be needed to adapt these developments to specific NASA needs.

4.10.2 Recommendations

Based on the information developed in Phase I of the ARAMIS study, the research team makes the following recommendations:

1) There should be more study on telepresence, for application to routine functions, servicing, failure diagnosis and repair, and construction of spacecraft. This should include:
   a) case design studies to develop quantitative estimates of the relative merits of options.
   b) experimental work, because design studies alone cannot fully evaluate the benefits and drawbacks of this multi-technology area.
   c) development of simulation facilities to aid in the development of operational telepresence systems.

   In all of the above objectives, the concept of supervisory control deserves special attention.

2) There should be more study of computer <u>expert systems</u>, for support of spacecraft decision functions. This should include:

   a) analyses of potential applications of expert systems in general, since their abilities are not yet fully projected.

   b) a study of the specific application of expert systems to the problems of spacecraft failure diagnosis and handling.

   c) an evaluation of the requirements in putting an expert system on a spacecraft or space platform.

   As spacecraft complexity increases, and Failure Modes and Effects Analyses become combinatorially impossible for traditional methods, the expert system may be the best method to deal with spacecraft failures, both during design and operation.

3) There should be more specific study of ARAMIS applications to <u>payload handling and launch vehicle operations</u> at Kennedy Space Center, including:

   a) a review of ARAMIS potential in helping payload handling functions, with attention to the respective roles of NASA and the spacecraft builder.

   b) analyses of the flow of Space Transportation System processing, to identify likely areas of ARAMIS enhancement.

   c) an evaluation of machine intelligence options to support the launch protocol during countdown.

4) There should be studies and developmental work on space-qualified microprocessors for spacecraft applications, including:

   a) a review of specific potential applications.

   b) an analysis of the relative merits of space-rating microprocessor chips versus flying redundant sets of chips as delivered by commercial manufacturers.

   c) analyses of the tradeoffs between developing dedicated chips for specific applications, or using generic chips and developing specialized software.

   NASA should develop an in-house capability to devise, design, debug, produce, test, and space-rate microprocessor chips for spacecraft. (If space-rating is not required, the production could be commercial.) Interactive computer-aided-design systems for chips, interfaced with rapid chip manufacturing facilities, are in use today (e.g. at the MIT A.I. Lab).

5) Other promising applications of ARAMIS identified by this study are described in section 4.7.2 of this report. Case design studies and experimental work should be done on these concepts, to develop quantitative estimates of their performance in specific space projects.

6) A central clearinghouse for information on ARAMIS would be a benefit to NASA, to improve transfer of information both within NASA and between the ARAMIS community and NASA.

An interactive network (modeled after DARPA's ARPANET) should also be considered. Links to the ARPANET should be established, as a means of access to ARAMIS research. The major conferences on ARAMIS now include tutorials on the state-of-the-art and technical displays, and should therefore receive more attention from potential users.

7) NASA should consider developing a computer simulation and data management system for satellites, to be implemented end-to-end, i.e. from the original mission definition, through spacecraft design, manufacture, test, integration, launch, on-orbit checkout, nominal operations, spacecraft modifications, and fault diagnosis and handling. Such a system would enhance communication between mission supervisors, and reduce documentation costs. As the study group found in its own data management system, important objectives are that each individual user should have access to <u>all</u> the data, and that paper should become <u>secondary</u> to the computer as a communication medium.

8) The ARAMIS technologies are currently in rapid development, and the optimum mix of humans and machines will change in character and degree as both human support and machine technologies evolve. Therefore, general updates on the overall state-of-the-art and potential of ARAMIS for space applications should be performed every four years, so that NASA can make informed decisions on which ARAMIS options to develop.

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APPENDIX 4.A
GENERIC FUNCTIONAL ELEMENT LIST
(GROUPED BY TYPES OF GFE's)

4.A.1 Notes on this Appendix

As discussed in Section 4.4.1, the Generic Functional Element List presented in Appendix 2.C (Volume 2) was rearranged for ease of access and clarity of presentation. The 330 generic functional elements (GFE's) were classified into 9 types, listed in Table 4.A.1.

TABLE 4.A.1: TYPES AND SUBTOTALS OF GFE'S

		Total GFE's
A.	Power Handling	14
B.	Checkout	21
C.	Mechanical Actuation	111
D.	Data Handling and Communication	22
E.	Monitoring and Control	85
F.	Computation	21
G.	Decision and Planning	20
H.	Fault Diagnosis & Handling	12
I.	Sensing	24
	Total	330

Each GFE was assigned to one (and only one) type, at the discretion of the study group. Since there are many overlaps between types of GFE's (e.g. between Computation and Decision and Planning), the reader may need to check more than one type before finding the desired GFE.

While producing the original space project breakdowns (presented in Appendix 2.A, Volume 2), the study group used several conventions in nomenclature. The GFE names including the world "checkout" (e.g. g23 Power Subsystem Checkout) refer to on-orbit checkout, either after launch or after maintenance and repair. The words "Verify ... Function" (e.g. g1 Verify Power System Function) indicate the verification of subsystems prior to launch, during payload integration at KSC. The wording "Check ..." (e.g. g10 Check Electrical Interfaces) indicates a final check of the payload, still before launch but after payload integration. "Container" refers to a container dedicated to the payload, i.e. what the contractor uses for shipping. "Canister" means the KSC orbiter-payload canister. Some acronyms were used:

GSP:	Geostationary Platform
AXAF:	Advanced Xray Astrophysics Facility
TMS:	Teleoperator Maneuvering System
SP:	Space Platform
PGHM:	Payload Ground Handling Mechanism
OTV:	Orbital Transfer Vehicle
RMS:	Remote Manipulator System
CITE:	Cargo Integration Test Equipment

(continued)

OMS:	Orbital Maneuvering Subsystem
TDRSS:	Tracking and Data Relay Satellite System
SAA:	South Atlantic Anomaly
FOV:	Field of view

The listing of the 330 GFE's, grouped by types, follows.

A. POWER HANDLING

g1: VERIFY POWER SYSTEM FUNCTION
g23: POWER SUBSYSTEM CHECKOUT
g84: MEASURE CURRENTS AND VOLTAGES
g85: COMPARE CURRENTS AND VOLTAGES TO REQUIRED LIMITS
g86: EVALUATE BATTERY CHARGING PERFORMANCE
g87: ADJUST CURRENTS AND VOLTAGES
g88: ADJUST BATTERY CHARGING CYCLE
g143: MONITOR BATTERIES
g210: REDUCE VOLTAGES IN SENSITIVE EQUIPMENT
g240: MAINTAIN SAFE BATTERY CHARGE LEVELS
g303: PAYLOAD INTERNAL POWER ACTIVATED
g308: REDUCE POWER TO SUBSYSTEMS
g313: SP ON INTERNAL POWER
g319: EVALUATE SOLAR ARRAY PERFORMANCE

B. CHECKOUT

g2: VERIFY COMMAND SYSTEM FUNCTION
g3: VERIFY MECHANICAL SYSTEM FUNCTION
g5: MISSION SEQUENCE SIMULATION
g9: CHECK SHUTTLE/PAYLOAD MECHANICAL INTERFACES
g10: CHECK ELECTRICAL INTERFACES
g11: CHECK PAYLOAD/BOOSTER MECHANICAL INTERFACES
g20: CLOSE-OUT PAYLOAD BAY
g33: VERIFY DEPLOYMENT SEQUENCES
g48: THERMAL SUBSYSTEM CHECKOUT
g49: STRUCTURE SUBSYSTEM CHECKOUT
g51: ATTITUDE CONTROL SUBSYSTEM CHECKOUT
g52: PROPULSTION SUBSYSTEM CHECKOUT
g54: CONSUMABLES LEVELS CHECKOUT
g123: CHECK TMS/PAYLOAD MECHANICAL INTERFACES
g130: INSTALLATION OF ORBITER PAYLOAD STATION CONSOLES
g139: STRUCTURAL SUBSYSTEM CHECKOUT

g154: CHECK FOR LEAKS
g171: VERIFY DETECTOR SYSTEM FUNCTION
g250: CHECK EXPERIMENTAL PACKAGE INTERFACE
g260: SP/PAYLOAD INTERFACE CHECKOUT
g304: ORBITER/PAYLOAD INTEGRATION CHECKOUT

C. MECHANICAL ACTUATION

[Note: g103 Apply Compensating Forces, g104 Apply Vibration Damping, and g191 Apply Compensating Torques, are listed under Computation, because the primary role of automation is expected to be in the computation of the control profiles.]

g6: LOAD PAYLOAD INTO CONTAINER
g7: TRANSPORT CONTAINER TO VERTICAL PROCESSING FACILITY
g8: UNLOAD CONTAINER
g12: LOAD PAYLOAD INTO CANISTER
g13: TRANSPORT TO ROTATING SERVICE STRUCTURE
g14: LOAD CANISTER INTO ROTATING SERVICE STRUCTURE
g15: LOAD PAYLOAD INTO ROTATING SERVICE STRUCTURE USING PGHM
g16: REMOVE CANISTER
g17: MATE ROTATING SERVICE STRUCTURE TO ORBITER
g18: EXTEND PAYLOAD INTO ORBITER USING PGHM
g19: CONNECT ORBITER/PAYLOAD INTERFACES
g21: OPEN PAYLOAD BAY DOORS
g22: ROTATE OTV/GSP PACKAGE OUT OF ORBITER
g25: RAISE CENTRAL MAST
g26: DEPLOY MAIN REFLECTORS
g27: DEPLOY ANTENNA RECEIVER ARRAYS
g28: DEPLOY ANTENNA TRANSMIT ARRAYS
g29: DEPLOY SUBREFLECTOR
g30: DEPLOY INTERFEROMETER
g31: DEPLOY SOLAR ARRAYS
g32: DEPLOY RADIATORS
g34: RETRACT SOLAR PANELS

g42: SEPARATE OTV FROM GSP
g45: DEPLOY SOLAR PANELS
g46: DEPLOY INTER-PLATFORM LINK ANTENNAS
g67: TRANSFER REPAIR EQUIPMENT TO REPAIR SITE
g68: OPEN ACCESS PANEL
g70: REMOVE COMPONENT
g71: STORE COMPONENT
g73: POSITION AND CONNECT NEW COMPONENT
g75: CLOSE ACCESS PANEL
g76: STOW REPAIR EQUIPMENT
g118: ANTENNA POSITIONER CORRECTS POINTING DIRECTION
g124: ATTACH STRONGBACK TO PAYLOAD
g125: REMOVE STRONGBACK
g126: CLOSE CANISTER
g127: TRANSPORT CANISTER TO ORBITER PROCESSING FACILITY
g128: UNLOAD CANISTER
g129: INSTALL PAYLOAD IN ORBITER
g133: MOVE RMS TO FIXTURE
g134: GRASP FIXTURE
g135: RELEASE PAYLOAD RESTRAINTS
g136: TRANSLATE PAYLOAD OUT OF PAYLOAD BAY
g137: RMS RELEASES PAYLOAD
g138: SECURE RMS IN PAYLOAD BAY
g140: RELEASE DOCKING LATCH
g141: RETRACT DOCKING MECHANISM
g145: EXTEND DOCKING MECHANISM
g146: FASTEN DOCKING LATCH
g148: EXTEND AND ATTACH UMBILICAL
g152: DETACH AND RETRACT UMBILICAL
g156: DISCONNECT OLD TANK
g157: REMOVE OLD TANK
g158: STORE OLD TANK
g160: INSTALL NEW TANK
g161: CONNECT NEW TANK

g163: TRANSFER DEBRIS TO DISPOSAL POSITION
g164: JETTISON DEBRIS
g165: STOW TMS ANTENNA
g168: TRANSLATE PAYLOAD TO CRADLE
g170: FASTEN PAYLOAD RESTRAINTS
g172: TRANSPORT TO OPERATIONS AND CHECKOUT BLDG.
g173: INSTALL PAYLOAD IN HORIZONTAL CITE
g174: INSTALLATION OF OMS KIT
g175: TILT PAYLOAD TO VERTICAL POSITION
g177: RELEASE SOLAR ARRAY RESTRAINTS
g179: RELEASE SUNSHADE RESTRAINTS
g180: OPEN SUNSHADE
g181: DEPLOY TDRSS ANTENNAS
g195: RETRACT TDRSS ANTENNAS
g196: CLOSE SUNSHADE
g197: RETRACT SOLAR ARRAYS
g198: TILT PAYLOAD TO HORIZONTAL POSITION
g199: CLOSE PAYLOAD BAY DOORS
g209: CLOSE OPTICAL SHUTTERS
g213: MOVE DETECTOR INTO POSITION
g229: DEPLOY RENDEZVOUR SENSOR
g233: DISCONNECT DETECTOR
g234: REMOVE DETECTOR
g235: STORE DETECTOR
g237: INSTALL DETECTOR
g238: CONNECT DETECTOR
g247: SPIN UP DEBRIS CAPTURE DEVICE
g248: BRAKE DEBRIS CAPTURE DEVICE
g249: RELEASE SPACECRAFT FROM DEBRIS CAPTURE DEVICE
g251: RETRACT RADIATORS
g252: ORIENT THRUSTERS
g255: DOCKING OF SHUTTLE ADAPTER TO SPACE PLATFORM
g256: SP BERTHING ON DOCKING ADAPTER
g257: STOW OLD PAYLOAD IN ORBITER
g259: ATTACH NEW PAYLOAD TO SP

g262: UNDOCKING OF ORBITER FROM SP
g267: POSITION MANIPULATOR (ON RAILS)
g268: GRASP SAMPLE
g269: TRANSPORT SAMPLE TO EXPERIMENT AREA
g270: OPEN HOLDER
g271: INSERT SAMPLE
g272: CLOSE HOLDER
g284: GET SAMPLE WITH SAMPLE HOLDER
g285: REMOVE SAMPLE FROM FURNACE
g286: RELEASE SAMPLE FROM SAMPLE HOLDER
g287: REMOVE SAMPLE FROM HOLDER
g288: TRANSPORT SAMPLE TO STORAGE BIN
g289: RELEASE SAMPLE IN BIN
g305: PRIORITY REMOVAL OF TIME-CRITICAL ITEMS
g306: PAYLOAD REMOVAL FROM ORBITER PROCESSING FACILITY
g310: ORIENT NEW PAYLOADS
g311: ATTACH NEW PAYLOADS
g328: EXCHANGE PERSONNEL, THROUGH DOCKING MODULE
g329: STORAGE OF CONSUMABLES IN HABITAT MODULE
g330: PRIORITY REMOVAL OF PERSONNEL

D. DATA HANDLING AND COMMUNICATION

g4: VERIFY COMMUNICATIONS SYSTEM FUNCTION
g50: COMMUNICATIONS SUBSYSTEM CHECKOUT
g53: TRAFFIC ROUTING SUBSYSTEM CHECKOUT
g78: DATA/COMMAND ENCODING
g79: DATA/COMMAND TRANSMISSION
g89: SHORT-TERM MEMORY STORAGE
g90: LONG-TERM MEMORY STORAGE
g91: DATA/COMMAND DECODING
g109: DATA/COMMAND DISPLAY
g119: RECEIVE COMMUNICATIONS INPUT
g120: ENTER COMMUNICATIONS INPUT INTO SWITCH CONTROL
g121: SWITCH CONTROL ENTERS COMMUNICATIONS INPUT INTO SWITCH MATRIX

g122: SWITCH MATRIX EXECUTES COMMUNICATIONS OUTPUT
g212: RECEIVE GROUND COMMANDS
g218: TAKE DATA FROM DETECTOR
g219: TAKE DATA FROM ASPECT SENSORS
g224: PROCESS IMAGE DATA
g225: DETERMINE ALIGNMENT CORRECTION
g241: MAINTAIN COMMUNICATION LINKS
g280: RECORDING AND ON-BOARD STORAGE OF DATA
g298: TRANSMIT DATA TO GROUND PROCESSING CENTER
g307: SEND GROUND SIGNAL TO SP TO BEGIN SERV. SEQ.

E. MONITORING AND CONTROL

g35: INITIALIZE GUIDANCE SYSTEM
g36: DETERMINE CURRENT ORBITAL PARAMETERS
g39: DETERMINE CURRENT ATTITUDE
g41: FIRE THRUSTERS
g43: SEPARATION COAST
g44: TRANSFER OF OTV TO SUPERSYNCHRONOUS ORBIT
g47: ACTIVATE SUBSYSTEMS
g82: COMPARE TEMPERATURES TO REQUIRED LIMITS
g83: ADJUST COOLING/HEATING SYSTEMS
g95: MONITOR PROPELLANT SUPPLIES
g96: MONITOR COOLING SYSTEM SUPPLIES
g111: ROTATE SPACECRAFT
g114: EXECUTE CONTROL COMMANDS
g115: RECEIVE INPUT FROM ANTENNA POINTING SENSORS
g116: TRANSMIT INFORMATION TO ANTENNA POINTING CONTROLLER
g117: DETERMINE ERROR FROM DESIRED ANTENNA POSITION
g131: ACTIVATE RMS
g142: MOVE AWAY FROM PAYLOAD
g147: CLOSE INTERNAL VALVES
g149: OPEN SUPPLY VALVE
g150: MONITOR FLUID TRANSFER

g151: CLOSE SUPPLY VALVE
g153: OPEN INTERNAL VALVES
g162: COAST TO SUPERSYNCHRONOUS ORBIT
g166: DEACTIVATE TMS SUBSYSTEMS
g182: COMMAND DETECTOR SELECTION
g183: OBSERVE DETECTOR SELECTION
g184: MONITOR TELEMETRY
g186: ACTIVATE AXAF SUBSYSTEMS
g187: COMMAND ATTITUDE CHANGE
g188: OBSERVE ATTITUDE CHANGE
g192: SHUTDOWN SPACECRAFT SYSTEMS
g193: MATCH AXAF VELOCITY AND ATTITUDE WITH ORBITER
g200: ADJUST HEATING/COOLING SYSTEMS
g201: MONITOR GAS SUPPLIES
g202: PRESSURIZE DETECTORS WHEN NEEDED
g203: DEPRESSURIZE DETECTORS WHEN NOT IN USE
g206: MONITOR BRIGHT OBJECT DETECTOR
g207: MONITOR SAA DETECTOR
g211: SHUTDOWN DETECTORS
g214: DETECTOR POWER ON
g215: DETECTOR COOLING ON
g216: OPEN DETECTOR APERTURES
g217: FINE FOCUS DETECTOR
g226: ACTIVATE TMS SUBSYSTEMS
g228: ALIGN ORBITER WITH EXPECTED TARGET POSITION
g230: ACTIVATE RENDEZVOUR SENSOR
g239: AVOID TANK OVERPRESSURES
g253: ORBITER AND SP VELOCITY AND TRAJECTORY ADJUSTMENTS
g254: ACTIVATE DOCKING ADAPTER
g261: TRANSFER OPERATIONAL CONTROL FROM MISSION TO PAYLOAD CONTROL
g263: COMPARE TEMPERATURE TO REQUIRED LIMITS
g264: MONITOR MICRO-GRAVITY LEVELS
g273: ACTIVATE FAIL-SAFE SUBSYSTEM(S)
g275: SET (OR EVACUATE) FURNACE ATMOSPHERE
g276: ACTIVATE EXPERIMENTAL PROCESS SPECIFIC EQUIPMENT
g278: ACTIVATE FURNACE TEMPERATURE-MAINTAINING UNIT

g279: INITIATE GAS ANALYZER OPERATION

g281: MEASURE EXPERIMENTAL DATA, WITH SPEC. INSTRUMENTATION

g282: COOL SAMPLE

g283: ADJUST FURNACE PRESSURE TO SAFE LEVEL

g290: PURGE GASES FROM FURNACE

g291: BAKEOUT FURNACE

g292: REPROGRAM PROCESS SET-POINTS AND CONTROLS

g293: DEFROST LIVE CELLS

g294: SUPPLY NUTRIENTS AND GASES

g295: REMOVE ORGANIC WASTES

g296: PUMP SAMPLE INTO CHAMBER

g297: PUMP MEDIA FLUID INTO CHAMBER

g299: WHEN SPECIFIED GROWTH PARAMS. REACHED, PREPARE SAMPLE FOR RETURN

g300: STORE PRODUCTS IN A CONTROLLED ENVIRONMENT FOR RETURN

g301: FLUSH SYSTEM WITH BIOCIDE, PRIOR TO NEXT CYCLE

g302: SP INTERFACE WITH PAYLOAD IS SHUTDOWN

g309: SHUTDOWN EXPERIMENTAL PACKAGES

g312: SHUTDOWN PAYLOADS

g315: COMPARE ATMOSPHERIC TEMPERATURES TO REQUIRED LIMITS

g316: MONITOR HABITAT PRESSURE, ATMOSPHERIC COMPOSITION

g317: COMPARE TO REQUIRED LIFE SUPPORT CONDITIONS

g318: ADJUST HABITAT-MAINTENANCE SUBSYSTEMS

g320: MONITOR HABITAT-MAINTENANCE SYSTEMS SUPPLIES

g321: MONITOR SUPPLIES, CONDITION OF PERISHABLES

g322: MONITOR EQUIPMENT INVENTORY

g324: MONITOR RADIATION LEVELS

g325: MONITOR VITAL SIGNS OF CREW MEMBERS

g326: MONITOR REST, NUTRITION OF CREW MEMBERS

F. COMPUTATION

g24: INFORMATION PROCESSING SUBSYSTEM CHECKOUT

g55: COMPARE MEASURED DATA TO MODEL

g80: COMPUTER FUNCTION CHECKS

g92: NUMERICAL COMPUTATION
g93: LOGIC OPERATIONS
g94: COMPUTER LOAD SCHEDULING
g101: COMPUTE STRESS AND VIBRATION PARAMETERS
g102: COMPARE STRESS AND VIBRATION PARAMETERS TO REQUIRED LIMITS
g103: APPLY COMPENSATING FORCES
g104: APPLY VIBRATION DAMPING
g113: COMPUTE CONTROL COMMANDS
g189: DETERMINE DISTURBING TORQUES
g190: COMPUTE REQUIRED RESULTANT
g191: APPLY COMPENSATING TORQUES
g204: COMPUTE POSITIONS OF SUN, EARTH, MOON
g205: DETERMINE ANGLES RELATIVE TO TELESCOPE LINE-OF-SIGHT
g208: COMPARE DETECTOR OUTPUT TO PRESET LIMITS
g221: DETERMINE IF TARGET IS WITHIN DETECTOR FOV
g222: DETERMINE IF TARGET IS WITHIN ASPECT SENSOR FOV
g232: COMPUTER TERMINAL PHASE OMS BURN
g274: CHECK ALIGNMENT WITH ALIGNMENT CRITERIA

G. DECISION AND PLANNING

g37: DETERMINE DESIRED ORBITAL PARAMETERS
g38: CHOOSE OPTIMAL TRAJECTORY
g40: DETERMINE DESIRED ATTITUDE
g64: UPDATE SPACECRAFT MODEL
g97: PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE
g98: COMPUTE OPTIMAL CONSUMABLES ALLOCATION
g105: PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE
g106: ESTIMATE RISKS FROM DESIRED FUNCTIONS
g107: DETERMINE CONSTRAINTS AND FIGURES OF MERIT
g108: COMPUTE OPTIMAL SEQUENCING
g110: DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS
g112: CHOOSE OPTIMAL CONTROL MODE
g185: EVALUATE SYSTEM PERFORMANCE
g220: PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART

g223: SELECT NEW TELESCOPE ATTITUDE IF NECESSARY
g227: COMPUTE EXPECTED TARGET POSITION
g242: AVOID EXPOSING SENSITIVE COMPONENTS TO DIRECT SUNLIGHT
g244: AVOID CONFLICTING OBJECTS
g323: MAINTAIN EMERGENCY CONSUMABLES RESERVE
g327: UPDATE HABITAT MODEL

H. FAULT DIAGNOSIS AND HANDLING

g56: DETERMINE ANOMALOUS DATA
g57: FORM HYPOTHESIS FOR PROBLEM
g58: DEVISE TEST FOR FAILURE HYPOTHESIS
g59: PERFORM TEST FOR FAILURE HYPOTHESIS
g60: IDENTIFY FAULTY COMPONENT
g61: SWITCH OUT FAULTY COMPONENT
g62: SWITCH IN REDUNDANT COMPONENT
g63: MAKE DIAGNOSTIC CHECKS
g65: DEFINE ACCESS SEQUENCE
g74: ADJUST COMPONENT
g77: DETERMINE CORRECTION ALGORITHM
g194: IDENTIFY FAULTY SOFTWARE

I. SENSING

g66: LOCATE ACCESS PANEL
g69: OBSERVE/LOCATE DEFECTIVE COMPONENT
g72: LOCATE NEW COMPONENT
g81: MEASURE COMPONENT TEMPERATURES
g99: MEASURE STRAINS IN STRUCTURE
g100: MEASURE RELATIVE DISPLACEMENTS
g132: LOCATE GRASPING FIXTURE ON TARGET
g144: LOCATE DOCKING TARGET
g155: LOCATE OLD TANK
g159: LOCATE NEW TANK
g167: LOCATE CRADLE IN PAYLOAD BAY

g169: LOCATE PAYLOAD RESTRAINTS
g176: LOCATE SOLAR ARRAY RESTRAINTS
g178: LOCATE SUNSHADE RESTRAINTS
g231: TRACK TARGET
g236: LOCATE DETECTOR
g243: TRACK NEARBY OBJECTS
g245: OBSERVE TUMBLING SPACECRAFT
g246: DETERMINE SPACECRAFT PRINCIPAL SPIN AXIS
g258: LOCATE NEW PAYLOAD
g265: IDENTIFY SHAPE, SIZE IN BIN
g266: MATCH WITH SAMPLE MODEL
g277: MEASURE COMPONENT TEMPERATURE
g314: MEASURE MODULE ATMOSPHERIC TEMPERATURES

APPENDIX 4.B:

REDUCED GENERIC FUNCTIONAL ELEMENT LIST

4.B.1 Notes on this Appendix

This appendix repeats the Generic Functional Element (GFE) List (grouped by types of GFE's) presented in Appendix 4.A. However, this appendix identifies those 69 GFE's selected for detailed study, and presents explanations for why the other GFE's were set aside.

The GFE's selected for further study are marked by a "+". As described in Section 4.4.2, the other GFE's were set aside according to one or more of six criteria. These are indicated by specific notations in this appendix:

1) "Current technology" - this GFE is adequately handled by current techniques; any proposed alternatives appear to degrade overall performance.
2) "Too specific" - this GFE would have to be very specifically defined before candidate ARAMIS capabilities could be identified for it; and then those capabilities would be closely tailored pieces of ARAMIS with no other useful applications. For example, g74 Adjust Component would require identification of the component being adjusted, and the candidate capabilities would then be specific to that component. This nomenclature is also applied to GFE's that are clearly the province of the spacecraft user, e.g. payload-specific functions on the Space Platform.

3) "Similar to ..." - two GFE's are similar, from the ARAMIS point of view, in that they both suggest the same list of candidate ARAMIS capabilities, and the relative merits of those capabilities are expected to be similar for both GFE's. For example, g210 Reduce Voltages in Sensitive Equipment is similar to g87 Adjust Currents and Voltages, since all the likely options to perform g210 are also options to perform g87. The user should note that some candidate capabilities to perform the GFE selected for study (g87, in this case) may not be appropriate for the more specific g210; in such cases the study group kept the GFE with the wider selection of candidate capabilities. Thus some engineering judgment is required in assessing the similarity of GFE's of interest, and in interpreting the evaluations of capabilities later in this study (e.g. the "best" candidate capability for GFE g87 is likely to be also the best for g210, but the user should consider the extent of the similarity before accepting that judgment).

4) "Inverse of ..." - indicates that two GFE's are the reverse task of each other (e.g. g73 Position and Connect New Component and g70 Remove Component). However, the tasks are similar to each other in the sense described above, i.e. the same candidate capabilities apply to both GFE's; therefore only one GFE is kept for further study.

5) "Indcluded in ..." - indicates that this GFE is so closely coupled to another that the same capability would be used for both. Therefore both GFE's would have the same candidate

capabilities and be "similar" in the sense described above; only one GFE is kept for detailed study.

6) "No ARAMIS suggested" - this GFE is an event (e.g. g43 Separation Coast) rather than a task, and therefore does not suggest any capabilities.

7) "Infrequent" - this GFE occurs so seldom that development of an ARAMIS capability for it would probably not be economical.

8) In addition, three typographical errors were identified, holdovers from the space project breakdowns (the computer program which collects the GFE list interprets typos as separate GFE's).

As in Appendix 4.A, the 330 generic functional elements are classified in 9 types. These types, together with subtotals of GFE's, are listed in Table 4.B.1.

