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(NASA-CR-171223) THE HUMAN ICLE IN SPACE. VOLUME 1: EXECUTIVE SUMMARY Final Report (McDonnell-Douglas Astronautics Co.) 27 p HC A03/MF A01 CSCL 05H
N85-13473
Unclas
G3/54 24544

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THE HUMAN ROLE IN SPACE

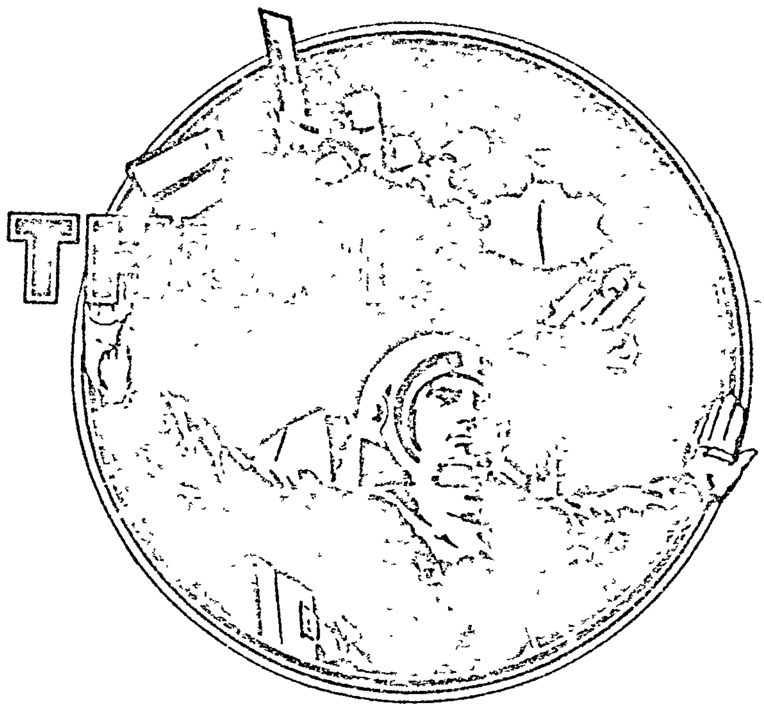
Volume I
Executive Summary

DR-4

OCTOBER 1984

MDC H1295

Contract No NAS 8 35611
DPD No 624
DR-4



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PREFACE

The Human Role in Space (THURIS) study was a 12-month effort to (1) investigate the role and the degree of direct involvement of humans that will be required in future space missions, (2) establish valid criteria for allocating functional activities between humans and machines; and (3) provide insight into the technological requirements, economics, and benefits of the human presence in space

The study started in October of 1983 and was completed in September of 1984

The final report has been prepared in three separate volumes:

Volume I ——— ***Executive Summary***

Volume II ——— ***Research Analysis and Technology Report***

Volume III ——— ***Generalizations on Human Roles in Space***

This document is Volume I in the series

The study results are intended to provide information and guidelines in a form that will enable NASA program managers and decision-makers to establish, early in the design process, the most cost-effective design approach for future space programs, through the optimal application of unique human skills and capabilities in space.

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THE HUMAN ROLE IN SPACE

Space project managers and engineers within NASA today are faced with a significant challenge. On the one hand, with the Shuttle's attainment of operational status, the National Space Transportation System has successfully completed one more step toward establishing the permanent presence of man in space. On the other hand, the competing demands on this Nation's limited economic resources are forcing an increasing awareness of the need to maximize economic efficiency in achieving the goals and objectives of future space missions. To meet this challenge, a rational methodology and set of performance and cost criteria are critically needed by space project managers and decision-makers if they are to design the most cost-effective man-machine systems to accomplish specific missions.

To be of value, these assessment procedures must clearly indicate to the decision-maker the optimal location of each activity and functional operation along the continuum from direct human intervention and control to independent system operations.

To this end, the Human Role in Space study (1) investigated the role and the degree of direct involvement of humans that will be required in future space missions, (2) established criteria for allocating functional activities between humans and machines, and (3) investigated the technology requirements, economics, and benefits of the human presence in space. The objective of the study was to provide a methodological framework by which system engineers and decision-makers could evaluate early in the conceptual design process the relative advantages and disadvantages of alternative modes of man-machine interaction.

As a point of reference, too often in system design an artificial dichotomy is created that attempts to classify systems as *manned* or *unmanned*. There is no such thing as an unmanned system: everything that is created by the system designer involves man in one context or another; everything in our human existence is done by, for, or against man. The point at issue is to establish in every system context the optimal role of each man-machine component.

Six basic categories of man-machine interaction were considered in the study: *MANUAL, SUPPORTED, AUGMENTED, TELEOPERATED, SUPERVISED,* and *INDEPENDENT*. These categories are defined in Table 1.

Table 1 Categories of Man-Machine Interaction

Manual	Unaided IVA EVA, with simple (unpowered) hand tools
Supported	Requires use of supporting machinery or facilities to accomplish assigned tasks (e.g. manned maneuvering units and foot restraint devices)
Augmented	Amplification of human sensory or motor capabilities (powered tools, exo skeletons, microscopes, etc.)
Teleoperated	Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)
Supervised	Replacement of direct manual control of system operation with computer directed functions although maintaining humans in supervisory control
Independent	Basically self actuating, self healing, independent operations minimizing requirement for direct human intervention (dependent on automation and artificial intelligence)

The criteria of *performance, cost,* and *technological readiness* (program confidence) are the principal factors that program or project managers and system engineers use in selecting the most cost-effective approach to meeting mission objectives. The decision-maker must base his judgment on knowledge that a particular implementation option can or cannot meet the performance requirements in terms of such factors as force, sensory discrimination, speed, and accuracy. If it can meet the performance requirements, can it do so within the system's environmental constraints of, e.g., temperature, pressure, radiation, atmospheric constituents, mass limitations, acceleration disturbance limits? In many cases, more than one implementation option can meet the performance requirements, and it is then necessary to examine the relative costs and the technological readiness or program confidence associated with each approach. While the final selection in the tradeoff between an acceptable probability of success and the resultant cost must rest with the decision-maker, the intent of this study was to provide a frame of reference in which the interrelationships of these pertinent parameters can be made visible, and from which rational or informed decisions can be derived.

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Section 1
PERFORMANCE FACTORS

The initial step in defining the man-machine role is to identify the performance factors that are key to meeting the specific mission objectives. This step involves defining the basic activities required to meet the mission objectives and examining human capabilities and limitations in conducting these basic activities.

1.1 DEFINITION OF ACTIVITIES

In order to derive a generic list of activities that could be used to describe any future space mission, various past and proposed space projects were analyzed. These projects included manned facilities, such as Skylab, as well as unmanned support concepts, such as the Space Platform (power system) and the Advanced X-Ray Astrophysics Facility (see Figure 1).

The first step was to identify the missions associated with each of these anticipated space projects. The missions resulting from these projects appear to cover the gamut of activities envisioned for space operations. These missions range from the initial deployment and free-flyer operations associated with unmanned systems to the manned operations involved with various subsystems, payloads, and experiments. In addition to these, we also examined intravehicular and extravehicular activities resulting from maintenance and servicing, construction, and growth operations. We also used the results of the ARAMIS study (MIT, Phase I Final Report, August 1982 and the Phase II Final Report, June 1983) which developed a listing of some 330 generic functional elements that also were derived from the analysis of several space projects.

The project analysis entailed defining the various levels of events used to describe each of the identified missions. Each mission was broken down to the sequence level to describe the detailed operations for the given mission. The sequences were then further defined through the identification of the activities that made up each of the

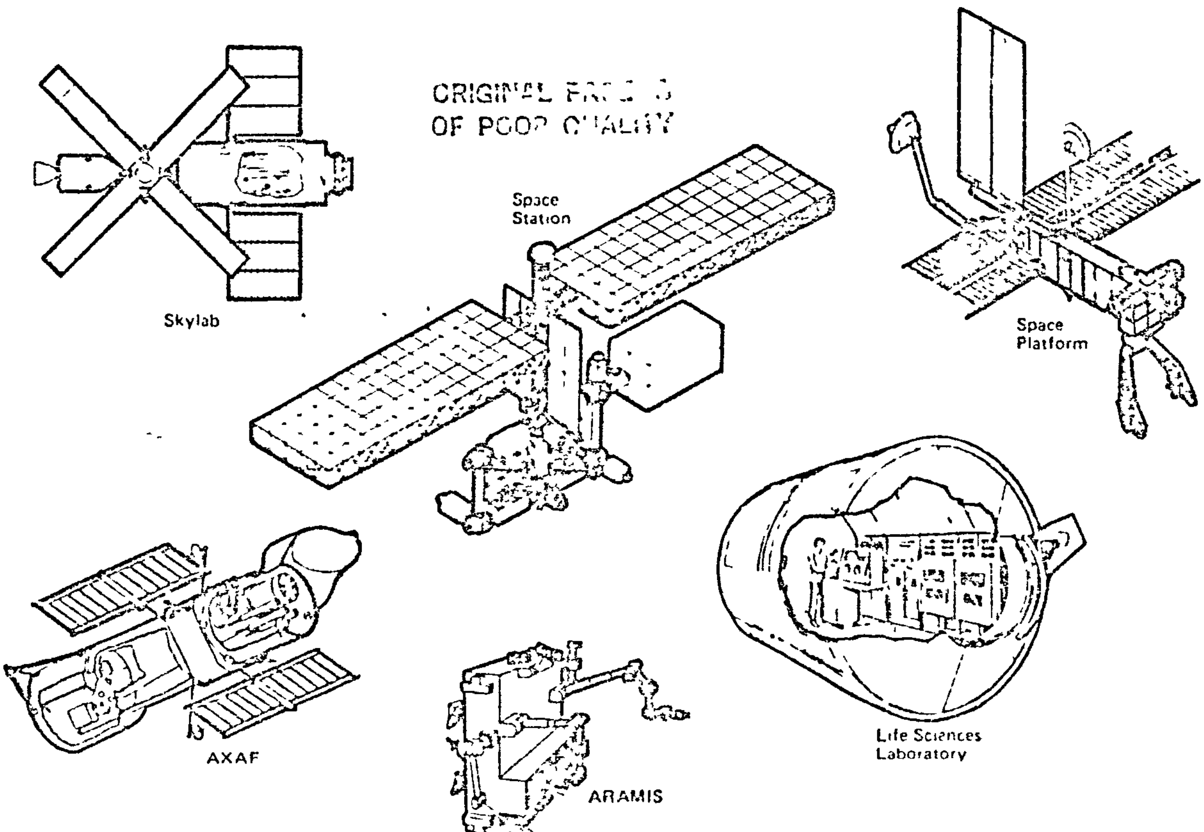

Figure 1. Space Projects Analyzed

operational sequences. Once the activity level events were defined, a great deal of commonality was found to exist among the activities comprising various operational sequences and the missions of each space system examined In other words, the same basic activities were found to be required in different operations and in different missions The objective was to develop a final list of basic or generic activities, each with unique characteristics that, when combined, could be used to describe future space missions (Figure 2)

The Space Platform project will serve as an example for defining the project analysis Space Platform was a conceptually designed free-flying platform that could provide services, such as electrical power, thermal control, and communications and data handling to a wide range of attached payloads With scheduled revisits by the Space Shuttle, the Space Platform missions provide the opportunities for using the human presence in maintenance and servicing, as well as in the initial deployment and/or assembly of payloads

Analysis of the Space Platform resulted in the identification of five mission categories (Figure 2) Each of the respective missions was defined by the sequence-level events required to perform those missions At the sequence level, several events may occur in more than one mission For example, the berthing operation between the Space Platform and Space Shuttle not only appears in the payload reconfiguration mission, as shown, but also in the initial deployment and maintenance missions, as well as in evolutionary growth missions The reason is that in order for those missions to be performed, the Space Platform and Space Shuttle must be berthed together The sequence-level operations were then further defined by identifying the activities necessary to accomplish that operation As stated previously, these identified activities were examined and combined, where appropriate.

