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SHUTTLE FREE-FLYING TELEOPERATOR SYSTEM EXPERIMENT DEFINITION

FINAL REPORT

VOLUME I-EXECUTIVE SUMMARY

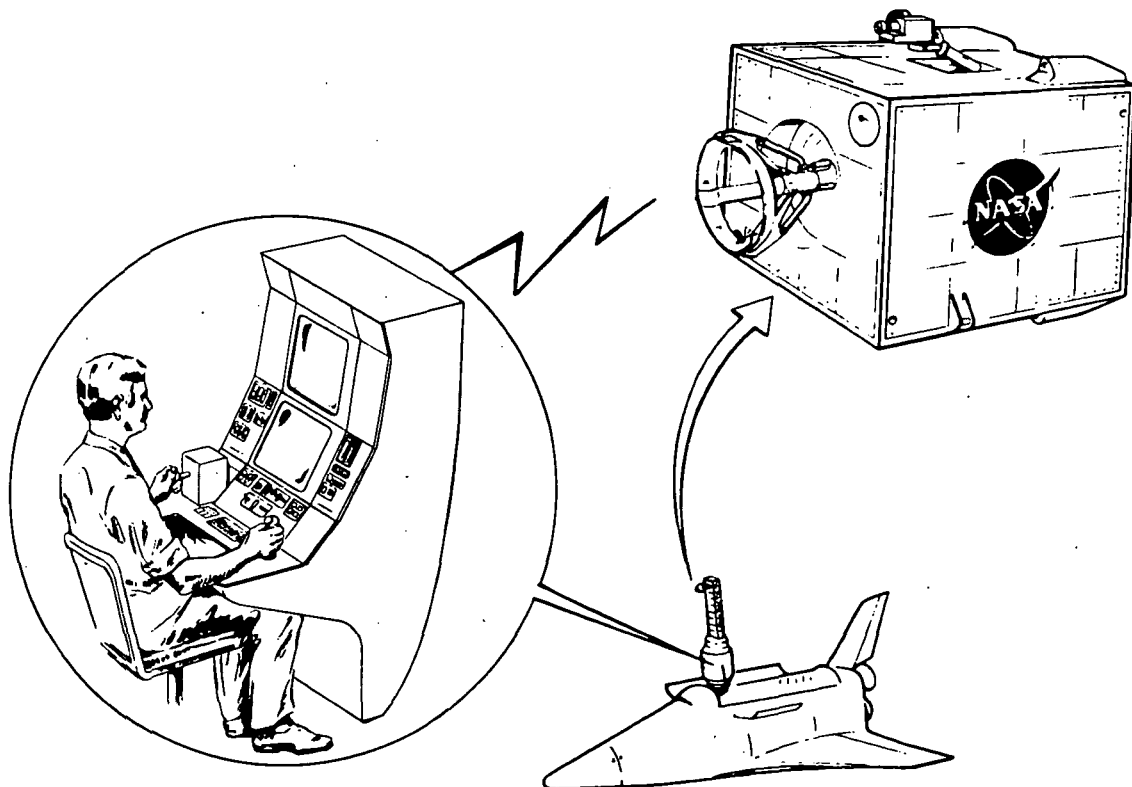
JUNE 1972

CONTRACT NAS8-27895

REPORT NO. D7425-953004

DPD 261 DR MA04

Prepared for NASA Marshall Space Flight Center
Huntsville Alabama



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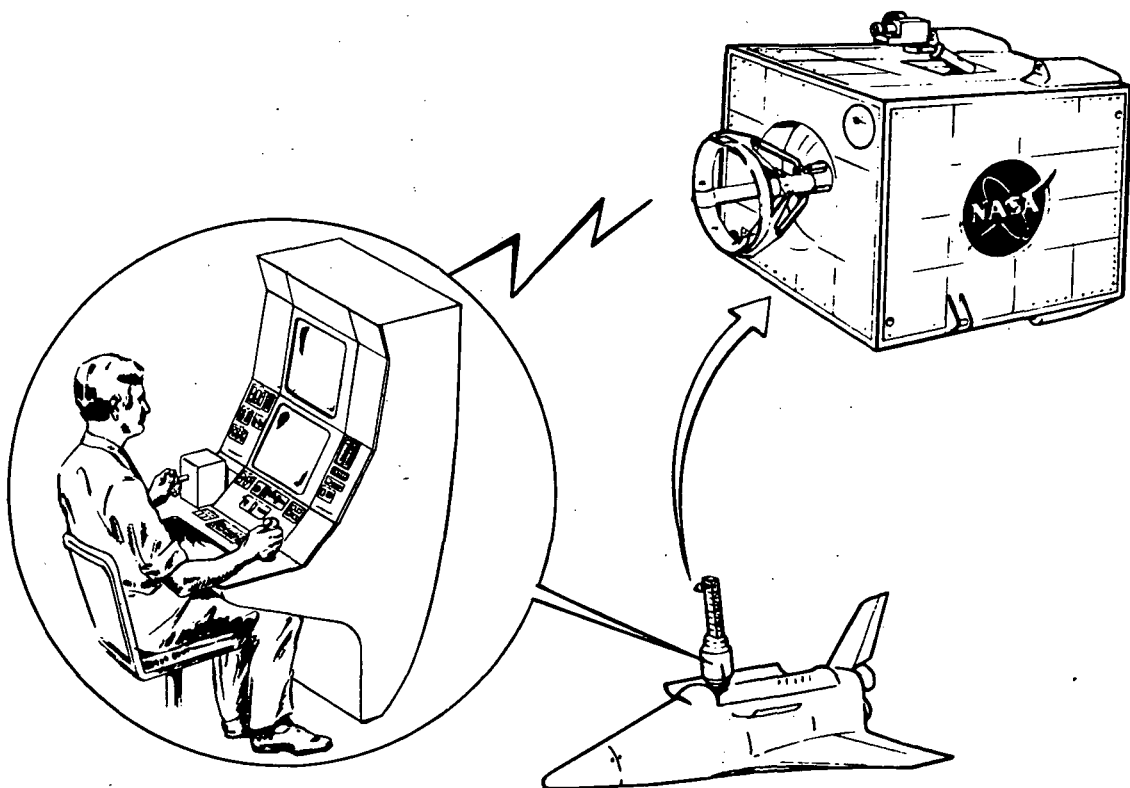
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Reviewed and Approved by H. Fornoff
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FOREWORD

This study was conducted by the Bell Aerospace Company, Buffalo, New York, for the NASA Marshall Space Flight Center, Huntsville, Alabama. It represents a six-month effort performed under contract NAS 8-27895. Mr. James H. Clingman was the NASA COR. George Onega was the Bell Study Manager. The following people contributed significantly to the study:

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The study final report is published in three volumes as follows:

Volume I:	Executive Summary
Volume II:	Technical Report
Volume III:	Program Development Requirements

I. INTRODUCTION

Continuing the extension of man's capabilities in space is one of NASA's objectives for the future space program. To meet this goal, emphasis is being placed on commonality and versatility of systems to perform many different functions, and reusability of systems to perform a variety of missions.