TABLE 4.B.1: TYPES AND SUBTOTALS OF GFE's (INCLUDING REDUCED LIST SUBTOTALS)

		Total GFE's	GFE's kept for detailed study
A.	Power Handling	14	5
B.	Checkout	21	9
C.	Mechanical Actuation	111	8
D.	Data Handling and Communication	22	9
E.	Monitoring and Control	85	9
F.	Computation	21	6
G.	Decision and Planning	20	12
H.	Fault Diagnosis & Handling	12	7
I.	Sensing	24	4
	Totals	330	69

The numbers in the Table show that the largest reduction was in Mechanical Actuation GFE's. As detailed in the listing later in this appendix, 19 of these GFE's involve payload check-out and handling functions at KSC, prior to launch. Most of these are labeled "current technology", in that current techniques are adequate to perform the task; several are labeled "too specific", since they vary from spacecraft to spacecraft. The study group feels that a number of these GFE's could probably be improved by ARAMIS. However, the problems in applying automation and robotics to payload integration and checkout at KSC are complex. First, these procedures involve close coordination of multiple tasks under stringent timelines and facility constraints, so that insertion of ARAMIS into one task requires an evaluation of its effect on many other tasks. Second, it is difficult to identify tasks sufficiently common to many satellites that the development of ARAMIS capabilities is warranted. At present, only 15% of the time spent in payload integration and checkout is actual testing; the rest is hands-on operations (assembly of components and support equipment, connection of interfaces, transport of payload between facilities) which tend to be specific to the payload, hence difficult to automate (Ref. 4.10). Third, this is one of the principal interfaces between NASA and the spacecraft contractors, and it is not yet clear which functions should be performed by NASA and which by the users; these distinctions will become more evident as experience with the Space Transportation System increases. Therefore the study group feels that a general study such as this one could not do justice to the complexities of these issues, and recommends that a more specific study be undertaken to explore the ARAMIS options for mechanical actuation tasks in payload integration and checkout at KSC. This is discussed further in Section 4.10 <u>Phase I Conclusions and Recommendations</u>. A number of payload integration GFE's of other types (e.g. g10 Check Electrical Interfaces in B. Checkout) were kept for detailed study.

Another 20 Mechanical Actuation GFE's deal with Shuttle operations during payload deployment and retrieval, and some post-flight operations. Most of these were labeled "current technology" because they are adequately handled by current methods. The application of ARAMIS to the Space Transportation System itself was outside the scope of this study.

Of the remaining Mechanical Actuation GFE's, 15 involved deployment or retraction of spacecraft components, and were therefore similar to g27 Deploy Antenna Receiver Arrays or g31 Deploy Solar Arrays, both kept for study. Another 19 involved positioning, attachment, or disconnection of spacecraft components, and were therefore similar to g73 Position and Connect New Component. Most of the other Mechanical Actuation GFE's that were set aside are relatively simple current spacecraft tasks, e.g. g209 Close Optical Shutters.

The next largest reduction is in E. Monitoring and Control, from 85 GFE's to 9. Many of the GFE's set aside are tasks commonly done by automation on current spacecraft, e.g. g36 Determine Orbital Parameters. Sixteen GFE's dealt with particular pieces of experimental equipment, and were therefore labeled "too specific". Thirteen GFE's were judged similar to g47 Activate Subsystems. Seven GFE's were similar to g93 Logic Operations (in F. Computation).

4.B.2 Nomenclature

While producing the original space project breakdowns (presented in Appendix 2.A, Volume 2), the study group used several conventions in nomenclature. The GFE names including the word "checkout" (e.g. g23 Power Subsystem Checkout) refer to on-orbit checkout, either after launch or after maintenance and repair. The words "Verify ... Function" (e.g. g1 Verify Power System Function) indicate the verification of subsystems prior to launch, during payload integration at KSC. The wording "Check ..." (e.g. g10 Check Electrical Interfaces) indicates a final check of the payload, still before launch but after payload integration. "Container" refers to a container dedicated to the payload, i.e. what the contractor uses for shipping. "Canister" means the KSC orbiter-payload canister. Some acronyms were used:

GSP:	Geostationary Platform
AXAF:	Advanced Xray Astrophysics Facility
TMS:	Teleoperator Maneuvering System
SP:	Space Platform
PGHM:	Payload Ground Handling Mechanism
OTV:	Orbital Transfer Vehicle
RMS:	Remote Manipulator System
CITE:	Cargo Integration Test Equipment
OMS:	Orbital Maneuvering Subsystem
TDRSS:	Tracking and Data Relay Satellite System

(continued)

SAA: South Atlantic Anomaly

FOV: Field of view

The listing of the Reduced Generic Functional Element List follows.

A. POWER HANDLING

+ g1: VERIFY POWER SYSTEM FUNCTION

+ g23: POWER SUBSYSTEM CHECKOUT

g84: MEASURE CURRENTS AND VOLTAGES
Current technology.

g85: COMPARE CURRENTS AND VOLTAGES TO REQUIRED LIMITS
Similar to g93 Logic Operations (in F. Computation).

g86: EVALUATE BATTERY CHARGING PERFORMANCE
Similar to g88.

+ g87: ADJUST CURRENTS AND VOLTAGES

+ g88: ADJUST BATTERY CHARGING CYCLE

g143: MONITOR BATTERIES
Similar to g88.

g210: REDUCE VOLTAGES IN SENSITIVE EQUIPMENT
Similar to g87.

+ g240: MAINTAIN SAFE BATTERY CHARGE LEVELS

g303: PAYLOAD INTERNAL POWER ACTIVATED
Similar to g87.

g308: RECUCE POWER TO SUBSYSTEMS
Similar to g87.

g313: SP ON INTERNAL POWER
Similar to g87.

g319: EVALUATE SOLAR ARRAY PERFORMANCE
Similar to g88.

B. CHECKOUT

g2: VERIFY COMMAND SYSTEM FUNCTION
Similar to gl Verify Power System Function (in A. Power Handling) and g24 Information Processing Subsystem Checkout (in F. Computation).

g3: VERIFY MECHANICAL SYSTEM FUNCTION
Similar to g1 (in A. Power Handling) and g49.

\+ g5: MISSION SEQUENCE SIMULATION

g9: CHECK SHUTTLE/PAYLOAD MECHANICAL INTERFACES
Current technology.

\+ g10: CHECK ELECTRICAL INTERFACES

g11: CHECK PAYLOAD/BOOSTER MECHANICAL INTERFACES
Current technology.

g20: CLOSE-OUT PAYLOAD BAY
Current technology, too specific.

\+ g33: VERIFY DEPLOYMENT SEQUENCES

\+ g48: THERMAL SUBSYSTEM CHECKOUT

\+ g49: STRUCTURE SUBSYSTEM CHECKOUT

\+ g51: ATTITUDE CONTROL SUBSYSTEM CHECKOUT

\+ g52: PROPULSION SUBSYSTEM CHECKOUT

\+ g54: CONSUMABLES LEVELS CHECKOUT

g123: CHECK TMS/PAYLOAD MECHANICAL INTERFACES
Current technology.

g130: INSTALLATION OF ORBITER PAYLOAD STATION CONSOLES
Current technology, too specific.

g139: STRUCTURAL SUBSYSTEM CHECKOUT
Typographical error - same as g49.

g154: CHECK FOR LEAKS
Current technology, or similar to g48, g54, or g150 Monitor Fluid Transfer (in E. Monitoring and Control).

g171: VERIFY DETECTOR SYSTEM FUNCTION
Similar to g1 (in A. Power Handling) or too specific.

g250: CHECK EXPERIMENTAL PACKAGE INTERFACE
Current technology, or similar to g10 or g260.

\+ g260: SP/PAYLOAD INTERFACE CHECKOUT

g304: ORBITER/PAYLOAD INTEGRATION CHECKOUT
Current technology, or similar to g10 or g260.

C. MECHANICAL ACTUATION

[Note: g103 Apply Compensating Forces, g104 Apply Vibration Damping, and g191 Apply Compensating Torques are listed under Computation, because the primary role of automation is expected to be in the computation of the control profiles.]

g6: LOAD PAYLOAD INTO CONTAINER
Current technology, too specific.

g7: TRANSPORT CONTAINER TO VERTICAL PROCESSING FACILITY
Current technology, too specific.

g8: UNLOAD CONTAINER
Current technology, too specific.

g12: LOAD PAYLOAD INTO CANISTER
Current technology.

g13: TRANSPORT TO ROTATING SERVICE STRUCTURE
Current technology.

g14: LOAD CANISTER INTO ROTATING SERVICE STRUCTURE
Current technology.

g15: LOAD PAYLOAD INTO ROTATING SERVICE STRUCTURE USING PGHM
Current technology.

g16: REMOVE CANISTER
Current technology.

g17: MATE ROTATING SERVICE STRUCTURE TO ORBITER
Current technology.

g18: EXTEND PAYLOAD INTO ORBITER USING PGHM
Current technology.

g19: CONNECT ORBITER/PAYLOAD INTERFACES
Too specific.

g21: OPEN PAYLOAD BAY DOORS
Current technology.

g22: ROTATE OTV/GSP PACKAGE OUT OF ORBITER
Current technology.

g25: RAISE CENTRAL MAST
Similar to g27 and g31.

g26: DEPLOY MAIN REFLECTORS
Similar to g27 and g31.

+ g27: DEPLOY ANTENNA RECEIVER ARRAYS

g28: DEPLOY ANTENNA TRANSMIT ARRAYS
Similar to g27.

g29: DEPLOY SUBREFLECTOR
Similar to g27 and g31.

g30: DEPLOY INTERFEROMETER
Similar to g27.

+ g31: DEPLOY SOLAR ARRAYS

g32: DEPLOY RADIATORS
Similar to g31.

g34: RETRACT SOLAR PANELS
Current technology or inverse of g31.

g42: SEPARATE OTV FROM GSP
Current technology.

g45: DEPLOY SOLAR PANELS
Current technology or similar to g31.

g46: DEPLOY INTER-PLATFORM LINK ANTENNAS
Similar to g27 and g31.

+ g67: TRANSFER REPAIR EQUIPMENT TO REPAIR SITE

g68: OPEN ACCESS PANEL
Current technology.

g70: REMOVE COMPONENT
Inverse of g73.

g71: STORE COMPONENT
Current technology, too specific.

+ g73: POSITION AND CONNECT NEW COMPONENT

g75: CLOSE ACCESS PANEL
Current technology.

g76: STOW REPAIR EQUIPMENT
Inverse of g67.

g118: ANTENNA POSITIONER CORRECTS POINTING DIRECTION
Current technology.

g124: ATTACH STRONGBACK TO PAYLOAD
Current technology.

g125: REMOVE STRONGBACK
Current technology.

g126: CLOSE CANISTER
Current technology.

g127: TRANSPORT CANISTER TO ORBITER PROCESSING FACILITY
Current technology.

g128: UNLOAD CANISTER
Current technology.

g129: INSTALL PAYLOAD IN ORBITER
Current technology, too specific.

g133: MOVE RMS TO FIXTURE
Current technology.

+ g134: GRASP FIXTURE

g135: RELEASE PAYLOAD RESTRAINTS
Current technology or similar to g177.

g136: TRANSLATE PAYLOAD OUT OF PAYLOAD BAY
Current technology.

g137: RMS RELEASES PAYLOAD
No ARAMIS suggested.

g138: SECURE RMS IN PAYLOAD BAY
Current technology, or inverse of g131 Activate RMS (similar to g47 Activate Subsystems, in E. Monitoring and Control).

g140: RELEASE DOCKING LATCH
Current technology, or inverse of g146.

g141: RETRACT DOCKING MECHANISM
Current technology, included in g146.

g145: EXTEND DOCKING MECHANISM
Current technology, included in g146.

+ g146: FASTEN DOCKING LATCH

+ g148: EXTEND AND ATTACH UMBILICAL

g152: DETACH AND RETRACT UMBILICAL
Inverse of g148.

g156: DISCONNECT OLD TANK
Inverse of g73.

g157: REMOVE OLD TANK
Inverse of g73.

g158: STORE OLD TANK
Current technology, too specific.

g160: INSTALL NEW TANK
Similar to g73.

g161: CONNECT NEW TANK
Similar to g73.

g163: TRANSFER DEBRIS TO DISPOSAL POSITION
Infrequent.

g164: JETTISON DEBRIS
Infrequent.

g165: STOW TMS ANTENNA
Current technology or inverse of g27.

g168: TRANSLATE PAYLOAD TO CRADLE
Current technology.

g170: FASTEN PAYLOAD RESTRAINTS
Current technology or inverse of g177.

g172: TRANSPORT TO OPERATIONS AND CHEKCOUT BLDG.
Current technology.

g173: INSTALL PAYLOAD IN HORIZONTAL CITE
Current technology.

g174: INSTALLATION OF OMS KIT
Current technology.

g175: TILT PAYLOAD TO VERTICAL POSITION
Current technology.

\+ g177: RELEASE SOLAR ARRAY RESTRAINTS

g179: RELEASE SUNSHADE RESTRAINTS
Similar to g177.

g180: OPEN SUNSHADE
Current technology.

g181: DEPLOY TDRSS ANTENNAS
Current technology, similar to g27.

g195: RETRACT TDRSS ANTENNAS
Current technology, inverse of g27.

g196: CLOSE SUNSHADE
Current technology.

g197: RETRACT SOLAR ARRAYS
Inverse of g31.

g198: TILT PAYLOAD TO HORIZONTAL POSITION
Current technology.

g199: CLOSE PAYLOAD BAY DOORS
Current technology.

g209: CLOSE OPTICAL SHUTTERS
Current technology or too specific.

g213: MOVE DETECTOR INTO POSITION
Current technology.

g229: DEPLOY RENDEZVOUS SENSOR
Current technology, similar to g27.

g233: DISCONNECT DETECTOR
Inverse of g73.

g234: REMOVE DETECTOR
Inverse of g73.

g235: STORE DETECTOR
Current technology.

g237: INSTALL DETECTOR
Similar to g73.

g238: CONNECT DETECTOR
Similar to g73.

g247: SPIN UP DEBRIS CATPURE DEVICE
Current technology.

g248: BRAKE DEBRIS CAPTURE DEVICE
Current technology.

g249: RELEASE SPACECRAFT FROM DEBRIS CAPTURE DEVICE
Current technology.

g251: RETRACT RADIATORS
Inverse of g31.

g252: ORIENT THRUSTERS
Current technology.

g255: DOCKING OF SHUTTLE ADAPTER TO SPACE PLATFORM
Current technology, or similar to g146.

g256: SP BERTHING ON DOCKING ADAPTER
Current technology, too specific.

g257: STOW OLD PAYLOAD IN ORBITER
Current technology.

g259: ATTACH NEW PAYLOAD TO SP
Current technology, or similar to g73.

g262: UNDOCKING OF ORBITER FROM SP
Current technology, or inverse of g146.

g267: POSITION MANIPULATOR (ON RAILS)
Current technology.

g268: GRASP SAMPLE
Similar to g73.

g269: TRANSPORT SAMPLE TO EXPERIMENT AREA
Current technology, or similar to g73.

g270: OPEN HOLDER
Current technology.

g271: INSERT SAMPLE
Similar to g73.

g272: CLOSE HOLDER
Current technology.

g284: GET SAMPLE WITH SAMPLE HOLDER
Inverse of g73.

g285: REMOVE SAMPLE FROM FURNACE
Inverse of g73.

g286: RELEASE SAMPLE FROM SAMPLE HOLDER
Current technology.

g287: REMOVE SAMPLE FROM HOLDER
Current technology or inverse of g73.

g288: TRANSPORT SAMPLE TO STORAGE BIN
Current technology or similar to g73.

g289: RELEASE SAMPLE IN BIN
Current technology.

g305: PRIORITY REMOVAL OF TIME-CRITICAL ITEMS
Current technology or too specific.

g306: PAYLOAD REMOVAL FROM ORBITER PROCESSING FACILITY
Current technology.

g310: ORIENT NEW PAYLOADS
Current technology or similar to g73.

g311: ATTACH NEW PAYLOADS
Current technology or similar to g73.

g328: EXCHANGE PERSONNEL, THROUGH DOCKING MODULE
Current technology, no ARAMIS suggested.

g329: STORAGE OF CONSUMABLES IN HABITAT MODULE
Current technology or too specific.

g330: PRIORITY REMOVAL OF PERSONNEL
Current technology, infrequent.

D. DATA HANDLING AND COMMUNICATION

g4: VERIFY COMMUNICATIONS SYSTEM FUNCTION
Similar to g1 Verify Power System Function (in A. Power Handling) and g50.

\+ g50: COMMUNICATIONS SUBSYSTEM CHECKOUT

g53: TRAFFIC ROUTING SUBSYSTEM CHECKOUT
Too specific. See also g121.

\+ g78: DATA/COMMAND ENCODING

\+ g79: DATA/COMMAND TRANSMISSION

\+ g89: SHORT-TERM MEMORY STORAGE

\+ g90: LONG-TERM MEMORY STORAGE

g91: DATA/COMMAND DECODING
Inverse of g78.

+ g109: DATA/COMMAND DISPLAY

g119: RECEIVE COMMUNICATIONS INPUT

Current technology or too specific. See also g121.

g120: ENTER COMMUNICATIONS INPUT INTO SWITCH CONTROL

Too specific. See also g121.

g121: SWITCH CONTROL ENTERS COMMUNICATIONS INPUT INTO SWITCH MATRIX

Switch-matrixing is the process of connecting together the appropriate receivers and transmitters within a multiband, multibeam communications platform. The application of automation to this switchboarding task is very much a current issue. However, a general study such as this one cannot do justice to the critical details of this very complex technology, and oversimplification of the issues would weaken the research efforts. Therefore the reader is referred to detailed studies, e.g. Geostationary Platform Systems Concepts Definition Study, Final Report, General Dynamics Convair Division and Comsat Labs, NASA contract NAS8-33527, June 1980. This publication, Volume III, section 3.4.3, describes several matrix switches in development by Comsat Labs, TRW, Hughes Aircraft, and Nippon Electric.

g122: SWICH MATRIX EXECUTES COMMUNICATIONS OUTPUT

Too specific. See also g121.

g212: RECEIVE GROUND COMMANDS

Current technology, or similar to g79.

+ g218: TAKE DATA FROM DETECTOR

g219: TAKE DATA FROM ASPECT SENSORS

Similar to g218.

+ g224: PROCESS IMAGE DATA

g225: DETERMINE ALIGNMENT CORRECTION

Included in g224.

+ g241: MAINTAIN COMMUNICATION LINKS

g280: RECORDING AND ON-BOARD STORAGE OF DATA

Similar to g89 and g90.

g298: TRANSMIT DATA TO GROUND PROCESSING CENTER

Similar to g79.

g307: SEND GROUND SIGNAL TO SP TO BEGIN SERV. SEQ.
Similar to g79.

E. MONITORING AND CONTROL

+ g35: INITIALIZE GUIDANCE SYSTEM

g36: DETERMINE CURRENT ORBITAL PARAMETERS
Current technology.

g39: DETERMINE CURRENT ATTITUDE
Current technology.

g41: FIRE THRUSTERS
Current technology.

g43: SEPARATION COAST
No ARAMIS suggested.

g44: TRANSFER OF OTV TO SUPERSYNCHRONOUS ORBIT
Current technology.

+ g47: ACTIVATE SUBSYSTEMS

g82: COMPARE TEMPERATURES TO REQUIRED LIMITS
Similar to g93 Logic Operations (in F. Computation).

+ g83: ADJUST COOLING/HEATING SYSTEMS

g95: MONITOR PROPELLANT SUPPLIES
Current technology, or similar to g54 Consumables Levels Checkout (in B. Checkout).

g96: MONITOR COOLING SYSTEM SUPPLIES
Current technology, or similar to g54 (in B. Checkout).

g111: ROTATE SPACECRAFT
Current technology.

g114: EXECUTE CONTROL COMMANDS
Current technology or too specific.

g115: RECEIVE INPUT FROM ANTENNA POINTING SENSORS
Current technology.

g116: TRANSMIT INFORMATION TO ANTENNA POINTING CONTROLLER
Current technology.

g117: DETERMINE ERROR FROM DESIRED ANTENNA POSITION
Current technology.

g131: ACTIVATE RMS
Current technology, or similar to g47.

g142: MOVE AWAY FROM PAYLOAD
No ARAMIS suggested.

g147: CLOSE INTERNAL VALVES
Current technology.

g149: OPEN SUPPLY VALVE
Current technology.

\+ g150: MONITOR FLUID TRANSFER

g151: CLOSE SUPPLY VALVE
Current technology.

g153: OPEN INTERNAL VALVES
Current technology.

g162: COAST TO SUPERSYNCHRONOUS ORBIT
No ARAMIS suggested.

g166: DEACTIVATE TMS SUBSYSTEMS
Inverse of g47.

g182: COMMAND DETECTOR SELECTION
Current technology.

g183: OBSERVE DETECTOR SELECTION
Current technology or similar to g184.

\+ g184: MONITOR TELEMETRY

g186: ACTIVATE AXAF SUBSYSTEMS
Similar to g47.

g187: COMMAND ATTITUDE CHANGE
Current technology, or similar to g93 Logic Operations (in F. Computation) or g98 Compute Optimal Consumables Allocation (in G. Decision and Planning).

g188: OBSERVE ATTITUDE CHANGE
Current technology or similar to g184.

g192: SHUTDOWN SPACECRAFT SYSTEMS
Inverse of g47.

g193: MATCH AXAF VELOCITY AND ATTITUDE WITH ORBITER
Current technology.

g200: ADJUST HEATING/COOLING SYSTEMS
Typographical error - same as g83.

g201: MONITOR GAS SUPPLIES
Current technology, or similar to g54 (in B. Checkout).

g202: PRESSURIZE DETECTORS WHEN NEEDED
Current technology, too specific.

g203: DEPRESSURIZE DETECTORS WHEN NOT IN USE
Current technology.

g206: MONITOR BRIGHT OBJECT DETECTOR
Too specific.

g207: MONITOR SAA DETECTOR
Too specific.

g211: SHUTDOWN DETECTORS
Inverse of g47, or similar to g93 (in F. Computation) or too specific.

g214: DETECTOR POWER ON
Current technology, similar to g47.

g215: DETECTOR COOLING ON
Similar to g47 and g83.

g216: OPEN DETECTOR APERTURES
Current technology, too specific.

g217: FINE FOCUS DETECTOR
Too specific.

g226: ACTIVATE TMS SUBSYSTEMS
Similar to g47.

g228: ALIGN ORBITER WITH EXPECTED TARGET POSITION.
Current technology.

g230: ACTIVATE RENDEZVOUR SENSOR
Current technology.

\+ g239: AVOID TANK OVERPRESSURES

g253: ORBITER AND SP VELOCITY AND TRAJECTORY ADJUSTMENTS
Current technology.

g254: ACTIVATE DOCKING ADAPTER
Current technology, similar to g47.

g261: TRANSFER OPERATIONAL CONTROL FROM MISSION TO PAYLOAD CONTROL
No ARAMIS suggested.

g263: COMPARE TEMPERATURE TO REQUIRED LIMITS
Typographical error - same as g82.

+ g264: MONITOR MICRO-GRAVITY LEVELS

g273: ACTIVATE FAIL-SAFE SUBSYSTEM(S)
Current technology or similar to g47 or too specific.

g275: SET (OR EVACUATE) FURNACE ATMOSPHERE
Similar to g318 (from the ARAMIS point of view, focusing on data evaluation and control functions).

g276: ACTIVATE EXPERIMENTAL PROCESS SPECIFIC EQUIPMENT
Too specific.

g278: ACTIVATE FURNACE TEMPERATURE-MAINTAINING UNIT
Current technology or similar to g83 or too specific.

g279: INITIATE GAS ANALYZER OPERATION
Too specific.

g281: MEASURE EXPERIMENTAL DATA, WITH SPEC. INSTRUMENTATION
Too specific.

g282: COOL SAMPLE
Too specific or similar to g83.

g283: ADJUST FURNACE PRESSURE TO SAFE LEVEL
Current technology, or similar to g318.

g290: PURGE GASES FROM FURNACE
Current technology, or similar to g318.

g291: BAKEOUT FURNACE
Similar to g83.

g292: REPROGRAM PROCESS SET-POINTS AND CONTROLS
Similar to g93 (in F. Computation).

g293: DEFROST LIVE CELLS
Similar to g83.

g294: SUPPLY NUTRIENTS AND GASES
Too specific.

g295: REMOVE ORGANIC WASTES
Too specific.

g296: PUMP SAMPLE INTO CHAMBER
Too specific.

g297: PUMP MEDIA FLUID INTO CHAMBER
Too specific.

g299: WHEN SPECIFIED GROWTH PARAMS. REACHED, PREPARE SAMPLE FOR RETURN
Too specific.

g300: STORE PRODUCTS IN A CONTROLLED ENVIRONMENT FOR RETURN
Too specific.

g301: FLUSH SYSTEM WITH BIOCIDE, PRIOR TO NEXT CYCLE
Too specific.

g302: SP INTERFACE WITH PAYLOAD IS SHUTDOWN
Inverse of g47, similar to g83 and g87 Adjust Currents and Voltages (in A. Power Handling). See also g260 SP/Payload Interface Checkout (in B. Checkout).

g309: SHUTDOWN EXPERIMENTAL PACKAGES
Too specific, or inverse of g47.

g312: SHUTDOWN PAYLOADS
Inverse of g47.

g315: COMPARE ATMOSPHERIC TEMPERATURES TO REQUIRED LIMITS
Similar to g93 (in F. Computation), included in g318.

g316: MONITOR HABITAT PRESSURE, ATMOSPHERIC COMPOSITION
Current technology, included in g318.

g317: COMPARE TO REQUIRED LIFE SUPPORT CONDITIONS
Similar to g93 (in F. Computation), included in g318.

+ g318: ADJUST HABITAT-MAINTENANCE SUBSYSTEMS

g320: MONITOR HABITAT-MAINTENANCE SYSTEMS SUPPLIES
Current technology, or similar to g54 (in B. Checkout).

g321: MONITOR SUPPLIES, CONDITION OF PERISHABLES
Too specific.

g322: MONITOR EQUIPMENT INVENTORY
Similar to g93 (in F. Computation).

g324: MONITOR RADIATION LEVELS
Similar to g264.

+ g325: MONITOR VITAL SIGNS OF CREW MEMBERS

g326: MONITOR REST, NUTRITION OF CREW MEMBERS
Included in g325.

F. COMPUTATION

+ g24: INFORMATION PROCESSING SUBSYSTEM CHECKOUT

g55: COMPARE MEASURED DATA TO MODEL
Similar to g93, or included in g56 Determine Anomalous Data (in H. Fault Diagnosis and Handling).

g80: COMPUTER FUNCTION CHECKS
Similar to g24.

+ g92: NUMERICAL COMPUTATION

+ g93: LOGIC OPERATIONS

+ g94: COMPUTER LOAD SCHEDULING

g101: COMPUTE STRESS AND VIBRATION PARAMETERS
Included in g103, similar to g92.

g102: COMPARE STRESS AND VIBRATION PARAMETERS TO REQUIRED LIMITS
Similar to g93, or included in g103.

+ g103: APPLY COMPENSATING FORCES

g104: APPLY VIBRATION DAMPING
Similar to g103.

g113: COMPUTE CONTROL COMMANDS
Current technology, or included in g92,g93, and g98 Compute Optimal Consumables Allocation (in G. Decision and Planning).

g189: DETERMINE DISTURBING TORQUES
Included in g103.

g190: COMPUTE REQUIRED RESULTANT
Included in g103.

g191: APPLY COMPONSATING TORQUES
Included in g103.

g204: COMPUTE POSITIONS OF SUN, EARTH, MOON
Current technology.

g205: DETERMINE ANGLES RELATIVE TO TELESCOPE LINE-OF-SIGHT
Similar to g110 Determine New Configuration for Spacecraft Components (in G. Decision and Planning).

g208: COMPARE DETECTOR OUTPUT TO PRESET LIMITS
Similar to g93.

\+ g221: DETERMINE IF TARGET IS WITHIN DETECTOR FOV

g222: DETERMINE IF TARGET IS WITHIN ASPECT SENSOR FOV
Similar to g221.

g232: COMPUTE TERMINAL PHASE OMS BURN
Similar to g38 Choose Optimal Trajectory (in G. Decision and Planning).

g274: CHECK ALIGNMENT WITH ALIGMENT CRITERIA
Current technology or too specific (this GFE refers to alignment of experimental samples in a furnace).

G. DECISION AND PLANNING

\+ g37: DETERMINE DESIRED ORBITAL PARAMETERS

\+ g38: CHOOSE OPTIMAL TRAJECTORY

g40: DETERMINE DESIRED ATTITUDE
Similar to g37.

\+ g64: UPDATE SPACECRAFT MODEL

\+ g97: PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE

\+ g98: COMPUTE OPTIMAL CONSUMABLES ALLOCATION

\+ g105: PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE

g106: ESTIMATE RISKS FROM DESIRED FUNCTIONS
Included in g107.

\+ g107: DETERMINE CONSTRAINTS AND FIGURES OF MERIT

g108: COMPUTE OPTIMAL SEQUENCING
Included in g98.

\+ g110: DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS

g112: CHOOSE OPTIMAL CONTROL MODE
Similar to g93 Logic Operations (in F. Computation), included in g98.

+ g185: EVALUATE SYSTEM PERFORMANCE

+ g220: PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART

+ g223: SELECT NEW TELESCOPE ATTITUDE IF NECESSARY

g227: COMPUTE EXPECTED TARGET POSITION
Similar to g37, included in g243 Track Nearby Objects (in I. Sensing).

g242: AVOID EXPOSING SENSITIVE COMPONENTS TO DIRECT SUNLIGHT
Current technology, similar to g110 and g93 (in F. Computation).

+ g244: AVOID CONFLICTING OBJECTS

g323: MAINTAIN EMERGENCY CONSUMABLES RESERVE
Current technology, or similar to g54 Consumables Levels Checkout (in B. Checkout).

g327: UPDATE HABITAT MODEL
Similar to g64.

H. FAULT DIAGNOSIS AND HANDLING

+ g56: DETERMINE ANOMALOUS DATA

+ g57: FORM HYPOTHESIS FOR PROBLEM

+ g58: DEVISE TEST FOR FAILURE HYPOTHESIS

g59: PERFORM TEST FOR FAILURE HYPOTHESIS
Current technology or included in g60 or too specific.