The analysis of the Space Platform's five identified missions yielded 35 operational sequences, which were further defined by 260 activities Because there appeared to be a great deal of redundancy at the activity level, we evaluated each activity against the remainder, eliminated redundancies, and combined similar activities This analysis then resulted in the identification of 27 generic activities that could be used in combination to describe all the Space Platform missions

Similarly, the analysis of the Life Sciences Laboratory project centered around three identified missions, as shown These missions were analyzed

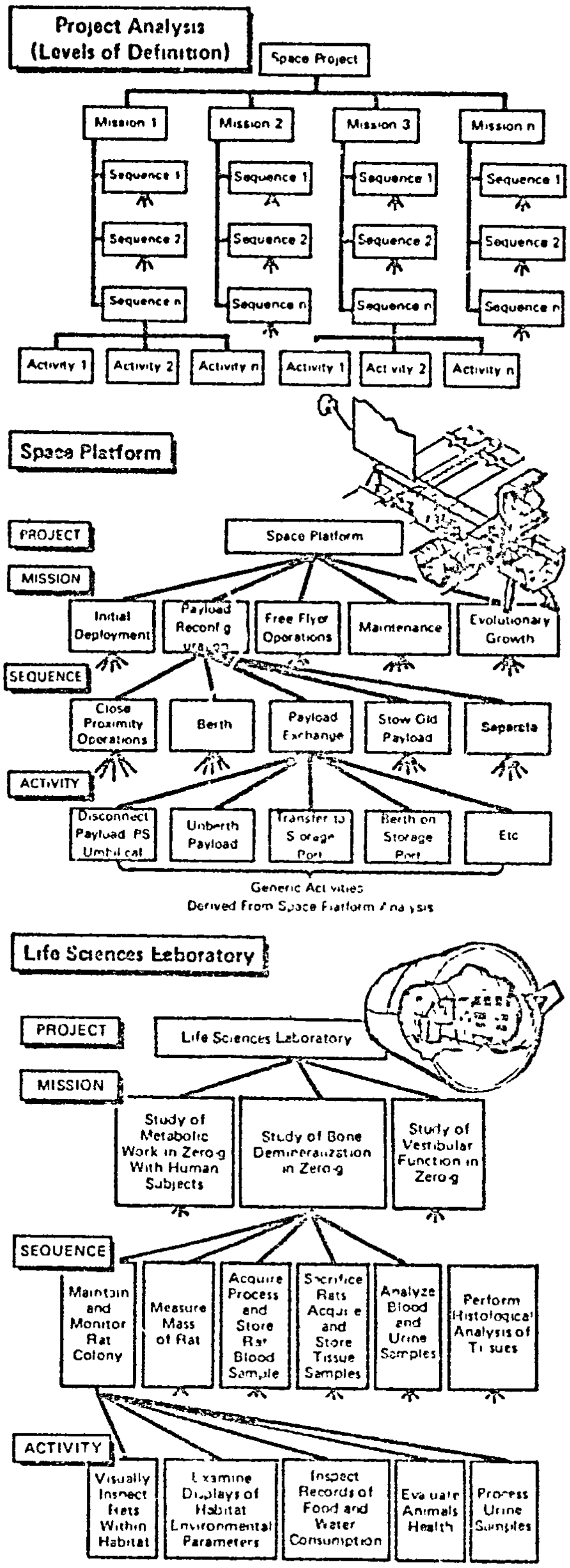

Figure 2. A "Top Down" Approach to Activity Analysis

at the sequence level, and each sequence in turn was redefined into its basic activities An interesting note about this analysis is that even though the sequence-level events were notably different for each life sciences mission, there was, once again, considerable commonality among the activities required in the different mission elements The life sciences activities were reduced to a listing of 29 generic activities, of which two were unique and the remaining 27 were similar to the generic activities derived from the analysis of the other space projects

As each new source of mission data or mission activities was examined, the previously defined listing of generic activities was matched against the new information. If a specific activity could not easily be described by one of the previously defined generic activities, a new activity category was identified for incorporation into the generic activity list

The analyses of these space projects down to the activity level has resulted in the identification of 37 unique generic space activities These activities are defined in Table 2 Table 3 summarizes the space project sources from which they evolved It is our belief that this list of generic activities can be used to describe the operational sequences required in the broad spectrum of potential space missions anticipated in the coming decades

1.2 HUMAN CAPABILITIES AND LIMITATIONS

In order to define the potential role of the human in accomplishing each of these activities, a detailed list of human capabilities applicable to space mission activities was compiled from previous studies, technical journals, NASA mission reports, human factors texts, and biomedical references These capabilities were grouped into the three categories of sensory/perceptual, intellectual, and psychomotor/motor The following capabilities were examined under each of these three categories:

A. Sensory/Perceptual Capabilities

- Visual acuity
- Brightness detection and discrimination
- Color discrimination
- Depth perception and discrimination
- Peripheral visual detection and discrimination
- Visual accommodation
- Detection and discrimination of tone
- Discrimination of sound intensity
- Sound localization
- Detection of light touch
- Tactile recognition of shape and texture
- Discrimination of force against limb
- Discrimination of limb movement and location
- Detection and discrimination of angular acceleration
- Equilibrium
- Detection and discrimination of vibration
- Detection of heat and cold
- Detection and discrimination of odors

B Intellectual Capabilities

- Cognition
- Memory
- Divergent and convergent production
- Evaluation

C. Psychomotor/Motor Capabilities

- Production and application of force
- Control of speed of motion
- Control of voluntary responses
- Continuous adjustment control (tracking)
- Arm/hand/finger manipulation
- Body positioning

For each capability, a definition was provided, its characteristics were identified, factors that tend to change or limit the capability were listed, and comments were made regarding the relevance and application of the capability to man's role in space. Table 4 summarizes key human capabilities for performing each of the 37 activities The activities highlighted in Table 4 are those where direct human participation is considered to be most beneficial or essential.

The limits of human capabilities may be altered by both environmental and task-related factors. Environmental stresses, such as vibration, noise, acceleration, light, and radiation, can affect human capabilities, however, they are generally avoided by specific approaches to spacecraft design characteristics or mission operations (see Table 5) Another stress factor affecting human capabilities is the space adaptation syndrome or space motion sickness (see Table 6) The symptoms are generally the same as those associated with conventional motion sickness; however, they occur early in the flight peak at about 24 to 36 hours, but may last as long as 4 days

Some system operational requirements specify performance beyond human sensory or psychomotor capabilities (e g , sensing outside the visible band of the electromagnetic spectrum, force actuation beyond normal human capability, or exposure to extreme pressure, temperature, or toxic environments

Table 2 The 37 Generic Activities

1 *Activate Initiate System Operation* Those events and or command sequences involved in the activation or initialization of a space-based system or subsystem

2 *Adjust Align Elements* Those adjustment activities involved in such operations as alignment of optical elements, fine tuning of precision electronic equipment antenna pointing and remote camera focusing operations

3 *Allocate Assign Distribute* Those activities involving the reallocation or redistribution of resources e g , the redistribution of power, coolant flow etc to sensitive subsystem equipment to reflect operational needs or contingency operations

4 *Apply Remove Biomedical Sensor* Those unique activities associated with the installation removal and cleaning of sensors used to obtain biomedical data from a test subject

5 *Communicate Information* Those activities involving the establishment of the communications link and the transmision of information from one source to another It includes the verbal or visual interchange between two crewmen as well as the electronic transference of scientific information from a space probe to a terrestrial based user

6 *Compensatory Tracking* Those activities involving continuous control adjustments to null an error signal against a fixed reference

7 *Compute Data* Those activities requiring a mechanized form of data processing such as in structural analyses computation of positions of celestial bodies or other forms of numerical computations

8 *Confirm Verify Procedures Schedules Operations* Those activities involving the assessment of whether or not a previous event has in fact been accomplished (such as a system verification or checkout) or a procedure satisfied or a schedule met

9 *Connect Disconnect Electrical Interface* Those activities requiring the completion or termination of an electrical interface They may involve use of blind mated self aligning connectors multiturn screw drive interface plates or similar devices

10 *Connect Disconnect Fluid Interface* Those activities requiring the completion or termination of a fluid interface They may involve use of a simple plug in sleeve lock connection multiturn screw drive interface plates or similar devices

11 *Correlate Data* Those activities involving the identification of positive or negative relationships or commonalities among data sets, such as organizational structures, characteristics, or processes

12 *Deactivate Terminate System Operation* Those events and or command sequences involved in the termination or deactivation of a space based system or subsystem

13 *Decode Encode Data* Those activities involving the conversion of data into either its original form or into a form compatible for transmission e g converting transmitted digitized data into its original analog form or digitizing analog data for transmission to the ground station

14 *Define Procedures Schedules Operations* Those activities involving logical deductions or convergent production leading to development of procedures, schedules or operations with predictable outcomes

15 *Deploy Retract Appendage* Those activities associated with the extension of a hardware element to a position where its assigned function can be realized or conversely the stowing of that hardware element based on task completion or safety considerations

16 *Detect Change in State or Condition* Those activities wherein the departure of a parameter from its original or reference state or condition is required to be sensed or observed

17 *Display Data* Those activities involving the presentation of information data by visual auditory or tactual means

18 *Gather Replace Tools Equipment* Those activities involved in the obtaining or returning of tools or equipment used to perform a specific task, such as collecting or replacing maintenance tools or donning doffing the Manned Maneuvering Unit

19 *Handle Inspect Examine Living Organisms* Those activities involving the unique operations associated with working with living organisms These activities involve the manipulation and general handling of animals, ranging from stroking to inspecting or examining anatomical characteristics

20 *Implement Procedures Schedules* Those activities involving the instituting and carrying out of procedures or schedules (such as updating a mission model schedule) as distinguished from activating or initiating system operations

21 *Information Processing* Those activities involving the categorizing extracting interpolating itemizing tabulating or translating of information