Remote Manipulator Systems (RMS) such as a Shuttle free-flying teleoperator system is a prime candidate for meeting this objective. A teleoperator, as defined by NASA, is a remotely controlled cybernetic man-machine system designed to augment and extend man's sensory, manipulative and cognitive capabilities. The sophistication and complexity of a teleoperator system to provide this capability, can vary over a wide range. Sensor subsystems can include video, force feedback sensors, tactile sensors, position and rate sensors. Manipulators can vary in the degree to which they represent human arms, in their degrees of freedom, in their articulation and dexterity, in the type of servo drive, mechanical, electro-mechanical or hydraulic. Locomotion can comprise selfcontained free-flying teleoperators, booms/manipulators attached to a spacecraft or surface roving vehicles.

Teleoperators or manipulators have been widely used in radiation hot cells for a number of years and are being applied for underwater operations.

The use of teleoperators for space application created great interest when in November 1969 the President's Science Advisory Committee called for the development of remote controlled devices to augment man's capabilities in our manned space effort.

In April 1970, at a request of Dr. George Low, then Acting Administrator for NASA, a task team was established within NASA with the goal to coordinate a program to develop the technology required concerning the potential use of teleoperators/robots to augment man's capabilities in space.

The main recommendation by the task team stated that NASA should establish a teleoperator program management organization to integrate and coordinate the technology development.

In August 1971 a Teleoperator/EVA committee under the chairmanship of Dr. Stanley Deutsch, Director Bioengineering, Office of Life Science within the Office of Manned Space Flight was announced. By establishing this committee NASA management recognized the teleoperator system as an important means of extending and augmenting man's capability in space.

There are two classes of Shuttle teleoperator systems; the free flier and the attached manipulator. Each class of teleoperator excels in certain types of capabilities. Within these types, some overlap of capabilities is evident. However, the scope of this study is restricted to the free-flier class of Shuttle Remote Manipulator System (RMS) and is designated as an FFTO (Free-Flying Teleoperator).

Such a device physically replaces man in a hostile space environment. It retains the advantages of manned missions since human decision-making and adaptability are still vital ingredients in the system, but eliminates the disadvantages of providing remote life support capabilities and hazard protection systems. The most efficient teleoperator system will include the best mix of man's decision making and control capabilities which can be built into a machine.

Teleoperator systems can fill an important role in the Space Shuttle program. They can retrieve automated satellites and other objects to the Space Shuttle. This is particularly important because of the inability of the Shuttle to dock with small payloads and the undesirability of using the Shuttle to retrieve a satellite which has adverse dynamics. Thus, spent satellites can be retrieved, refurbished and reused. Further, teleoperators can increase the useful life of existing satellites by providing on-orbit maintenance and servicing capabilities. (Currently, NASA is pursuing a low-cost standardized spacecraft concept, specifically designed for on-orbit servicing.) Teleoperators extend man's vision to remote and hazardous places to accomplish critical monitoring and inspecting of operations and surfaces, without exposing man to a dangerous environment. Teleoperators provide a means for transferring cargo over short distances or large distances, in support of orbital operations. Teleoperators can be used to gather engineering and scientific data by flying special instrumentation at remote distances from the Shuttle. Finally, the teleoperator cannot only relieve man from performing difficult, tiring or dangerous tasks but can rescue man in the event that problems develop during necessary EVA operations.

Earlier studies conducted by the General Electric Co., Martin, North American Rockwell and others have identified potential teleoperator applications, examined the state of the art, configured candidate systems and examined costs. It was timely in the current study to draw on these previous studies and extend them in defining a free-flying teleoperator system flight experiment/test which would demonstrate the operational capabilities of an FFTO.

This study complements NASA's in-house and contractor efforts on satellite retrieval, manipulator/grapppler design, FFTO video system studies, Shuttle payload support equipment and low-cost modular payload design. The current Bell study provides baseline configuration data which is useful in these other efforts, it identifies the FFTO operational capabilities which can be used by mission planners and it defines an FFTO experiment/test which will be used by the technical community for systems verification and operations and procedures validation.

Because of the abundance of related efforts and the modest demands in many of the subsystem technology areas, this pre-phase A effort shows a level of detail greater than is usually found in such studies. It is this fact, however, which will provide useful engineering data needed by NASA in the development of the Sortie Can, Shuttle interfaces and payload cooperative design requirements.

The major elements of the FFTO system concept are the teleoperator spacecraft, the control station and the required support equipment as shown in Figure 1. A shirt sleeved operator located at the control station in the Shuttle will control and maneuver the FFTO in the vicinity of the Shuttle while accomplishing typical operations described above. The support equipment provides for all physical and functional interfaces between the free-flying teleoperator and the control station and the interfaces of these two major elements with the Space Shuttle.