+ g60: IDENTIFY FAULTY COMPONENT

g61: SWITCH OUT FAULTY COMPONENT
Current technology.

g62: SWITCH IN REDUNDANT COMPONENT
Current technology.

g63: MAKE DIAGNOSTIC CHECKS
Too specific.

+ g65: DEFINE ACCESS SEQUENCE

g74: ADJUST COMPONENT
Too specific.

+ g77: DETERMINE CORRECTION ALGORITHM

+ g194: IDENTIFY FAULTY SOFTWARE

I. SENSING

g66: LOCATE ACCESS PANEL
Similar to g69 or included in g65 Define Access Sequence (in H. Fault Diagnosis and Handling).

+ g69: OBSERVE/LOCATE DEFECTIVE COMPONENT

g72: LOCATE NEW COMPONENT
Similar to g69.

g81: MEASURE COMPONENT TEMPERATURES
Current technology.

g99: MEASURE STRAINS IN STRUCTURE
Current technology.

g100: MEASURE RELATIVE DISPLACEMENTS
Current technology. See also g243.

+ g132: LOCATE GRASPING FIXTURE ON TARGET

g144: LOCATE DOCKING TARGET
Included in g146 Fasten Docking Latch (in C. Mechanical Actuation).

g155: LOCATE OLD TANK
Similar to g69.

g159: LOCATE NEW TANK
Similar to g69.

g167: LOCATE CRADLE IN PAYLOAD BAY
Current technology.

g169: LOCATE PAYLOAD RESTRAINTS
Similar to g69 and g132.

g176: LOCATE SOLAR ARRAY RESTRAINTS
Similar to g69, g132.

g178: LOCATE SUNSHADE RESTRAINTS
Similar to g69, g132.

g231: TRACK TARGET
Current technology, similar to g132.

g236: LOCATE DETECTOR
Similar to g69.

+ g243: TRACK NEARBY OBJECTS

+ g245: OBSERVE TUMBLING SPACECRAFT

g246: DETERMINE SPACECRAFT PRINCIPAL SPIN AXIS
Included in g245.

g258: LOCATE NEW PAYLOAD
Current technology. See also g69, g132.

g265: IDENTIFY SHAPE, SIZE IN BIN
Similar to g69 and g93 Logic Operations (in F. Computation).

g266: MATCH WITH SAMPLE MODEL
Similar to g69 and g93 (in F. Computation).

g277: MEASURE COMPCNENT TEMPERATURE
Typographical error - same as g81.

g314: MEASURE MODULE ATMOSPHERIC TEMPERATURES
Current technology.

APPENDIX 4.C:
DEFINITIONS OF GFE'S SELECTED FOR FURTHER STUDY

4.C.1 Notes on this Appendix

The 69 GFE's selected for detailed study were identified in Appendix 4.B. This Appendix presents those 69 GFE's (grouped by types of GFE's), with brief definitions. Some GFE's represent other GFE's, i.e. those GFE's in Appendix 4.B labeled "similar to" the defined GFE. In those cases the definition includes a list of those "similar" GFE's.

The definitions of some GFE's have been expanded beyond their restricted meanings in the original project breakdowns. This makes these GFE's more likely to occur in other projects, including those of study users. The increased generality also allows these GFE's to cover other similar GFE's, as described above.

In general, this study defines GFE's from the ARAMIS point of view, concentrating on those aspects of the task to which ARAMIS applies. For example, in payload checkout functions, the study focuses more on overall methods of defining and commanding the tests, and of collecting and evaluating test data, than on specific instrumentation. Similarly, in many monitoring functions, the study concentrates on data evaluation and response systems rather than on measurement sensors.

4.C.2 Nomenclature

While producing the original space project breakdowns (presented in Appendix 2.A, Volume 2), the study group used several conventions in nomenclature. The GFE names including the word "checkout" (e.g. g23 Power Subsystem Checkout) refer to on-orbit checkout, either after launch or after maintenance and repair. The words "Verify ... Function" (e.g. g1 Verify Power System Function) indicate the verification of subsystems prior to launch, during payload integration at KSC. The wording "Check ..." (e.g. g10 Check Electrical Interfaces) indicates a final check of the payload, still before launch but after payload integration. "Container" refers to a container dedicated to the payload, i.e. what the contractor uses for shipping. "Canister" means the KSC orbiter-payload canister. Some acronyms were used:

GSP:	Geostationary Platform
AXAF:	Advanced Xray Astrophysics Facility
TMS:	Teleoperator Maneuvering System
SP:	Space Platform
OTV:	Orbital Transfer Vehicle
RMS:	Remove Manipulator System
OMS:	Orbital Maneuvering Subsystem
TDRSS:	Tracking and Data Relay Satellite System
FOV:	Field of View

The listing of GFE's and their definitions follows.

A. POWER HANDLING

g1: VERIFY POWER SYSTEM FUNCTION

Verification of the proper function of spacecraft power subsystems, during payload assembly and integration at KSC (usually done by the spacecraft contractor). This GFE includes verification of subsystems, prior to launch, in general.

Also covers: g2 Verify Command System Function
g3 Verify Mechanical System Function
g171 Verify Detector System Function
g4 Verify Communications System Function

g23: POWER SUBSYSTEM CHECKOUT

On-orbit checkout of spacecraft power subsystems, either after launch or after maintenance and repair. This study focuses on methods of controlling the checkout process and evaluating subsystem performance, rather than specific sensors. As spacecraft state-of-the-art moves toward fully integrated power management systems, this task may include g48 Thermal Subsystem Checkout(in B. Checkout).

g87: ADJUST CURRENTS AND VOLTAGES

The control of spacecraft power systems, including evaluation of operational and state-of-health data, power allocation and network configuration, switching and power level control, mechanical actuation (e.g. solar array pointing), and contingency management. This study concentrates on the evaluation and control functions, rather than specific switching or measurement equipment. As spacecraft state-of-the-art moves toward fully integrated power management systems, this task may include g83 Adjust Cooling/Heating Systems (in E. Monitoring and Control).

Also covers: g210 Reduce Voltages in Sensitive Equip.
g303 Payload Internal Power Activated
g308 Reduce Power to Subsystems
g313 SP on Internal Power
g302 SP Interface with Payload is Shutdown

g88: ADJUST BATTERY CHARGING CYCLE

The monitoring, evaluation, and adjustment of the charging cycle for spacecraft batteries. This includes switching to reconditioning cycles as needed.

Also covers: g86 Evaluate Battery Charging Performance
g143 Monitor Batteries
g319 Evaluate Solar Array Performance

g240: MAINTAIN SAFE BATTERY CHARGE LEVELS

The evaluation of the state of charge of spacecraft batteries, and the avoidance of discharge or overcharge conditions which may damage the batteries. This can range from a local protection circuit dedicated to one battery to a spacecraft power control system that trades off battery state-of-health with other mission objectives.

B. CHECKOUT

g5: MISSION SEQUENCE SIMULATION

The simulation of spacecraft mission tasks, during payload integration and checkout, prior to launch. Intended to verify the proper function and interaction of spacecraft subsystems, this task can be performed either with the spacecraft hardware, or with computer simulation, or with a mixture of both.

g10: CHECK ELECTRICAL INTERFACES

Checks of the integrity and proper function of electrical interfaces, after payload integration, but before launch. This includes interfaces within a spacecraft, between a spacecraft and a booster stage, and between a spacecraft and the Shuttle Orbiter.

Also covers: g250 Check Experimental Package Interface
g304 Orbiter/Payload Integration Checkout

g33: VERIFY DEPLOYMENT SEQUENCES

On-orbit check that the deployed components (e.g. solar arrays, radiators, instrument booms) have properly deployed and latched into position. Although usually done shortly after launch, deployment and this verification may need to be repeated later in the spacecraft life; for such repetitions, it may be more difficult to provide onsite humans (e.g. in GEO).

g48: THERMAL SUBSYSTEM CHECKOUT

On-orbit check that thermal components (e.g. heaters, pumps, radiators) are functioning properly. Usually done shortly after launch, this checkout may have to be repeated later in the spacecraft life (e.g. after modifications or repairs). As the spacecraft state-of-the-art moves toward fully integrated power management systems, this task may be incorporated with g23 Power Subsystem Checkout (in A. Power Handling).

Also covers: g154 Check for Leaks

g49: STRUCTURE SUBSYSTEM CHECKOUT

On-orbit check of the mechanical integrity of spacecraft components. Usually done shortly after launch, this may need to be repeated later in the spacecraft life (e.g. after modifications or repairs). The study concentrates more on the data handling and evaluation aspects of this

task than on the actual sensors (e.g. strain gauges).
Also covers: g3 Verify Mechanical System Function

g51: ATTITUDE CONTROL SUBSYSTEM CHECKOUT

On-orbit check of the proper function of the attitude control subsystem of the spacecraft. Usually done in the vicinity of the Shuttle after launch and deployment, this task may be repeated later in the spacecraft life, especially after modifications to the spacecraft which modify its dynamic properties.

g52: PROPULSION SUBSYSTEM CHECKOUT

On-orbit check of the components of a spacecraft propulsion system. Currently done by successive tests of individual components, without actually firing the system. This procedure is not expected to change; the study focuses on commanding the tests and evaluating the return data.

g54: CONSUMABLES LEVELS CHECKOUT

On-orbit check of fluid levels in consumables tanks (e.g. propellant, cooling fluids, gas supplies, life-support fluids). The study concentrates on data evaluation rather than specific sensors.

Also covers: g154 Check for Leaks
g95 Monitor Propellant Supplies
g96 Monitor Cooling System Supplies
g201 Monitor Gas Supplies
g323 Maintain Emergency Consumables Reserve
g320 Monitor Habitat-Maintenance Systems Supplies

g260: SP/PAYLOAD INTERFACE CHECKOUT

On-orbit check of the electrical power, cooling, computer, and communications interfaces between a newly installed payload and the Space Platform. More generally, this task includes checking the interface between a retrieved payload and the Shuttle Orbiter, and the interface between an experimental package and an SP pallet.

Also covers: g250 Check Experimental Package Interface
g304 Orbiter/Payload Integration Checkout

C. MECHANICAL ACTUATION

Note: g103 Apply Compensating Forces is listed under F. Computation, because the primary role of automation is expected to be in the computation of the control profiles.

g27: DEPLOY ANTENNA RECEIVER ARRAYS

The on-orbit deployment of the GSP antenna receiver arrays and, more generally, of any spacecraft components which are not extremely fragile (fragile components are deployed under g31 Deploy Solar Arrays). Most of these deployments happen once, at the beginning of spacecraft on-orbit life; some components are later retracted and redeployed, usually as part of servicing and repair sequences.

Also covers: g25 Raise Central Mast
g26 Deploy Main Reflectors
g28 Deploy Antenna Transmit Arrays
g29 Deploy Subreflector
g30 Deploy Interferometer
g46 Deploy Inter-Platform Link Antennas
g165 Stow TMS Antenna
g181 Deploy TDRSS Antennas
g195 Retract TDRSS Antennas
g229 Deploy Rendezvous Sensor

g31: DEPLOY SOLAR ARRAYS

The on-orbit deployment of solar arrays and, more generally, of spacecraft components. This includes fragile components (e.g. solar panels, radiators) that require safe geometries and minimal stresses during deployment. Most of these components require retractions and redeployment during spacecraft life.

Also covers:
- g25 Raise Central Mast
- g26 Deploy Main Reflectors
- g29 Deploy Subreflector
- g32 Deploy Radiators
- g34 Retract Solar Panels
- g45 Deploy Solar Panels
- g46 Deploy Inter-Platform Link Antennas
- g197 Retract Solar Arrays
- g251 Retract Radiators

g67: TRANSFER REPAIR EQUIPMENT TO REPAIR SITE

The movement of necessary repair tools and replacement parts to the specific location requiring repair. This can include: the swiveling into place of dedicated repair equipment flown on the spacecraft; the movement of a repair platform or unit to the site; the movement of repair-qualified end-effectors on long manipulators; or the use of free-flying repair devices.

Also covers:
- g76 Stow Repair Equipment

g73: POSITION AND CONNECT NEW COMPONENT

The movement, alignment, insertion, and fastening of a component to (or into) a spacecraft. This includes the fastening of mechanical, electrical, and fluid interfaces. The inverse of this task covers the disconnection and removal of components from a spacecraft. Since the task includes alignment of the component, it requires either a close-tolerance actuator in a close-tolerance worksite geometry, or compliance in actuator or worksite, or feedback to the actuator control.

Also covers:
- g70 Remove Component
- g156 Disconnect Old Tank
- g157 Remove Old Tank
- g160 Install New Tank
- g161 Connect New Tank
- g233 Disconnect Detector
- g234 Remove Detector
- g237 Install Detector
- g238 Connect Detector
- g259 Attach New Payload to SP
- g268 Grasp Sample
- g269 Transport Sample to Experiment Area
- g271 Insert Sample
- g284 Get Sample with Sample Holder
- g285 Remove Sample from Furnace
- g287 Remove Sample from Holder
- g288 Transport Sample to Storage Bin
- g310 Orient New Payloads
- g311 Attach New Payloads

g134: GRASP FIXTURE

The grasping of the Shuttle RMS grapple fixture on a spacecraft or payload. More generally, the grasping of any dedicated grappling fixture on a free-floating or attached payload or spacecraft.

g146: FASTEN DOCKING LATCH

The process of hard-docking two spacecraft together. Includes the final approach of the docking spacecraft (i.e. the location of the docking target and the control of the closing motion) and the operation of mechanical docking hardware. The inverse of this task covers undocking of spacecraft.

Also covers: g140 Release Docking Latch
g141 Retract Docking Mechanism
g145 Extend Docking Mechanism
g255 Docking of Shuttle Adapter to Space Platform
g262 Undocking of Orbiter from SP
g144 Locate Docking Target

g148: EXTEND AND ATTACH UMBILICAL

The extension and fastening of a propellant-refueling umbilical between two spacecraft, after the spacecraft have hard-docked. More generally, the extension and attachment of any type of umbilical between hard-docked spacecraft or between components of a spacecraft.

Also covers: g152 Detach and Retract Umbilical

g177: RELEASE SOLAR ARRAY RESTRAINTS

The unlatching of restraints on the AXAF solar arrays. More generally, the release of component or payload restraints on or between spacecraft. The restraints are assumed to be standardized, so that any capability developed for one set of restraints could apply to many others. The inverse of this task is the fastening of component or payload restraints.

Also covers: g135 Release Payload Restraints
g170 Fasten Payload Restraints
g179 Release Sunshade Restraints

D. DATA HANDLING AND COMMUNICATION

g50: COMMUNICATIONS SUBSYSTEM CHECKOUT

On-orbit check of the proper function of spacecraft communications equipment. Usually done shortly after launch, this task may be repeated later, after spacecraft repairs or modifications. It can include communication with the Orbiter or with the ground. This task also covers the verification of the communications system at KSC, prior to launch, since this usually includes an all-up simulated test.

Also covers: g4 Verify Communications System Function

g78: DATA/COMMAND ENCODING

The conversion of data or commands from raw form to a digital bit stream suitable for transmission to or from the spacecraft. This task may involve different equipment for transmission from ground to spacecraft than vice-versa.

Also covers: g91 Data/Command Decoding

g79: DATA/COMMAND TRANSMISSION

The process of transmitting a bit stream to or from the spacecraft. The study focuses on the alternative transmission links, rather than the specific transmission hardware.

Also covers: g212 Receive Ground Commands
g298 Transmit Data to Ground Processing Center
g307 Send Ground Signal to SP to Begin Serv. Seq.

g89: SHORT-TERM MEMORY STORAGE

Storage of data or commands on board the spacecraft, prior to data manipulation, command execution, or transmission from the spacecraft. This storage is expected to be repeatedly erased and refilled with other data during nominal spacecraft operations.

Also covers: g280 Recording and On-Board Storage of Data

g90: LONG-TERM MEMORY STORAGE

The storage of data or canned command procedures, on the spacecraft, or, in some cases, on the ground. This storage is expected to be either never altered, or altered by hardware exchange (e.g. module replacement during spacecraft modification), or altered through an occasional procedure involving release of protection systems.

Also covers: g280 Recording and On-Board Storage of Data

g109: DATA/COMMAND DISPLAY

The display of data or commands to humans, either in space or on the ground. This might include state-of-health data on components, task scheduling commands and status information, scientific and operational data, output from computer calculations and evaluations.

g218: TAKE DATA FROM DETECTOR

The acceptance of data from an AXAF detector by the spacecraft, prior to any data processing or transmission from the spacecraft. More generally, the taking of data from any scientific instrument. This data can be either recorded as generated, or coded in a more useful format. [For low-level data processing, see g224 Process Image Data; for data transmission, see g79 Data/Command Transmission; for data storage, see g89 Short-Term Memory Storage or g90 Long-Term Memory Storage; for high-level data processing, see g92 Numerical Computation or g93 Logic Operations (both in F. Computation).]

Also covers: g219 Take Data from Aspect Sensors

g224: PROCESS IMAGE DATA

A low-level processing function, part of the AXAF observation sequence: the position of the Xray target is found on sensor arrays, so that the target acquisition can be confirmed and a final alignment correction to center the target in the telescope can be calculated. By extension, this includes data processing to find a known and expected pattern (without doing any pattern interpretation) in a simple image.

Also covers: g225 Determine Alignment Correction g241: MAINTAIN COMMUNICATION LINKS

The process of keeping spacecraft communications links active, either to the ground or to other spacecraft. This includes ensuring adequate antenna pointing (if directional antennas are used) and sufficient communications component functions to receive incoming signals and (usually) to transmit responses. This study focuses on the evaluation of problems and the definition and command of corrective actions, rather than on the specific sensors or actuators involved.

E. MONITORING AND CONTROL

g35: INITIALIZE GUIDANCE SYSTEM

The initial and occasional calibration of the spacecraft guidance system, using either onboard navigation equipment (e.g. star trackers), data from other satellites (e.g. the Global Positioning System), or information from the ground. This study focuses on the data processing and evaluation, and on the calibration command generation, rather than on the specific navigation or guidance hardware.

g47: ACTIVATE SUBSYSTEMS

The timely activation of components within spacecraft subsystems, to bring equipment to the operational state. This task requires that a sequence of components be activated in the proper order, possibly with verification of spacecraft status between certain steps, to ensure the safety of hardware and software. Such components might include electronic and power systems, mechanical actuators, optical equipment, thermal components, and fluid pumps and valves. This task may become critical in contingency management during failures. Its inverse covers subsystem shutdown.

Also covers: g138 Secure RMS in Payload Bay
g131 Activate RMS
g166 Deactivate TMS Subsystems
g186 Activate AXAF Subsystems
g192 Shutdown Spacecraft Systems
g211 Shutdown Detectors
g214 Detector Power On
g215 Detector Cooling On
g226 Activate TMS Subsystems
g254 Activate Docking Adapter
g273 Activate Fail-Safe Subsystem(s)
g302 SP Interface with Payload is Shutdown
g309 Shutdown Experimental Packages
g312 Shutdown Payloads

g83: ADJUST COOLING/HEATING SYSTEMS

The control of spacecraft or instrument heating and cooling systems, including evaluation of operational and state-of-health data, capacity allocation and network configuration, fluid system switching and level control, mechanical actuator command (e.g. louvers, radiator pointing), and contingency management. This study concentrates on the evaluation and control functions, rather than specific thermal equipment. As spacecraft state-of-the art moves toward fully integrated power management systems, this task may be incorporated with g87 Adjust Currents and Voltages (in A. Power Handling).

Also covers: g215 Detector Cooling On
g278 Activate Furnace Temperature-Maintaining Unit
g282 Cool Sample
g291 Bakeout Furnace
g293 Defrost Live Cells
g302 SP Interface with Payload is Shutdown

g150: MONITOR FLUID TRANSFER

The real-time check of the proper function of fluid transfer between two spacecraft (via umbilical) or between two components of a spacecraft. Includes checks of valve operations in the proper order, measurement of fluid quantity transferred, and checks for leaks or overpressures. [See also g239 Avoid Tank Overpressures.]

Also covers: g154 Check for Leaks

g184: MONITOR TELEMETRY

The monitoring of ground telemetry during the AXAF checkout and observation sequences. More generally, the monitoring of spacecraft telemetry on the ground, to obtain status data, to review instrument output, and to confirm completion of tasks. See also g56 Determine anomalous Data (in H. Fault Diagnosis and Handling).

Also covers: g183 Observe Detector Selection
g188 Observe Attitude Change

g239: AVOID TANK OVERPRESSURES

The process of ensuring that hazardous overpressures do no occur in spacecraft tankage, either by controlling tank feeds and outputs to avoid creating the hazard, by venting the tank as needed, or both. The study concentrates more on the methods to determine the hazardous condition and to command corrective action than on specific tank hardware.

g264: MONITOR MICROGRAVITY LEVELS

The measurement, recording, and (possibly) evaluation of microgravity levels during zero-g materials processing. More generally, the monitoring of environmental factors during sensitive activities. This can range from recording of the parameters for later review of test results, to real-time data processing and evaluation to determine corrective action.

Also covers: g324 Monitor Radiation Levels g318: ADJUST HABITAT-MAINTENANCE SUBSYSTEMS

The measurement of habitat life-support parameters (e.g. atmospheric pressure, composition, temperature), the comparison of these parameters to acceptable limits and ranges, the choice and computation of any corrective action, and the control of appropriate life-support devices. More generally, the monitoring and control of atmospheric and other environmental parameters in sensitive instrumentation (e.g. furnaces).

Also covers: g275 Set (or Evacuate) Furnace Atmosphere
g283 Adjust Furnace Pressure to Safe Level
g290 Purge Gases from Furnace
g315 Compare Atmospheric Temperatures to Required Limits
g316 Monitor Habitat Pressure, Atmospheric Composition
g317 Compare to Required Life Support Conditions

g325: MONITOR VITAL SIGNS OF CREW MEMBERS

The measurement, recording, and evaluation of medical data on spacecraft crew members, including real-time parameters (e.g. heart rate and body temperature during EVA) and long-term effects (e.g. rest patterns, nutrition, cardiovascular and skeletal adaptation to zero-g), and the formulation of corrective action as needed. The study focuses on methods of evaluation and decision, rather than on specific sensor equipment.

Also covers: g326 Monitor Rest, Nutrition of Crew Members

F. COMPUTATION

g24: INFORMATION PROCESSING SUBSYSTEM CHECKOUT

On-orbit checks of the proper function of spacecraft computer hardware and software (including verification of memory). These checks occur shortly after launch, and occasionally during spacecraft life, particularly after spacecraft hardware modifications or repair and after reprogramming of spacecraft or ground support software.

Also covers: g2 Verify Command System Function
g80 Computer Function Checks

g92: NUMERICAL COMPUTATION

The numerical processing of spacecraft status data (e.g. structural or thermal data from many points on the spacecraft) or instrument output (e.g. telescope images, time histories of furnace parameters), for the purpose of real-time evaluation and response, data compression and display, or calculation of control profiles.

Also covers: g113 Compute Control Commands
g101 Compute Stress and Vibration Parameters

g93: LOGIC OPERATIONS

Evaluation and decision processes applied to spacecraft data, either on the spacecraft or on the ground. Such processes include: comparison of spacecraft component data to set-points or functional models; maintenance of checklists covering task scheduling, safety interlocks, equipment inventory; avoidance of potentially hazardous conditions and procedures; confirmation of proper communication (between spacecraft, to the ground, or between components on a spacecraft); choice of appropriate next actions, or of new set-points and limits, based on spacecraft status data and mission objectives. The actual logic operations consist primarily of comparisons of data to models, leading to if-then decisions. In their simplest form, they merely involve commanding spacecraft functions in a preset manner; in their most complex form, they involve evaluation and response to a wide array of spacecraft data, including simulation of possible future actions to determine optimal courses of action. The logic operations result in commands to spacecraft components and (possibly) status messages and information requests to spacecraft controllers.

Also covers:
- g85 Compare Currents & Voltages to Req. Limits
- g82 Compare Temperatures to Required Limits
- g187 Command Attitude Change
- g211 Shutdown Detectors
- g292 Reprogram Process Set-Points and Controls
- g315 Compare Atmospheric Temperatures to Required Limits
- g317 Compare to Required Life Support Conditions
- g322 Monitor Equipment Inventory
- g55 Compare Measured Data to Model
- g102 Compare Stress and Vibration Parameters to Required Limits
- g113 Compute Control Commands
- g208 Compare Detector Output to Preset Limits
- g112 Choose Optimal Control Mode
- g242 Avoid Exposing Sensitive Components to Direct Sunlight
- g265 Identify Shape, Size in Bin
- g266 Match with Sample Model

g94: COMPUTER LOAD SCHEDULING

The process of setting priorities and allocating computer hardware use to the various software functions on a spacecraft. This process attempts to optimize the use of core capacity, memory, and input/output functions to run the software as rapidly as possible, subject to operational constraints (e.g. a particular software function <u>must</u> be run every five minutes, or certain types of memory should not be run during certain other spacecraft functions).

g103: APPLY COMPENSATING FORCES

The computation of stress and vibration parameters for spacecraft structures, their comparison to acceptable ranges or limits, the computation of appropriate responses to the conditions, and the formulation of corrective control commands to active force, torque, and damping actuators. The study focuses on data evaluation and formulation of corrective action, rather than on specific sensors or actuators. [See also g92 Numerical Computation and g93 Logic Operations.]

Also covers: g101 Compute Stress and Vibration Parameters
g102 Compare Stress and Vibration Parameters to Required Limits
g104 Apply Vibration Damping
g189 Determine Disturbing Torques
g190 Compute Required Resultant
g191 Apply Compensating Torques

g221: DETERMINE IF TARGET IS WITHIN DETECTOR FOV

A low-level data processing function on the AXAF detector image (or AXAF aspect sensor image) to determine if the desired X-ray target is within the detector field of view. [See also g224 Process Image Data, in D. Data Handling and Communication, and g223 Select New Telescope Attitude if Necessary, in G. Decision and Planning.]

Also covers: g222 Determine if Target is Within Aspect Sensor FOV

G. DECISION AND PLANNING

g37: DETERMINE DESIRED ORBITAL PARAMETERS

The determination of the desired orbital parameters of a spacecraft from knowledge of its current parameters and of mission objectives. If the spacecraft is expected to rendezvous with another, this task includes the computation of the expected position of the target. By extension, this task also covers

the determination of desired spacecraft attitude.
Also covers: g40 Determine Desired Attitude
g227 Compute Expected Target Position

g38: CHOOSE OPTIMAL TRAJECTORY

The choice of a precomputed trajectory (or the computation of one) to achieve the spacecraft's desired orbital parameters in an optimal manner. Optimality is defined according to the mission objectives (e.g. minimum time, minimum propellant use) and available hardware.
Also covers: g232 Compute Terminal Phase OMS Burn

g64: UPDATE SPACECRAFT MODEL

The updating of the functional representation of a spacecraft used by the decision and planning agency. This update uses status data from the spacecraft. The model itself can be as simple as an identification of the present modes of operation of spacecraft components, or as complex as a full-spacecraft computer simulation including cause-and-effect relationships between components and procedures. This includes updates showing degradation or failure of components, or modifications to the spacecraft.
Also covers: g327 Update Habitat Model

g97: PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE

The identification and estimation of quantities of consumables required by mission objectives. This includes estimation of propellant and other fluid requirements for nominal operations, losses from fluid leakage, degradation of replaceable hardware (e.g. solar cells, batteries), and safety margins for contingencies.

g98: COMPUTE OPTIMAL CONSUMABLES ALLOCATION

The determination of the optimal sequencing of tasks, and the optimal mode of performance of each task, to minimize consumables usage while meeting mission objectives. This determination is based on knowledge of the mission requirements, of the spacecraft hardware characteristics, and of the available procedural options. This task can run into combinatorial difficulties for complex spacecraft, when the number of procedural options is large.

Also covers: g187 Command Attitude Change
g113 Compute Control Commands
g108 Compute Optimal Sequencing
g112 Choose Optimal Control Mode

g105: PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE

The definition of the spacecraft or ground support activities required or desired to meet the mission objectives. [The space project breakdowns used in this study are one method to do this task.] Originally done during the mission design process, this task may need repetition if the mission profiles are modified during the life of the spacecraft.

g107: DETERMINE CONSTRAINTS AND FIGURES OF MERIT

The definition of procedural constraints and acceptable ranges of operation for spacecraft components (e.g. voltage limits, mechanical motion envelopes, safe sequences of valve actuations). Also, the definition of optimality criteria for the expected spacecraft functions (e.g. minimum propellant use, maximum data return, minimum wear). This determination is based on the estimation of risks to the spacecraft and to the mission objectives from the projected spacecraft activities.

Also covers: g106 Estimate Risks from Desired Functions g110: DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS

The modeling of the overall attitude and geometric configuration of spacecraft components, including solar arrays, radiators, communications antennas, sensors and instruments. This modeling can serve three purposes: to determine what a new configuration should be, to fullfill the next mission objective (e.g. to reorient the AXAF while keeping solar arrays and communication antennas properly pointed); before a new configuration is assumed, to verify the safety of that configuration (e.g. to avoid collisions between spacecraft components); while the configuration is in effect, to support the structural dynamic analysis of the spacecraft.