22 *Inspect Observe* Those activities involving the critical appraisal of events or objects They may include the verification or identification of a particular elements, such as damage inspection of a returning orbital test vehicle, observation and identification of a celestial object, or behavior of a living organism

23 *Measure (Scale) Physical Dimensions* Those activities involving the estimation or appraisal of a dimension against a graduated standard or criterion

24 *Plot Data* Those activities involving the mapping displaying or locating of data by means of a specified coordinate system

25 *Position Module* Those activities involving the positioning of a component into a desired orientation e g , installing a new component, or tilting a payload into its launch orientation

26 *Precision Manipulation of Objects* Those activities involving tasks that require a high degree of manual dexterity, such as the assembly disassembly of small intricate mechanisms or the installation of measurement sensors i e , strain gages, thermocouples, etc

27 *Problem Solving Decision Making Data Analysis* Those judgmental and sometimes creative activities involving the drawing of inferences or conclusions through the use of cognition convergent or divergent production memory, and comparative evaluation Functions to be performed may include analyzing, calculating choosing comparing estimating or planning

28 *Pursuit Tracking* Those activities involving continuous control adjustment to match actual and desired signals when the desired or reference signal is continually changing

29 *Release Secure Mechanical Interface* Those activities involving the manipulation of a mechanical interface ranging from a simple one-handed, over-center latch application to a high torque, multiturn threaded fastener May involve manipulation of multiple fasteners arranged in various patterns or configurations

30 *Remove Module* Those activities involving the physical extraction or removal of a component after the mechanical, electrical or thermal interfaces have been released or disconnected

31 *Remove Replace Covering* Those activities involving the removal or reinstallation of an access covering or a protective covering as required to gain access to system elements or to cover them up upon completion of the work

32 *Replace Clean Surface Coatings* Those unique activities involving the restoration of a degraded contaminated surface coating, such as replacing a radiator s thermal coating or cleaning an optical system s viewing surface

33 *Replenish Materials* Those activities involving the resupplying of consumables, such as refueling a spacecraft, recharging an optics cryo-based cooling system or providing food supplies to an animal holding facility

34 *Store Record Element* Those activities involving the recording or storage of items for both short term and long-term periods e g , recording storage of experimental data or the temporary storage of a biomedical sample

35 *Surgical Manipulations* Those activities such as a surgical procedure or a dissection, including tissue sample acquisitions, that require a high degree of skill and knowledge as well as manual dexterity

36 *Transport Loaded* Those activities involving the conveying of a physical object by some transportation device from one location to another e g , the transporting of a component via a crewman or a remote manipulator system

37 *Transport Unloaded* Those activities involving the movements of an unloaded individual or device from one location to another e g , the movement of a crewman to a worksite without carrying tools or equipment or the movement of a remote manipulator system with nothing attached

Table 3. Sources of Generic Activities

Generic Space Activities	Source					
	AXAF	(1) Skylab	(2) Space Platform	Space Station	(3) ARAMIS Study (MIT)	Life Sciences Laboratory
1 Activate/Initiate System Operation	•	•	•	•	•	•
2 Adjust/Align Elements		•		•	•	•
3 Allocate/Assign/Distribute		•	•	•	•	•
4 Apply/Remove Biomedical Sensor		•		•	•	•
5 Communicate Information	•	•	•	•	•	•
6 Compensatory Tracking				•	•	
7 Compute Data	•	•	•	•	•	•
8 Confirm/Verify Procedures/Schedules/Operations		•	•	•	•	•
9 Connect/Disconnect Electrical Interface		•	•	•	•	•
10 Connect/Disconnect Fluid Interface		•	•	•	•	
11 Correlate Data		•	•	•	•	•
12 Deactivate/Terminate System Operation	•	•	•	•	•	•
13 Decode/Encode Data			•	•	•	
14 Define Procedures/Schedules/Operations		•	•	•	•	•
15 Deploy/Retract Appendage	•	•	•	•	•	
16 Detect Change in State or Condition		•		•	•	•
17 Display Data		•	•	•	•	•
18 Gather/Replace Tools/Equipment	•	•	•	•	•	•
19 Handle/Inspect/Examine Living Organisms						•
20 Implement Procedures/Schedules		•	•	•	•	•
21 Information Processing		•		•	•	•
22 Inspect/Observe		•	•	•	•	•
23 Measure (Scale) Physical Dimensions		•			•	
24 Plot Data		•	•	•		•
25 Position Module	•	•	•	•	•	•
26 Precision Manipulation of Objects		•		•		
27 Problem Solving/Decision Making/Data Analysis		•	•	•	•	•
28 Pursuit Tracking		•	•	•	•	
29 Release/Secure Mechanical Interface	•	•	•	•	•	•
30 Remove Module	•	•	•	•	•	•
31 Remove/Replace Covering		•	•		•	•
32 Replace/Clean Surface Coatings	•		•			•
33 Replenish Materials	•	•		•	•	•
34 Store/Record Elements		•	•	•	•	•
35 Surgical Manipulations						•
36 Transport Loaded	•	•	•	•	•	•
37 Transport Unloaded	•	•	•	•	•	

(1) Includes EREP and ATM Activities
(2) Includes Activities Derived from the Analysis of Space Platform Ground System Data Management Study
(3) Includes 330 Generic Functional Elements Derived from the Geosynchronous Platform, Advanced X Ray Astrophysics Facility, Teleoperator Maneuvering System and Space Platform

Table 4 Benefit of Man's Participation in Space Activities

No	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation			Overall benefit from man's onboard participation	Rationale
			Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased		
1	Activate/initiate system operation	Evaluation Vision Manipulation	Minimal	In some cases	Negligible	Not significant	Automatically activated systems will predominate
2	Adjust/align elements	Vision Cognition Evaluation	Yes	In some cases	No	Beneficial	Most alignment operations within man's capabilities
3	Allocate assign/distribute	Cognition Convergent Prod	No	In some cases	Minimal	Not significant	Primarily automated operations
4	Apply/remove biomedical sensors	Cognition Manipulation	Not applicable	Yes	Yes	Essential	Operations cannot easily be automated
5	Communicate information	Cognition Vision	No	In some cases	No	Not significant	Communication link established automatically
6	Compensatory tracking	Cognition Evaluation Vision Manipulation	Minimal	No	Minimal	Not significant	Highly dependent on nature of tracking task Nullifying error signal could be automatic
7	Compute data	Cognition Evaluation	No	No	Minimal	Not significant	Man will play negligible role in most data computation
8	Confirm/verify procedures/schedules/operations	Cognition Evaluation	No	No	Minimal	Not significant	Man would usually function in a backup role only
9	Connect/disconnect electrical interfaces	Vision Gross Motor Act Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
10	Connect/disconnect fluid interfaces	Vision Gross Motor Act Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
11	Correlate data	Cognition Evaluation	No	In some cases	Minimal	Not significant	Man would usually function in a backup role only
12	Deactivate/terminate system operation	Manipulation Vision Evaluation	Minimal	In some cases	Negligible	Not significant	Automatically deactivated systems will be the norm
13	Decode/encode data	Cognition Convergent Prod	No	No	No	Not significant	Computer function only
14	Define procedures/schedules operations	Cognition Divergent Prod	Yes	Yes	Yes	Essential	Activity is wholly dependent on man's intellectual capabilities
15	Deploy/retract appendage	Vision Gross Motor Act	Yes	In some cases	In some cases	Beneficial	Seldom repeated activities are poor candidates for automation
16	Detect change in state or condition	Cognition Evaluation Vision	No	In some cases	In some cases	Beneficial or essential	Strongly dependent on characteristics of activity
17	Display data	Cognition Evaluation	No	Yes	Yes	Beneficial to essential	Man important in selection of data to be displayed
18	Gather/replace tools/equipment	Cognition	Yes	Yes	Minimal	Beneficial to essential	Man can vary tool selection with respect to task
19	Handle inspect examine living organisms	Cognition Vision Manipulation	Not applicable	Yes	Yes	Essential	Activity cannot be automated in most cases
20	Implement procedures schedules	Cognition Evaluation Convergent Prod	Not applicable	Yes	Yes	Essential	Activity dependent on man's involvement by definition
21	Information processing	Cognition Evaluation	Minimal	Yes	Yes	Beneficial to essential	Essential interaction between man and computer

Table 4. Benefit of Man's Participation in Space Activities (Continued)

No	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation: Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased	Overall benefit from man's onboard participation	Rationale
22	Inspect observe	Vision Cognition Evaluation Divergent Prod	Yes	Yes	Yes	Highly beneficial	Man's selective observations superior to automated monitoring
23	Measure (scale) physical dimensions	Vision Evaluation	In some cases	No	In some cases	Beneficial in some cases	Man is best alternative in some situations
24	Plot data	Cognition	No	Minimal	No	Not significant	Primarily a computer function
25	Position module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some cases	Beneficial for some activities	Man's benefit highly dependent on type of activity
26	Precision manipulation of objects	Vision Manipulation Cognition	Yes	Yes	Yes	Most often essential	Man's manipulative skills cannot be duplicated by automatic devices
27	Problem solving decision making data analysis	Cognition Divergent Prod Convergent Prod Evaluation	Yes	Yes	Yes	Essential	Man essential by definition
28	Pursuit tracking	Cognition Manipulation	Minimal	Yes	Minimal	Could be significant	Dependent on specific tracking task
29	Release secure mechanical interface	Vision Gross Motor Act Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Exemplary utilization of man's capabilities in space activity
30	Remove module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some case	Beneficial for some mission activities	Man's benefit highly dependent on type of activity
31	Remove replace covering	Vision Evaluation Gross Motor Act	In some cases	In some cases	In some cases	Beneficial for some cover removal/ replacement activities	Man's benefit highly dependent on task characteristics
32	Replace clean surface coatings	Vision Evaluation Gross Motor Act	Yes	Yes	Yes	Beneficial to essential	Infrequency of activity negates automation
33	Replenish materials	Vision Evaluation Gross Motor Act	Yes	In some cases	Yes	Beneficial to essential	Degree of benefit is dependent on nature of task
34	Store/record element	Cognition	No	No	No	Not significant	Man's participation of benefit only in isolated cases
35	Surgical manipulations	Vision Manipulation Cognition	Not applicable	Yes	Yes	Essential	Activity not appropriate for automation
36/37	Transport loaded or unloaded	Vision Cognition Gross Motor Act	In some cases	In some cases	In some cases	Dependent on characteristics of task	Characteristics of tasks can vary extensively for this activity

Highlighted activities are those where direct human participation is considered most beneficial or essential

To provide a frame of reference for comparing the levels of performance possible with each man-machine mode, summary timeline profiles, as illustrated in Figure 3, were prepared for each of the 37 activities. The ranges of times for accomplishing each activity were based upon specific tasks identified during the analysis of the representative sample of space projects. The times are based either on actual space performance, simulation of space activities in neutral buoyancy simulators, or engineering estimates derived from conceptual designs or from similar operational experiences.

In addition to the timeline data, potential requirements for human involvement and the possible limiting factors in direct human involvement were also flagged on these summary sheets.