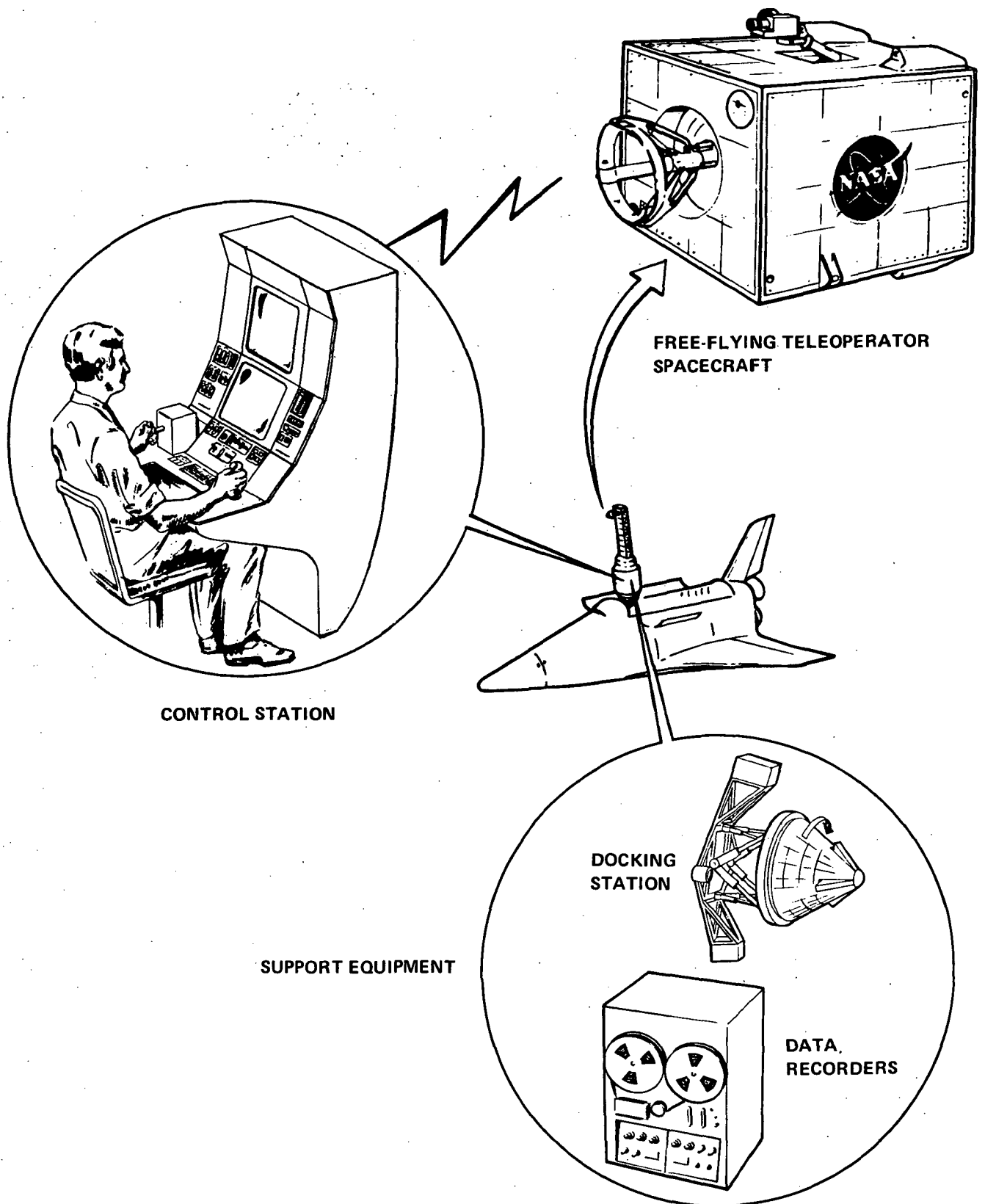


Figure 1. Free-Flying Teleoperator System Elements

II. STUDY OBJECTIVES

The three primary objectives of this study were to:

1. Evaluate the applicability and utility of a free-flying teleoperator system to support future earth orbital missions, with specific emphasis on the early mission of the Space Shuttle. Prior studies have indicated gross FFTO activities of the type generally suited to space operations. The primary users of FFTO's will be Shuttle payloads. This study will define the specific activities which are potentially useful for supporting shuttle missions and will evaluate the suitability of those activities for contributing to Shuttle operations resulting in the selection of a few high-payoff activities.
2. Specify in-flight experiments and tests which will provide sufficient experience and data applicable to the development of future operational systems. After having identified the high-payoff FFTO activities, it is necessary to structure an in-flight experiment/test program to validate the man-machine system's ability to perform these activities. These experiments/tests will include total activity demonstration and partial activity and basic technology task demonstrations.
3. Provide the definition of a useful early experimental system that will be checked out and used with early Shuttle missions. An important aspect of experiment definition is the description of hardware requirements. In specifying the FFTO experimental system, the following information will be generated: (a) FFTO conceptual designs and their capabilities and limitations, (b) technologies required for FFTO development, and (c) useful management planning information, including costs and schedules, for an experimental FFTO development program.

III. RELATIONSHIP TO OTHER NASA EFFORT

Developing an experimental teleoperator will advance operational technology, thereby, benefitting many NASA areas of responsibility by providing an increase in man's capability to operate in space.

The free-flying teleoperator is unique in that it must interface with both the Shuttle and the Shuttle payloads. For this reason, the FFTO is related to virtually all other Shuttle/payload efforts to properly accommodate its dual interface role.

It is important to the Space Shuttle itself since it offers services to the Shuttle which can best be performed by a free-flying teleoperator, such as monitoring Shuttle/payload operations and inspecting the orbiter's thermal protection system. Shuttle operations planners have in the FFTO, a new system and method for accomplishing a variety of mission objectives. It can be used in either a primary or backup mission role. It can replace man in hazardous environment situations while utilizing his perceptive and cognitive capabilities.

The FFTO relates directly to NASA's efforts to reduce the cost of space systems by developing standard systems or payload designs for space operations. Work in this area sponsored by NASA, has indicated a need for servicing these standard systems on orbit. These future payload systems, therefore, become candidates for teleoperator services. Their design and operation will depend on the mode of servicing applied to them to extend their on-orbit life.

In a similar way, a teleoperator offers a way of servicing satellites at synchronous altitudes, thereby removing man from a hazardous radiation environment. This application of the FFTO impacts directly on the tug program, both from a systems design and tug operations point of view.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

To meet the study objectives, a logical sequence of six tasks was followed. Figure 2 presents a simplified flow diagram of the work tasks. The approach utilizes existing mission data to extract FFTO system requirements, defines a flight experiment to validate FFTO performance and generates system concepts suitable for conducting the experiment.