Also covers: g205 Determine Angles Relative to Telescope Line-of-Sight

g242 Avoid Exposing Sensitive Components to Direct Sunlight

g185: EVALUATE SYSTEM PERFORMANCE

The evaluation of spacecraft and ground support performance in achieving mission objectives. This includes evaluation of spacecraft state-of-health and suitability for further activities. This may also include definition of desirable improvements in hardware or procedures.

g220: PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART

The choice of the next target for the AXAF. Issues in the choice are minimization of telescope movement and avoidance of occultation of the target by sun, moon, or planet during the observation sequence (even a near-occultation can damage AXAF sensors).

g223: SELECT NEW TELESCOPE ATTITUDE IF NECESSARY

The selection of another telescope attitude for AXAF, if the first attempt to find a new Xray target is unsuccessful. Success is defined by acquisition of the target by both optical and X-ray sensors. If there are misalignments between sensors (e.g. due to thermal deformations in the telescope) the target may appear only to one type of sensor; or the target may be out of view entirely. The task involves trying to deduce the necessary attitude correction from partial or circumstantial data, or using a preset systematic search pattern.

g244: AVOID CONFLICTING OBJECTS

The determination that one or more objects are on collision courses with the spacecraft; the choice of avoidance procedure; the formulation of the corrective action; and the computation of the appropriate control commands to avoid contact. This includes avoidance of components potentially in the way of a target spacecraft's docking hardware, or of free-flying objects in the target's vicinity.

H. FAULT DIAGNOSIS AND HANDLING

g56: DETERMINE ANOMALOUS DATA

The process of evaluating spacecraft data to identify information from defective hardware or software. This does not include data made defective by transmission (e.g. dropped bits in a bit stream). The task involves analysis of the data stream (or comparison to a model) to notice and pinpoint off-nominal parts of the information. These could come from defective instruments or sensors, or from unforeseen interactions between components and pieces of software (e.g. from a new piece of software inadequately integrated to the old spacecraft programs).

Also covers: g55 Compare Measured Data to Model g57: FORM HYPOTHESIS FOR PROBLEM

The formulation of a hypothesis to explain anomalous data, identifying suspected defective hardware or software.

g58: DEVISE TEST FOR FAILURE HYPOTHESIS

The definition of a test to validate or disprove a hypothesis on a spacecraft failure. The output of this task is a set of commands to be sent to the spacecraft, and a description of the expected responses which would confirm the suspected failure. The output of the task could also be a sequence of procedures (e.g. disassembly and examination of components) to be carried out onsite.

g60: IDENTIFY FAULTY COMPONENT

The confirmed identification of a specific piece of defective spacecraft hardware. This task includes the application of methods to trace the cause of the failure.

Also covers: g59 Perform Test for Failure Hypothesis

g65: DEFINE ACCESS SEQUENCE

The formulation of a sequence of commands and procedures to yield physical access to a particular spacecraft component, usually for the purpose of repair. Besides the definition of the proper sequence of disassembly and removal of any surrounding hardware (e.g. thermal blankets, micrometeorite shields), this task also includes the formulation of an acceptably safe sequence of equipment shutdowns and disconnections, to avoid causing damage to other spacecraft components. Also involved is the safety of the human or device which will access the component of interest. This task may involve choices between alternative methods of access.

Also covers: g66 Locate Access Panel

g77: DETERMINE CORRECTION ALGORITHM

The definition of a piece of spacecraft or ground support software, to replace or patch defective software, thus restoring the system's nominal operation. This may involve trying potential correction algorithms on a simulation of the overall system. In some cases, an alternative computer procedure (e.g. reloading the system) may be sufficient to solve the problem.

g194: IDENTIFY FAULTY SOFTWARE

The confirmed identification of a specific piece of defective spacecraft or ground support software, or of a specific computer procedure causing anomalous responses. This task includes the application of methods to trace the problem (e.g. test subroutines on simulations).

I. SENSING

g69: OBSERVE/LOCATE DEFECTIVE COMPONENT

The determination of the position of a defective spacecraft component, with sufficient accuracy to allow close scanning (e.g. with diagnostic sensors) or repair and adjustment (e.g. with a manipulator). It is assumed that the system already knows which component is defective; but it must recognize the correct component amid other spacecraft components. More generally, this task includes the recognition and location of any spacecraft component, assuming that the approximate shape and location of the component are known (so that template-matching pattern recognition can be used, rather than total scene interpretation).

Also covers: g66 Locate Access Panel
g72 Locate New Component
g155 Locate Old Tank
g159 Locate New Tank
g169 Locate Payload Restraints
g176 Locate Solar Array Restraints
g178 Locate Sunshade Restraints

g236 Locate Detector
g258 Locate New Payload
g265 Identify Shape, Size in Bin
g266 Match with Sample Model

g132: LOCATE GRASPING FIXTURE ON TARGET

The location of a dedicated fixture (e.g. the Shuttle RMS grapple fixture) on a free-floating or attached target, with sufficient accuracy that it can be grasped. [For the grasping, see g134 Grasp Fixture, in C. Mechanical Actuation.] If the target is free-floating (e.g. a spacecraft to be retrieved), this task may require determination of the velocity of the grasping fixture as well. More generally, the task covers the location of any clearly recognizable fixture (e.g. standardized restraints) on a payload.

Also covers: g169 Locate Payload Restraints
g176 Locate Solar Array Restraints
g178 Locate Sunshade Restraints
g231 Track Target
g258 Locate New Payload

g243: TRACK NEARBY OBJECTS

The determination of the positions and velocities of any objects on potential collision courses with a spacecraft. Also, the location of a target object, for either close approach or docking. Also, the location of attached spacecraft components, to confirm the expected spacecraft configuration (e.g. measuring the position of solar arrays and antennas).

Also covers: g227 Compute Expected Target Position
g100 Measure Relative Displacements

g245: OBSERVE TUMBLING SPACECRAFT

The location and tracking of a tumbling spacecraft or object, for the purpose of capture or grasping. This includes determination of the spin axis (the line of safest approach).

Also covers: g246 Determine Spacecraft Principal Spin Axis

APPENDIX 4.D:

MATRIX: GENERIC FUNCTIONAL ELEMENTS AND CANDIDATE ARAMIS CAPABILITIES

4.D.1 Notes on this Appendix

This appendix presents the list of 69 GFE's selected for detailed study, grouped by types of GFE's. (For definitions of these GFE's, see Appendix 4.C). For each GFE, the appendix lists the ARAMIS capabilities which were defined or identified as candidates for that task (as described in Section 4.5.2). Note that each candidate capability listed under a GFE can, by itself, satisfy that GFE. The study group established this rule in the definition process, to lock together the levels of detail of GFE's and capabilities.

Many of the capabilities are candidates for several GFE's. If the reader is interested in a particular capability and its multiple applications, Appendix 4.G presents the transpose of the study matrix, listing each capability followed by the GFE's to which it applies.

Altogether, 78 ARAMIS capabilities were defined. The study matrix therefore identifies the potential matches between the 69 GFE's and the 78 capabilities. The number of capabilities associated with a GFE ranges from 3 to 13. The number of GFE's associated with a capability ranges from 1 to 30. Altogether, 465 potential applications of capabilities to GFE's were identified.

The ARAMIS capabilities are code-numbered by topics. Each capability was assigned to the topic which seemed to describe the technical challenge in the capability most accurately (in the opinion of the study group). The capability code numbers were formed by taking the ARAMIS topic number (as listed in Table 4.5 in Section 4.3.3) and adding sequential numbers to them. Thus 14.2 Dextrous Manipulator under Human Control is the second capability listed under topic 14: Teleoperation Techniques.

The listing of GFE's and their candidate ARAMIS capabilities follows.

A. POWER HANDLING

g1 VERIFY POWER SYSTEM FUNCTION

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.6 MANUAL TESTING ON GROUND
- 16.1 COMPUTER MODELING AND SIMULATION
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN

g23 POWER SUBSYSTEM CHECKOUT

- 14.3 HUMAN IN EVA WITH TOOLS
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY
- 27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
- 27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
- 27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g87 ADJUST CURRENTS AND VOLTAGES

- 1.6 AUTOMATIC SWITCHING SYSTEMS
- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 21.1 ONBOARD SEQUENCER
- 21.2 OPERATIONS OPTIMIZATION PROGRAM
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.2 ONBOARD MICROPROCESSOR HIERARCHY
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND
- 25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g88 ADJUST BATTERY CHARGING CYCLE

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g240 MAINTAIN SAFE BATTERY CHARGE LEVELS

1.6 AUTOMATIC SWITCHING SYSTEMS

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

B. CHECKOUT

g5 MISSION SEQUENCE SIMULATION

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.6 MANUAL TESTING ON GROUND

16.1 COMPUTER MODELING AND SIMULATION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g10 CHECK ELECTRICAL INTERFACES

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.6 MANUAL TESTING ON GROUND

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER

27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN

27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER g33 VERIFY DEPLOYMENT SEQUENCES

6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)
11.1 IMAGING (STEREO) WITH MACHINE PROCESSING
11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING
13.1 HUMAN EYESIGHT VIA VIDEO
14.1 DIRECT HUMAN EYESIGHT
14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY
27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g48 THERMAL SUBSYSTEM CHECKOUT

10.1 THERMAL IMAGING SENSOR WITH HUMAN PROCESSING
11.3 THERMAL IMAGING SENSOR WITH MACHINE PROCESSING
14.3 HUMAN IN EVA WITH TOOLS
14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY
27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g49 STRUCTURE SUBSYSTEM CHECKOUT

- 6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)
- 11.1 IMAGING (STEREO) WITH MACHINE PROCESSING
- 11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING
- 13.1 HUMAN EYESIGHT VIA VIDEO
- 14.1 DIRECT HUMAN EYESIGHT
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY
- 27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
- 27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
- 27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY
- 27.7 INTERNAL ACOUSTIC SCANNING

g51 ATTITUDE CONTROL SUBSYSTEM CHECKOUT

- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

g52 PROPULSION SUBSYSTEM CHECKOUT

- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

g54 CONSUMABLES LEVELS CHECKOUT

- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
- 27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
- 27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g260 SP/PAYLOAD INTERFACE CHECKOUT

- 14.3 HUMAN IN EVA WITH TOOLS
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.2 ONBOARD MICROPROCESSOR HIERARCHY
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

C. MECHANICAL ACTUATION

g27 DEPLOY ANTENNA RECEIVER ARRAYS

- 1.1 STORED ENERGY DEPLOYMENT DEVICE
- 1.2 SHAPE MEMORY ALLOYS
- 1.3 INFLATABLE STRUCTURE
- 2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR
- 2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
- 4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
- 4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
- 4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
- 14.3 HUMAN IN EVA WITH TOOLS
- 15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
- 15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
- 15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g31 DEPLOY SOLAR ARRAYS

1.1 STORED ENERGY DEPLOYMENT DEVICE

2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR

2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL

4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR

4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK

4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK

14.3 HUMAN IN EVA WITH TOOLS

15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL

15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL

15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE

2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR

2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL

4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK

4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK

14.3 HUMAN IN EVA WITH TOOLS

15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL

15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL

15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g73 POSITION AND CONNECT NEW COMPONENT

2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL

4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR

4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK

4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK

14.3 HUMAN IN EVA WITH TOOLS

15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL

15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL

15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT g134 GRASP FIXTURE

- 2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
- 4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
- 4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
- 4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
- 14.3 HUMAN IN EVA WITH TOOLS
- 15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
- 15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
- 15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g146 FASTEN DOCKING LATCH

- 3.1 AUTOMATED DOCKING MECHANISM
- 13.3 DOCKING UNDER ONSITE HUMAN CONTROL
- 14.3 HUMAN IN EVA WITH TOOLS
- 15.4 TELEOPERATED DOCKING MECHANISM

g148 EXTEND AND ATTACH UMBILICAL

- 2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR
- 2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
- 4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
- 4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
- 4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
- 14.3 HUMAN IN EVA WITH TOOLS
- 15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
- 15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
- 15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

g177 RELEASE SOLAR ARRAY RESTRAINTS

- 2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR
- 2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
- 4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
- 4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
- 4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
- 14.3 HUMAN IN EVA WITH TOOLS
- 15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
- 15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
- 15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

D. DATA HANDLING AND COMMUNICATION

g50 COMMUNICATIONS SUBSYSTEM CHECKOUT

- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER
- 27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN
- 27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

g78 DATA/COMMAND ENCODING

- 19.1 ANALOG/DIGITAL CONVERTER
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g79 DATA/COMMAND TRANSMISSION

- 17.1 TRACKING AND DATA RELAY SATELLITE SYSTEM
- 17.2 DIRECT TRANSMISSION TO/FROM GROUND
- 17.3 DIRECT TRANSMISSION TO/FROM ORBITER
- 17.4 DIRECT COMMUNICATION TO/FROM ORBITER VIA CABLE

g89 SHORT-TERM MEMORY STORAGE

- 18.2 RANDOM ACCESS MEMORY
- 18.3 MAGNETIC TAPE
- 18.4 MAGNETIC BUBBLE MEMORY
- 18.5 MAGNETIC DISC MEMORY
- 18.7 ERASABLE OPTICAL DISC
- 18.8 HOLOGRAPHIC STORAGE
- 18.11 CRYOELECTRONIC MEMORY
- 18.12 ELECTRON BEAM MEMORY
- 18.13 CHARGE-COUPLED DEVICE MEMORY

g90 LONG-TERM MEMORY STORAGE

18.3 MAGNETIC TAPE

18.4 MAGNETIC BUBBLE MEMORY

18.5 MAGNETIC DISC MEMORY

18.6 OPTICAL DISC

18.7 ERASABLE OPTICAL DISC

18.8 HOLOGRAPHIC STORAGE

18.9 MICROFORM ON GROUND

18.10 ELECTRICALLY ALTERABLE READ ONLY MEMORY

18.12 ELECTRON BEAM MEMORY

g109 DATA/COMMAND DISPLAY

13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY

13.4 COMPUTER PRINTOUT

13.5 COMPUTER-GENERATED AUDIO

13.6 STEREOPTIC VIDEO

13.7 3-D DISPLAY

g218 TAKE DATA FROM DETECTOR

18.1 ONBOARD DATA RECORDER

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

g224 PROCESS IMAGE DATA

13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g241 MAINTAIN COMMUNICATIONS LINKS

1.6 AUTOMATIC SWITCHING SYSTEMS

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

26.1 FAULT TOLERANT SOFTWARE

E. MONITORING AND CONTROL

g35 INITIALIZE GUIDANCE SYSTEM

- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g47 ACTIVATE SUBSYSTEMS

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 21.1 ONBOARD SEQUENCER
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.2 ONBOARD MICROPROCESSOR HIERARCHY
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g83 ADJUST COOLING/HEATING SYSTEMS

- 1.6 AUTOMATIC SWITCHING SYSTEMS
- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 21.1 ONBOARD SEQUENCER
- 21.2 OPERATIONS OPTIMIZATION PROGRAM
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.2 ONBOARD MICROPROCESSOR HIERARCHY
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND
- 25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g150 MONITOR FLUID TRANSFER

1.6 AUTOMATIC SWITCHING SYSTEMS
14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
25.1 ONBOARD DEDICATED MICROPROCESSOR
27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g184 MONITOR TELEMETRY

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
14.4 HUMAN WITH CHECKLIST
14.5 HUMAN JUDGMENT ON GROUND
23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g239 AVOID TANK OVERPRESSURES

1.6 AUTOMATIC SWITCHING SYSTEMS
25.1 ONBOARD DEDICATED MICROPROCESSOR
25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g264 MONITOR MICRO-GRAVITY LEVELS

18.1 ONBOARD DATA RECORDER
25.1 ONBOARD DEDICATED MICROPROCESSOR
27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g325 MONITOR VITAL SIGNS OF CREW MEMBERS

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

F. COMPUTATION

g24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.4 HUMAN WITH CHECKLIST

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN g92 NUMERICAL COMPUTATION

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g93 LOGIC OPERATIONS

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.4 HUMAN WITH CHECKLIST

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g94 COMPUTER LOAD SCHEDULING

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.4 HUMAN WITH CHECKLIST

21.2 OPERATIONS OPTIMIZATION PROGRAM

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g103 APPLY COMPENSATING FORCES

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

25.1 ONBOARD DEDICATED MICROPROCESSOR

25.2 ONBOARD MICROPROCESSOR HIERARCHY

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW

- 13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY
- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 25.1 ONBOARD DEDICATED MICROPROCESSOR
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

G. DECISION AND PLANNING

g37 DETERMINE DESIRED ORBITAL PARAMETERS

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g38 CHOOSE OPTIMAL TRAJECTORY

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 21.2 OPERATIONS OPTIMIZATION PROGRAM
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g64 UPDATE SPACECRAFT MODEL

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 16.1 COMPUTER MODELING AND SIMULATION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 16.1 COMPUTER MODELING AND SIMULATION
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g98 COMPUTE OPTIMAL CONSUMABLES ALLOCATION

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 21.2 OPERATIONS OPTIMIZATION PROGRAM
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g105 PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE

- 14.4 HUMAN WITH CHECKLIST
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g107 DETERMINE CONSTRAINTS AND FIGURES OF MERIT

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.5 HUMAN JUDGMENT ON GROUND
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 16.1 COMPUTER MODELING AND SIMULATION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g185 EVALUATE SYSTEM PERFORMANCE

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.4 HUMAN WITH CHECKLIST

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g220 PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART

14.4 HUMAN WITH CHECKLIST

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g223 SELECT NEW TELESCOPE ATTITUDE IF NECESSARY

14.5 HUMAN JUDGMENT ON GROUND

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

g244 AVOID CONFLICTING OBJECTS

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.5 HUMAN JUDGMENT ON GROUND

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

H. FAULT DIAGNOSIS & HANDLING

g56 DETERMINE ANOMALOUS DATA

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND
- 26.1 FAULT TOLERANT SOFTWARE
- 27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER
- 27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN
- 27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY

g57 FORM HYPOTHESIS FOR PROBLEM

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 14.5 HUMAN JUDGMENT ON GROUND
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 14.8 ONSITE HUMAN JUDGMENT
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
- 24.1 THEOREM PROVING PROGRAM

g58 DEVISE TEST FOR FAILURE HYPOTHESIS

- 14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE
- 14.4 HUMAN WITH CHECKLIST
- 14.5 HUMAN JUDGMENT ON GROUND
- 14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE
- 14.8 ONSITE HUMAN JUDGMENT
- 23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION
- 23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

g60 IDENTIFY FAULTY COMPONENT

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.4 HUMAN WITH CHECKLIST

14.5 HUMAN JUDGMENT ON GROUND

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER

27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN

27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

g65 DEFINE ACCESS SEQUENCE

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

14.5 HUMAN JUDGMENT ON GROUND

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

24.1 THEOREM PROVING PROGRAM

g77 DETERMINE CORRECTION ALGORITHM

14.5 HUMAN JUDGMENT ON GROUND

16.1 COMPUTER MODELING AND SIMULATION

22.1 AUTOMATIC PROGRAMMER AND PROGRAM TESTER

24.1 THEOREM PROVING PROGRAM

26.1 FAULT TOLERANT SOFTWARE

g194 IDENTIFY FAULTY SOFTWARE

14.4 HUMAN WITH CHECKLIST

14.5 HUMAN JUDGMENT ON GROUND

14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

14.8 ONSITE HUMAN JUDGMENT

16.1 COMPUTER MODELING AND SIMULATION

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

24.1 THEOREM PROVING PROGRAM

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

26.1 FAULT TOLERANT SOFTWARE

27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER

27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN

27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY

I. SENSING

g69 OBSERVE/LOCATE DEFECTIVE COMPONENT

- 6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)
- 6.2 PROXIMITY SENSORS
- 7.1 DEAD RECKONING FROM STORED MODEL
- 8.1 TACTILE SENSORS
- 11.1 IMAGING (STEREO) WITH MACHINE PROCESSING
- 11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING
- 13.1 HUMAN EYESIGHT VIA VIDEO
- 13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY
- 14.1 DIRECT HUMAN EYESIGHT

g132 LOCATE GRASPING FIXTURE ON TARGET

- 6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)
- 6.3 RADAR (PASSIVE TARGET)
- 6.4 RADAR (ACTIVE TARGET)
- 11.1 IMAGING (STEREO) WITH MACHINE PROCESSING
- 11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING
- 13.1 HUMAN EYESIGHT VIA VIDEO
- 13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY
- 14.1 DIRECT HUMAN EYESIGHT

g243 TRACK NEARBY OBJECTS

- 6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)
- 6.3 RADAR (PASSIVE TARGET)
- 6.4 RADAR (ACTIVE TARGET)
- 6.5 ONBOARD NAVIGATION AND TELEMETRY
- 11.1 IMAGING (STEREO) WITH MACHINE PROCESSING
- 11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING
- 13.1 HUMAN EYESIGHT VIA VIDEO
- 13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY
- 14.1 DIRECT HUMAN EYESIGHT

g245 OBSERVE TUMBLING SPACECRAFT

6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)

6.3 RADAR (PASSIVE TARGET)

6.4 RADAR (ACTIVE TARGET)

11.1 IMAGING (STEREO) WITH MACHINE PROCESSING

11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING

13.1 HUMAN EYESIGHT VIA VIDEO

13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY

14.1 DIRECT HUMAN EYESIGHT

NOTE

Since Appendix 4.E: Candidate ARAMIS Capabilities: Comparison Charts and Application Forms includes 465 Application Forms, it is presented in a separate binding as Volume 4 (Supplement), to keep the size of the Volume 4 binding manageable. This separation is also for the convenience of the reader, as it allows Appendix 4.E to be consulted simultaneously with other appendices in Volume 4.

APPENDIX 4.F:

SUGGESTED DATA MANAGEMENT SYSTEM

4.F.1 Suggested System for ARAMIS Study Method

The study group developed an overall data management system to handle the large amounts of data (descriptions of capabilities, criteria values, commentary and data sources, technology trees) involved in the research. This section describes this overall system. The following section presents some general comments on the computer method. The next section details how the study group applied the system, including some shortcuts that were required by time constraints. The appendix concludes with listings of computer programs used in the study.

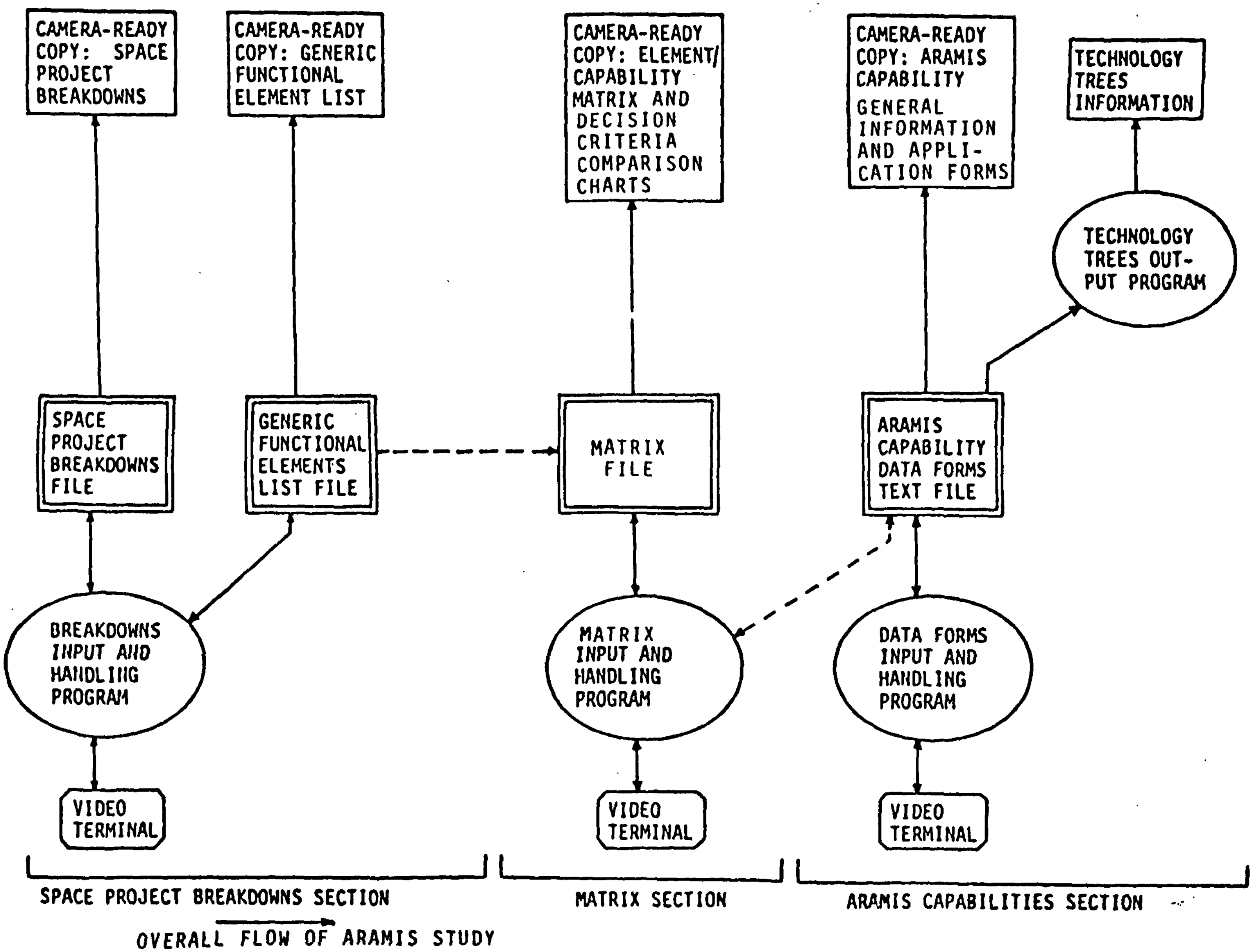
The suggested ARAMIS study computer system uses a set of four data files, tended by four computer programs. These are flow-charted in Fig. 4.F.1. As can be seen in the figure, the over-all computer system can be separated into a Space Projects Break-down Section, a Matrix Section, and an ARAMIS Capabilities Section. The following discussion describes the data files and programs for each section in turn.

SPACE PROJECT BREAKDOWNS SECTION:

Data Files

The Space Projects Breakdowns File contains code numbers and names for projects, missions, sequences, activities, and functional elements, including any alternative options at the mission,

FIGURE 4.F.1 FLOW CHART OF SUGGESTED ARAMIS STUDY COMPUTER SYSTEM



sequence, and activity levels; it also includes comments on any of the items in the breakdowns. The code numbers identify the levels and options within the breakdowns. The successively finer levels are: project (e.g. Geostationary Platform); mission (e.g. Deployment); sequence (e.g. Orbital Deployment and Checkout); activity (e.g. Tests of Attached Payload); functional element (e.g. Deploy Solar Arrays). Thus a functional element would have a five-component code number (e.g. 2.1.6B.2A.8), identifying the project, mission, sequence, and activity within which the element appears; the mission, sequence, and activity numbers may carry letters as well, identifying options for those items (the code number above indicates option A for activity 2, and option B for sequence 6; mission 1 has only one option, and therefore carries no letter). The space project breakdowns are listed in Appendix 2.A (Volume 2); a partial example of a breakdown is shown in Table 4.F.1.

The Generic Functional Elements List File contains a list of all the functional element names, without repetitions ("generic functional elements"). Under each generic functional element are listed the code numbers under which the element appears in the space project breakdowns; this allows the operator to see where a generic functional element came from, and to look up the element's context in the original breakdown, if desired. A partial example of the Generic Functional Element List appears in Table 4.F.2. The Generic Functional Element List is presented in Appendix 2.B (Volume 2). The computer can also produce an abbreviated GFE list, without the space project breakdown code numbers; this is presented in Appendix 2.C (Volume 2).

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- 1.2A.7B.8.5 CLOSE-OUT PAYLOAD BAY
- 1.2A.7B.8.6 INSTALLATION OF ORBITER PAYLOAD STATION CONSOLES

1.2A.8 COUNTDOWN AND LAUNCH

1.2A.9 ORBITAL DEPLOYMENT AND CHECKOUT

- 1.2A.9.1 SHUTTLE ATTAINS DELIVERY ORBIT
- 1.2A.9.2 TESTS OF ATTACHED PAYLOAD
  - 1.2A.9.2.1 POWER SUBSYSTEM CHECKOUT
  - 1.2A.9.2.2 INFORMATION PROCESSING SUBSYSTEM CHECKOUT
- 1.2A.9.3 EXTENSION OF PAYLOAD FROM PAYLOAD BAY
  - 1.2A.9.3.1 OPEN PAYLOAD BAY DOORS
  - 1.2A.9.3.2 ACTIVATE RMS
  - 1.2A.9.3.3 LOCATE GRASPING FIXTURE ON TARGET
  - 1.2A.9.3.4 MOVE RMS TO FIXTURE
  - 1.2A.9.3.5 GRASP FIXTURE
  - 1.2A.9.3.6 RELEASE PAYLOAD RESTRAINTS
  - 1.2A.9.3.7 TRANSLATE PAYLOAD OUT OF PAYLOAD BAY
- 1.2A.9.4 SEPARATION OF PAYLOAD FROM ORBITER
  - 1.2A.9.4.1 RMS RELEASES PAYLOAD
  - 1.2A.9.4.2 SECURE RMS IN PAYLOAD BAY
- 1.2A.9.5 OPERATIONAL CHECKOUT
  - 1.2A.9.5.1 ACTIVATE SUBSYSTEMS
  - 1.2A.9.5.2 INFORMATION PROCESSING SUBSYSTEM CHECKOUT
  - 1.2A.9.5.3 POWER SUBSYSTEM CHECKOUT
  - 1.2A.9.5.4 THERMAL SUBSYSTEM CHECKOUT
  - 1.2A.9.5.5 STRUCTURAL SUBSYSTEM CHECKOUT

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TABLE 4.F.1:

PARTIAL EXAMPLE OF SPACE PROJECT BREAKDOWN

Programs

The Breakdowns Input and Handling Program has three major functions. The first is the input of the space project breakdowns into their File. The program is interactive, prompting the operator for the data input. To save time and aggravation, the program creates the code numbers, assuming the next one in sequence and accepting corrections from the operator. It also has a copy feature, allowing the operator to repeat blocks of data without having to reenter them (e.g. different options within the breakdown can be created by copying the entered listing, then revising those items that are different); the program automatically renumbers copied blocks of data.