As a general statement, response time was found to be the most generally applicable discriminator between the manually controlled modes and

Table 5 Limiting Factors – Effects of Other Environmental Stresses on Human Performance

Type of stress	Intensity of stress: Performance degrading	Intensity of stress: Injurious or life threatening
Vibration	0 08 g s at ~ 4 to 8 Hz	2 g s at ~ 3 to 8 Hz
Noise	80 to 85 dB	100 to 120 dB
G_z acceleration	2 to 3 g s	5 to 6 g s
G_x acceleration	5 to 6 g s	12 to 15 g s
Light	Complex	2 3 × 10^5 lumens/ft²
Ionizing radiation	—	> 5 rads/day

Table 6 Limiting Factors – Space Adaptation Syndrome (Exposure to Weightlessness)

Human capabilities impacted	Duration of exposure (hours): < 3	3-12	12-14	24-48	48-72	72-96	96
Vision	None	Mod	Mod	Neg	Neg	None	None
Discrimination	None	Mod	Mod	Neg	Neg	None	None
Discrimination of angular acceleration	Neg	Mod	Sig	Sig	Sig	Sig	Sig
Cognition	None	Mod	Sig	Sig	Mod	Neg	None
Memory	None	Mod	Sig	Sig	Mod	Neg	None
Evaluation	None	Mod	Sig	Mod	Neg	None	None
Visual-motor tracking	Mod	Sig	Sig	Mod	Neg	Neg	None
Manipulative skills	None	Mod	Sig	Sig	Mod	Neg	None
Body positioning	Mod	Sig	Sig	Mod	Mod	Neg	None

Impact code (Decrease in observed capability)

None	(None)
Negligible	(Neg)
Moderate	(Mod)
Significant	(Sig)

the supervised and independent modes of operation If responses in time periods of seconds or less are required, then the activity is generally best performed in the supervised or independent modes In the "Connect/Disconnect Electrical Interface" or "Release/Secure Mechanical Interface" classifications, for example, applications where speed of response would dictate that the

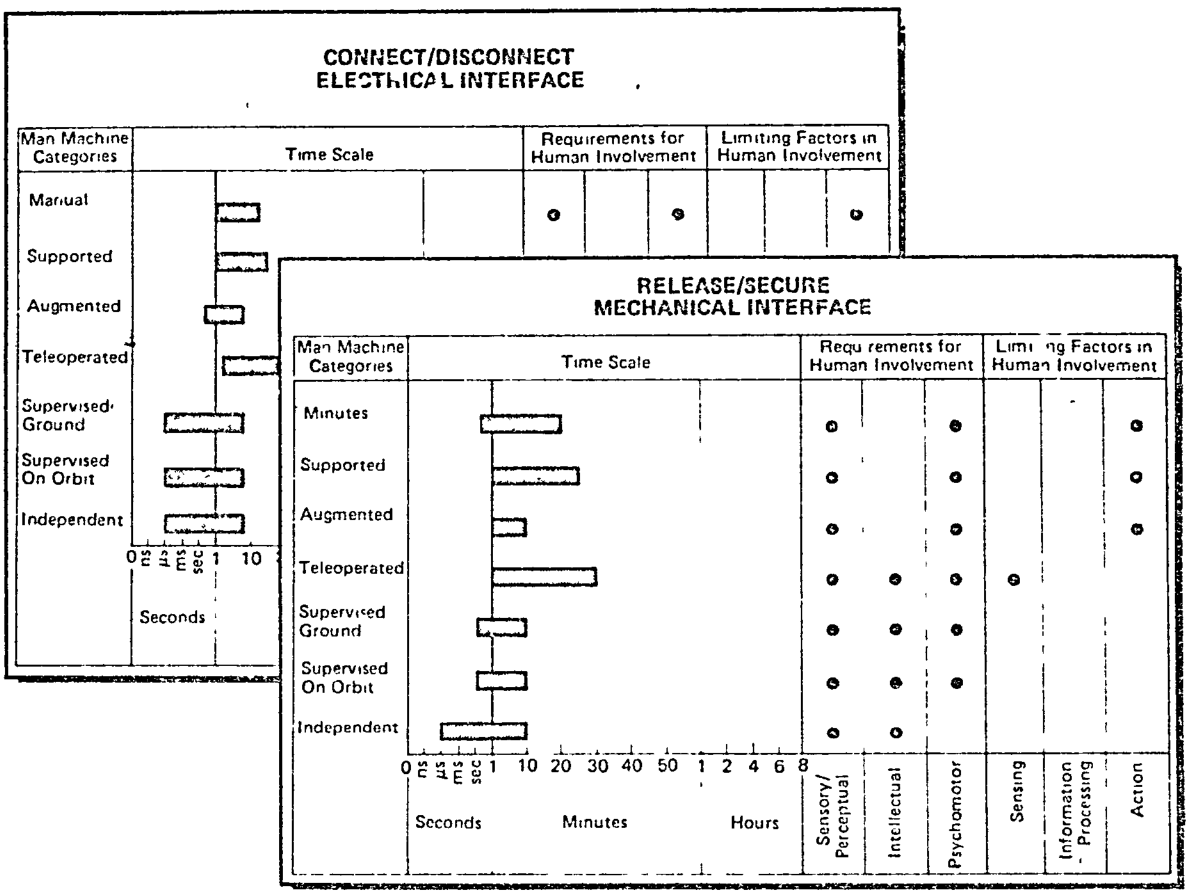

Figure 3 Performance Requirements

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activities be performed in the supervised or independent modes might include launch abort procedures or emergency separation procedures. If allowable response times become minutes or hours, then all modes might be applicable, and other criteria, such as cost effectiveness, would provide a more appropriate basis for the selection of a particular mode of implementation.

An important consideration when evaluating manual task performances is whether or not times differ for accomplishing similar tasks in an extravehicular as compared to an intravehicular mode of operation. In 1983, McDonnell Douglas Astronautics Company performed two series of neutral buoyancy tests in which the same maintenance and servicing tasks were performed. The first test was performed in SCUBA only, which equates to the simulated intravehicular environment. The second test series involved pressure-suited subjects, which simulated the extravehicular environment. Specific tasks in both the fine-motor and coarse-motor movements were demonstrated. The fine-motor activities involved manipulating electrical connectors (Figure 4) as well as removing and installing a quick-disconnect fluid connection (Figure 5). Average task times and extra-to-intravehicular activity ratios are summarized in Table 7. Based on the test simulation, it appears that in the case of fine-motor movements, extravehicular accomplishment requires about 50% more time than does intravehicular. This difference might be attributed to the sensitivity and dexterity differences between the gloved and the ungloved hand.

The information presented for the fine-motor movements has also been developed for the coarse-motor movements. As an example of coarse-motor movements, a handcranking operation, such as might be involved in deploying an appendage, was selected (Figure 6). Observational data were available for three crank radii (3 inches, 6 inches, and 9 inches). Here again, average task times and extra-to-intravehicular activity ratios are identified (Table 8).

In the case of the coarse-motor tasks, the ratio is close to 1:1. However, the coarse-motor movement data illustrated in Figure 7 suggests that the greater the required movement, the greater the discrepancy between performance times. This difference reflects the restrictions associated with the pressure-suit articulations.

Figure 4 Manipulating Electrical Connectors

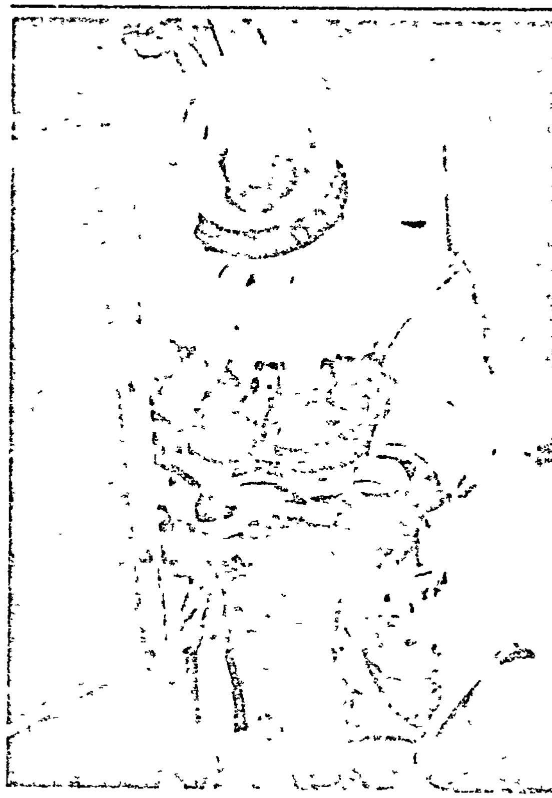

Figure 5 Installing a Quick Disconnect Fluid Connection

Table 7 IVA and EVA Task Time Comparisons (Fine-Motor Movements)

Task	Average times (sec) IVA	EVA	Ratio EVA IVA
Electrical connectors			
Coax – 6 turns threaded	19	31	1 63
Bayonet – 120-deg lock and unlock	9	14	1 75
Fluid interface			
Remove	10	13	1 30
Install	14	20	1 44
		Average	1 53

Figure 6. Deploying an Appendage

Table 8 IVA and EVA Task Time Comparisons (Coarse-Motor Movements)

Task	Average times (sec) IVA	EVA	Ratio EVA IVA
Manual hand crank			
3 inch radius	20	21	1 05
6 inch radius	22	24	1 09
9 inch radius	23	26	1 13
		Average	1 09

It is believed that the timeline data derived from the neutral buoyancy environment is a reasonable approximation of the actual times that will be experienced in zero gravity. To substantiate this hypothesis, an evaluation was performed to compare the planned times based on neutral buoyancy simulations and the actual times observed in space for ten composite extravehicular tasks on Skylabs 2, 3, and 4. Out of a total of 2642 minutes of planned operations, the actual EVA times totaled 2491 minutes or 6% less (faster) than had been allocated (see Table 9). On the basis of this previous experience, it was concluded that the time estimates derived from the recently conducted neutral buoyancy simulations provide reasonable estimates of on-orbit performance times.