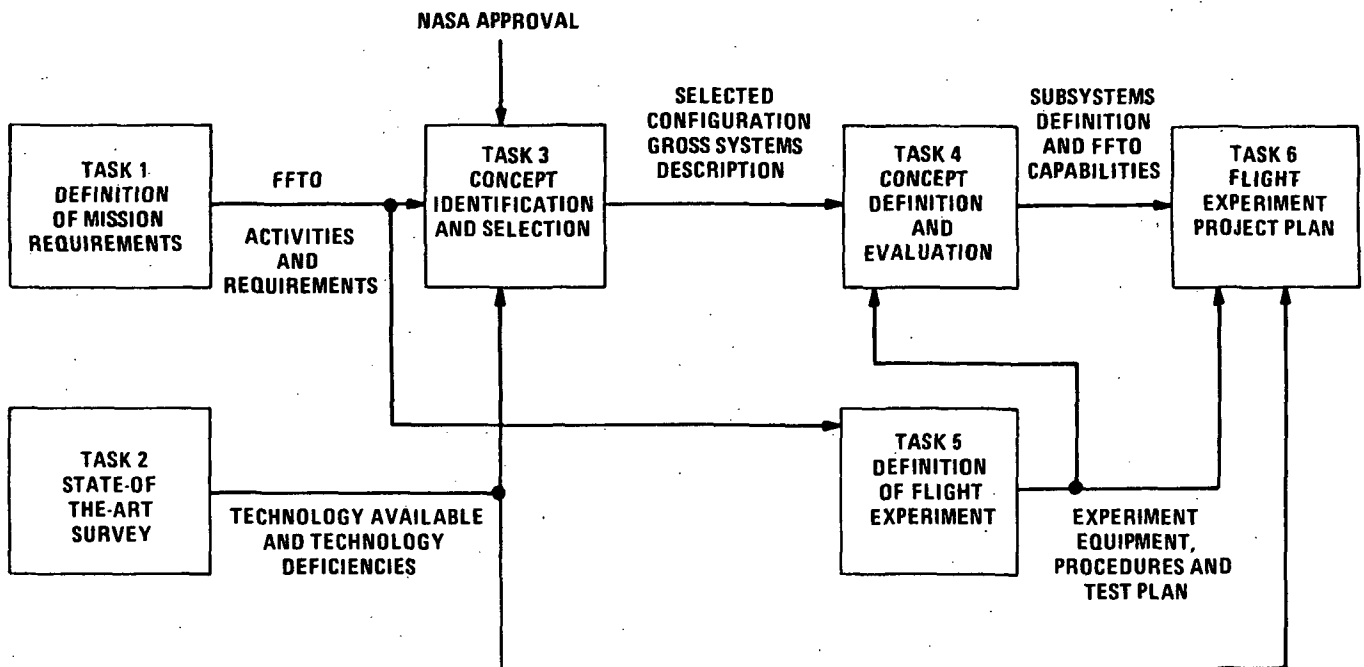


Figure 2. Study Flow Diagram

Using data provided by NASA, missions – both planned and anticipated – for the early Shuttle flights were reviewed, and brief overall mission profiles established in Task 1, Definition of Mission Requirements. From these, and from teleoperator capabilities projected from past studies, potential teleoperator activities were identified. These were screened for commonality of functions and grouped into sets ranging from minimum to maximum system demands. The outputs of this task constitute the baseline activities on which the design and later evaluation of the teleoperator system was based. Task 2 – Definition of the State of the Art – was conducted in parallel with Task 1.

The results of the mission analysis were used in Task 5, Definition of Flight Experiments, for identifying and defining flight experiments which demonstrate the operational capability of the teleoperator for supporting early Shuttle missions.

The outputs of Tasks 1 and 2 were used to generate a number of candidate teleoperator design concepts – Task 3 – from which one “best” overall concept was selected as being a suitable baseline which could be tailored to meet the specific requirements of the flight experiment. In carrying out Task 3, it was necessary to first define the relationships between subsystem design and teleoperator overall performance, and then reflect these in the different candidate designs.

Task 4 – Concept Definition and Evaluation – includes analyses and trade studies within each subsystem, leading to a preliminary design of the teleoperator flight vehicle, its control, launch and

retrieval and reservicing checkout stations which meets the experiment requirements. The selected system was evaluated as to how well it can accomplish the prescribed mission requirements. The impact that varying mission requirements have on the design was determined.

Task 6 identifies and plans the tasks, including supporting research and technology and development schedules and cost estimates for subsequent program phases.

The major study outputs are:

- Teleoperator System Design and Specification,
- Flight Experiment Time — Lines and Procedures,
- Development Program Cost and Schedules for Phases A, B and C/D, and finally
- Teleoperator Mockup.

Ten basic assumptions and guidelines were used in the performance of this investigation.

1. The experimental teleoperator system will be available for Shuttle integration by the end of 1977.
2. Use of off-the-shelf hardware will be considered when it minimizes development costs and adheres to the required safety and design standards.
3. The teleoperator system will be launched and returned to earth by the Shuttle.
4. The payload delivery capability of the Shuttle will be 45,000 — 65,000 pounds to a 100 nautical mile altitude at a 28.5 degree inclination. The Shuttle cargo bay size will be 15 feet in diameter by 60 feet in length — with no cargo bay environmental control.
5. The teleoperator will have a two-mile operational range from the Shuttle. The actual required range will be determined as part of the study.
6. All materials selected for use in pressurized areas will be nontoxic, nonflammable and non-explosive to the maximum extent possible.
7. An O_2N_2 atmosphere of 14.7 psi will be provided with an O_2 partial pressure of 3.1 psi for any equipment associated with the control station.
8. A modular approach will be considered in developing design concepts for the free-flying teleoperator spacecraft.
9. Emphasis will be placed on flexible systems with growth potential.
10. The complexity of the manipulator mechanisms will be determined during the course of study. Until the requirements are more firmly established, these mechanisms shall be considered to range in complexity from simple docking mechanisms to a complex set of manipulator arms.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

This section is separated into four parts:

- Mission Analysis and Experiment Definition,
- Concept Definition and Evaluation,
- Project Plans, and
- Conclusions.

These four subsections answer the four questions:

- What should the FFTO do?
- What are its characteristics?
- What will it cost? and
- What was learned in the study?

A. MISSION ANALYSIS AND EXPERIMENT DEFINITION

The mission analysis was divided into two related – but separate – studies, which included:

- (1) a general analysis considering all pertinent mission inputs and applications, and
- (2) a specific analysis aimed at identifying teleoperator activities limited to supporting the first 10 Shuttle flights

The general analysis resulted in defining broad operational categories of teleoperator support and translated these supporting activities into design requirements. The specific analysis identified – by example – realistic roles for the FFTO in the early Shuttle program.

Many data sources – provided by NASA – were used to establish potential uses of a free-flying teleoperator. Table I lists these sources.

On the basis of the Shuttle flight objectives and the capabilities of potential FFTO systems, a list of activities which an FFTO can perform was established. An activity is a specific FFTO “mission” or application used to support the Shuttle mission. The definitions of the activities are given in Table II.

The last five activities – ASTRONAUT RESCUE, REPAIR, OPERATE, COMPONENT DEPLOY AND COMPONENT RETRACT – are considered to be potential activities; but for missions later than the first ten. The first four of these activities are not planned, and although they might be performed in an emergency, there is no basis for assuming their need or occurrence. Furthermore, the mission descriptions do not indicate any planned astronaut EVA; and so, there is no expectation for ASTRONAUT RESCUE. Consequently, considerations of these activities have been discontinued in the analysis.

The value of the remaining activities to the Shuttle program was established by a double screening procedure. The first screening assessed the applicability or suitability of using an FFTO to accomplish the activity (as opposed to using other means). A second screening judged the value of the activities in achieving the Shuttle flight objectives – that is, the mission need was assessed. Figure 3 presents the results of this value analysis.