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```
*gfe g1: VERIFY POWER SYSTEM FUNCTION
    FE 4.3.7.3.1
    FE 4.2.7.3.1
    FE 4.1B.7.3.1
    FE 4.1A.7.3.1
    FE 3.5.7B.3.1
    FE 3.5.7A.3.1
    FE 3.4.7B.3.1
    FE 3.4.7A.3.1
    FE 3.3.7B.3.1
    FE 3.3.7A.3.1
    FE 3.2.7B.3.1
    FE 3.2.7A.3.1
    FE 3.1B.7B.3.1
    FE 3.1B.7A.3.1
    FE 3.1A.7B.3.1
    FE 3.1A.7A.3.1
    FE 2.3B.7.3.1
    FE 2.3A.7.3.1
    FE 2.2B.7.3.1
    FE 2.2A.7.3.1
    FE 2.1B.7.3.1
    FE 2.1A.7.3.1
    FE 1.2B.7.3.1
    FE 1.2A.7B.3.1
    FE 1.2A.7A.3.1
    FE 1.1.7.3.1
*gfe g2: VERIFY COMMAND SYSTEM FUNCTION
    FE 4.3.7.3.2
    FE 4.2.7.3.2
    FE 4.1B.7.3.2
    FE 4.1A.7.3.2
    FE 3.5.7B.3.2
    FE 3.5.7A.3.2
    FE 3.4.7B.3.2
    FE 3.4.7A.3.2
    FE 3.3.7B.3.2
    FE 3.3.7A.3.2
    FE 3.2.7B.3.2
        •
        •
        •
```

TABLE 4.F.2:

PARTIAL EXAMPLE OF GENERIC FUNCTIONAL ELEMENT LIST

The program's second function is the selective display of the Space Project Breakdowns File to the operator, either on the screen of a video terminal or as camera-ready hard-copy output. This display can be the result of special searches, if desired (e.g. a list of activities only; or a list of all the functional elements whose names include, for example, the word "deploy").

The third function of the program is to assemble the Generic Functional Elements List File from the space project breakdowns. For the computer to perceive commonalities between functional elements in different breakdowns (or in different sections of a breakdown) these functional elements must have precisely the same names, so that the computer can assemble the list by word-comparison. In the process of collecting the GFE list, the computer assigns numbers to the GFE's, identified by the first character "g" (e.g. "g1" in the example in Table 4.F.2). The program also retains the original space project breakdown code numbers for each generic functional element, thus forming the Generic Functional Elements List File, as shown in Table 4.F.2. This procedure can also be applied to single breakdowns, or pairs of breakdowns, to identify the percentages of commonalities between projects. The program can also generate an abbreviated GFE List, by omitting the project breakdown code numbers. Both types of GFE List can be selectively displayed on video terminals or printed out as camera-ready output.

MATRIX SECTION:

Data File:

The Matrix File consists of several types of data, from several sources. First, it contains code numbers and names of those generic functional elements selected for detailed study. The procedure used in this study to reduce the original GFE List

(330 elements) to those GFE's considered most worthy of study (69 elements) is described in Section 4.4.2. In addition, the GFE's were grouped into 9 types (e.g. Power Handling, Computation; see Section 4.4.1) for clarity of presentation. Thus the 69 GFE's (grouped by types of GFE's) were entered into the computer to set up the Matrix File. These GFE's retain the nomenclature and code numbers they have in the full GFE List.

For each generic functional element, the File contains the names of several candidate ARAMIS capabilities. These are each separately capable of performing the GFE. They are defined by the study group, based on literature search, consultation, and conceptual design. This definition procedure is described in Section 4.5.2; it is a critical step in this study, in that it links the space project tasks with the appropriate ARAMIS options. Each ARAMIS capability is also classified under a topic (see Section 4.5.3), leading to the assignment of capability code numbers. These numbers are also entered into the Matrix File. A particular ARAMIS capability may be a candidate for several GFE's; in that case it is named in several places in the File, and receives the same code number in each instance.

Also included in the Matrix File are the decision criteria values estimated for each capability applied to each GFE. The decision criteria and the estimation of their values are discussed in Section 4.6.1. For each of the 69 GFE's on which this study focused, the Matrix File contains from 3 to 13 candidate capabilities (depending on the GFE), for a total of 465 potential applications of capabilities to GFE's. For each candidate capability's application to a GFE, seven decision criteria values are entered, for a total of 3255 decision criteria values stored in the entire Matrix File.

For each GFE, the File also includes a notation identifying which of the candidate capabilities was defined as "current technology" (C.T.) during the evaluation of decision criteria. Table 4.F.3 presents a section of the Matrix File, showing two GFE's, their candidate capabilities (noting the C.T. capability), and the estimated decision criteria values.

Programs:

The Matrix Input and Handling Program has four principal functions. First, it handles the input of data from the operator to the Matrix File. This includes the names and numbers of the generic functional elements to be studied (which can be selectively copied from the GFE List File), the names and numbers of ARAMIS capabilities (as they are defined and classified), the identification of the current technology capability for each GFE, and the decision criteria values (as they are estimated).

The program's second function is the selective display of the Matrix File to the operator. This display can be the whole File, or part of it (see example above). This function was used to produce the matrix listing (GFE's and candidate capa-

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TABLE 4.F.3: PARTIAL EXAMPLE OF MATRIX FILE

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g67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE

2.1	ONBOARD DEPLOYMENT/RETRACTION ACTUATOR	1	2	3	1	4	4	1	
2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL	3	2	3	2	4	2	2	
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK	3	2	4	2	4	2	3	
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK	3	2	5	2	3	1	4	
14.3	HUMAN IN EVA WITH TOOLS	3	3	2	3	3	3	1	C.T.
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL	3	2	3	3	3	2	1	
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL	3	2	3	3	3	2	2	
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT	2	3	3	3	3	1	2	

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g73 POSITION AND CONNECT NEW COMPONENT

2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL	1	1	3	2	5	4	2	
4.1	COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR	2	2	4	2	3	3	3	
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK	2	2	4	2	4	2	4	
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK	1	2	5	2	3	1	5	
14.3	HUMAN IN EVA WITH TOOLS	3	3	2	3	3	3	1	C.T.
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL	3	2	3	3	4	2	2	
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL	3	2	4	3	3	2	3	
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT	3	3	3	3	4	2	2	

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bilities) presented in Appendix 4.D. It was also used to generate the lower half of each of the Decision Criteria Comparison Charts in Appendix 4.E. Both outputs were produced camera-ready.

This program function can also display the results of special searches. Examples of such searches might be: a list of all generic functional elements with eight or more candidate capabilities; a list of all the generic functional elements for which a given capability yields a decision criterion value of 1 for "time to complete functional element" (in other words, for which applications is this capability much faster than present method?); a list of all the capabilities with average decision criteria values below 2.2 in any of their potential applications (a first-cut "looks-good" list). It is this function that the study group uses to search for promising applications of ARAMIS, by applying weighting and summing algorithms to the decision criteria values.

The third function of the program is to transpose the matrix. In other words, the program produces a list of ARAMIS capability numbers and names (with no repetitions); after each name it collects the numbers and names of the generic functional elements to which that capability applies. In addition, the program carries over the decision criteria values for each application of a capability to a GFE. Such a listing was produced (again, camera-ready) for Appendix 4.G.

The fourth function is to generate information useful in setting up and filling in the ARAMIS Capability Data Forms Text

File. This information is identified in the description of that File, below.

Note: The Matrix Input and Handling Program can also include the ability to retrieve information from the ARAMIS Capability Data Forms Text File, for display to the operator. This would allow the user, while examining the Matrix, to request more information on capabilities and decision criteria values, without having to execute another program. The study group did not use such a function, and therefore cannot judge how useful it might be.

ARAMIS CAPABILITIES SECTION:

Data File:

The ARAMIS Capability Data Forms Text File contains two types of data forms: ARAMIS Capability General Information Forms, and ARAMIS Capability Application Forms. The General Information Forms are presented in Appendix 3.C (Volume 3). Each of these contains background information on a capability: name and number of capability, date of completion and names of contributors to the form, description of capability, individuals and organizations working on the concept, current and future technology levels (with remarks and data sources, if available), estimates of R&D costs between technology levels (with remarks and data sources, if available), remarks on any special aspects of the capability, technology trees information (i.e. which other capabilities or technologies should logically be developed before this capability), and the numbers of the GFE's to which this capability applies. Of this information, the first and last items (name and number of capability and numbers of GFE's to which it applies) can be extracted from the Matrix File by the Matrix File Input and Handling Program, and then transferred into the ARAMIS capability Data Forms Text File, thus setting up each General Information Form. The study group fills in the rest of the information as it is developed.

The ARAMIS Capability Application Forms complement the decision criteria values in the Matrix File by presenting commentary on those values. For each candidate application of a capability to a GFE, one of these forms contains: name and number of capability, date of completion and names of contributors to form, number and name of GFE to which capability is applied, decision criteria values, commentary and data sources on each of the seven criteria values, and any remarks on special aspects of this application. Here again, the capability name and number, and the number and name of the GFE, can be transferred from the Matrix File to set up each Application Form. Also, the decision criteria values can be transferred from the Matrix File. The remainder of the information is filled in by the study group.

Both types of forms are kept in memory as legible text files, for ease of accession.

Programs:

The Data Forms Input and Handling Program has three major functions. First, it can set up General Information Forms and Application Forms with the data transferred from the Matrix File. In each General Information Form, the program inserts name and number of capability, and the list of numbers of GFE's the capability applies to. For each of those applications, the program then sets up an Application Form, inserting the name and number of the capability, the number and name of the GFE, and the appropriate decision criteria values.

The program's second function is to handle the input of the contents of the General Information and Application Forms from the operator. This input is interactive: the program prompts the operator with request headings, then slots the data into the text file.

The third function is the selective display of the ARAMIS Capability General Information and Application Forms text files to the operator. This display can be the whole Forms or parts of them, or the result of special searches (e.g. a search for all capabilities currently at technology level 4). This function was used to generate the camera-ready General Information Forms in Appendix 3.C in Volume 3 (see example in Table 4.F.4) and the Application Forms in Appendix 4.E (see example in Table 4.F.5).

The Technology Trees Output Program converts the technology tree information (from the ARAMIS Capability General Information

TABLE 4.F.4:

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator with Force Feedback

CODE NUMBER: 4.2 DATE: 6/28/82 NAME(S): Kurtzman/Paige/Ferreira

DESCRIPTION OF CAPABILITY: A multipurpose multifingered manipulator, under computer control, and capable of operating under various geometries. The system would be reprogrammable and would use input from force-feedback sensors for final guidance and motion control.

WHO IS WORKING ON IT AND WHERE: Ewald Heer and Antal Bejczy (JPL); Marvin Minsky (MIT AI Lab); Dan Whitney (Draper Labs); Victor Sheinman (Automatix, Burlington, MA); Tom Williams (DEC, Maynard, MA).

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: 1986 LEVEL6: 1986 LEVEL7: 1989

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Present and future levels were provided by Marvin Minsky. The intermediate levels were computed by interpolation based on the background of the study group.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: $10-20 Million 5-6: N/A 6-7: $2.5 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: Dan Whitney suggested a figure of $10-20 million to develop the whole system to level 6. Cost to go from level 6 to level 7 was estimated at $2.5 million by extrapolating from a figure of $1 million to space rate a dedicated manipulator under computer control (Robert F. Goeke, MIT Center for Space Research)

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 4.1 Computer-Controlled Specialized Compliant Manipulator; 15.2 Dextrous Manipulator under Human Control; 19.1 A/D Converter.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

TABLE 4.F.5:

ARAMIS CAPABILITY APPLICATION FORM

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator With Force Feedback
CODE NUMBER: 4.2 DATE: 6/21/82 NAMES: Kurtzman/Paige/Ferreira
GENERIC FUNCTIONAL ELEMENT NUMBER AND NAME: g27 Deploy Antenna Receiver Arrays

DECISION CRITERIA (1 TO 5 SCALES; CURRENT TECH.=3 UNLESS NOTED)

TIME TO COMPLETE FUNCTIONAL ELEMENT (1 SHORT, 5 LONG): 4
REMARKS AND DATA SOURCES: The dextrous manipulator requires more time than an Onboard Deployment/Retraction Actuator as the actuator does not need to be transported to the payload as a manipulator would.

MAINTENANCE (1 LITTLE, 5 LOTS): 4
REMARKS AND DATA SOURCES: Maintenance would be low since the only parts likely to need service are the mechanical parts. The software and sensors would be very reliable (Minsky). The current technology capability, however, requires no maintenance.

NONRECURRING COST (1 LOW, 5 HIGH; CURRENT TECH.=2): 4
REMARKS AND DATA SOURCES: This cost is high since no system has yet been developed which incorporates the abilities of this manipulator. Some of the R&D will probably be done commercially.

RECURRING COST (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: This capability was judged greater than current technology in recurring costs as the Onboard Deployment/Retraction Actuator costs very little to procure and operate. This capability may cost slightly more than a dedicated manipulator since the end-effector would require more maintenance.

FAILURE-PRONENESS (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: The failure-proneness is higher than that of a human (who can correct problems after they occur) since the programming is neither adaptive or intelligent. The dedicated Onboard Deployment/Retraction Actuator is less likely to fail, although it is also more failure-prone than a human.

USEFUL LIFE (1 LONG, 5 SHORT): 2
REMARKS AND DATA SOURCES: The dextrous manipulator has a useful life which is longer than the more obsolescent dedicated manipulator. Eventually it should be replaced by manipulators with vision. Its useful life is judged longer than the single use current technology as it is capable of performing many tasks. For this functional element, the number of potential uses of the capability rather than when obsolescence will occur was the primary criterion for evaluating useful life.

DEVELOPMENTAL RISK (1 LOW, 5 HIGH; CURRENT TECH.=1): 4
REMARKS AND DATA SOURCES: This is high since there is currently no manipulator that can be called dextrous, and to advance to computer control would also be a large step.

OTHER REMARKS AND SPECIAL ASPECTS: This manipulator has the advantage of being adaptable to a number of tasks. The system could probably be built with a modular design, so that a vision capability could easily be added as it comes online. The current technology capability for performing this functional element is an Onboard Deployment/Retraction Actuator.

Forms described above) to a format suitable for printout. Since the presentation of these trees may require graphical display, the computer output may be supplemented by manual graphics.

4.F.2 General Comments on the Computer Method

The exact choice of computer language is not critical to the method presented above. In fact, the method can be implemented on paper only, and then resembles a multiple-entry bookkeeping system; the information files are then kept in notebooks. The study group used such notebooks as paper backups to the computer system, and in any case all the relevant information is published on paper in this final report.

Thus the computer system described above is not a hard-and-fast necessity; it is, however, a considerable asset, for several reasons. First, the selective search commands and the category sort commands can extract information far more rapidly than their paper lookup equivalents. Second, the output programs can produce camera-ready copy for report preparation, avoiding a large amount of repetitious secretarial work (e.g. typing up data forms). Third, the display features allow the operator rapid access to all the relevant information in the study. Fourth, the interactive input features of the programs make the entry of the large amounts of data in this study relatively painless - in particular, the copy feature (described above under the Breakdowns Input and Handling Program) can save considerable time and aggravation. Fifth, the system allows any user access to any other user's work, in a standard format, using common nomenclature. Sixth, the assembly of a bibliography is relatively simple, and the result can be camera-ready output. Seventh, the study manager can rapidly assess study status.

As described in the next section, the study group used a modified text editor for several of the described programs. There are some specific advantages to using text files and text editors for data management. The first is portability: a standard ASCII-code text file can be transferred to virtually any computer system for examination. The second advantage is versatility of access: such a file can be displayed or added to by a wide range of commands, including other text editors; the user does not have to use the editor originally used to set up the file. A third advantage is that printouts are easy to produce and exactly represent the file, which makes paper backup simple and accurate.

A word of caution is in order. Computer programmers often refer to an interactive data-handling program as being "transparent" to the user, meaning that the user can operate the program without ever needing any awareness of the language in which it is written. This is a myth. No matter how well written, an interactive computer program will sooner or later run into some situation requiring more knowledge than the user possesses. This application of Murphy's Laws requires that someone thoroughly knowledgeable be available for consultation whenever a user operates the system. And this consultation must include giving the knowledgeable person direct access to the system; in other words, if the expert is at home, he or she should have a terminal there. Otherwise one should expect delays until the expert is brought on-line, and if the system is so narrow-minded that the problem encountered stops all its functions, such delays can be very costly. Of the available computer programs, established text editors tend to be more transparent than most, because they have been used by many untrained operators, and most of the potential problems have already surfaced and have been fixed.

4.F.3 Use of the Computer in this Study

In general, the data management method described in the preceding section was followed in this study. The research team made some concessions to time and computer constraints, including applying some steps on paper rather than in software. The computer system used was the M.I.T. Information Processing Service's Multics system, implemented on Honeywell Computers. The computer tools used were the text editor EMACS (written in LISP), extended by defining special LISP commands ("macros"), and the computer language APL. A significant factor in the choice of these tools was their availability. Use of the ARAMIS method in another location might suggest other machines and programs.

The study group first attempted to develop the Space Project Breakdowns Section of the system using the language APL. The interactive input section of the Breakdowns Input and Handling Program was developed and debugged, and an attempt was made to develop the software to generate the Generic Functional Element List File. Several problems surfaced, however. First, the program was slow (APL is an interpreted language, while most text editors are compiled), using a lot of CPU time; CPU time is free on the graveyard shift on MIT's Multics system, but the operator's personal time, waiting for the computer's response, was not. Second, the files created by APL are in multi-segment format, and must therefore be either accessed in APL or translated into another format first. Third, as the Space Project Breakdowns File became large the time to input new data and generate the GFE list began to grow, apparently proportional to the square of the size of the file; this in turn led to system-level error messages requiring expert help to interpret and correct. Therefore the study group concluded that while it is possible to use APL to develop a versatile data management system, the language is not very efficient in this application, especially as it is implemented on the Multics system.

The research team therefore used the text editor EMACS for the Space Project Breakdowns Section. EMACS is a versatile, screen-oriented, full-page text editor, implemented on M.I.T.'s Multics system in the computer language LISP. One advantage of this editor is that it can be "extended": additional commands can be developed in LISP ("LISP macros"), and these commands can then be used as text editor commands. This permits a very wide variety of interactions between the operator and the text files in the computer. Another advantage of this system is that the Space Project Breakdowns File and the Generic Functional Elements List File are standard ASCII-code text files; these are easy to display and print out by a variety of methods (not necessarily requiring the text editor).

The Space Project Breakdowns File was set up, filled, corrected, and formatted for printout by the extended EMACS editor. This File contains the breakdowns presented in Appendix 2.A (Volume 2). The Generic Functional Elements List File was created and filled (in about four minutes) by a LISP macro. This file contains the full 330-element GFE List with breakdown code numbers, presented in Appendix 2.B (Volume 2). The LISP macro used to produce this File from the breakdowns is listed out in the following section. Another macro produced the GFE List without breakdown code numbers shown in Appendix 2.C (Volume 2).

The Matrix Section is written in APL. As mentioned in the Section 4.F.1, the Matrix File contains data on those 69 GFE's selected for detailed study. The classification and reduction of the GFE List, from 330 elements to 69, could have been done on the computer, using EMACS and macros to rearrange the GFE List File. However, this would have eventually required converting the list of GFE's from standard ASCII-code to the Matrix File's APL format. To avoid the time requirement and complexity of this process, the study group decided that the names and numbers of the GFE's in the Matrix File would be entered by the operator, from the terminal. Thus the GFE List (Grouped by Types of GFE's) in Appendix 4.A, the Reduced GFE List in Appendix 4.B, and the Definitions of GFE's Selected for Further Study in Appendix 4.C were written out by hand and typed separately.

The Matrix Input and Handling Program actually consists of several APL programs. The first, called ENTER_GFE_NAMES (listed in the following section), sets up the Matrix File as the operator enters the numbers and names of the 69 GFE's mentioned above. The second (ENTER_CAP_NAMES, also listed) lets the operator enter the code numbers and names of the 78 ARAMIS capabilities defined by the study group. The third (ENTER_CRIT, also listed) lets the operator enter the seven decision criteria values estimated by the study group for each application of a capability to a GFE.

The fourth (LIST_GFE, also listed) creates a file of GFE numbers and names, each GFE followed by a list of its candidate capabilities and their criteria values; this was used to produce the study matrix listing in Appendix 4.D and the lower half of the Decision Criteria Comparison Charts in Appendix 4.E. The fifth (LIST_CAP, also listed) creates a file of ARAMIS capability numbers and names, each followed by a list of the GFE's to which it applies, and of the appropriate decision criteria values; this was used to generate the transpose matrix listing in Appendix 4.G.

In addition, several minor APL programs were written to produce: a list of GFE's and the number of candidate capabilities for each GFE; a list of capabilities and the number of GFE's to which each capability applies; various weighted sums and averages of decision criteria values, to support the selection of promising ARAMIS applications; and various upper-case and lower-case versions of the alphanumeric parts of the the Matrix File, which are handled differently in APL than in standard ASCII-code files.

The Matrix File includes an alphanumeric section where the names of GFE's and capabilities are stored. However, most of the File consists of a three-dimensional array, with 69 GFE's along one axis, 78 capabilities along another, and 7 decision criteria along the third. When the file is first set up, all of the 37,674 elements are initialized to zero. As decision criteria values are inserted into the matrix, the programs ignore the zero-value columns, recognizing nonzero criteria values as indicators of candidate applications of capabilities to GFE's. Thus the listing programs LIST_GFE and LIST_CAP only display the valid intersections in the GFE/capability matrix, where nonzero criteria values have been entered. In addition, LIST-GFE identifies which candidate capability was identified as "current technology" (C.T.) by checking decision criteria values, and indicates it in the output (if two capabilities have C.T. values, both are tagged, and the study group cleans up the output later). LIST_CAP checks the Matrix File to find the code number of the C.T. capability for each GFE; such numbers are indicated after each line of decision criteria values in the program's output (see Appendix 4.G).

The Matrix File is in APL format, and therefore not directly visible to the operator. The File is displayed either through APL display commands, or through the listing programs mentioned above, which create ASCII-code files from the APL data. These files are then displayed on screen, cleaned up with EMACS if needed, and printed out if desired.

Despite its complexity of programming, the use of APL for the Matrix Section of the study's computer system was a success. This language is particularly well adapted to the setting up and manipulation of arrays of numbers. The language has built-in interactive commands for input, and special search commands to scan blocks of data including both numbers and text. Provided that an APL program's data base is not too large, the language is reasonably fast. The output formatting commands are sufficiently versatile that APL can produce nearly or fully camera-ready printout.

The ARAMIS Capabilities Section of the study's data management system was developed using an ASCII-code text file and the extended EMACS text editor. The editor was extended by a LISP program which sets up either ARAMIS Capability General Information Forms or ARAMIS Capability Application Forms, at the request of the user. When the operator enters a new capability number, the program creates a blank General Information Form in the text file, which can then be filled in using EMACS. Similarly, if the operator enters a capability number and a GFE number, the program creates a blank Application Form to be filled out. Entering old capability and GFE numbers retrieves the appropriate forms from the file. Because the forms are created in a text file in standard format, they are readily displayed and printed out as camera-ready output. This function was used to produce the General Information Forms in Appendix 3.C (Volume 3) and the Application Forms in Appendix 4.E.

The study group did not use the computer to transfer capability names and numbers, GFE names and numbers, and decision criteria values from the Matrix File, to set up the ARAMIS Capability Data Forms Text File, as was discussed in the Section 4.F.1. Due to time constraints and the complexities of converting APL-format data to ASCII-code data, the study group reentered this information into the General Information Forms and Application Forms from the terminal. A visual check between printouts was made to verify the accuracy of transcription.

Due to time constraints, the Technology Trees Output Program was not developed. The Technology Trees in Appendix 3.D (Volume 3) were produced by hand.

In general, it is difficult to develop both a study method and an associated software system concurrently, and the time constraints of this study repeatedly forced the study group to perform certain tasks by hand rather than by computer. One of the keys to the success of a new data management system is that <u>all</u> the data should be handled by computer; otherwise the time and effort spent transcribing information between paper and machine (or between different machines) can more than offset gains from the use of the computer.

Despite these drawbacks, the computer system proved invaluable to this study, manipulating and displaying quantities of information well above what traditional methods could have dealt with in this short a time. The study group looks forward to further uses of such systems in the future.

4.F.4 Computer Program Listings

The first listing, called naramis3 by the study, is the LISP file which was used to extend the EMACS text editor. This extended editor was used to handle both space project breakdowns and ARAMIS capability data forms. From the project breakdowns, the program generates the Generic Functional Element List File, numbering the GFE's as it does so.

For the data forms, the program responds to the operator's request for a data form and entry of capability number by creating a file with a blank ARAMIS Capability General Information Form. If the operator enters both a capability and a GFE number, the program sets up a blank ARAMIS Capability Application Form. These forms can then be filled in using the EMACS text editor. The program also includes access codes to these files, so that they can be retrieved by the program later. The forms are set up as standard ASCII-code text files.

The listing of the naramis3 file follows.

```
(%include e-macros)

(defvar data-base-file-alist
  '((gfe . "GFElist.GFE")
    (acap . "X-Mlist.X-M")
    (x-m . "X-Mlist.X-M")
    (x-m-c . "X-Mcomments.X-M-C")))

(defvar data-base-english-item-type-name-alist
  '((gfe . "a gfe")
    (acap . "an acap")
    (x-m . "a cross-matrix group header")
    (x-m-c . "a cross-matrix group header")))

(defvar data-base-english-subitem-type-name-alist
  '((gfe . nil)
    (acap . nil)
    (x-m . "a cross-matrix element")
    (x-m-c . "a cross-matrix element")))

(defvar data-base-item-type-alist
  '((gfe . "gfe")
    (acap . "acap")
    (x-m . "x-m")
    (x-m-c . "x-m-comment")))

(defvar subitem-item-data-base-alist
  '((x-m . acap)))

;Alist associating data base name with the sequence of keys of
;the normal item.  The cdr of the alist element is the list of keys.
(defvar data-base-needed-keys-alist
  '((gfe gfe)
    (acap acap)
    (x-m acap gfe)
    (x-m-c acap gfe)))

(defvar data-base-additional-create-function-alist
  '((x-m . x-m-additional-create-function)))

(defvar data-base-template-alist
  '((acap ."