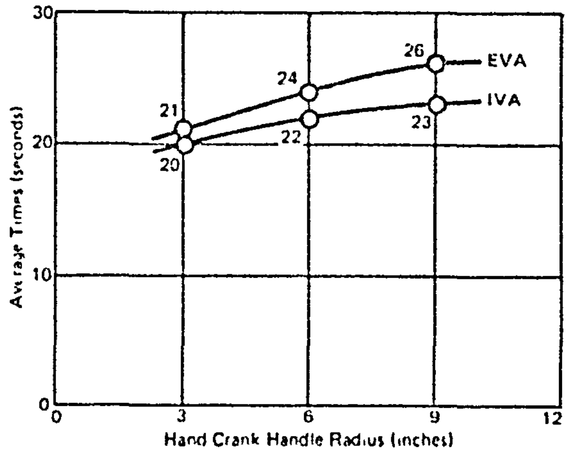

Figure 7. Coarse-Motor Movements

Table 9 Skylab EVA Tasks

EVA events	Planned time (minutes)	Actual time (minutes)	Δ time (minutes)
1	45	35	- 10
2	248	203	- 45
3	105	96	9
4	448	391	- 57
5	275	270	- 5
6	156	161	+ 5
7	388	394	+ 6
8	442	413	- 29
9	212	209	- 3
10	323	319	4
Total	2642	2491	- 151

Overall – 6% under estimate (151 2642 minutes)

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Section 2
COST FACTORS

Once the capabilities and limitations of each man-machine mode have been established and their impact on the performance of each activity identified, the next step is to determine the relative cost of each of the applicable modes of implementation. Assuming that two or more alternative implementation concepts will be feasible for accomplishing a specific activity, the determining factor in the mind of the system engineer becomes the question of cost. Accordingly, the resources and support equipment needed to accomplish each activity in each of the feasible man-machine modes was identified to a depth sufficient to allow comparative cost data to be developed.

The initial compilation of the resources and the support equipment was derived in conjunction with the timeline analyses. In addition, several past and ongoing space projects, such as the Skylab missions and the Unmanned Space Platform missions, were reviewed to ensure that the final listing of resource needs and support equipment represented all the most pertinent items.

The support equipment necessary for the various man-machine modes included facilities, extravehicular activity support items, tool kits and mechanical support equipment, command, control, communication, and data management equipment; orbital mobility systems, and operating systems software.

These items of support equipment were used to establish relative costs for performing an activity by each of the alternative man-machine categories.

No firm guidelines or charge policies for developing operational user costs in the space station era are currently available from government sources. Accordingly, the general approach taken in this study was to establish a mission-related incremental cost as the basis for charging space activities requiring direct human involvement at the space station. The incremental cost was defined as the cost difference between full mission-support capability and "zero-mission" man-in-space-only capability. The basic space station sizing parameters (crew size, number of modules, electrical power, communications data rate, and thermal control) were defined for both a full-capability initial-operating-capability station and a hypothetical "zero-mission" station that supported no payloads and was required only to maintain itself in orbit. The differences in design parameters between the "zero-mission" and the "full-capability" configuration are illustrated in Figures 8 and 9.

The MDAC computerized space facility cost prediction model was then run with these two sets of values to establish the incremental cost associated with the support of potential users or specific missions. The cost difference between the zero-capability and the full-capability facility was adjusted to exclude design and development cost, assuming that nonrecurring cost should not be included when developing a baseline for estimating user charges. A 10-year life was assumed for the hardware represented by the resulting incremental space station facility cost. A straight-line amortization results in an average cost per year that,

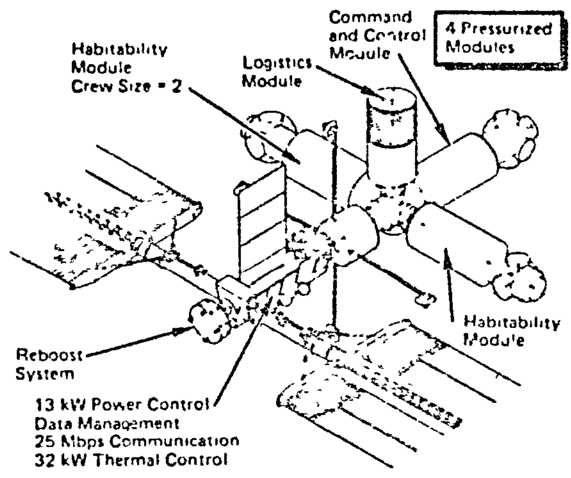

Figure 8. Space Station (Zero-Mission Capability)

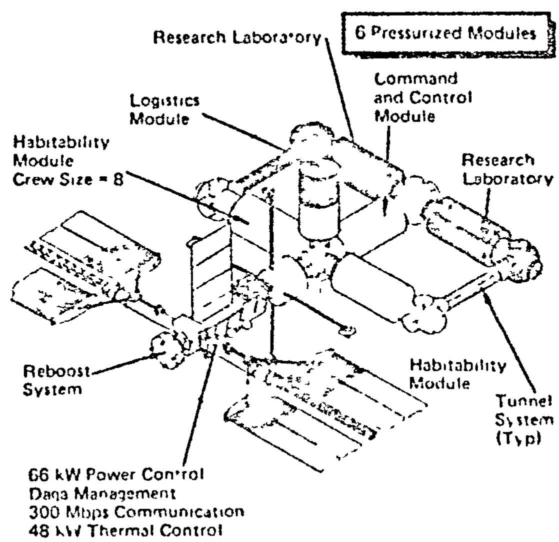

Figure 9. Space Station (Full Capability)

when divided by available operating man-hours per year, yields a cost of $10,427 per operating hour for manned use of the space station pressurized volume and utility services This calculation is illustrated in Table 10

Table 10 Pressurized Volume and Utility Services Cost[1]

	Full capability station ($ millions)	Zero mission station ($ millions)	Incremental cost ($ millions)
Simulator development hardware	1380	794	586
Flight hardware	2244	1366	878
Total	3624	2160	1464

$$\text{Amortized incremental cost} = \frac{\$1464M}{10\ yr} = \$146\ 4M\ yr$$

$$\text{Cost per operating hour} = \frac{\$1464M\ yr}{14\ 044\ \text{man-hr}\ yr^{(2)}} = \$10\ 427\ \text{man-hour}$$

(1) Production cost only, excludes design and development cost
(2) 6 mem x 9 hr day x 5 days week x 52 weeks year = 14 040 man hours year

A similar incremental cost approach to that used in developing the basic space station facility costs was used to estimate the logistics operations costs (replacement spares, consumables maintenance, and repairs) This resulted in a cost of $12 201 per operating hour for space station logistics operations The values for this calculation, which were generated by the McDonnell Douglas Astronautics Company cost model, are summarized in Table 11

Table 11 Logistics Operations Cost

	Full capability station ($ millions)	Zero mission station ($ millions)	Incremental cost ($ millions)
Replacement spaces and consumables	261 5 yr	129 7 yr	131 8 yr
Maintenance and re pairs	97 8 yr	58 3 yr	39 5 yr
Total	359 3 yr	188 0 yr	171 3 yr

$$\text{Cost per operating hour} \quad \frac{\$171\ 3M\ yr}{14\ 040\ \text{man hours yr}} = \$12\ 201\ \text{man hour}$$

The incremental cost for logistics transportation was determined by allocating the Space Shuttle flight cost in proportion to the ratio of incremental cost for logistics operations to full capability cost, with a further cost-sharing adjustment This resulted in a cost of $9402 per hour calculated as illustrated in Table 12

Table 12 Logistics Transportation Cost

$$\text{Total cost} = \$86M\ \text{flight} \times 80\%^{(1)} \times 4\ \text{flights year} = \$275\ 2M\ \text{year}$$

$$\text{Incremental cost} = \$275\ 2M\ \text{year} \times 48\%^{(2)} = \$132M\ \text{year}$$

$$\text{Cost per operating hour} = \frac{\$132M\ \text{year}}{14\ 040\ \text{man-hours year}} = \$9\ 402\ \text{hour}$$

(1) Assuming 20% sharing with other payloads and 4 STS flights per year
(2) Allocation factor (from logistics operations) = $\frac{\$171\ 3M}{\$359\ 3M}$ = 48%

In addition to the three major elements described above, estimates were added for use of airlock and safe-haven resources to complete the space station facility usage charge Based on data contained in the McDonnell Douglas cost data bank, these two items were estimated at $164 per hour and $328 per hour, respectively The sum of all five elements amounts to $32,522 per hour (or $542 per minute) for use of the space station facilities to directly support human activities in space (see Table 13)

Table 13 Space Station Facility Cost per Operating Hour for Activities Requiring Direct Human Involvement in Space (1984 Dollars)

Pressurized volume and utility services	$10 427
Logistics operations	12 201
Logistics transporation	9 402
Airlock	164
Safe haven	328
Total space station facility	$32 522

A number of different factors were originally considered by the study team as having the potential to significantly impact the cost of space operations As the analysis proceeded the nine costing elements summarized in Tables 14 and 15 were found to be the most significant determiners of space activity costs

The costing methodology differed for each of the nine elements, depending upon whether a specific cost element was driven by the *time-of-use* or the *frequency-of-use* The *time-related* group is characterized by the requirement for a support element to be used over an estimated activity timeline and includes use of the space station facility, the ground control and data handling facilities the tracking and data relay satellite system, and the extravehicular activity support items The frequency-of-use-related group is characterized by the

Table 14 Activity Costing Factors – Cost Elements That Are Primarily a Function of Time Use (Cost Per Minute)

Element	Computational Base
■ Space station facilities and logistics operations	Delta cost (full up)–(zero mission station) / Available crew time
■ Ground control and data handling facilities	Production cost + Operations cost / Availability time
■ Tracking and data relay satellite system	U S use and reimbursement policy
■ EVA support items	Production cost Operations cost / Availability time

Table 15 Activity Costing Factors – Cost Elements That Are Primarily a Function of Number (N) of Uses (Cost Per Use)

Element	Computational base
■ Tool kits and mechanical support equipment	Production cost (C) / N^[illegible] + 0 25 (C) [illegible]
■ Command control communication and data management equipment	Production cost (C) / N^[illegible] + 0 25 (C) [illegible]
■ Unmanned platform resources	Production cost + Operations cost / N^[illegible]
■ Orbital mobility systems	Production cost + Operations cost / N^[illegible]
■ Operating systems software	Software development cost (C) / N + 0 55C / N^[illegible]

requirement for a multiuse support item needed to perform an activity and includes tool kits and mechanical support equipment, command control, communication and data management equipment, unmanned platform basic resources, orbital mobility systems, and operating systems software

For those man-machine modes involving direct human participation (i e , Manual, Supported, Augmented, and Teleoperated), the most significant cost drivers were the prorated facility costs, transportation costs, orbital support equipment costs, logistics costs and the crew time or duty cycles For those man-machine modes involving indirect human participation (i e Supervised and Independent), the most significant cost drivers were prorated facility resources orbital support equipment, orbital mobility systems software and ground support operations costs

Application of the costing methodology resulted in the development of a family of cumulative cost versus frequency-of-use curves for each of the 37 activities As illustrated in Figure 10, these curves portray the relative economics associated with the performance of each activity by the seven alternative modes of man-machine interaction

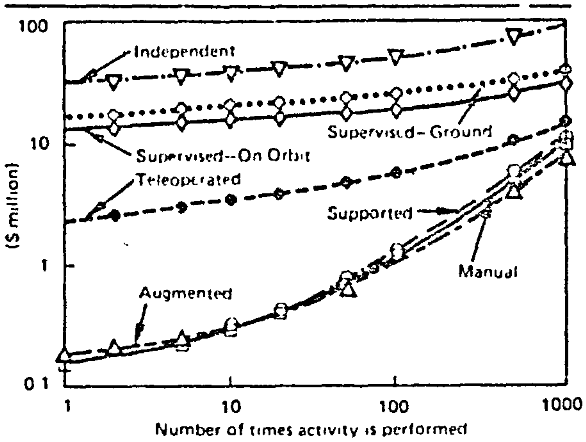

Figure 10 Activity 29 Release/Secure Mechanical Interface (Cumulative Cost Versus Number of Times Activity Is Performed)