**TABLE I
MISSION DATA SOURCES**

- SOAR STUDIES
- PAYLOAD DESIGN REQUIREMENTS FOR SHUTTLE/PAYLOAD INTERFACE
- SHUTTLE PHASE B STUDY REPORTS
- TELEOPERATOR REQUIREMENTS STUDY BY MATRIX
- PRELIMINARY REQUIREMENTS FOR TELEOPERATOR INTERFACE WITH SHUTTLE PAYLOADS BY LMSC
- HEADQUARTERS DATA PACKAGE ON FIRST 10 MISSIONS
- REVIEW OF 10 PROPOSED SPACE SHUTTLE MISSIONS
- INTEGRATED OPERATIONS/PAYLOADS/FLEET ANALYSIS, FINAL REPORT BY THE AEROSPACE CORPORATION

**TABLE II
POTENTIAL FFTO ACTIVITIES**

- SATELLITE DEPLOY - DOCKS WITH SATELLITE, MOVE IT AWAY FROM ORBITER, RELEASE IT, RETURN
- SATELLITE RETRIEVE
 - NORMAL - GO TO STABLE SATELLITE, DOCK WITH IT, MOVE IT TO ORBITER, DOCK IT, RETURN
 - ABNORMAL - SAME AS NORMAL BUT SATELLITE IS SPINNING AND NUTATING
- CARGO TRANSFER - MOVE MATERIALS BETWEEN ORBITER AND ANOTHER STABLE SPACECRAFT
- MONITOR/INSPECT - WATCH ORBITER/PAYLOAD OPERATIONS/CRITICALLY EXAMINE SURFACES
- EXPERIMENT DATA ACQUISITION - MOVE SENSORS IN SPACE TO ACQUIRE SCIENTIFIC DATA
- SATELLITE SERVICE - PERFORM SCHEDULED SERVICES TO SUSTAIN SATELLITE/PAYLOAD EFFICIENCY
- ORBITER SUPPORT - SERVICE ORBITER TO SUSTAIN OPERATING EFFICIENCY
- ASSEMBLE - TRANSFER COMPONENTS TO SPACE ASSEMBLAGE, JOIN THEM, RETURN
- ASTRONAUT RESCUE - RESCUE ASTRONAUT IN DIFFICULTY ON EVA
- REPAIR - PERFORM UNSCHEDULED SERVICES WITH SPECIAL AIDS TO RESTORE SATELLITE OPERATIONS
- OPERATE - CONDUCT A PLANNED SEQUENCE OF TASKS TO CONTINUE SATELLITE OPERATIONS
- COMPONENT DEPLOY/RETRACT - EXTEND/DEPLOY A SATELLITE APPENDAGE AS PLANNED

FFTO APPLICABILITY	ACTIVITY IMPORTANCE TO FLIGHT	OVERALL
BETTER SATELLITE RETRIEVE ABNORMAL MONITOR/INSPECT SATELLITE SERVICE SHUTTLE SUPPORT MONITOR/INSPECT	NECESSARY SATELLITE DEPLOY SATELLITE RETRIEVE NORMAL SATELLITE RETRIEVE ABNORMAL CARGO TRANSFER SATELLITE SERVICE ASSEMBLE	HIGH VALUE SATELLITE RETRIEVE ABNORMAL SATELLITE SERVICE MONITOR/INSPECT
EQUAL SATELLITE DEPLOY SATELLITE RETRIEVE NORMAL EXP DATA ACQUISITION	DESIREABLE + MONITOR/INSPECT EXP. DATA ACQUISITION	MID VALUE SATELLITE DEPLOY SATELLITE RETRIEVE NORMAL EXP DATA ACQUISITION
LESS CARGO TRANSFER ASSEMBLE	UNNECESSARY SHUTTLE SUPPORT	LOW VALUE CARGO TRANSFER SHUTTLE SUPPORT ASSEMBLE

Figure 3. FFTO Activity Values

As indicated in the figure, there are three activities which are high-value activities to the Shuttle program. These are SATELLITE ABNORMAL RETRIEVAL, SATELLITE SERVICING, and MONITOR/INSPECT. Furthermore, there are three mid-value activities identified: SATELLITE DEPLOY, NORMAL RETRIEVAL and EXPERIMENTAL DATA ACQUISITION. These, then, become the important activities which must be demonstrated in the FFTO flight experiment.

The objective of the flight experiment is to demonstrate the operational capability of a free-flying teleoperator in support of early Shuttle missions. Figure 4 lists the activities in the time sequence which is expected to be of greater utility. The satellite servicing activity requires that the payload satellite be cooperatively designed. It is not expected that such sophisticated designs will be available until the mid-to-late 80's; and so, there is little urgency for demonstrating that capability in the early shuttle flights. Further, the unique aspect of this function is the manipulative task – that is, the ability to do useful work at a worksite. This aspect of the demonstration task can be demonstrated with good fidelity on earth based simulation. So, the early shuttle experiment will be focused on demonstrating MONITOR/INSPECT, DATA ACQUISITION, DEPLOY and RETRIEVE activities.

Many operational options are open in specifying experiment procedural and hardware requirements. Operator location and FFTO deployment options are illustrated in Figure 5. An operator could be located in the Sortie Can or in the payload support area of the orbiter. Furthermore, a short Sortie Can (overall length of 15 ft) or a long Sortie Can (overall length of 25 ft) could be selected. The FFTO could be deployed by:

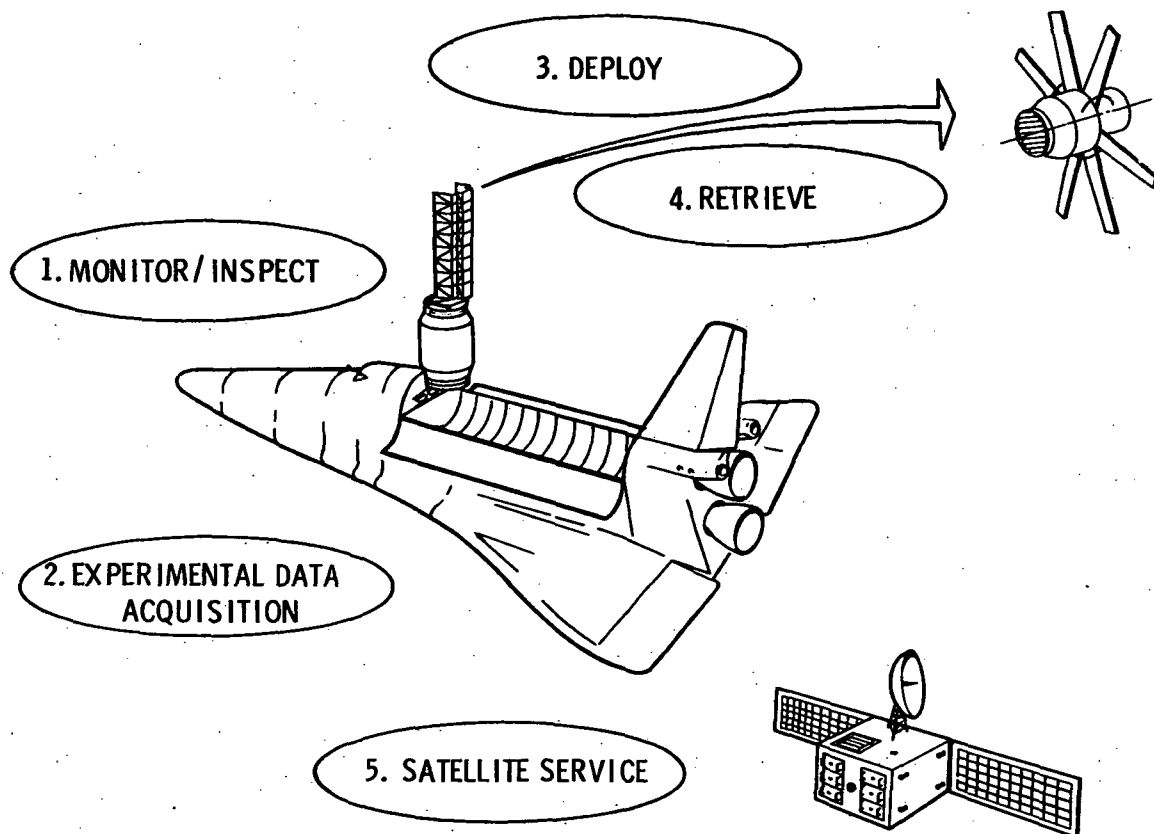


Figure 4. Functions to be Demonstrated

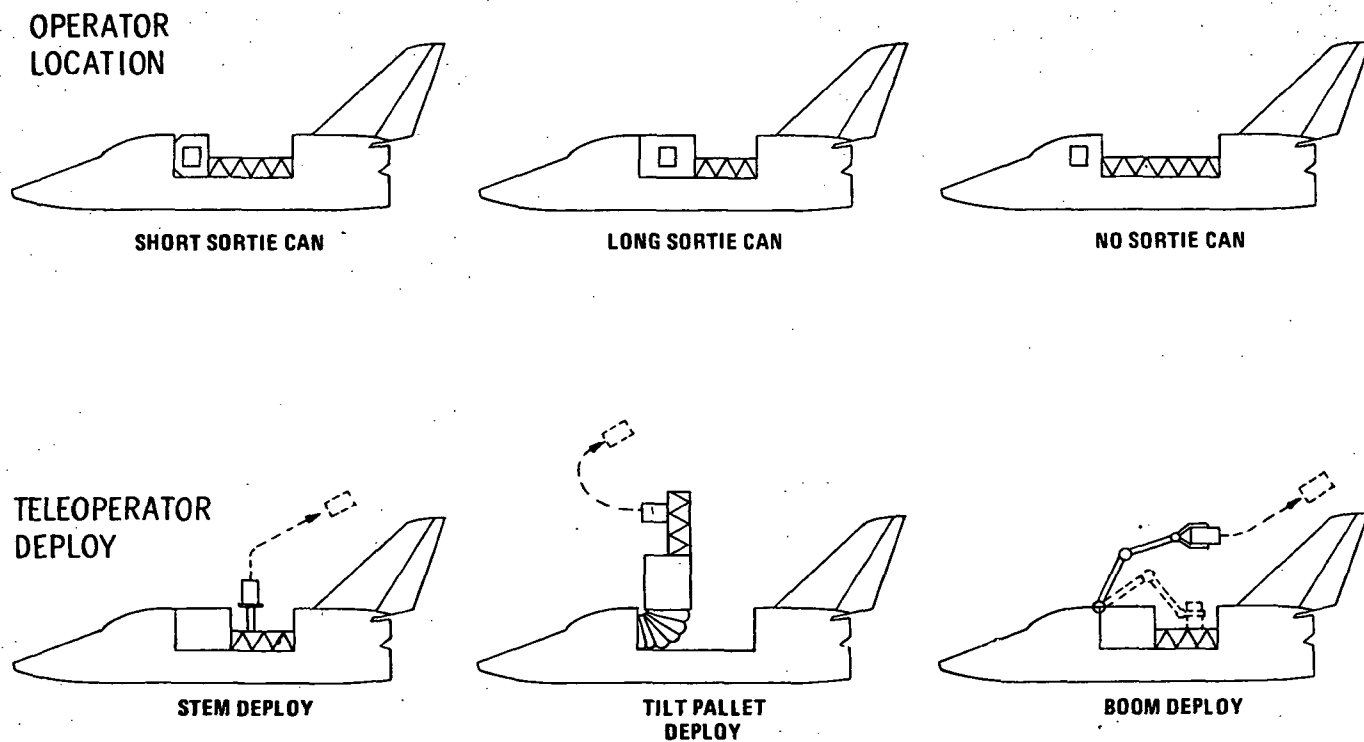


Figure 5. Operational Options

- a stem type deployment system (one which elevates the teleoperator alone out of the cargo bay,
- tilting the Sortie Can and pallet out the cargo bay and flying directly off the pallet, or
- using a remotely controlled boom (mechanical arm) permanently attached to the orbiter.

Any combination of these options could be used by making minor modifications in the experiment procedures and hardware requirements.

Operational procedures which identify the subtasks to be demonstrated are defined for each of the six activities and for an operational check activity. The operational check activity is included to demonstrate system operability and to renew a trained operator's familiarity with the teleoperator control and maneuvering characteristics.

1. Operational Check

The objective of this activity is to demonstrate system operability and operator familiarity. During this activity, attitude and translational controls are exercised, mode options are tested, visual system controls are checked out and finally satisfactory operation of the telemetry and data recording equipment is verified. The procedure for performing the subtasks is outlined in Figure 6. Before conducting the operational checks, the Sortie Can and attached pallet tip out of the cargo bay. While the FFTO is still latched to its docking station, its systems are activated and a functional check is conducted. After the functional check is completed, the operational check procedures begin, following the sequence shown in the figure. The phasing of the task in the shuttle orbit is selected to offer good lighting conditions for the TV systems. Flight operations will begin early in the sunlit phase of the orbit and continue for about 128 degrees of orbit.