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                    ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME:
```

CODE NUMBER: DATE: NAME(S):

DESCRIPTION OF CAPABILITY:

WHO IS WORKING ON IT AND WHERE:

TECHNOLOGY LEVELS: LEVEL1: LEVEL2: LEVEL3:
LEVEL4: LEVEL5: LEVEL6: LEVEL7:

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS:

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: 2-3:
3-4: 4-5: 5-6: 6-7:

REMARKS AND DATA SOURCES ON COST ESTIMATES:

REMARKS ON SPECIAL ASPECTS:

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.):

CAPABILITY APPLIES TO (GFE NUMBERS):

")
(x-m . "

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ARAMIS CAPABILITY APPLICATION FORM

CAPABILITY NAME:
CODE NUMBER: DATE: NAME(S):
GENERIC FUNCTIONAL ELEMENT NUMBER AND NAME:

DECISION CRITERIA (1 TO 5 SCALES; CURRENT TECH.=3 UNLESS NOTED)

TIME TO COMPLETE FUNCTIONAL ELEMENT (1 SHORT, 5 LONG):
REMARKS AND DATA SOURCES:

MAINTENANCE (1 LITTLE, 5 LOTS):
REMARKS AND DATA SOURCES:

NONRECURRING COST (1 LOW, 5 HIGH; CURRENT TECH.=2):
REMARKS AND DATA SOURCES:

RECURRING COST (1 LOW, 5 HIGH):
REMARKS AND DATA SOURCES:

```
FAILURE-PRONENESS (1 LOW, 5 HIGH):
REMARKS AND DATA SOURCES:

USEFUL LIFE (1 LONG, 5 SHORT):
REMARKS AND DATA SOURCES:

DEVELOPMENTAL RISK (1 LOW, 5 HIGH; CURRENT TECH.=1):
REMARKS AND DATA SOURCES:

OTHER REMARKS AND SPECIAL ASPECTS:

")))

 (defun go-to-data-base (name)
   (find-file-subr (cdr (assq name data-base-file-alist))))

 (defun next-word-string ()
   (with-mark m




     (forward-word)
     (prog1 (point-mark-to-string m)
            (go-to-mark m))))

(defun rest-of-line-string ()
  (with-mark m
    (go-to-end-of-line)
    (skip-back-whitespace)
    (prog1 (point-mark-to-string m)
           (go-to-mark m))))

(defun fe-number-string ()
  (with-mark m
    (skip-to-whitespace)
    (prog1 (point-mark-to-string m)
           (go-to-mark m))))

;An alist of elements (gfe-name-as-string gfe-code-string fe-codes)
;such as ("Buy coke" "g25" "3.1A.1.1.2" "3.1.4.1.5")
(defvar gfe-alist ())

;Code number to assign the next GFE we create.
;Incremented each time one is created.
;Left unbound until the list of existing GFEs is read in.
;Then it is set to 1 plus the highest code read in.
(defvar last-gfe-code)

(defun next-gfe-code ()
  (let ((base 10.) (*nopoint t))
    (catenate "g" (apply-catenate (explode (setq last-gfe-code (1+ last-gfe-code)))))))
```

```
;Skip past the "*GFE " or other such entry type on this line.
(defun skip-entry-type ()
  (if (forward-search-in-line " ")
      (skip-over-whitespace)))

;Construct the value of GFE-ALIST, reading in the gfe data base.
(defun make-alist-of-gfe-names ()
  (save-excursion-buffer
    (go-to-data-base 'gfe)
    (go-to-beginning-of-buffer)
    (setq last-gfe-code 0)
    (do ((alist)) ((lastlinep) alist)
      (if (looking-at "*gfe ")
          (skip-entry-type)
          (let ((code (next-word-string))
                (title nil) (uses nil))
            (forward-char)                                   ;Skip the "g".
            (setq last-gfe-code (max last-gfe-code (read-from-string (next-word-string))))
            (or (forward-search-in-line ":")
                (display-error "Malformatted gfe entry"))
            (skip-over-whitespace)
            (setq title (rest-of-line-string))
            (do-forever
              (next-line)
              (if (looking-at "*gfe") (return nil))
              (if (lastlinep) (return nil))
              (skip-over-whitespace)
              (if (looking-at "FE ")
                  (skip-to-whitespace)


                  (skip-over-whitespace)
                  (setq uses (cons (fe-number-string) uses))))
           (setq alist (cons (cons title (cons code uses)) alist)))
        else
          (next-line)))))

;Make sure that the gfe-alist is available for use.
(defun setup-gfe-alist ()
  (or gfe-alist
      (setq gfe-alist (make-alist-of-gfe-names))))

;Go through the breakdown file and find every functional element.
;If there is no GFE for one, create a GFE.
(defun merge-new-fes ()
  (setup-gfe-alist)
  (save-excursion-buffer
    (go-to-breakdown-file)
    (save-excursion
      (go-to-beginning-of-buffer)
      (do ((fe-number nil nil)) ((lastlinep))
        (if (looking-at "                ")
```

```
            (skip-over-whitespace)
            (setq fe-number (fe-number-string))
            (skip-to-whitespace)
            (skip-over-whitespace)
            (let ((title (rest-of-line-string))
                  (gfe-alist-elt nil))
              (setq gfe-alist-elt (assoc title gfe-alist))
              (cond ((null gfe-alist-elt)
                     (make-new-gfe title fe-number))
                    ((not (member fe-number (cddr gfe-alist-elt)))
                     (make-new-gfe-use gfe-alist-elt fe-number)))))
        (next-line))))
  (if (yesp "Update fe's recorded for each gfe? ")
      (update-gfe-usage-records)))

(defun make-new-gfe (title fe-number-string)
  (save-excursion-buffer
    (let ((code (next-gfe-code)))
      (setq gfe-alist (cons (list title code fe-number-string) gfe-alist))
      (go-to-data-base 'gfe)
      (save-excursion
        (go-to-end-of-buffer)
        (insert-string (catenate "*gfe " code ": " title NL))))))

(defun make-new-gfe-use (gfe-alist-elt fe-number-string)
  (rplacd (cdr gfe-alist-elt) (cons fe-number-string (cddr gfe-alist-elt))))

;Value is string which is filename of file containing mission breakdowns.
(defvar breakdown-file "Breakdowns.text")

(defun go-to-breakdown-file ()
  (find-file-subr breakdown-file))

;Given the lists of fe numbers stored in gfe-alist,
;update the text in the entry for each gfe.
(defun update-gfe-usage-records ()
  (or gfe-alist (setq gfe-alist (make-alist-of-gfe-names)))
  (go-to-data-base 'gfe)
  (go-to-beginning-of-buffer)



  (do ((title nil)) ((lastlinep))
    (if (looking-at "*gfe ")
        (or (forward-search-in-line ":")
            (display-error "Malformatted gfe entry"))
        (skip-over-whitespace)
        (setq title (rest-of-line-string))
        ;; Delete old FEs
        (next-line)
        (with-mark m
          (prev-line)
          (or (forward-search "
*gfe ")
```

```
            (go-to-end-of-buffer))
          (go-to-beginning-of-line)
          (without-saving (wipe-point-mark m)))
        ;; Insert new list of FEs.
        (let ((gfe-alist-elt (assoc title gfe-alist)))
          (do ((fes (cddr gfe-alist-elt) (cdr fes))) ((null fes))
            (insert-string (catenate "    FE " (car fes) NL))))
      else
        (next-line))))

;Find a particular item in a particular data base.
;Returns a string of what is in the item's first line after its code;
;or T if item was just created, or NIL if no item found and none created.
(defun find-item (data-base code allow-create)
  (go-to-data-base data-base)
  (go-to-beginning-of-buffer)
  (let ((ibase 10.))
    (let ((typestr (catenate "*" (cdr (assq data-base data-base-item-type-alist)) " "))
          (code-number (read-from-string (substr code 2))))
      (do-forever
        (or (forward-search typestr)
            (progn (go-to-end-of-buffer)
                   (return (and allow-create (maybe-create-item data-base code)))))
        (cond ((looking-at code)
               (do ((i 0 (1+ i)) (len (stringlength code))) ((= i len))
                 (forward-char))
               (cond ((or (at " ") (at ":"))
                      (forward-search-in-line ":")
                      (skip-over-whitespace-in-line)
                      (return (rest-of-line-string)))))
              ((< code-number (read-from-string (substr (next-word-string) 2)))
               (return (and allow-create (maybe-create-item data-base code)))))))))

(defun maybe-create-item (data-base code)
  (go-to-beginning-of-line)
  (cond ((yesp (catenate "Create " (cdr (assq data-base data-base-english-item-type-name-a
                         " for code " code "? "))
         (insert-string "*")
         (insert-string (cdr (assq data-base data-base-item-type-alist)))
         (insert-string " ")
         (insert-string code)
         (insert-string ":
")
           (let ((template (cdr (assq data-base data-base-template-alist))))
             (cond (template (save-excursion (insert-string template)))))
           (backward-char)
         t)))


;Find an item which has two keys (code and subcode).
;This is useful for cross-matrix elements and their comments.
(defun find-subitem (data-base code subcode)
  (let ((item-data (find-item (cdr (assq data-base subitem-item-data-base-alist)) code nil
    (let ((ibase 10.))
      (let ((codespace (catenate code " "))
```

```
          (subcode-number (read-from-string (substr subcode 2))))
        (do-forever
          (next-line)
          (if (lastlinep) (return (maybe-create-subitem data-base code subcode item-data)
          (if (at "*")
              (skip-entry-type)
            (or (looking-at codespace)
                (return (maybe-create-subitem data-base code subcode item-data)))
            (forward-search " ")
            (let ((this-subcode (next-word-string)))
              (cond ((looking-at subcode)
                     (forward-search-in-line ":")
                     (return t))
                    ((< subcode-number (read-from-string (substr this-subcode 2)))
                     (return (maybe-create-subitem data-base code subcode item-data)))))

(defun maybe-create-subitem (data-base code subcode item-data)
  (go-to-beginning-of-line)
  (do () ((lastlinep))
    (if (at "*") (return nil))
    (next-line))
  (cond ((yesp (catenate "Create " (cdr (assq data-base data-base-english-subitem-type-nam
                          " for codes " code ", " subcode "? "))
         (create-subitem data-base code subcode item-data)
         t)))

(defun create-subitem (data-base code subcode item-data)
  (insert-string "*")
  (insert-string (cdr (assq data-base data-base-item-type-alist)))
  (insert-string " ")
  (insert-string code)
  (insert-string " ")
  (insert-string subcode)
  (insert-string ":
")
  (let ((additional-create-function
          (cdr (assq data-base data-base-additional-create-function-alist))))
    (if additional-create-function
        (funcall additional-create-function code subcode item-data)))
  (let ((template (cdr (assq data-base data-base-template-alist))))
    (cond (template (save-excursion (insert-string template)))
          (t (backward-char))))
  t)

(defun x-m-additional-create-function (code subcode item-data)
  (setup-gfe-alist)
  (insert-string "GFE: ")
  (do ((tail gfe-alist (cdr tail))) ((null tail))
    (cond ((equal (cadr (car tail)) subcode)
           (insert-string (caar tail))
           (return nil))))
  (insert-string "
ACAP: ")
  (insert-string item-data)
```

```
  (insert-string "
"))

(defvar x-m-parameter-list '("TC" "MN" "NC" "RC" "UL" "TR"))

(comment
(defun x-m-additional-create-function ()
  (do ((l x-m-parameter-list (cdr l))) ((null l))
    (insert-string " ")
    (insert-string (car l))
    (insert-string "=")
    (minibuffer-print (catenate "Type the value for " (car l)))
    (redisplay)
    (let ((ch (do ((ch1 (get-char) (get-char)))
                  (())
               (cond ((and (> ch1 057) (< ch1 072))
                      (return ch1))
                     ((= ch1 7) (return ch1))
                     ((not (= ch1 012))
                      (display-error-noabort "Type a digit please, or Control-G to abort")
                      (redisplay))))))
       (cond ((= ch 7) (return nil)))
       (insert-string (ItoC ch))))
  (minibuffer-print NL NL)))

(defun create-x-m ()
  (create-subitem-prompting 'x-m))

(defun create-x-m-comment ()
  (create-subitem-prompting 'x-m-c))

(defun create-subitem-prompting (data-base)
  (backward-char)
  (let ((keys (current-item-keys)) (acap nil) (gfe nil))
    (next-line)
    (setq acap (or (cdr (assq 'acap keys)) (minibuf-response "acap: " NL)))
    (setq gfe (minibuf-response "gfe code: " NL))
    (create-subitem data-base acap gfe (save-excursion-buffer (find-item 'acap acap t)))))

;Extract the key information from the item point is in.
;Returns an alist with elements (acap . <acapcode>) and (gfe . <gfecode>),
;but the elements are present only if the current item contains such
;information in its key.
(defun current-item-keys ()
 (save-excursion
  (do ((first t nil)) (())
    (if first
        (go-to-beginning-of-line)
       else
        (if (at-beginning-of-buffer) (return nil))
        (prev-line))
    (if (at "*")
        (return
```

```
        (do ((alist))
            ((not (forward-search-in-line " "))
             alist)
          (backward-char)
          (if (back-at ":") (return alist))
          (forward-char)
          (cond ((at "g")


                  (setq alist (cons (cons 'gfe (next-word-string)) alist)))
                 ((at "a")
                  (setq alist (cons (cons 'acap (next-word-string)) alist)))
                 (t (display-error "Item key cannot be analyzed"))))))))

(defun go-to-related-gfe ()
  (let ((alist (current-item-keys)))
    (if (assq 'gfe alist)
        (find-item 'gfe (cdr (assq 'gfe alist)) t)
      else
        (display-error "No gfe code is associated with current location"))))

(defun go-to-related-acap ()
  (let ((alist (current-item-keys)))
    (if (assq 'acap alist)
        (find-item 'acap (cdr (assq 'acap alist)) t)
      else
        (display-error "No acap code is associated with current location"))))

(defun go-to-related-x-m ()
  (let ((alist (current-item-keys)))
    (if (not (assq 'acap alist))
        (display-error "No acap code is associated with current location,
so cannot decide which cross-matrix element to find")
      else
        (if (assq 'gfe alist)
            (find-subitem 'x-m (cdr (assq 'acap alist)) (cdr (assq 'gfe alist)))
          else
            (find-item 'acap (cdr (assq 'acap alist)) t)))))

(defun go-to-related-x-m-comment ()
  (let ((alist (current-item-keys)))
    (if (not (assq 'acap alist))
        (display-error "No acap code is associated with current location,
so cannot decide which cross-matrix comment to find")
      else
        (if (assq 'gfe alist)
            (find-subitem 'x-m-c (cdr (assq 'acap alist)) (cdr (assq 'gfe alist)))
          else
            (find-item 'x-m-c (cdr (assq 'acap alist)) t)))))


;; Major modes used in the various data base files
```

```
(setq find-file-set-modes t)

(defprop GFE gfe-mode suffix-mode)
(defun gfe-mode ()
  (setq current-buffer-mode 'gfe)
  (set-key '^ZX 'go-to-related-x-m))

(defprop ACAP acap-mode suffix-mode)
(defun acap-mode ()
  (setq current-buffer-mode 'acap))

(defprop X-M x-m-mode suffix-mode)
(defun x-m-mode ()
  (setq current-buffer-mode 'x-m)
  (set-key '^ZI 'create-x-m)
  (set-key '^ZG 'go-to-related-gfe)

  (set-key '^ZA 'go-to-related-acap)
  (set-key '^ZC 'go-to-related-x-m-comment))

(defprop X-M-C x-m-comments-mode suffix-mode)
(defun x-m-comments-mode ()
  (setq current-buffer-mode 'x-m-comments)
  (set-key '^ZI 'create-x-m-c)
  (set-key '^ZG 'go-to-related-gfe)
  (set-key '^ZA 'go-to-related-acap)
  (set-key '^ZX 'go-to-related-x-m))

;Keyboard command for going back to a data base at its old position.
;Allowed in all modes.  Prompts for initial of data base name.
(set-permanent-key '^ZP 'go-to-data-base-previous-position)
(defun go-to-data-base-previous-position ()
  (let ((data-base (prompt-for-data-base)))
    (if data-base
        (go-to-data-base data-base)
      else
        (minibuffer-print "Aborted."))))

;Keyboard command for going to another data base
;to the item related to the item we are now in.
(set-permanent-key '^ZR 'go-to-related-item-prompting)
(defun go-to-related-item-prompting ()
  (let ((data-base (prompt-for-data-base)))
    (cond ((eq data-base 'gfe)
           (go-to-related-gfe))
          ((eq data-base 'acap)
           (go-to-related-acap))
          ((eq data-base 'x-m)
           (go-to-related-x-m))
          ((eq data-base 'x-m-c)
           (go-to-related-x-m-comment))
          (t (minibuffer-print "Aborted.")))))
```

```
;Keyboard command for going to a specified item of a specified data base.
(set-permanent-key '^ZS 'go-to-specified-item-prompting)
(defun go-to-specified-item-prompting ()
  (let ((data-base (prompt-for-data-base))
        (keys nil))
    (if data-base
        (let ((needed-keys (cdr (assq data-base data-base-needed-keys-alist))))
          ;; Find out what keys are needed for the specified data base,
          ;; then ask for each of those keys.
          (do ((ks needed-keys (cdr ks))) ((null ks))
            (setq keys (cons (minibuf-response (catenate (car ks) ": ") NL)
                             keys)))
          (setq keys (reverse keys))
          ;; If there are two keys, it is a subitem; otherwise, an item.
          (if (cdr keys)
              (find-subitem data-base (car keys) (cadr keys))
            else
              (find-item data-base (car keys) t)))
      else
        (minibuffer-print "Aborted."))))

(set-permanent-key '^T 'go-to-next-template-space)
(defun go-to-next-template-space ()
  (do () ((at-end-of-buffer))

    (forward-char)
    (if (or (back-at "=") (back-at ":"))
        (return nil))))

;Return a data base name by reading a single character from the tty
;and interpreting it as the initial of a data base.
(defun prompt-for-data-base ()
  (minibuffer-print "Data base letter (g, a, or x): ")
  (let ((ch1
          (do ((ch)) (())
            (setq ch (get-char))
            (cond ((= ch 012))
                  ((member (ascii ch) '(g a x c G A X C))
                   (return ch))
                  ((= ch 7) (return ch))
                  (t (minibuffer-print "Please type g, a, or x: "))))))
    (cond ((= ch1 7) (ring-tty-bell) nil)
          ((member (ascii ch1) '(a A))
           'acap)
          ((member (ascii ch1) '(g G))
           'gfe)
          ((member (ascii ch1) '(c C))
           'x-m-c)
          ((member (ascii ch1) '(x X))
           'x-m))))

(defun save-data-base ()
  (save-excursion-buffer
    (do ((db data-base-file-alist (cdr db)))
        ((null db))
      (go-to-data-base (car db))
      (save-same-file))))
```

The next listings are the APL programs described in the previous section: ENTER_GFE_NAMES, ENTER_CAP_NAMES, ENTER_CRIT, LIST_GFE, LIST_CAP.

```
    ∇ ENTER_GFE_NAMES;GNUM;GNAM;GFE;POS;A    ⍝THIS PROGRAM IS USED TO ENTER THE
~C   NAMES AND NUMBERS OF THE GFES
[1]   B:'ENTER GFE NUMBER AND NAME'
[2]    GFE←,⍞
[3]    →(0=⍴GFE)/0    ⍝IF A CARRIAGE RETURN IS ENTERED, EXIT THE PROGRAM
[4]    GNUM←⍎(GFE⍳' ')↑GFE    ⍝GNUM STORES THE GFE NUMBER
[5]    GNAM←(GFE⍳' ')↓GFE    ⍝GNAM STORES THE GFE NAME
[6]    POS←+/GN<GNUM    ⍝GN IS A VECTOR OF THE PREVIOUSLY ENTERED GFE NUMBERS
[7]    ⍝POS GIVES THE POSITION WHICH THE NEW GFE NUMBER OCCURS IN THE GN VECTOR
[8]    →(GNUM∊GN)/C    ⍝IF THE GFE IS ALREADY ENTERED, GO TO BRANCH C
[9]    GN←(POS↑GN),GNUM,POS↓GN    ⍝ADD THE NEW GFE NUMBER TO THE GN VECTOR
[10]   A←⌈/(⍴GNA)[2],⍴GNAM
[11]   CMAT←((7,POS,(⍴CMAT)[3])↑CMAT),[2]((7,1,(⍴CMAT)[3])⍴0),[2](7,(POS-(⍴GNA)[
~C1]),(⍴CMAT)[3])↑CMAT    ⍝THIS ADDS SPACE IN THE
[12]   ⍝CRITERIA VALUE ARRAY (CMAT) FOR THE NEW GFE
[13]   GNA←((POS,A)↑GNA),[1]((1,A)⍴A↑GNAM),[1]((POS-(⍴GNA)[1]),A)↑GNA    ⍝THIS
~C    ENTERS THE GFE NAME INTO THE MATRIX OF
[14]   ⍝PREVIOUSLY ENTERED GFE NAMES (GNA)
[15]   →B    ⍝RETURN TO TBRANCH B TO ENTER A NEW GFE
[16]  C:A←⌈/(⍴GNA)[2],⍴GNAM
[17]   GNA←((⍴GNA)[1],A)↑GNA
[18]   GNA[POS+1;]←A↑GNAM    ⍝THIS BRANCH IS FOR REPLACING THE NAME OF A
~C   PREVIOUSLY ENTERED GFE
[19]   →B    ⍝RETURN TO BRANCH B TO ENTER A NEW GFE
    ∇


    ∇ ENTER_CAP_NAMES;CAP;CNUM;CNAM;POS;A    ⍝THIS PROGRAM IS USED TO ENTER THE
~C    CODE NUMBERS AND NAMES OF THE ARAMIS CAPABILITIES
[1]   B:'ENTER CAPABILITY NUMBER AND NAME'
[2]    CAP←,⍞
[3]    →(0=⍴CAP)/0    ⍝IF A CARRIAGE RETURN IS ENTERED, EXIT THE PROGRAM
[4]    CNUM←⍎(CAP⍳' ')↑CAP    ⍝CNUM STORES THE CAPABILITY NUMBER
[5]    CNAM←(CAP⍳' ')↓CAP    ⍝CNAM STORES THE CAPABILITY NAME
[6]    POS←+/CN<CNUM    ⍝CN IS A VECTOR OF THE PREVIOUSLY ENTERED CAPABILITY
~C    NUMBERS
[7]    ⍝POS GIVES THE POSITION WHICH THE NEW CAPABILITY NUMBER OCCURS IN THE CN
~C     VECTOR
[8]    →(CNUM∊CN)/C    ⍝IF THE CAPABILITY IS ALREADY ENTERED, GO TO BRANCH C
[9]    CN←(POS↑CN),CNUM,POS↓CN    ⍝ADD THE NEW CAPABILITY NUMBER TO THE CN VECTOR
[10]   A←⌈/(⍴CNA)[2],⍴CNAM
[11]   CMAT←((7,(⍴CMAT)[2],POS)↑CMAT),((7,(⍴CMAT)[2],1)⍴0),(7,(⍴CMAT)[2],POS-(⍴C
~CNA)[1])↑CMAT   ⍝THIS ADDS SPACE IN THE CRITERIA VALUE
[12]   ⍝ARRAY (CMAT) FOR THE NEW CAPABILITY
[13]   CNA←((POS,A)↑CNA),[1]((1,A)⍴A↑CNAM),[1]((POS-(⍴CNA)[1]),A)↑CNA    ⍝THIS
~C   ENTERS THE CAPABILITY NAME INTO THE MATRIX OF
[14]   ⍝PREVIOUSLY ENTERED CAPABILITY NAMES (CNA)
[15]   →B    ⍝RETURN TO BRANCH B TO ENTER A NEW CAPABILITY
[16]  C:A←⌈/(⍴CNA)[2],⍴CNAM
[17]   CNA←((⍴CNA)[1],A)↑CNA
[18]   CNA[POS+1;]←A↑CNAM    ⍝THIS BRANCH IS FOR REPLACING THE NAME OF A
~C   PREVIOUSLY ENTERED CAPABILITY
[19]   →B    ⍝RETURN TO BRANCH B TO ENTER A NEW CAPABILITY
    ∇
```

```
    ∇ ENTER_CRIT;CNUM;DC;GNUM ⍝THIS PROGRAM IS USED TO INPUT THE DECISION
⍝C   CRITERIA VALUES
[1]   A2:'ENTER GFE NUMBER'
[2]    GNUM←,⎕
[3]    →(0=⍴GNUM)/0    ⍝IF A CARRIAGE RETURN IS ENTERED, EXIT THE PROGRAM
[4]    GNUM←⍎GNUM   ⍝GNUM STORES THE FUNCTIONAL ELEMENT NUMBER
[5]    →(GNUM∊GN)/A1    ⍝GN IS A VECTOR OF ALLOWABLE GFE NUMBERS
[6]    'NOT AN ENTERED GFE'
[7]    →A2
[8]   A1:'ENTER CAPABILITY NUMBER AND DECISION CRITERIA VALUES'
[9]    DC←,⎕
[10]   →(0=⍴DC)/A2    ⍝IF A CARRIAGE RETURN IS ENTERED, RETURN TO ENTER A NEW GFE
⍝C NUMBER
[11]   CNUM←⍎(DC⍳' ')↑DC    ⍝CNUM STORES THE CAPABILITY NUMBER
[12]   →(CNUM∊CN)/A6    ⍝CN IS A VECTOR OF ALLOWABLE CAPABILITY NUMBERS
[13]   'NOT AN ENTERED CAPABILITY'
[14]   →A1
[15] A6:DC←(DC⍳' ')↓DC    ⍝DC IS THE VECTOR OF CRITERIA VALUES
[16]   →('G'∊DC)/A3    ⍝IF ANOTHER GFE NUMBER IS ENTERED INSTEAD OF CRITERIA
⍝C   VALUES, GO TO BRANCH A3
[17]   →(','∊DC)/A5    ⍝IF ANOTHER CAPABILITY NUMBER IS ENTERED INSTEAD OF
⍝C   CRITERIA VALUES, GO TO BRANCH A5
[18]   →(∧/'CT'=2↑DC)/A4    ⍝IF 'CT' IS ENTERED INSTEAD OF CRITERIA VALUES, GO TO
⍝C BRANCH A4
[19]   CMAT[⍳7;GN⍳GNUM;CN⍳CNUM]←⍎DC    ⍝ENTER THE CRITERIA VALUES INTO THE
⍝C   CRITERIA VALUE ARRAY (CMAT)
[20]   →A1   ⍝RETURN TO ENTER ADECISION CRITERIA VALUES FOR ANOTHER CAPABILITY
[21] A4:CMAT[⍳7;GN⍳GNUM;CN⍳CNUM]←3 3 2 3 3 3 1    ⍝ENTER THE CURRENT TECHNOLOGY
[22]   ⍝CRITERIA VALUES INTO THE CRITERIA VALUE ARRAY (CMAT)
[23]   →A1    ⍝RETURN TO ENTER DECISION CRITERIA VALUES FOR ANOTHER CAPABILITY
[24] A3:CMAT[⍳7;GN⍳GNUM;CN⍳CNUM]←CMAT[⍳7;GN⍳⍎1↓DC;CN⍳CNUM]   ⍝ENTER THE CRITERIA
⍝C VALUES FOR THE GFE DC, CAPABILITY CNUM, AS THE
[25]   ⍝CRITERIA VALUES FOR GFE GNUM, CAPABILITY CNUM
[26]   →A1    ⍝RETURN TO ENTER DECSION CRITERIA VALUES FOR ANOTHER CAPABILITY
[27] A5:CMAT[⍳7;GN⍳GNUM;CN⍳CNUM]←CMAT[⍳7;GN⍳GNUM;CN⍳⍎(DC⍳' ')↑DC]    ⍝ENTER THE
⍝C  CRITERIA VALUES FOR THE GFE GNUM, CAPABILITY DC,
[28]   ⍝AS THE CRITERIA VALUES FOR GFE GNUM, CAPABILITY CNUM
[29]   →A1    ⍝RETURN TO ENTER DECISION CRITERIA VALUES FOR ANOTHER CAPABILITY
    ∇
```

```
∇ LIST_GFE;GFE;CNS;CAPN;CRIT;ALL;GF;GY;CD;CC;OUT;TC;CT
   ⍝THIS PROGRAM LISTS THE GFES, THE CAPABILITIES WHICH APPLY
   ⍝TO THEM, AND THE ASSOCIATED DECISION CRITERIA VALUES
   ALL←DC←CD←0
  A2:'WHICH GFE DO YOU WISH LISTED?'
   GFE←,⍞
   →(0=⍴GFE)/0   ⍝IF A CARRIAGE RETURN IS ENTERED, EXIT THE PROGRAM
   →(∧/'ALL'=3↑GFE)/A1   ⍝IF THE WORD 'ALL' IS ENTERED, GO TO BRANCH
   ⍝ A1 AND LIST ALL THE GFES
  A5:GF←GN⍳⍎GFE   ⍝GN STORES THE GFE NUMBERS
   ⍝  GF IS THE LOCATION OF THE ENTERED GFE IN THE GN VECTOR
  A6:''
   'G',GFE,' ',GNA[GF;]   ⍝PRINT THE GFE NAME AND NUMBER
   ''
   CNS←(CMAT[1;GF;]≠0)/⍳(⍴CMAT)[3]   ⍝STORE IN CNS THE NUMBER OF
   ⍝  THE CAPABILITIES WHICH APPLY TO THE GFE
   ⍝CMAT IS THE DECISION CRITERIA VALUE ARRAY
   CAPN←(((⍴CNS),¯6)↑((⍴CNS),7)↑⍕((⍴CNS),1)⍴CN[CNS]),CNA[CNS;],((⍴CNS),1)⍴'
~C'
   ⍝STORE IN CAPN  THE NAMES AND NUMBERS OF THE CAPABILITIES WHICH
   ⍝  APPLY TO THE GFE
   CRIT←⍉CMAT[⍳7;GF;CNS]   ⍝THIS TAKES THE DECISION CRITERIA VALUES THAT
   ⍝  APPLY TO THE CAPABILITIES AND STORES THEM IN CRIT
   TC←(7=+/CRIT=(⍴CRIT)⍴3 3 2 3 3 3 1)/⍳(⍴CRIT)[1]
   ⍝DECIDE WHICH OPTION IS THE CURRENT TECHNOLOGY CAPABILITY
   CT←((⍴CRIT)[1],8)⍴' |     '
   CT[TC;5 6 7 8]←((⍴TC),4)⍴'C.T.'
   CRIT←(⍕CRIT)   ⍝FORMAT OUTPUT
   CRIT[;1 3 5 7 9 11 13]←'|'
   OUT←((⍴CRIT)[1],3×(⍴CRIT)[2])⍴' '
   OUT[;3×⍳(⍴CRIT)[2]]←CRIT
   CAPN←CAPN,OUT,CT   ⍝STORE IN CAPN THE CAPABILITY NUMBERS, NAMES, AND
~C    CRITERIA VALUES
   →A3   ⍝GOTO BRANCH A3 TO PRINT OUTPUT
  A1:ALL←1   ⍝THIS BRANCH IS FOR LISTING MORE THAN ONE GFE AT A TIME
   'DO YOU WISH TO LIST THE GFES SEQUENTIALLY (YES) OR IN SOME OTHER ORDER
~C (NO)?'
   CC←,⍞
   →('N'=1↑CC)/A8   ⍝IF NO, GO TO BRANCH A8
   GFE←⍕GN[GF←1]   ⍝THIS STARTS THE LISTING WITH THE FIRST GFE
   →A6   ⍝RETURN TO PRODUCE THE MATRIX FOR THE FIRST GFE
  A4:→CD/A9   ⍝IF THE GFES ARE BEING LISTED IN NON-SEQUENTIAL
   ⍝  ORDER, GO TO A9
   GF←GF+1   ⍝LIST THE NEXT GFE
   →(GF>⍴GN)/0   ⍝IF ALL THE GFES HAVE BEEN LISTED, EXIT THE PROGRAM
   GFE←⍕GN[GF]   ⍝STORE THE  NUMBER OF THE NEXT GFE IN GFE
   →A6   ⍝BRANCH TO A6 TO LIST GFE
  A3:OUT←((2×(⍴CAPN)[1]),(⍴CAPN)[2])⍴I   ⍝FORMAT OUTPUT
   OUT[2×⍳(⍴CAPN)[1];]←CAPN
   (((1+(⍴OUT)[1]),3)⍴' '),OUT,[1]I   ⍝PRINT OUT CAPABILITY NUMBERS,
   ⍝CAPABILITY NAMES, AND DECISION CRITERIA VALUES
   →(A2,A4)[1+ALL]   ⍝IF MORE THAN ONE GFE IS BEING LISTED, GOTO A4.
   ⍝  OTHERWISE, GOTO A2 FOR THE NEXT GFE
  A8:CD←1   ⍝START WITH THE FIRST GFE NUMBER STORED IN GX
   GFE←⍕GX[GY←1]   ⍝THIS BRANCH IS FOR LISTING GFES IN AN ARBITRARY
   ⍝ ORDER DETERMINED BY THE USER.  BEFORE RUNNING THE PROGRAM, THE
   ⍝USER STORES THE GFE NUMBERS IN THE ORDER TO BE LISTED IN
   ⍝THE VECTOR GX
   →A5   ⍝GO TO A5 TO PRINT THE MATRIX FOR THE FIRST GFE
  A9:GY←GY+1   ⍝LIST THE NEXT GFE IN THE GX VECTOR
   →(GY>⍴GX)/0   ⍝IF ALL THE GFES HAVE BEEN LISTED, EXIT THE PROGRAM
   GFE←⍕GX[GY]   ⍝STORE THE NUMBER OF THE NEXT GFE IN GFE
   →A5   ⍝BRANCH TO A5 TO LIST GFE
∇
```