Although the implementation costs for each individual activity in each man-machine interaction mode are somewhat different, a rather significant observation is that the cost level for direct human involvement (manual, supported augmented, or teleoperated modes) generally remains considerably lower than the cost for remote human involvement (supervised and independent modes) over a large number of times that the activity might be performed (1 to 10 000 times) Figure 10 illustrates this general case As may be noted, the cost differentials span two orders of magnitude when only a few activations are required (1 to 10) but narrow to one order of magnitude when the number of activations approaches 1000 For most activities, the manual mode can be performed in a relatively short time period (less than 1 hour) with only minimal inexpensive support equipment Even a $32 522-per-hour space station facility charge (although a significant factor if lengthy times are involved) is still a relatively small cost factor until the frequency of use approaches 1000 Performing activities in the independent, supervised, or teleoperated modes requires in most cases, a relatively expensive initial investment in support equipment and software, which does not compare favorably with the manual mode unless amortized over a large number of uses

Variations from the general pattern observed in the preceding case occurred for a few activities where unusual equipment or timeline requirements were specified for a particular mode of man-machine interaction For example, in *Activity 32 – Replace/Clean Surface Coatings* (see Figure 11) the manual and supported modes become relatively costly when the number of times the activity is to be performed increases to one hundred or more This is due primarily to the average time (150 minutes) required for this activity in the manual mode, as derived from the timeline data It would be more cost effective to provide some degree of augmentation or remotely (teleoperated) actuated mechanisms to aid in accomplishing this specific activity if it had to be performed daily over a period of a year or more

The more activities that are required to accomplish a specific mission objective, the more time required and the higher the cost. This is true of the manual, supported augmented and teleoperated modes of operation In the case of the operational modes where human involvement is more indirect (i e , the supervised-ground, the supervised-on-orbit, and the independent modes), the principal contributor to the cost of performing a set of activities is more directly dependent on the cost of the resources and the supporting equipment items required to perform each activity in orbit than on the time required to accomplish the activity This means that in the modes requiring indirect human involvement the cost reduction due to the potential of sharing common equipment items and common resources can be a significant factor in the cost equation

In the example shown in Figure 12, if only the one activity were required to be performed, it would need to be repeated thousands of times before it would be cost effective to provide some degree of automated support (i e the supervised mode of operation) On the other hand, if a total of 16 activities has to be performed to accomplish the mission objective, and if Activity 29 has to be performed only two hundred times designing the mission objective to be accomplished in the supervised mode becomes an attractive option

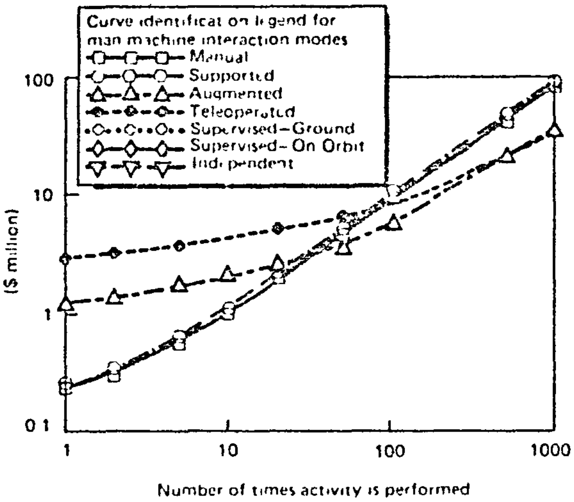

Figure 11. Activity 32 Replace/Clean Surface Coatings (Cumulative Cost Versus Number of Times Activity Is Performed)

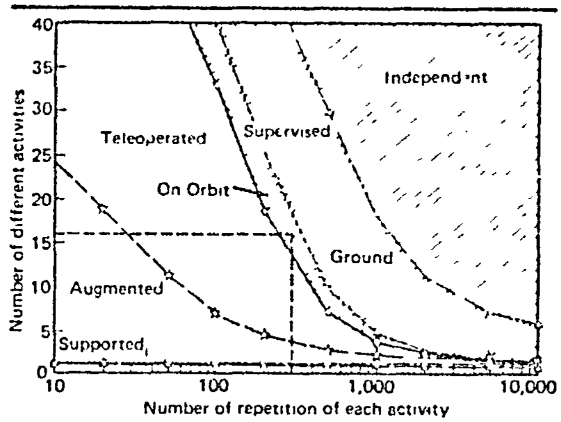

Figure 12. Activity Number 29 Release/Secure Mechanical Interface

Section 3
TECHNOLOGICAL READINESS

In developing the conceptual design for an advanced space system, a very important consideration is the level of technological readiness of each of the critical elements comprising the system. The closer the technological readiness level of each of the key elements is to full operational capability, the greater the probability of successfully implementing the system concept. The level of technological readiness is an especially important factor for the decision-maker in selecting the optimal mode of man-machine interaction. The eight levels of technological readiness considered in the THURIS study are defined in Table 16.

Table 16 Levels of Technological Readiness

Readiness level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function characteristic demonstration
5	Component breadboard tested in relevant environment
6	Prototype engineering model tested in relevant environment
7	Engineering model tested in space
8	Full operational capability (baselined into production design)

The time scale required to achieve each level of technological readiness depends in large part upon the degree of complexity of the system to be developed. For relatively simple systems, the times required to move from level 1 to level 7 may take from 1 to 5 years. This time range often reflects the impact of factors other than technical progress on the development process, such as political or budgeting constraints, or the availability of corollary systems required to demonstrate or aid in the development of the item in question. An example of the development path for a simple system is illustrated in Figure 13. The devices in this case are small electrical connector tools to be used in changing out orbital replacement units on a Space Platform. During neutral buoyancy tests at the Marshall Space Flight Center in 1981, the need for such tools was identified. The steps from conceptual design (level 2) to testing an engineering model (level 6) took about 1 year. To proceed to

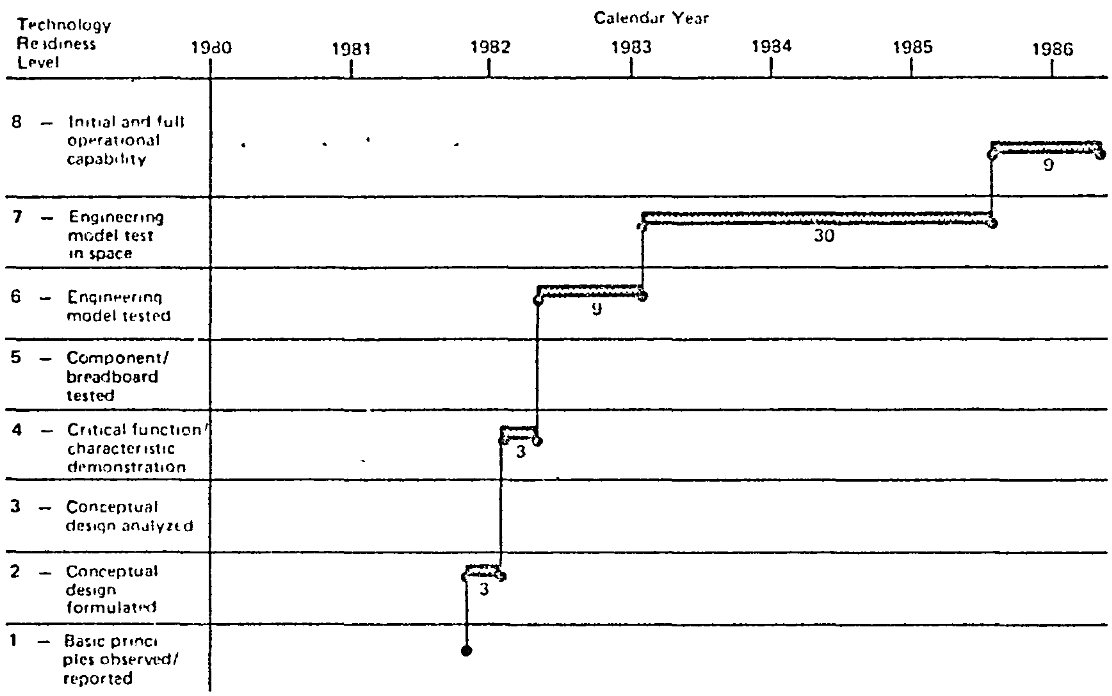

Figure 13 Development Path for Electrical Connector Tools

the next ~~level of~~ testing an engineering model in space and then to obtain full operational capability, approximately 30 months will be required because of scheduling and National Space Transportation System manifest constraints

The time requirement to move from level 1 to level 7 for a more complex system may take from 10 to 20 years An example of the development path for a more complex system is illustrated in Figure 14 The system illustrated is an Electrophoretic Production Unit currently under development at McDonnell Douglas Although the potential of electrophoresis as a separation technique has been known since the turn of the century, the specific application and value of a space-based system was initially conceived in the period between 1972 and 1974 By 1975 a conceptual design (level 2) had been developed and engineering models were developed and tested (level 6) in the 1979-81 time period The first test of the engineering model in space occurred on STS-4 in June of 1982 Tests will continue through 1984 The development of a full-scale production facility in all probability will depend upon the availability of a manned space station with a current estimate of full operational capability in 1992 Similar examples of the time required for technological advancement can be drawn from the historic data of other complex space systems The concept of building and launching a diffraction-limited infrared-visible-ultraviolet orbiting telescope was advanced in the early 1960s Over 20 years will have elapsed between the early conceptual design (level 2) and achievement of full operational capability of the space telescope in 1986

Figure 15 summarizes the expected relationships between technological readiness levels and the time required to achieve full operational capability for single, moderately complex and complex systems

Simple Systems may be defined as requiring

- Implementation of a single action
- Operations generally independent of other functions
- Unique applications, although basic principles well understood

An example might be a ratchet wrench that is required to remove and install mechanical fasteners Most manual and supported modes of man-machine interaction would fall into this category