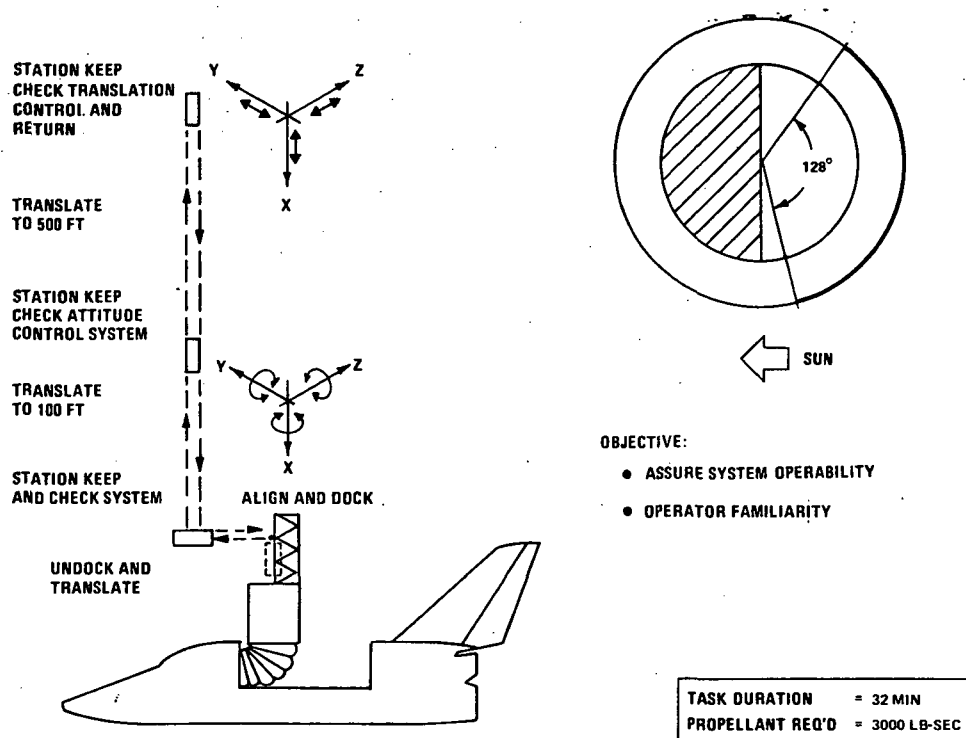


Figure 6. Operational Check

2. Monitor/Inspect

The objective of this activity is to demonstrate:

- station-keeping capability of sufficient accuracy to allow a detailed inspection to be accomplished,
- a smooth maneuvering capability to show monitoring while moving, and
- the adequacy of the video system characteristics and design in the orbital environment under actual operating conditions.

An important spin-off of this activity is that it gives useful information to the shuttle crew regarding the conditions of the thermal protection system. Through the monitoring and inspection of the heat shield, the FFTO operator can identify flaws or damage incurred during launch and ascent to orbit. Besides supplying this data, a test panel located on the pallet will provide calibration data which will allow the characteristics of the video system to be determined.

The MONITOR/INSPECT activity is phased to occur during the sunlit portion of the shuttle orbit as shown in Figure 7. For this activity, the teleoperator is controlled to stationkeep near a test panel (Figure 8) and to inspect the panel with its cameras. The camera zoom and focus controls are checked and the ability of the camera to track an object is verified. The teleoperator is then controlled to circumnavigate the shuttle and to stationkeep at points along the flight path which enable the cameras to inspect the top, bottom and leading edge surfaces of the orbiter thermal protection system.

3. Experimental Data Acquisition

The objective of this activity is to demonstrate maneuverability and controllability suitable for gathering engineering and scientific data in close proximity to the shuttle. The specific objective is to gather data on the nature of the contamination in the vicinity of the Shuttle. This is done by using an Integrated Real-Time Contamination Monitor (IRTCM) carried aboard the FFTO. Using a residual gas analyzer and quartz crystal monitors, the instrument measures contamination fluxes about the orbiter on a real-time basis (see Figure 10).

The IRTCM is flown out to a position about 500 ft from the Shuttle as shown in Figure 9. The FFTO circumnavigates the Shuttle in two planes at this radius and gathers samples every 45° in its traverse. It then closes to 250 ft and repeats the process. Subsequent flights will be used to gather additional data, covering more planes, different ranges and various sun angles. The sample measurement cycle time is 3.3 minutes at the larger radius and 1.65 minutes for the 250 ft radius circles and is compatible with the planned IRTCM minimum measurement cycle time. The long duration of this activity will check the operator and the teleoperator's capabilities over extended duty cycles. The maneuvering capability of the teleoperator during the dark portion of the shuttle orbit will be verified for the 500 ft circumnavigation maneuver as indicated in the shuttle orbit phase diagram of Figure 9.

4. Deploy

The objective of this activity is to demonstrate the deployment capability of the FFTO by deploying a satellite such as a bioresearch module (BRM). The capabilities within this activity which will be shown are the maneuverability and controllability of the FFTO and an attached payload.

The FFTO/BRM system will be maneuvered to a position 1000 ft out of the Shuttle's orbital plane as shown in Figure 11. Figure 12 illustrates the BRM. Operationally, this location is desirable to ensure that the plume of the Shuttle is directed away from the BRM when the Shuttle retrofires. Because