```
    ∇ LIST_CAP;ALL;CAPS;CF;GFE;GFEN;CC;CRIT;CY;CD;OUT   ⍝THIS PROGRAM LISTS THE
~C CAPABILITIES, THE GFES WHICH
[1]    ⍝APPLY TO THEM, AND THE ASSOCIATED DECISION CRITERIA VALUES
[2]    ALL←CD←DC←0
[3]   A2:'WHICH CAPABILITY DO YOU WISH LISTED?'
[4]    CAPS←,⍞
[5]    →(0=⍴CAPS)/0   ⍝IF A CARRIAGE RETURN IS ENTERED, EXIT THE PROGRAM
[6]    →(∧/'ALL'=3↑CAPS)/A1   ⍝IF THE WORD 'ALL' IS ENTERED, GO TO BRANCH A1 AND
~C LIST ALL THE CAPABILITIES
[7]   A5:CF←CN⍳⍎CAPS   ⍝CN STORES THE CAPABILITY NUMBERS
[8]    ⍝CF IS THE LOCATION OF THE ENTERED CAPABILITY NUMBER IN THE CN VECTOR
[9]   A6:''
[10]   CAPS,' ',CNA[CF;]   ⍝PRINT THE CAPABILITY NUMBER AND NAME
[11]   ''
[12]   GFE←(CMAT[1;;CF]≠0)/⍳(⍴CMAT)[2]   ⍝STORE IN GFE THE NUMBER OF THE
~C  FUNCTIONAL ELEMENTS WHICH APPLY TO THE
[13]   ⍝CAPABILITY.  CMAT IS THE DECISION CRITERIA VALUE ARRAY
[14]   GFEN←(((⍴GFE),1)⍴'G'),(((⍴GFE),¯4)↑((⍴GFE),5)↑⍕((⍴GFE),1)⍴GN[GFE]),
~C GNA[GFE;],((⍴GFE),1)⍴' '   ⍝STORE IN GFEN THE NAMES
[15]   ⍝AND NUMBERS OF THE FUNCTIONAL ELEMENTS WHICH APPLY TO THE CAPABILITY
[16]   GFEN←((⍴GFEN)[1],77)↑GFEN
[17]   CRIT←⍉CMAT[⍳7;GFE;CF]   ⍝THIS TAKES THE DECISION CRITERIA VALUES THAT
~C     APPLY TO THE GFES AND STORES THEM IN CRIT
[18]   CRIT←⍕CRIT
[19]   CRIT[;1 3 5 7  9 11 13]←'|'   ⍝THIS AND THE NEXT TWO LINES ARRANGE THE
~C    FORMAT IN WHICH THE CRITERIA VALUES PRINT OUT
[20]   OUT←((⍴CRIT)[1],3×(⍴CRIT)[2])⍴' '
[21]   OUT[;3×⍳(⍴CRIT)[2]]←CRIT
[22]   GFEN←GFEN,OUT
[23]   →A3   ⍝GOTO BRANCH A3
[24]  A1:ALL←1   ⍝THIS BRANCH IS FOR LISTING MORE THAN ONE CAPABILITY AT A TIME
[25]   'DO YOU WISH THE CAPABILITIES LISTED SEQUENTIALLY (YES) OR IN SOME OTHER
~C  ORDER (NO)?'
[26]   CC←,⍞
[27]   →('N'=1↑CC)/A8   ⍝IF NO, GO TO BRANCH A8
[28]   CAPS←⍕CN[1]   ⍝THIS STARTS THE LISTING WITH THE FIRST CAPABILITY
[29]   CF←1
[30]   →A6   ⍝RETURN TO PRODUCE THE MATRIX FOR THE FIRST CAPABILITY
[31]  A4:→CD/A9  ⍝IF THE CAPABILITIES ARE BEING LISTED IN NON-SEQUENTIAL ORDER,
~C GO TO A9
[32]   CF←CF+1   ⍝LIST THE NEXT CAPABILITY
[33]   →(CF)⍴CN)/0   ⍝IF ALL THE CAPABILITIES HAVE BEEN LISTED, EXIT THE PROGRAM
[34]   CAPS←⍕CN[CF]   ⍝STORE THE NUMBER OF THE NEXT CAPABILITY IN CAPS
[35]   →A6   ⍝BRANCH TO A6 TO LIST CAPABILITY CAPS
[36]  A3:OUT←((2×(⍴GFEN)[1]),(⍴GFEN)[2])⍴1↓¯8↓,I   ⍝THIS LINE AND THE NEXT ARE
~C     TO FORMAT THE OUTPUT
[37]   OUT[2×⍳(⍴GFEN)[1];]←GFEN
[38]   (((1+(⍴OUT)[1]),1)⍴' '),(OUT,[1](0 1)↓(0 ¯8)↓I),(((1+(⍴OUT)[1]),3)⍴'--|
~C|'),(((2×⍴GFE),9)⍴(((⍴GFE),9)⍴'-'),(((⍴GFE),5)⍴'C.T.='),C[GFE;]),[1]9⍴'-'
[39]   ⍝THE PREVIOUS LINE PRINTS OUT THE FUNCTINAL ELEMENT NUMBER, NAMES,
[40]   ⍝DECISION CRITERIA VALUES, AND THE CURRENT TECHNOLOGY OPTION FOR EACH GFE
[41]   →(A2,A4)[1+ALL]   ⍝IF MORE THAN ONE CAPABILITY IS BEING LISTED, GOTO A4,
~C OTHERWISE, GO TO A2 FOR THE NEXT CAPABILITY
[42]  A8:CAPS←⍕CX[CY←1]   ⍝THIS BRANCH IS FOR LISTING CAPABILITIES IN AN
~C  ARBITRARY ORDER DETERMINED BY THE USER
[43]   ⍝BEFORE RUNNING THE PROGRAM, THE USER STORES THE CAPABILITY NUMBERS IN
~C     THE ORDER TO BE LISTED IN THE VECTOR CX
[44]   CD←1   ⍝START WITH THE FIRST CAPABILITY NUMBER STORED IN CX
[45]   →A5   ⍝GO TO A5 TO PRINT THE MATRIX FOR THE FIRST CAPABILITY
[46]  A9:CY←CY+1   ⍝LIST THE NEXT CAPABILITY IN THE CX VECTOR
[47]   →(CY>⍴CX)/0   ⍝IF ALL THE CAPABILITIES HAVE BEEN LISTED, EXIT THE PROGRAM
[48]   CAPS←⍕CX[CY]   ⍝STORE THE NUMBER OF THE NEXT CAPABILITY IN CAPS
[49]   →A5   ⍝BRANCH TO A5 TO LIST CAPABILITY CAPS
    ∇
```

APPENDIX 4.G:

TRANSPOSE MATRIX: ARAMIS CAPABILITIES AND THEIR APPLICATIONS TO GFE'S

4.G.1 Notes on this Appendix

The matrix presented in Appendices 4.D and 4.E is transposed in this appendix. For each of the 78 ARAMIS capabilities defined by the study group, this appendix lists those generic functional elements for which the capability is a candidate. As the listing shows, the number of GFE's to which capabilities apply ranges from 1 (e.g. 1.3 Inflatable Structure, which is a candidate for g27 Deploy Antenna Receiver Arrays) to 30 (i.e. 14.2 Human on Ground with Computer Assistance, a candidate for nearly half the GFE's focused on by this study). Altogether, there are 465 potential applications of the 78 capabilities to the 69 GFE's in this study.

The capabilities are listed in the order of their code numbers. These numbers are based on the ARAMIS topics described in Appendix 3.A (Volume 3), and listed here in Table 4.G.1. As described in Section 4.5.3, the capabilities were associated with topics by the study group and numbered accordingly (e.g. 15.4 Teleoperated Docking Mechanism is the fourth capability listed under topic number 15: Teleoperation Techniques).

For each GFE listed under each capability, this appendix repeats the estimated decision criteria values presented in Appendix 4.E. Each line of seven criteria values matches the appropriate line in the Comparison Charts of Appendix 4.E. The decision

TABLE 4.G.1: LIST OF ARAMIS "AREAS" AND "TOPICS"

(6 Areas, 28 Topics)

MACHINERY

1. Automatic Machines
2. Programmable Machines
3. Intelligent Machines
4. Manipulators
5. Self-Replication

SENSORS

6. Range & Relative Motion Sensors
7. Directional & Pointing Sensors
8. Tactile Sensors
9. Force & Torque Sensors
10. Imaging Sensors
11. Machine Vision Techniques
12. Other Sensors (Thermal, Chemical, Radiation, etc.)

HUMAN-MACHINE

13. Human-Machine Interfaces
14. Human Augmentation & Tools
15. Teleoperation Techniques
16. Computer-Aided Design

DATA HANDLING

17. Data Transmission Technology
18. Data Storage and Retrieval
19. Data & Command Coding
20. Data Manipulation

COMPUTER INTELLIGENCE

21. Scheduling & Planning
22. Automatic Programming
23. Expert Consulting Systems
24. Deductive Techniques (Theorem Proving)
25. Computer Architecture

FAULT DETECTION & HANDLING

26. Reliability & Fault Tolerance
27. Status Monitoring & Failure Diagnosis
28. Reconfiguration & Fault Recovery

criteria are defined and discussed in Section 4.6.1.

As mentioned in Section 4.6.3, some care should be used in comparing the criteria values of a particular capability in its applications to various GFE's. This is because the estimation of those values involves the selection of one candidate capability as "current technology" (C.T.), which then receives set criteria values ("3, 3, 2, 3, 3, 3, 1" as presented in the listing); the other capabilities are then rated relative to the C.T. capability. Thus, for a particular capability's applications to two GFE's, the criteria values will not be directly comparable if different capabilities were selected as current technology for those GFE's. To alleviate this problem, each line of criteria values in this appendix is followed by identification of the code number of the C.T. capability for that generic functional element, to allow the user to adjust the evaluations.

Also mentioned in Section 4.6.3 is the user's need to read the commentary associated with the estimated decision criteria values. In most cases, this commentary is more instructive than the numbers themselves. For each line of criteria values, the appropriate remarks can be found in one of the ARAMIS Capability Application Forms in Appendix 4.E. In that appendix, these forms are located by first finding the GFE, then the candidate capability of interest.

The listing of the ARAMIS capabilities, their associated GFE's, and their decision criteria values follows. Some abbreviations were used: maint.-maintenance; nonrec.-nonrecurring cost; rec.cost-recurring cost; fail.prone.-failure-proneness; use.life-useful life; dev.risk-developmental risk; cur.tech.-current technology.

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
1.1 STORED ENERGY DEPLOYMENT DEVICE								
g27 DEPLOY ANTENNA RECEIVER ARRAYS	3	3	2	2	3	5	1	C.T.= 2.1
g31 DEPLOY SOLAR ARRAYS	3	3	2	3	4	5	1	C.T.= 2.1
1.2 SHAPE MEMORY ALLOYS								
g27 DEPLOY ANTENNA RECEIVER ARRAYS	3	3	4	4	3	5	4	C.T.= 2.1
1.3 INFLATABLE STRUCTURE								
g27 DEPLOY ANTENNA RECEIVER ARRAYS	3	5	4	4	4	4	2	C.T.= 2.1
1.6 AUTOMATIC SWITCHING SYSTEMS								
g 83 ADJUST COOLING/HEATING SYSTEMS	3	3	2	3	3	3	1	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	1	3	2	1	3	3	1	C.T.=14.2
g150 MONITOR FLUID TRANSFER	2	1	2	2	4	3	1	C.T.=14.7
g239 AVOID TANK OVERPRESSURES	3	3	2	3	3	3	1	C.T.= 1.6
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	3	3	2	3	3	3	1	C.T.= 1.6
g241 MAINTAIN COMMUNICATIONS LINKS	3	3	2	3	3	3	1	C.T.= 1.6

NOTE: ARAMIS capabilities 1.4 and 1.5 do not exist in this final listing. Although originally defined, they were later found to be covered by other capabilities, and therefore removed.

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
2.1 ONBOARD DEPLOYMENT/RETRACTION ACTUATOR								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	3	3	2	3	3	3	1	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	3	3	2	3	3	3	1	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	1	2	3	1	4	4	1	C.T.=14.3
g148 EXTEND AND ATTACH UMBILICAL	3	3	2	3	3	3	1	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	3	3	2	3	3	3	1	C.T.= 2.1
2.2 DEDICATED MANIPULATOR UNDER COMPUTER CONTROL								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	4	4	3	4	4	2	2	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	4	4	3	4	4	2	2	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	2	3	2	4	2	2	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	1	1	3	2	5	4	2	C.T.=14.3
g134 GRASP FIXTURE	1	1	3	2	3	4	2	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	3	4	3	3	4	3	2	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	3	4	3	3	4	4	2	C.T.= 2.1
3.1 AUTOMATED DOCKING MECHANISM								
g146 FASTEN DOCKING LATCH	2	1	3	1	4	2	2	C.T.=13.3

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	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
4.1 COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	4	4	4	4	4	2	3	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	4	4	4	4	4	2	3	C.T.= 2.1
g 73 POSITION AND CONNECT NEW COMPONENT	2	2	4	2	3	3	3	C.T.=14.3
g134 GRASP FIXTURE	2	2	4	2	3	3	3	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	4	4	3	4	4	2	3	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	3	4	4	3	3	C.T.= 2.1
4.2 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	4	4	4	4	4	2	4	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	4	4	4	4	4	2	4	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	2	4	2	4	2	3	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	2	2	4	2	4	2	4	C.T.=14.3
g134 GRASP FIXTURE	2	3	4	2	3	2	3	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	4	4	4	4	4	2	4	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	4	4	4	3	4	C.T.= 2.1
4.3 COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	4	4	5	4	2	1	5	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	4	4	5	4	2	1	5	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	2	5	2	3	1	4	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	1	2	5	2	3	1	5	C.T.=14.3
g134 GRASP FIXTURE	1	4	5	2	2	1	4	C.T.=15.1

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	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g148 EXTEND AND ATTACH UMBILICAL	4	4	5	4	2	1	5	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	5	4	2	3	5	C.T.= 2.1
6.1 OPTICAL SCANNER (PASSIVE COOPERATIVE TARGET)								
g 33 VERIFY DEPLOYMENT SEQUENCES	2	3	3	2	3	2	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	2	3	3	2	5	5	2	C.T.=27.3
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	1	1	3	1	2	2	2	C.T.=13.1
g132 LOCATE GRASPING FIXTURE ON TARGET	1	1	3	1	2	2	2	C.T.=13.1
g243 TRACK NEARBY OBJECTS	3	3	2	3	2	2	1	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	2	1	3	1	2	2	2	C.T.=13.1
6.2 PROXIMITY SENSORS								
g69 OBSERVE/LOCATE DEFECTIVE COMPONENT	5	1	3	1	4	5	1	C.T.=13.1
6.3 RADAR (PASSIVE TARGET)								
g132 LOCATE GRASPING FIXTURE ON TARGET	1	1	4	2	4	5	3	C.T.=13.1
g243 TRACK NEARBY OBJECTS	3	3	2	3	3	3	1	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	2	1	3	2	4	3	2	C.T.=13.1
6.4 RADAR (ACTIVE TARGET)								
g132 LOCATE GRASPING FIXTURE ON TARGET	1	2	3	3	3	3	2	C.T.=13.1
g243 TRACK NEARBY OBJECTS	3	3	2	3	2	2	1	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	2	1	3	2	3	2	2	C.T.=13.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
6.5 ONBOARD NAVIGATION AND TELEMETRY								
g243 TRACK NEARBY OBJECTS	2	4	4	3	2	2	2	C.T.= 6.3
7.1 DEAD RECKONING FROM STORED MODEL								
g69 OBSERVE/LOCATE DEFECTIVE COMPONENT	1	2	2	1	5	5	2	C.T.=13.1
8.1 TACTILE SENSORS								
g69 OBSERVE/LOCATE DEFECTIVE COMPONENT	4	1	3	1	4	4	2	C.T.=13.1
10.1 THERMAL IMAGING SENSOR WITH HUMAN PROCESSING								
g48 THERMAL SUBSYSTEM CHECKOUT	4	3	4	4	2	3	2	C.T.=27.6
11.1 IMAGING (STEREO) WITH MACHINE PROCESSING								
g 33 VERIFY DEPLOYMENT SEQUENCES	5	4	5	3	3	2	4	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	5	4	5	3	4	3	4	C.T.=27.3
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	3	2	5	2	3	2	5	C.T.=13.1
g132 LOCATE GRASPING FIXTURE ON TARGET	3	2	5	2	3	1	4	C.T.=13.1
g243 TRACK NEARBY OBJECTS	4	4	5	3	3	3	4	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	3	2	5	2	2	1	4	C.T.=13.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
11.2 IMAGING (NON-STEREO) WITH MACHINE PROCESSING								
g 33 VERIFY DEPLOYMENT SEQUENCES	5	4	5	3	3	2	4	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	5	4	5	3	4	3	4	C.T.=27.3
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	3	2	5	2	3	2	5	C.T.=13.1
g132 LOCATE GRASPING FIXTURE ON TARGET	3	2	5	2	3	1	4	C.T.=13.1
g243 TRACK NEARBY OBJECTS	4	4	5	3	4	3	4	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	3	2	5	2	3	1	4	C.T.=13.1
11.3 THERMAL IMAGING SENSOR WITH MACHINE PROCESSING								
g48 THERMAL SUBSYSTEM CHECKOUT	2	3	5	3	2	2	3	C.T.=27.6
13.1 HUMAN EYESIGHT VIA VIDEO								
g 33 VERIFY DEPLOYMENT SEQUENCES	4	4	1	4	4	3	1	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	4	4	1	4	4	3	1	C.T.=27.3
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	3	3	2	3	3	3	1	C.T.=13.1
g132 LOCATE GRASPING FIXTURE ON TARGET	3	3	2	3	3	3	1	C.T.=13.1
g243 TRACK NEARBY OBJECTS	5	5	2	5	5	5	1	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	3	3	2	3	3	3	1	C.T.=13.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
13.2 HUMAN EYESIGHT VIA GRAPHIC DISPLAY								
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	3	3	3	3	2	2	3	C.T.=13.1
g109 DATA/COMMAND DISPLAY	3	3	2	3	3	3	1	C.T.=13.2
g132 LOCATE GRASPING FIXTURE ON TARGET	3	3	3	3	2	2	2	C.T.=13.1
g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW	3	2	2	3	3	4	1	C.T.=14.2
g224 PROCESS IMAGE DATA	3	3	2	3	3	3	1	C.T.=13.2
g243 TRACK NEARBY OBJECTS	4	5	3	4	3	3	2	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	3	3	3	3	2	2	2	C.T.=13.1
13.3 DOCKING UNDER ONSITE HUMAN CONTROL								
g146 FASTEN DOCKING LATCH	3	3	2	3	3	3	1	C.T.=13.3
13.4 COMPUTER PRINTOUT								
g109 DATA/COMMAND DISPLAY	4	3	2	3	3	5	1	C.T.=13.2
13.5 COMPUTER-GENERATED AUDIO								
g109 DATA/COMMAND DISPLAY	4	2	2	1	4	2	1	C.T.=13.2
13.6 STEREOPTIC VIDEO								
g109 DATA/COMMAND DISPLAY	2	4	3	4	3	3	2	C.T.=13.2
13.7 3-D DISPLAY								
g109 DATA/COMMAND DISPLAY	2	5	5	4	4	2	3	C.T.=13.2

14.1 DIRECT HUMAN EYESIGHT

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 33 VERIFY DEPLOYMENT SEQUENCES	5	4	1	4	3	2	1	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	3	4	1	4	4	4	1	C.T.=27.3
g 69 OBSERVE/LOCATE DEFECTIVE COMPONENT	3	4	2	4	2	4	1	C.T.=13.1
g132 LOCATE GRASPING FIXTURE ON TARGET	2	4	2	4	2	4	1	C.T.=13.1
g243 TRACK NEARBY OBJECTS	5	5	2	5	5	5	1	C.T.= 6.3
g245 OBSERVE TUMBLING SPACECRAFT	3	4	2	4	2	4	1	C.T.=13.1

14.2 HUMAN ON GROUND WITH COMPUTER ASSISTANCE

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 1 VERIFY POWER SYSTEM FUNCTION	3	3	2	3	3	3	1	C.T.=14.2
g 5 MISSION SEQUENCE SIMULATION	3	3	2	3	3	3	1	C.T.=14.2
g 10 CHECK ELECTRICAL INTERFACES	3	3	2	3	3	3	1	C.T.=14.2
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	4	3	2	4	2	3	1	C.T.=25.4
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	3	3	2	3	3	3	1	C.T.=14.2
g 38 CHOOSE OPTIMAL TRAJECTORY	3	3	2	3	3	3	1	C.T.=14.2
g 47 ACTIVATE SUBSYSTEMS	3	3	2	3	3	3	1	C.T.=14.2
g 56 DETERMINE ANOMALOUS DATA	3	3	2	3	3	3	1	C.T.=14.2
g 57 FORM HYPOTHESIS FOR PROBLEM	2	4	3	3	2	2	1	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	2	4	3	3	2	2	1	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	2	4	3	3	2	3	1	C.T.=14.4
g 64 UPDATE SPACECRAFT MODEL	3	3	2	3	3	3	1	C.T.=14.2
g 65 DEFINE ACCESS SEQUENCE	2	4	3	3	2	3	1	C.T.=14.5
g 83 ADJUST COOLING/HEATING SYSTEMS	4	2	2	5	2	4	1	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	3	3	2	3	3	3	1	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	3	3	2	3	3	3	1	C.T.=14.2
g 92 NUMERICAL COMPUTATION	4	3	2	4	2	2	1	C.T.=25.4
g 93 LOGIC OPERATIONS	3	3	2	3	3	3	1	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	4	3	2	4	2	3	1	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	3	3	2	3	3	3	1	C.T.=14.2
g 98 COMPUTE OPTIMAL CONSUMABLES ALLOCATION	3	3	2	3	3	3	1	C.T.=14.2
g103 APPLY COMPENSATING FORCES	3	3	2	3	3	3	1	C.T.=14.2

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	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g107 DETERMINE CONSTRAINTS AND FIGURES OF MERIT	3	3	2	3	3	3	1	C.T.=14.2
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	3	3	2	3	3	3	1	C.T.=14.2
g184 MONITOR TELEMETRY	3	3	2	3	3	3	1	C.T.=14.2
g185 EVALUATE SYSTEM PERFORMANCE	3	3	2	3	3	3	1	C.T.=14.2
g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW	3	3	2	3	3	3	1	C.T.=14.2
g244 AVOID CONFLICTING OBJECTS	4	2	1	2	4	5	1	C.T.=14.7
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	4	2	3	4	4	5	1	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	3	3	2	3	3	3	1	C.T.=14.2

14.3 HUMAN IN EVA WITH TOOLS

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 23 POWER SUBSYSTEM CHECKOUT	4	5	3	5	3	4	1	C.T.=27.3
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	5	5	2	5	1	1	1	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	5	5	2	5	1	1	1	C.T.= 2.1
g 48 THERMAL SUBSYSTEM CHECKOUT	5	5	2	5	4	4	1	C.T.=27.6
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	3	2	3	3	3	1	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	3	3	2	3	3	3	1	C.T.=14.3
g134 GRASP FIXTURE	4	5	2	4	2	3	1	C.T.=15.1
g146 FASTEN DOCKING LATCH	5	4	1	4	2	4	1	C.T.=13.3
g148 EXTEND AND ATTACH UMBILICAL	5	5	2	5	1	2	1	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	5	5	2	5	3	3	1	C.T.= 2.1
g260 SP/PAYLOAD INTERFACE CHECKOUT	4	4	1	4	2	2	1	C.T.=14.7

14.4 HUMAN WITH CHECKLIST

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	5	1	1	4	3	4	1	C.T.=25.4
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	4	2	2	2	4	4	1	C.T.=14.2
g 38 CHOOSE OPTIMAL TRAJECTORY	4	2	2	2	4	4	1	C.T.=14.2
g 47 ACTIVATE SUBSYSTEMS	4	2	1	2	3	2	1	C.T.=14.2
g 57 FORM HYPOTHESIS FOR PROBLEM	3	3	2	3	3	3	1	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	3	3	2	3	3	3	1	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	3	3	2	3	3	3	1	C.T.=14.4
g 64 UPDATE SPACECRAFT MODEL	4	2	2	3	4	4	1	C.T.=14.2
g 83 ADJUST COOLING/HEATING SYSTEMS	5	1	1	5	3	5	1	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	4	2	2	4	4	5	1	C.T.=14.2
g 93 LOGIC OPERATIONS	4	1	1	4	4	5	1	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	4	1	1	4	4	3	1	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	4	1	2	4	4	4	1	C.T.=14.2
g105 PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE	3	3	2	3	3	3	1	C.T.=14.4
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	4	2	2	3	4	4	1	C.T.=14.2
g184 MONITOR TELEMETRY	4	2	1	4	4	4	1	C.T.=14.2
g185 EVALUATE SYSTEM PERFORMANCE	4	2	2	4	4	4	1	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	5	2	1	2	4	5	1	C.T.=16.1
g220 PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART	3	3	2	3	3	3	1	C.T.=14.4

	CUR. TECH.	DEV. RISK	USE. LIFE	FAIL. PRONE.	REC. COST	NONREC.	MAINT.	TIME
14.5 HUMAN JUDGMENT ON GROUND								
g 57 FORM HYPOTHESIS FOR PROBLEM	C.T.=14.4	1	3	4	3	2	2	3
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	C.T.=14.4	1	3	4	3	2	2	3
g 60 IDENTIFY FAULTY COMPONENT	C.T.=14.4	1	3	4	3	2	2	3
g 65 DEFINE ACCESS SEQUENCE	C.T.=14.5	1	3	3	3	2	3	3
g 77 DETERMINE CORRECTION ALGORITHM	C.T.=14.5	1	3	3	3	2	3	3
g107 DETERMINE CONSTRAINTS AND FIGURES OF MERIT	C.T.=14.2	1	4	4	3	1	1	4
g184 MONITOR TELEMETRY	C.T.=14.2	1	4	4	4	1	1	4
g194 IDENTIFY FAULTY SOFTWARE	C.T.=16.1	1	4	4	2	1	1	5
g223 SELECT NEW TELESCOPE ATTITUDE IF NECESSARY	C.T.=14.5	1	3	3	3	2	3	3
g244 AVOID CONFLICTING OBJECTS	C.T.=14.7	1	5	5	1	1	1	4
14.6 MANUAL TESTING ON GROUND								
g 1 VERIFY POWER SYSTEM FUNCTION	C.T.=14.2	1	4	4	2	1	1	4
g 5 MISSION SEQUENCE SIMULATION	C.T.=14.2	1	4	4	2	1	2	5
g10 CHECK ELECTRICAL INTERFACES	C.T.=14.2	1	4	4	4	1	2	5

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14.7 ONSITE HUMAN WITH COMPUTER ASSISTANCE

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 23 POWER SUBSYSTEM CHECKOUT	3	5	3	4	2	3	2	C.T.=27.3