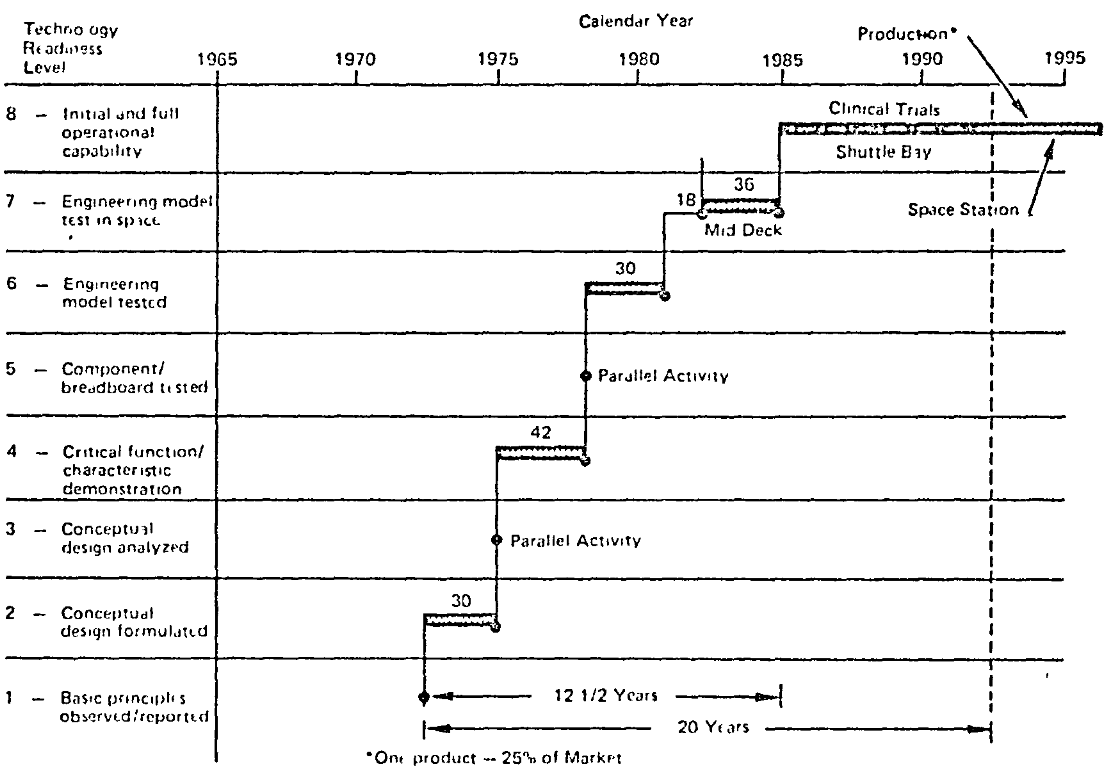

Figure 14 Development Path for Space Based Electrophoresis Production Units

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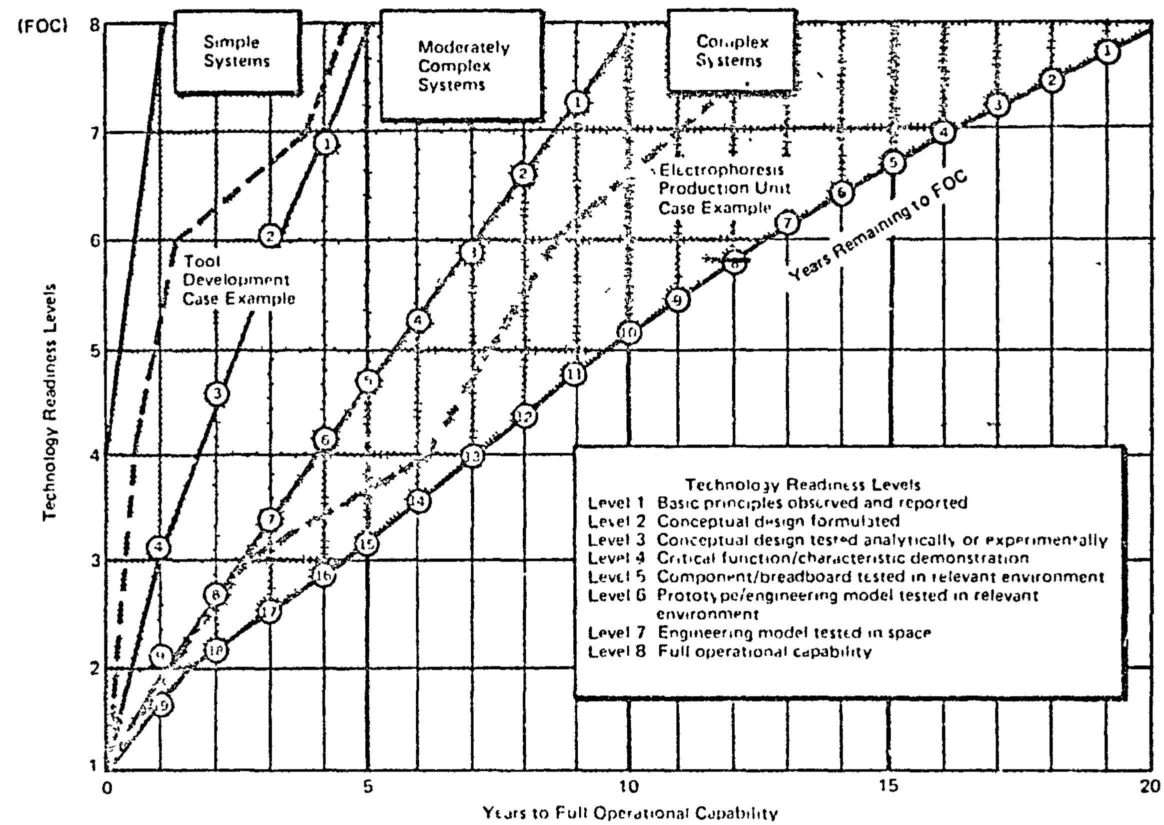

Figure 15. Technology Advancement Classifications

Moderately Complex Systems may be defined as requiring

- Multiple interacting functions or actions
- Complex control logic or networks
- Basic implementation techniques similar to previously developed systems

An example might be a computer work station that provides data computation, correlation, and plotting capabilities. Most augmented and teleoperated, and some supervised modes of man-machine interaction would fall into this category.

Complex Systems may be defined as requiring

- Multiple interacting functions or actions
- Complex control logic or networks
- Reduction to practice of design concepts (comparable system has not been developed.)

An example might be a remotely controlled satellite servicing system capable of self-actuating or self-healing operations in response to external stimuli. Most remotely supervised and independent man-machine interactions would fall into this category.

One of the objectives of the Human Role in Space study was to identify the requirements for technological developments needed to enable and enhance the human role in future space activities. A review of NASA planning documents indicated that the required enabling technologies as currently defined do include the major issues of concern. As described in NASA's Space Systems Technology Model[1] three key human-factors research and development areas include *crew station design, extravehicular activity and teleoperations*.

As a general observation, those projects associated with extravehicular activities and teleoperations reach full operational capability in a time domain consistent with the initial operational capability of the space station. Hence, activities depending upon the successful completion of these

(1) NASA Space Systems Technology Model, Fifth Issue dated January 1984. NASA Office of Aeronautics and Space Technology, Code RS, Washington, D.C. 20546. Issued under the authority of Stan R. Sadin, Deputy Director, Program Development, OAST RS.

projects can be accomplished with a reasonable and acceptable level of technical risk. For the intravehicular work-station-related projects, however, the risk assessment acceptability is less clear.

The current mission model developed by the Mission Requirements Working Group of the Space Station Task Force suggests that as the sophistication of future payloads increases, there will be an accompanying shift in crew support skills and requirements. A transition occurs from the more physical tasks to the more intellectually oriented work activities with the progression of time. This pattern appears to be analogous to the industrial development dynamic wherein the blue-collar worker changes to a white-collar worker as the transition from production of goods to provision of services takes place.

As the emphasis changes in the workplace, the design of the crew work station must also change to reflect the change from the physical to the intellectual. To more effectively use human intelligence, a better match is required with machine intelligence and with "expert" systems. Work stations must (1) communicate fluently with humans (speaking, writing, drawing, etc.), (2) assist in interactive problem solving and inference functions, and (3) provide knowledge base functions (information storage, retrieval and "expert" systems) for support.

Some of the specific issues related to work-station design that fall in the domain of "enhancing" technology and can be considered technology gaps at the present time are:

1. The Nature of Human Intelligence. Continuing effort should be directed toward developing a better understanding of the nature of human intelligence in order to develop work stations permitting more effective use of human intellectual capabilities.

2. Measurement of Human Productivity. Continuing effort is required to develop valid measures of human performance and productivity in order to have meaningful criteria for evaluating performance and productivity adjustments caused by changes in operational procedures and system design concepts.

3. Critical Incident Analysis of Human Performance. Continuing effort is required to investigate and understand the causes of "human error" in space system operations, as well as incidents of exceptional performance, in order to identify and classify the causal factors and establish guidelines for the design of future space systems.

4. Space Station Workshop Design. Continuing effort is required to develop the technology needed to provide an organized, integrated, on-orbit maintenance depot-workshop for the space station. Tools, techniques, and support facilities must be defined.

5. Visual Display Development. Continuing effort is required in the development of visual display terminals, inasmuch as it is anticipated that, just as today, 80% of the information required by future space crews will be obtained through the sense of sight.

The estimated time-phased technology readiness levels of these five areas and the recommended timetable for systematic studies of these areas are plotted in Figure 16 to show their relationship to the space station reference schedule.

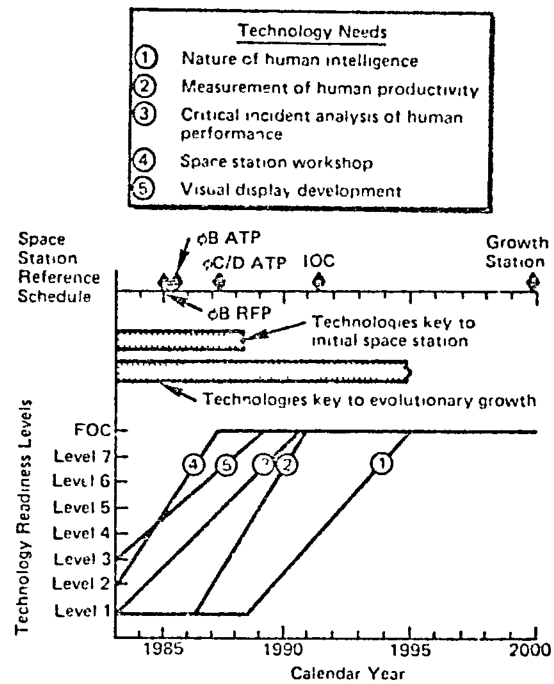

Figure 16 A Time Phased Technology Plan for Critical Areas of Enhancing Technology

Section 4
A DECISION GUIDE FOR ALLOCATION OF FUNCTIONAL ACTIVITIES BETWEEN HUMANS AND MACHINES

Based upon the criteria of *performance, cost,* and *technological readiness* the study team has attempted to formulate a decision guide that can be used to logically allocate space activities to alternative man-machine implementation modes. In developing this decision guide, we recognized that such decisions are highly dependent upon the time period in which a given system will be implemented. That is to say, the capabilities to support man in space will continue to evolve as will the other technologies, including the applications of artificial intelligence and the advanced development of micro- and macro- manipulators. Furthermore, the index numbers (performance times, cost data, technological readiness, etc.) used in the decision process at this time can be expected to change as better information becomes available from future studies and from operational experience. Accordingly, the decision model should be considered as still in the evolving stage and viewed in that context. Even so, the procedure as outlined should be useful in the early conceptual design process to help decision-makers formulate a strategy for selecting an initial reference design configuration. As the design concept crystallizes, design solutions will presumably be iterated to take advantage of the better data on performance, cost, and success probability that become available with a maturing design. In some cases the preferred mode of implementation may be expected to change in later stages of the preliminary design process as better design data is developed.