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	4	5	3	5	2	3	2	C.T.=25.4
g 33 VERIFY DEPLOYMENT SEQUENCES	4	5	3	3	3	2	2	C.T.=27.6
g 35 INITIALIZE GUIDANCE SYSTEM	4	4	3	4	3	3	1	C.T.=25.3
g 47 ACTIVATE SUBSYSTEMS	3	5	3	4	3	3	1	C.T.=14.2
g 48 THERMAL SUBSYSTEM CHECKOUT	4	4	4	4	2	2	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	4	5	3	3	3	3	2	C.T.=27.3
g 50 COMMUNICATIONS SUBSYSTEM CHECKOUT	4	5	4	4	2	3	2	C.T.=27.3
g 51 ATTITUDE CONTROL SUBSYSTEM CHECKOUT	4	5	3	4	3	4	2	C.T.=27.3
g 52 PROPULSION SUBSYSTEM CHECKOUT	4	5	3	4	3	4	2	C.T.=27.3
g 54 CONSUMABLES LEVELS CHECKOUT	3	5	4	4	2	4	2	C.T.=27.6
g 56 DETERMINE ANOMALOUS DATA	3	5	3	4	3	3	2	C.T.=14.2
g 57 FORM HYPOTHESIS FOR PROBLEM	2	5	3	4	2	2	1	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	2	5	3	4	2	2	1	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	2	5	4	4	2	2	2	C.T.=14.4
g 65 DEFINE ACCESS SEQUENCE	2	5	4	4	2	2	1	C.T.=14.5
g 92 NUMERICAL COMPUTATION	4	5	3	4	2	3	1	C.T.=25.4
g150 MONITOR FLUID TRANSFER	3	3	2	3	3	3	1	C.T.=14.7
g185 EVALUATE SYSTEM PERFORMANCE	2	5	3	4	2	2	1	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	4	5	3	4	3	4	2	C.T.=16.1
g244 AVOID CONFLICTING OBJECTS	3	3	2	3	3	3	1	C.T.=14.7
g260 SP/PAYLOAD INTERFACE CHECKOUT	3	3	2	3	3	3	1	C.T.=14.7
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	4	4	3	4	3	4	1	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	3	5	3	4	2	1	1	C.T.=14.2

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
14.8 ONSITE HUMAN JUDGMENT								
g 57 FORM HYPOTHESIS FOR PROBLEM	3	4	2	4	4	3	1	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	3	4	2	4	4	3	1	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	3	4	2	4	4	3	1	C.T.=14.4
g 65 DEFINE ACCESS SEQUENCE	3	4	2	4	3	3	1	C.T.=14.5
g185 EVALUATE SYSTEM PERFORMANCE	2	4	2	4	3	2	1	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	5	4	2	4	4	4	1	C.T.=16.1
g244 AVOID CONFLICTING OBJECTS	3	2	1	3	4	3	1	C.T.=14.7
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	3	5	2	4	2	1	1	C.T.=14.2
15.1 SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	5	5	4	4	2	2	2	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	5	5	4	4	2	2	2	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	2	3	3	3	2	1	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	3	2	3	3	4	2	2	C.T.=14.3
g134 GRASP FIXTURE	3	3	2	3	3	3	1	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	4	4	3	4	2	2	2	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	3	4	4	3	2	C.T.= 2.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
15.2 DEXTROUS MANIPULATOR UNDER HUMAN CONTROL								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	5	5	3	4	2	2	2	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	5	5	3	4	2	2	2	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	3	2	3	3	3	2	2	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	3	2	4	3	3	2	3	C.T.=14.3
g134 GRASP FIXTURE	3	2	4	3	3	2	3	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	4	4	4	4	2	2	3	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	4	4	4	3	3	C.T.= 2.1
15.3 TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT								
g 27 DEPLOY ANTENNA RECEIVER ARRAYS	5	5	4	5	3	1	2	C.T.= 2.1
g 31 DEPLOY SOLAR ARRAYS	5	5	4	4	3	1	2	C.T.= 2.1
g 67 TRANSFER REPAIR EQUIPMENT TO REPAIR SITE	2	3	3	3	3	1	2	C.T.=14.3
g 73 POSITION AND CONNECT NEW COMPONENT	3	3	3	3	4	2	2	C.T.=14.3
g134 GRASP FIXTURE	3	3	2	3	3	2	2	C.T.=15.1
g148 EXTEND AND ATTACH UMBILICAL	3	4	2	4	3	2	1	C.T.= 2.1
g177 RELEASE SOLAR ARRAY RESTRAINTS	4	4	4	4	4	3	2	C.T.= 2.1
15.4 TELEOPERATED DOCKING MECHANISM								
g146 FASTEN DOCKING LATCH	4	2	2	2	4	3	1	C.T.=13.3

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
16.1 COMPUTER MODELING AND SIMULATION								
g 1 VERIFY POWER SYSTEM FUNCTION	2	3	4	2	2	1	2	C.T.=14.2
g 5 MISSION SEQUENCE SIMULATION	1	3	3	1	2	2	2	C.T.=14.2
g 64 UPDATE SPACECRAFT MODEL	2	3	4	2	2	2	3	C.T.=14.2
g 77 DETERMINE CORRECTION ALGORITHM	2	4	3	2	2	2	2	C.T.=14.5
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	1	3	4	2	2	1	3	C.T.=14.2
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	2	3	4	2	2	2	3	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	3	3	2	3	3	3	1	C.T.=16.1
17.1 TRACKING AND DATA RELAY SATELLITE SYSTEM								
g79 DATA/COMMAND TRANSMISSION	3	2	3	1	2	1	2	C.T.=17.2
17.2 DIRECT TRANSMISSION TO/FROM GROUND								
g79 DATA/COMMAND TRANSMISSION	3	3	2	3	3	3	1	C.T.=17.2
17.3 DIRECT TRANSMISSION TO/FROM ORBITER								
g79 DATA/COMMAND TRANSMISSION	2	3	2	3	3	3	1	C.T.=17.2
17.4 DIRECT COMMUNICATION TO/FROM ORBITER VIA CABLE								
g79 DATA/COMMAND TRANSMISSION	2	3	1	2	1	4	1	C.T.=17.2
18.1 ONBOARD DATA RECORDER								
g218 TAKE DATA FROM DETECTOR	3	3	2	3	3	3	1	C.T.=18.1
g264 MONITOR MICRO-GRAVITY LEVELS	3	3	2	3	3	3	1	C.T.=18.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
18.2 RANDOM ACCESS MEMORY								
g89 SHORT-TERM MEMORY STORAGE	3	3	2	3	3	3	1	C.T.=18.2
18.3 MAGNETIC TAPE								
g89 SHORT-TERM MEMORY STORAGE	5	5	2	4	5	5	1	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	3	3	2	3	3	3	1	C.T.=18.3
18.4 MAGNETIC BUBBLE MEMORY								
g89 SHORT-TERM MEMORY STORAGE	4	3	3	2	4	3	2	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	1	1	4	1	3	2	3	C.T.=18.3
18.5 MAGNETIC DISC MEMORY								
g89 SHORT-TERM MEMORY STORAGE	4	4	4	2	4	4	3	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	2	2	3	2	2	3	2	C.T.=18.3
18.6 OPTICAL DISC								
g90 LONG-TERM MEMORY STORAGE	2	2	3	1	2	2	3	C.T.=18.3
18.7 ERASABLE OPTICAL DISC								
g89 SHORT-TERM MEMORY STORAGE	4	4	5	1	3	4	4	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	2	2	4	1	2	2	4	C.T.=18.3

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
18.8 HOLOGRAPHIC STORAGE								
g89 SHORT-TERM MEMORY STORAGE	4	4	5	1	2	4	5	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	2	2	4	1	2	1	3	C.T.=18.3
18.9 MICROFORM ON GROUND								
g90 LONG-TERM MEMORY STORAGE	5	1	1	2	1	2	1	C.T.=18.3
18.10 ELECTRICALLY ALTERABLE READ ONLY MEMORY								
g90 LONG-TERM MEMORY STORAGE	1	1	2	2	2	4	2	C.T.=18.3
18.11 CRYOELECTRONIC MEMORY								
g89 SHORT-TERM MEMORY STORAGE	1	4	5	2	4	1	5	C.T.=18.2
18.12 ELECTRON BEAM MEMORY								
g89 SHORT-TERM MEMORY STORAGE	3	4	5	4	4	5	4	C.T.=18.2
g90 LONG-TERM MEMORY STORAGE	1	2	5	4	3	5	4	C.T.=18.3
18.13 CHARGE-COUPLED DEVICE MEMORY								
g89 SHORT-TERM MEMORY STORAGE	4	3	3	2	3	3	2	C.T.=18.2
19.1 ANALOG/DIGITAL CONVERTER								
g78 DATA/COMMAND ENCODING	3	3	2	3	3	3	1	C.T.=19.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
21.1 ONBOARD SEQUENCER								
g47 ACTIVATE SUBSYSTEMS	1	3	1	1	4	5	1	C.T.=14.2
g83 ADJUST COOLING/HEATING SYSTEMS	3	3	2	3	4	5	1	C.T.= 1.6
g87 ADJUST CURRENTS AND VOLTAGES	1	2	2	1	5	4	1	C.T.=14.2
21.2 OPERATIONS OPTIMIZATION PROGRAM								
g38 CHOOSE OPTIMAL TRAJECTORY	2	4	3	1	2	1	2	C.T.=14.2
g83 ADJUST COOLING/HEATING SYSTEMS	3	2	3	3	1	1	2	C.T.= 1.6
g87 ADJUST CURRENTS AND VOLTAGES	3	3	3	2	1	2	2	C.T.=14.2
g94 COMPUTER LOAD SCHEDULING	2	4	3	2	2	2	2	C.T.=25.4
g98 COMPUTE OPTIMAL CONSUMABLES ALLOCATION	2	3	3	1	2	1	2	C.T.=14.2
22.1 AUTOMATIC PROGRAMMER AND PROGRAM TESTER								
g77 DETERMINE CORRECTION ALGORITHM	2	4	3	1	2	2	3	C.T.=14.5

23.1 EXPERT SYSTEM WITH HUMAN SUPERVISION

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	3	5	3	2	2	2	2	C.T.=25.4
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	1	3	3	3	3	1	2	C.T.=14.2
g 57 FORM HYPOTHESIS FOR PROBLEM	2	5	3	2	1	1	2	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	2	5	3	2	1	1	2	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	1	5	3	2	2	2	2	C.T.=14.4
g 93 LOGIC OPERATIONS	2	4	3	2	2	1	2	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	3	4	3	2	2	2	2	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	2	4	4	3	2	2	3	C.T.=14.2
g105 PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE	2	5	4	2	2	2	2	C.T.=14.4
g107 DETERMINE CONSTRAINTS AND FIGURES OF MERIT	2	4	4	2	2	2	3	C.T.=14.2
g184 MONITOR TELEMETRY	2	4	4	3	2	2	3	C.T.=14.2
g185 EVALUATE SYSTEM PERFORMANCE	2	4	4	3	2	2	3	C.T.=14.2
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	1	5	3	3	2	1	2	C.T.=14.2

23.2 LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 5 MISSION SEQUENCE SIMULATION	1	3	5	1	1	1	5	C.T.=14.2
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	2	4	5	1	1	1	4	C.T.=25.4
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	1	4	5	2	2	1	5	C.T.=14.2
g 56 DETERMINE ANOMALOUS DATA	1	4	5	2	1	1	4	C.T.=14.2
g 57 FORM HYPOTHESIS FOR PROBLEM	1	4	5	2	1	1	5	C.T.=14.4
g 58 DEVISE TEST FOR FAILURE HYPOTHESIS	1	4	5	2	1	1	5	C.T.=14.4
g 60 IDENTIFY FAULTY COMPONENT	1	4	5	1	1	1	5	C.T.=14.4
g 64 UPDATE SPACECRAFT MODEL	1	4	5	1	1	1	5	C.T.=14.2
g 87 ADJUST CURRENTS AND VOLTAGES	2	4	5	2	1	1	4	C.T.=14.2
g 93 LOGIC OPERATIONS	1	4	5	1	1	1	4	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	2	4	5	1	1	1	4	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	1	4	5	1	1	1	4	C.T.=14.2
g 98 COMPUTE OPTIMAL CONSUMABLES ALLOCATION	1	4	5	1	1	1	4	C.T.=14.2
g105 PROJECT DESIRED FUNCTIONS FROM MISSION PROFILE	1	4	5	1	1	1	4	C.T.=14.4
g107 DETERMINE CONSTRAINTS AND FIGURES OF MERIT	2	4	5	1	1	1	5	C.T.=14.2
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	2	4	5	2	1	1	4	C.T.=14.2
g184 MONITOR TELEMETRY	1	3	5	1	1	1	4	C.T.=14.2
g185 EVALUATE SYSTEM PERFORMANCE	1	4	5	2	1	1	5	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	2	4	5	1	1	1	5	C.T.=16.1
g223 SELECT NEW TELESCOPE ATTITUDE IF NECESSARY	1	5	4	2	2	1	4	C.T.=14.5
g244 AVOID CONFLICTING OBJECTS	2	2	4	1	2	1	4	C.T.=14.7
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	1	4	5	2	2	1	5	C.T.=14.2

24.1 THEOREM PROVING PROGRAM

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 57 FORM HYPOTHESIS FOR PROBLEM	2	4	4	2	2	1	3	C.T.=14.4
g 65 DEFINE ACCESS SEQUENCE	1	4	5	2	2	1	4	C.T.=14.5
g 77 DETERMINE CORRECTION ALGORITHM	2	4	4	2	1	1	4	C.T.=14.5
g194 IDENTIFY FAULTY SOFTWARE	3	3	4	3	2	2	4	C.T.=16.1

25.1 ONBOARD DEDICATED MICROPROCESSOR

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	2	4	3	1	3	3	2	C.T.=25.4
g 35 INITIALIZE GUIDANCE SYSTEM	3	3	2	3	3	3	2	C.T.=25.3
g 47 ACTIVATE SUBSYSTEMS	1	4	3	2	3	2	2	C.T.=14.2
g 78 DATA/COMMAND ENCODING	4	3	2	3	2	1	2	C.T.=19.1
g 83 ADJUST COOLING/HEATING SYSTEMS	3	2	3	3	2	3	2	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	2	4	3	2	2	2	2	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	1	4	3	1	2	2	2	C.T.=14.2
g 92 NUMERICAL COMPUTATION	2	4	3	1	3	3	1	C.T.=25.4
g 93 LOGIC OPERATIONS	1	4	3	1	3	2	2	C.T.=14.2
g103 APPLY COMPENSATING FORCES	2	4	3	2	3	2	2	C.T.=14.2
g150 MONITOR FLUID TRANSFER	2	1	2	2	4	2	2	C.T.=14.7
g218 TAKE DATA FROM DETECTOR	2	2	2	2	2	2	2	C.T.=18.1
g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW	1	4	3	2	3	2	2	C.T.=14.2
g224 PROCESS IMAGE DATA	1	5	3	2	2	1	2	C.T.=13.2
g239 AVOID TANK OVERPRESSURES	2	3	3	3	4	3	2	C.T.= 1.6
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	2	3	3	3	3	1	2	C.T.= 1.6
g241 MAINTAIN COMMUNICATIONS LINKS	2	3	3	2	2	2	2	C.T.= 1.6
g260 SP/PAYLOAD INTERFACE CHECKOUT	1	2	3	1	2	1	2	C.T.=14.7
g264 MONITOR MICRO-GRAVITY LEVELS	3	1	3	1	2	2	2	C.T.=18.1
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	3	3	2	2	2	2	2	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	1	4	3	2	4	2	2	C.T.=14.2

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25.2 ONBOARD MICROPROCESSOR HIERARCHY

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	2	3	4	2	2	1	3	C.T.=25.4
g 47 ACTIVATE SUBSYSTEMS	1	3	4	2	2	1	3	C.T.=14.2
g 83 ADJUST COOLING/HEATING SYSTEMS	3	2	4	3	1	2	3	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	2	3	4	2	1	1	3	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	1	3	4	1	1	1	3	C.T.=14.2
g 92 NUMERICAL COMPUTATION	2	3	4	2	2	1	3	C.T.=25.4
g 93 LOGIC OPERATIONS	1	3	4	1	2	1	3	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	2	3	4	2	2	1	3	C.T.=25.4
g103 APPLY COMPENSATING FORCES	2	3	4	2	2	1	3	C.T.=14.2
g218 TAKE DATA FROM DETECTOR	2	1	3	3	1	1	3	C.T.=18.1
g224 PROCESS IMAGE DATA	1	4	4	2	1	1	3	C.T.=13.2
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	2	2	4	3	2	1	3	C.T.= 1.6
g241 MAINTAIN COMMUNICATIONS LINKS	2	2	4	2	2	1	3	C.T.= 1.6
g260 SP/PAYLOAD INTERFACE CHECKOUT	1	1	3	1	2	1	3	C.T.=14.7
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	3	2	4	3	1	1	3	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	1	3	4	2	3	2	3	C.T.=14.2

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	2	4	3	3	2	3	2	C.T.=25.4
g 35 INITIALIZE GUIDANCE SYSTEM	3	3	2	3	3	3	1	C.T.=25.3
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	1	4	3	2	3	2	2	C.T.=14.2
g 38 CHOOSE OPTIMAL TRAJECTORY	2	4	3	2	3	2	2	C.T.=14.2
g 47 ACTIVATE SUBSYSTEMS	1	4	3	2	3	2	2	C.T.=14.2
g 78 DATA/COMMAND ENCODING	4	3	3	3	2	1	2	C.T.=19.1
g 83 ADJUST COOLING/HEATING SYSTEMS	3	2	3	3	2	2	2	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	2	4	3	2	2	2	2	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	1	4	3	1	2	2	2	C.T.=14.2
g 92 NUMERICAL COMPUTATION	2	4	3	3	3	3	2	C.T.=25.4
g 93 LOGIC OPERATIONS	1	4	3	1	3	2	2	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	2	4	3	3	3	3	2	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	2	4	3	2	3	2	2	C.T.=14.2
g103 APPLY COMPENSATING FORCES	2	4	3	2	3	2	2	C.T.=14.2
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	2	4	4	2	3	2	2	C.T.=14.2
g218 TAKE DATA FROM DETECTOR	2	2	3	2	2	2	2	C.T.=18.1
g220 PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART	2	5	3	2	3	1	1	C.T.=14.4
g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW	1	4	3	2	3	2	2	C.T.=14.2
g223 SELECT NEW TELESCOPE ATTITUDE IF NECESSARY	2	5	3	2	4	2	2	C.T.=14.5
g224 PROCESS IMAGE DATA	1	5	3	2	2	1	2	C.T.=13.2
g239 AVOID TANK OVERPRESSURES	2	3	3	3	4	3	2	C.T.= 1.6
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	2	3	2	3	3	2	2	C.T.= 1.6

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	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g241 MAINTAIN COMMUNICATIONS LINKS	2	3	3	2	2	2	2	C.T.= 1.6
g244 AVOID CONFLICTING OBJECTS	2	2	2	2	4	2	2	C.T.=14.7
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	3	3	2	3	3	3	1	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	1	4	3	2	3	2	2	C.T.=14.2

25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 10 CHECK ELECTRICAL INTERFACES	2	3	2	2	2	2	2	C.T.=14.2
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=25.4
g 35 INITIALIZE GUIDANCE SYSTEM	4	2	2	3	4	4	1	C.T.=25.3
g 37 DETERMINE DESIRED ORBITAL PARAMETERS	2	3	2	2	3	3	2	C.T.=14.2
g 38 CHOOSE OPTIMAL TRAJECTORY	2	3	3	2	3	3	2	C.T.=14.2
g 47 ACTIVATE SUBSYSTEMS	2	3	3	2	3	2	1	C.T.=14.2
g 56 DETERMINE ANOMALOUS DATA	1	3	3	2	3	3	1	C.T.=14.2
g 60 IDENTIFY FAULTY COMPONENT	2	4	3	1	2	2	1	C.T.=14.4
g 78 DATA/COMMAND ENCODING	5	2	2	3	2	2	2	C.T.=19.1
g 83 ADJUST COOLING/HEATING SYSTEMS	3	2	3	3	2	2	1	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	3	3	2	2	2	3	1	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	2	3	2	1	2	3	1	C.T.=14.2
g 92 NUMERICAL COMPUTATION	3	3	2	3	3	3	1	C.T.=25.4
g 93 LOGIC OPERATIONS	2	3	3	1	3	2	2	C.T.=14.2
g 94 COMPUTER LOAD SCHEDULING	3	3	2	3	3	3	1	C.T.=25.4
g 97 PROJECT CONSUMABLES REQUIREMENTS FROM MISSION PROFILE	2	3	3	2	3	2	2	C.T.=14.2

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	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g110 DETERMINE NEW CONFIGURATION FOR SPACECRAFT COMPONENTS	2	3	3	2	3	3	2	C.T.=14.2
g184 MONITOR TELEMETRY	2	3	3	2	4	2	2	C.T.=14.2
g194 IDENTIFY FAULTY SOFTWARE	3	3	2	3	3	3	1	C.T.=16.1
g220 PICK X-RAY SOURCE WITH KNOWN OPTICAL COUNTERPART	2	4	3	2	3	2	1	C.T.=14.4
g221 DETERMINE IF TARGET IS WITHIN DETECTOR FIELD OF VIEW	2	3	3	1	3	3	2	C.T.=14.2
g223 SELECT NEW TELESCOPE ATTITUDE IF NECESSARY	2	4	3	2	4	2	2	C.T.=14.5
g224 PROCESS IMAGE DATA	2	4	2	1	2	2	1	C.T.=13.2
g239 AVOID TANK OVERPRESSURES	3	2	3	3	4	4	2	C.T.= 1.6
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	4	2	2	3	3	4	1	C.T.= 1.6
g244 AVOID CONFLICTING OBJECTS	4	1	1	2	5	4	2	C.T.=14.7
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	3	2	2	3	3	4	1	C.T.=25.3
g325 MONITOR VITAL SIGNS OF CREW MEMBERS	2	3	2	2	3	3	2	C.T.=14.2

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

g 83 ADJUST COOLING/HEATING SYSTEMS	3	1	4	3	1	1	3	C.T.= 1.6
g 87 ADJUST CURRENTS AND VOLTAGES	2	2	4	2	1	1	3	C.T.=14.2
g 88 ADJUST BATTERY CHARGING CYCLE	1	2	4	2	1	1	3	C.T.=14.2
g103 APPLY COMPENSATING FORCES	2	2	4	2	1	1	3	C.T.=14.2
g240 MAINTAIN SAFE BATTERY CHARGE LEVELS	2	1	4	3	2	1	3	C.T.= 1.6
g318 ADJUST HABITAT-MAINTENANCE SUBSYSTEMS	3	2	4	2	1	1	3	C.T.=25.3

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
26.1 FAULT TOLERANT SOFTWARE								
g 56 DETERMINE ANOMALOUS DATA	1	2	4	2	1	1	4	C.T.=14.2
g 77 DETERMINE CORRECTION ALGORITHM	1	3	5	1	2	1	5	C.T.=14.5
g194 IDENTIFY FAULTY SOFTWARE	2	1	3	2	2	1	3	C.T.=16.1
g241 MAINTAIN COMMUNICATIONS LINKS	2	1	4	2	1	1	3	C.T.= 1.6
27.1 EQUIPMENT FUNCTION TEST BY ONBOARD COMPUTER								
g 1 VERIFY POWER SYSTEM FUNCTION	1	3	4	3	2	1	2	C.T.=14.2
g 10 CHECK ELECTRICAL INTERFACES	2	3	3	2	1	1	3	C.T.=14.2
g 23 POWER SUBSYSTEM CHECKOUT	2	3	3	2	3	1	2	C.T.=27.3
g 33 VERIFY DEPLOYMENT SEQUENCES	2	3	4	2	2	1	2	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	3	3	4	2	2	1	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	2	3	3	2	3	2	2	C.T.=27.3
g 50 COMMUNICATIONS SUBSYSTEM CHECKOUT	2	3	3	2	3	1	2	C.T.=27.3
g 51 ATTITUDE CONTROL SUBSYSTEM CHECKOUT	2	3	3	2	3	2	2	C.T.=27.3
g 52 PROPULSION SUBSYSTEM CHECKOUT	2	3	3	2	3	2	2	C.T.=27.3
g 60 IDENTIFY FAULTY COMPONENT	1	4	3	1	2	1	2	C.T.=14.4
g194 IDENTIFY FAULTY SOFTWARE	2	4	2	2	3	3	2	C.T.=16.1
g260 SP/PAYLOAD INTERFACE CHECKOUT	1	2	4	2	2	1	3	C.T.=14.7

27.2 EQUIPMENT FUNCTION TEST BY ONSITE HUMAN

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
g 1 VERIFY POWER SYSTEM FUNCTION	3	2	2	2	3	2	2	C.T.=14.2
g 10 CHECK ELECTRICAL INTERFACES	3	3	3	3	3	3	2	C.T.=14.2
g 23 POWER SUBSYSTEM CHECKOUT	3	4	3	4	2	3	2	C.T.=27.3
g 24 INFORMATION PROCESSING SUBSYSTEM CHECKOUT	3	4	2	5	3	4	2	C.T.=25.4
g 33 VERIFY DEPLOYMENT SEQUENCES	4	5	4	4	1	2	2	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	4	4	4	4	1	2	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	4	5	3	4	2	3	2	C.T.=27.3
g 50 COMMUNICATIONS SUBSYSTEM CHECKOUT	4	4	3	4	2	2	2	C.T.=27.3
g 51 ATTITUDE CONTROL SUBSYSTEM CHECKOUT	4	4	3	4	2	3	2	C.T.=27.3
g 52 PROPULSION SUBSYSTEM CHECKOUT	4	4	3	4	3	3	2	C.T.=27.3
g 60 IDENTIFY FAULTY COMPONENT	3	5	3	4	1	2	2	C.T.=14.4
g194 IDENTIFY FAULTY SOFTWARE	4	5	3	4	3	3	2	C.T.=16.1
g260 SP/PAYLOAD INTERFACE CHECKOUT	3	3	3	3	2	3	2	C.T.=14.7

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
27.3 EQUIPMENT FUNCTION TEST VIA TELEMETRY								
g 23 POWER SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.3
g 33 VERIFY DEPLOYMENT SEQUENCES	3	3	3	3	2	2	1	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	4	3	3	3	2	2	1	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.3
g 50 COMMUNICATIONS SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.3
g 51 ATTITUDE CONTROL SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.3
g 52 PROPULSION SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.3
g 60 IDENTIFY FAULTY COMPONENT	3	4	3	3	2	2	1	C.T.=14.4
g194 IDENTIFY FAULTY SOFTWARE	3	3	2	3	4	4	1	C.T.=16.1
g260 SP/PAYLOAD INTERFACE CHECKOUT	2	2	2	2	3	3	2	C.T.=14.7
27.4 EQUIPMENT DATA CHECKS BY ONBOARD COMPUTER								
g 10 CHECK ELECTRICAL INTERFACES	2	2	2	2	2	1	2	C.T.=14.2
g 23 POWER SUBSYSTEM CHECKOUT	1	3	2	2	4	1	2	C.T.=27.3
g 33 VERIFY DEPLOYMENT SEQUENCES	2	3	3	2	3	2	2	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	2	3	3	2	3	1	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	2	3	2	2	4	3	2	C.T.=27.3
g 54 CONSUMABLES LEVELS CHECKOUT	2	3	3	2	3	2	2	C.T.=27.6
g 56 DETERMINE ANOMALOUS DATA	1	3	3	2	2	2	2	C.T.=14.2
g150 MONITOR FLUID TRANSFER	2	2	3	2	4	2	2	C.T.=14.7
g264 MONITOR MICRO-GRAVITY LEVELS	3	1	3	1	2	2	2	C.T.=18.1

	TIME	MAINT.	NONREC.	REC. COST	FAIL. PRONE.	USE. LIFE	DEV. RISK	CUR. TECH.
27.5 EQUIPMENT DATA CHECKS BY ONSITE HUMAN								
g 23 POWER SUBSYSTEM CHECKOUT	3	4	2	4	3	3	2	C.T.=27.3
g 33 VERIFY DEPLOYMENT SEQUENCES	3	5	3	4	2	3	2	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	3	4	3	4	2	3	2	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	4	5	2	4	3	3	2	C.T.=27.3
g 54 CONSUMABLES LEVELS CHECKOUT	3	5	3	4	2	3	2	C.T.=27.6
g 56 DETERMINE ANOMALOUS DATA	3	5	3	4	3	3	2	C.T.=14.2
g150 MONITOR FLUID TRANSFER	3	3	2	3	3	3	1	C.T.=14.7
27.6 EQUIPMENT DATA CHECKS VIA TELEMETRY								
g 23 POWER SUBSYSTEM CHECKOUT	2	3	1	3	4	3	1	C.T.=27.3
g 33 VERIFY DEPLOYMENT SEQUENCES	3	3	2	3	3	3	1	C.T.=27.6
g 48 THERMAL SUBSYSTEM CHECKOUT	3	3	2	3	3	3	1	C.T.=27.6
g 49 STRUCTURE SUBSYSTEM CHECKOUT	3	3	1	3	4	4	1	C.T.=27.3
g 54 CONSUMABLES LEVELS CHECKOUT	3	3	2	3	3	3	1	C.T.=27.6
g 56 DETERMINE ANOMALOUS DATA	3	3	2	2	2	3	1	C.T.=14.2
g150 MONITOR FLUID TRANSFER	3	2	2	2	4	4	2	C.T.=14.7
g264 MONITOR MICRO-GRAVITY LEVELS	4	2	2	2	2	4	1	C.T.=18.1
27.7 INTERNAL ACOUSTIC SCANNING								
g49 STRUCTURE SUBSYSTEM CHECKOUT	2	3	3	2	2	2	2	C.T.=27.3