With these caveats in mind, and recognizing that the guide might take many forms, a simplified schematic of the decision process is presented in Figure 17. A worksheet format has been prepared, as illustrated in Figure 18, to develop the steps in this decision process.

For using this worksheet, seven modes of man-machine interaction have been selected to represent the steps along the continuum from direct manual operation at one extreme to completely independent self-healing–self-actuating systems at the other. These modes are designated as manual, supported, augmented, teleoperated, supervised-ground, supervised-orbit, and independent

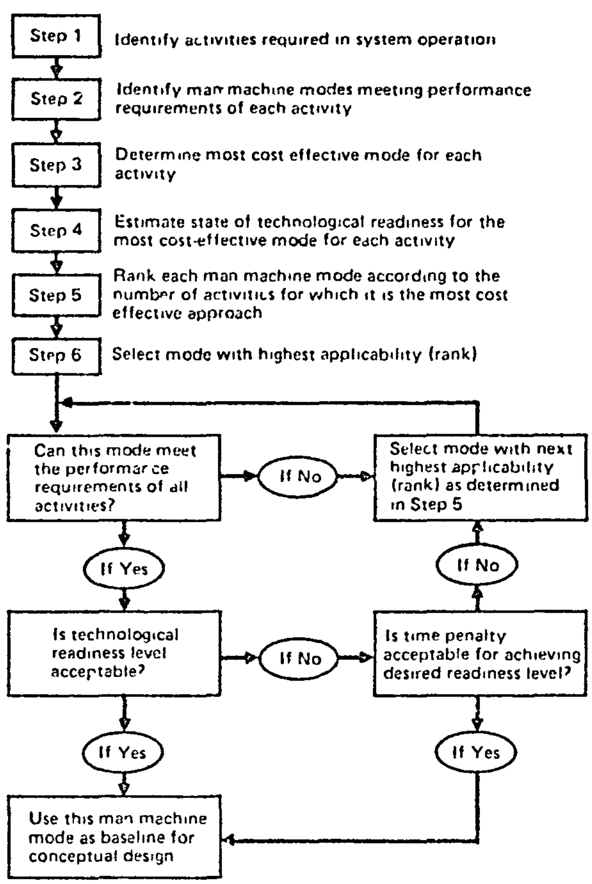

Figure 17. Decision Process for Identifying the Man-Machine Mode to Use in the Initial Conceptual Design Effort for an Advanced Space System

The cost charges for the activities to be conducted in the direct manual modes (manual, supported, augmented, and teleoperated) were based primarily on a cost-per-unit-time factor. Assuming that an 8-psi extravehicular activity suit will be available in the time period for missions now in the conceptual design stage, the delta costs for extra over intravehicular activities were negligible compared to the overall cost of manned space operations. Thus, it was unnecessary for the initial approach to selecting the baseline operational modes to determine whether the activity would be intra or extravehicular. This issue can be resolved later in the design process on the basis of more detailed performance and operational requirements, and not by cost per se.

The suggested procedure for determining the man-machine category to consider in the initial

	Activity name	Check if activity required	No of times Performed	Man-machine categories: Manual	Sup-ported	Aug-mented	Tele-operated	Super-vised -ground-	Super-vised -orbit-	Inde-pendent	Techno-logical Readi-ness (TR)	Cost ratio for TR of 7 at IOC	Years to TR of 7
		A	B	C	D	E	F	G	H	I	J	K	L
1	Activate initiate system operation												
2	Adjust align elements												
3	Allocate assign distribute												
4	Apply remove biomedical sensor												
5	Communicate information												
6	Compensatory tracking												
7	Compute data												
8	Confirm verify procedure schedule operations												
9	Connect disconnect electrical interface												
10	Connect disconnect fluid interface												
11	Correlate data												
12	Deactivate terminate system operation												
13	Decode encode data												
14	Define procedures schedules operations												
15	Deploy retract appendage												
16	Detect change in state or condition												
17	Display data												
18	Gather replace tools equipment												
19	Handle inspect examine living organisms												
20	Implement procedures schedules												
21	Information processing												
22	Inspect observe												
23	Measure (scale) physical dimensions												
24	Plot data												
25	Position module												
26	Precision manipulation of objects												
27	Problem solving decision making data analysis												
28	Pursuit tracking												
29	Release secure mechanical interface												
30	Remove module												
31	Remove replace covering												
32	Replace clean surface coatings												
33	Replenish materials												
34	Store record element												
35	Surgical manipulations												
36	Transport loaded												
37	Transport unloaded												
	Summary Data												
	(shaded) Man machine categories not appropriate to activity implementation	Total Required		Number of times selected							Median Readiness Level	Program Cost Increase	Maximum No of years

Figure 18. Worksheet for Defining the Human Role in Space

conceptual design of a space system (see Figure 19) is as follows:

Step 1: Which of the 37 unique activities are involved in meeting the mission objectives?

1. Place a check mark in column A of the worksheet by each of the 37 activities that are required for accomplishing the mission objective

2. For each activity checked in column A, estimate the number of times that activity will be performed during the mission and enter the numeric estimate in column B

3. Add the number of checks in column A and enter total in box M

Step 2: Which modes of man-machine interaction can meet the performance requirements of each activity?

1. Place a check in each of the man-machine categories, columns C through I, that could be used to satisfy the mission requirements, basing your judgment on

- Time requirements for performing activity
- Limiting factors that may restrict human involvement

Step 3: Which man-machine mode represents the most cost-effective approach to the performance of each activity?

1. For each activity, circle the check mark in columns C through I that represents the most cost-effective man-machine implementation mode, as determined from each set of cost versus number-of-repetitions curves

Step 4: What is the state of technological readiness for the most cost-effective man-machine modes identified in Step 3?

1. For the man-machine mode circled in columns C through I, estimate the technological readiness level and enter this value in column J of the worksheet

2. Find the median level of all the technological readiness values entered in column J and enter this median value in box U This median value defines the overall technological readiness of the aggregate of the proposed implementation concepts for the mission being analyzed

Step 5: What is the relative degree of applicability (rank) of each man-machine mode in accomplishing the mission objective?

1. Enter the total number of circled check marks in columns C through I in boxes N through T, respectively These totals indicate the relative degree of applicability of the alternative man-machine modes

Many considerations must be taken into account in selecting the man-machine mode to use as the baseline for initiating the conceptual design of an advanced system The principal factors of interest

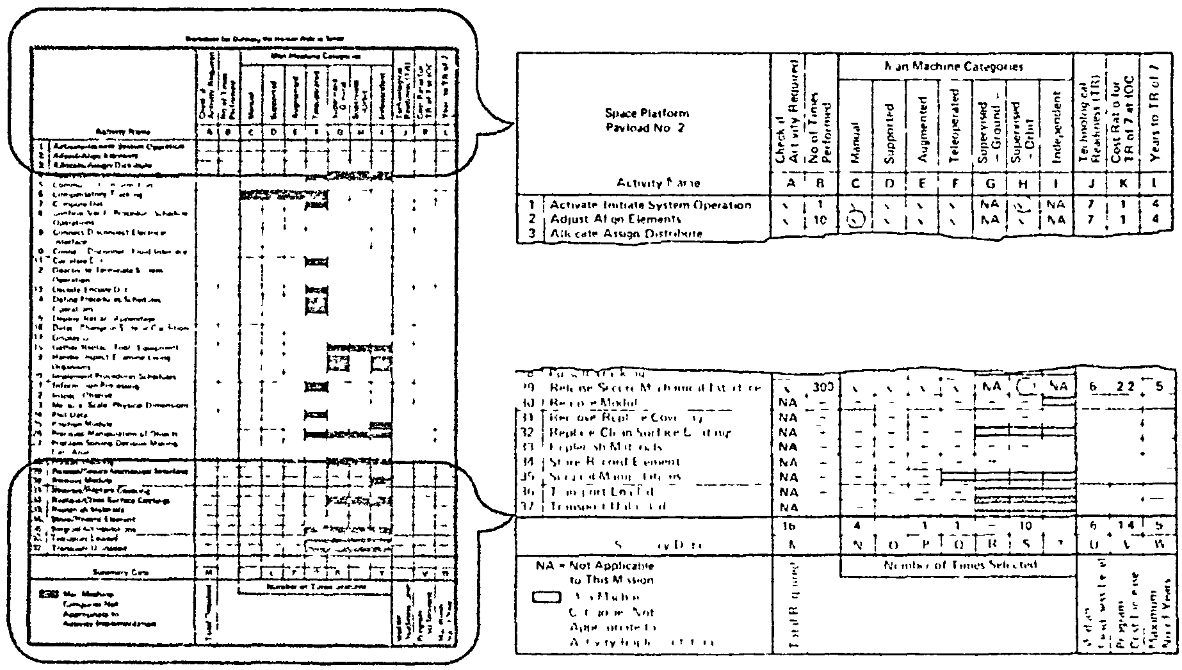

Figure 19 Worksheet for Optimizing the Human Role in Space

to system engineers will be performance, cost, and technological readiness The relative importance to place upon each of these factors, however, will rest on the judgment of the decision-maker

The **sixth step** in the decision process will involve an iterative process to determine, in the judgment of the decision-maker, the man-machine mode with the highest applicability for the specific mission objectives

If no single mode is found to be acceptable, it may be necessary to select a combination of modes that represents the minimum number of modes required to achieve the mission objectives within the time constraints imposed

This procedural methodology has attempted to provide a technique for logically determining early in the conceptual design process for a new space system which of the various modes of man-machine interaction can be used to most effectively perform the activities required.

Our analyses to date have confirmed once again the conventional wisdom that the human role in future space systems will draw heavily upon the intellectual capabilities, the sensory and perceptual capabilities, and the fine manipulative skills of the human observer Of all of man's sense modalities, vision is the most important for future space applications Man's capabilities for recognizing information in various forms and understanding it, his capabilities for creative imagination, his ability to rigorously structure problems and develop solutions, and his ability to make decisions will continue to be essential ingredients in future systems Many examples from experiences on previous space missions illustrate these capabilities

Performance, Cost, and Technological Readiness remain the principal criteria in determining where along the continuum from direct manual intervention to independent operations the mission requirements of future space programs can best be met By defining a generic set of activities from which systems meeting future mission requirements can be synthesized, and by assigning performance, cost, and technological readiness metrics to each of these generic activities, a mechanism becomes available for developing a logical rationale for selecting the optimal man-machine interface

Using the methodology developed in this study, it will become possible to establish early in the design process the most cost-effective design approach for future space programs through the optimal application of unique human skills and capabilities

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