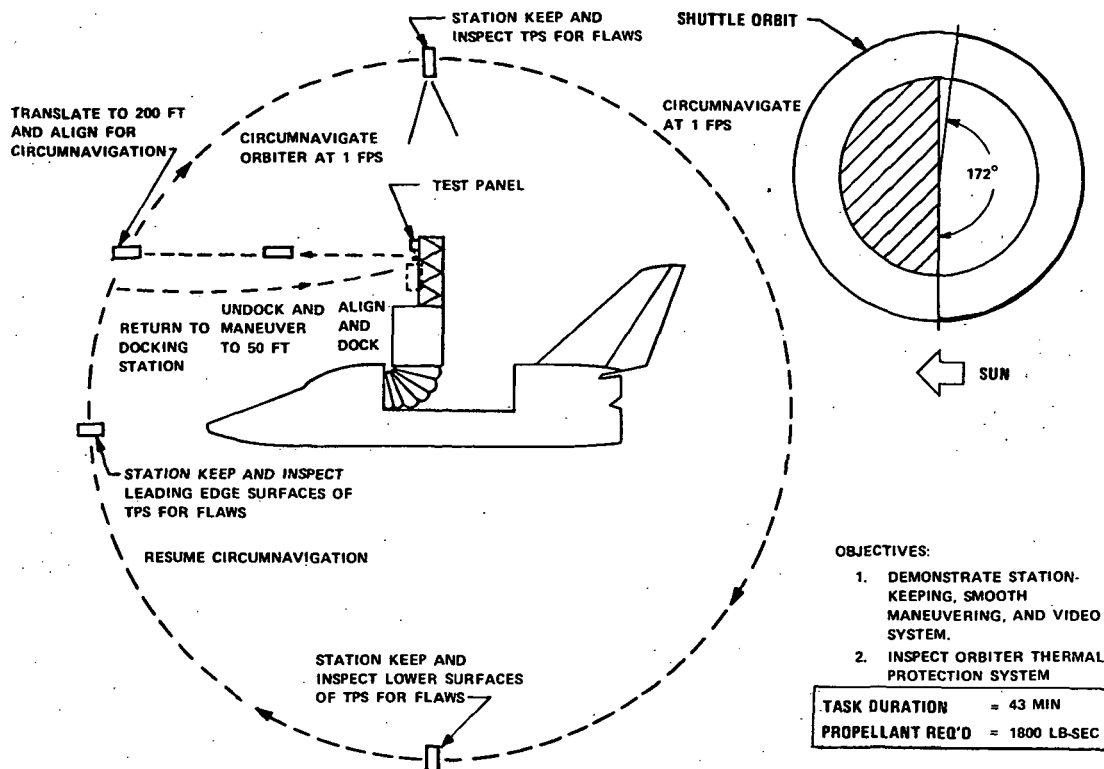


Figure 7. Monitor/Inspect

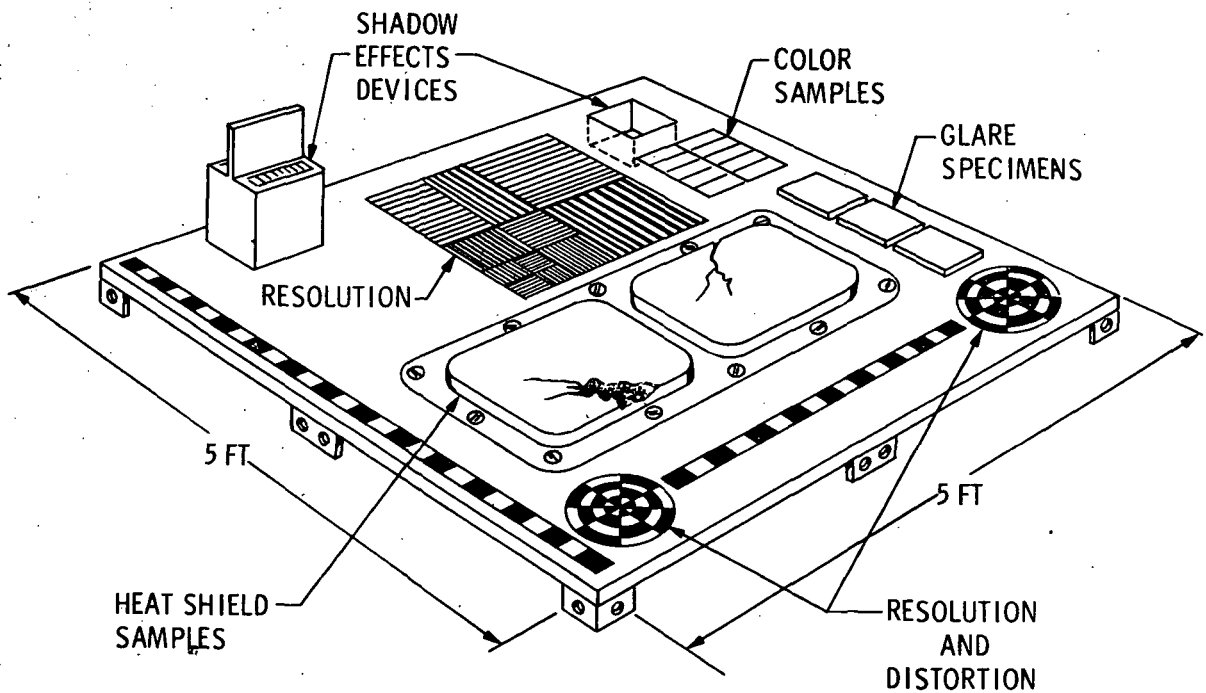


Figure 8. Inspection Panel

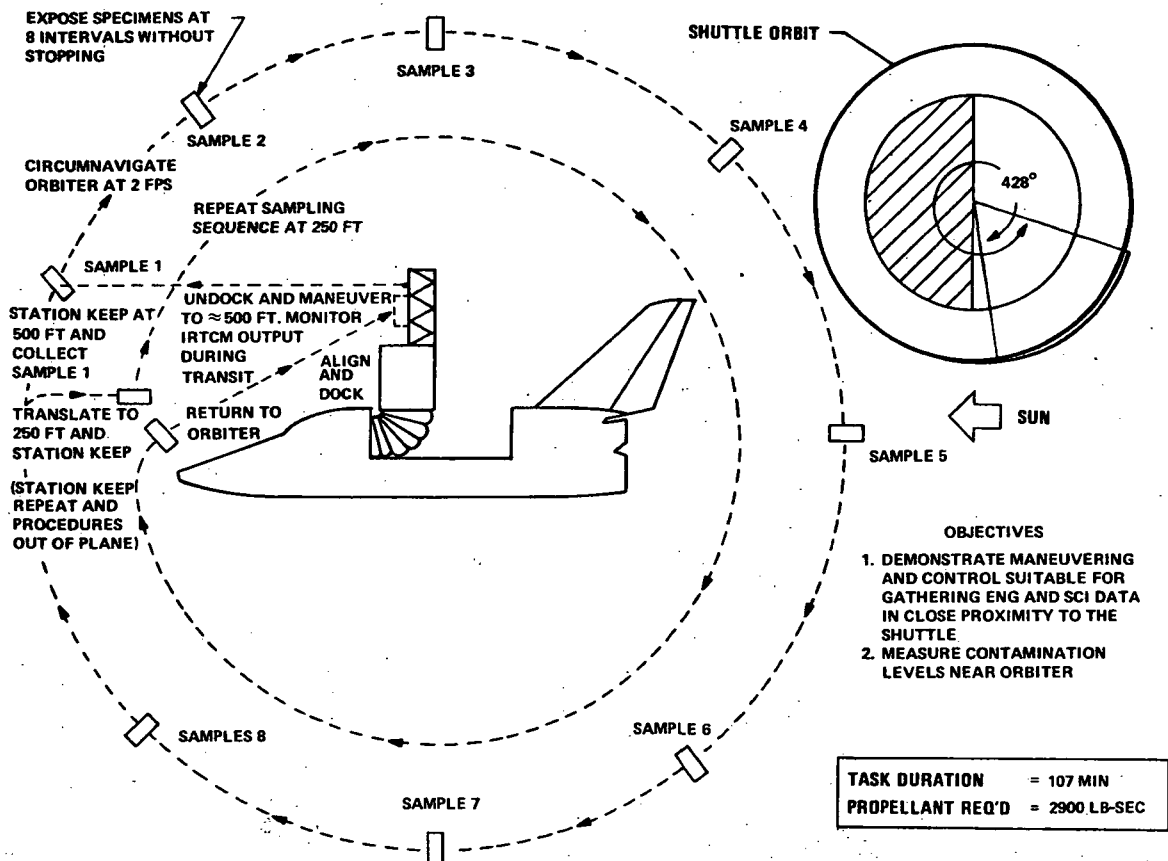


Figure 9. Experimental Data Acquisition

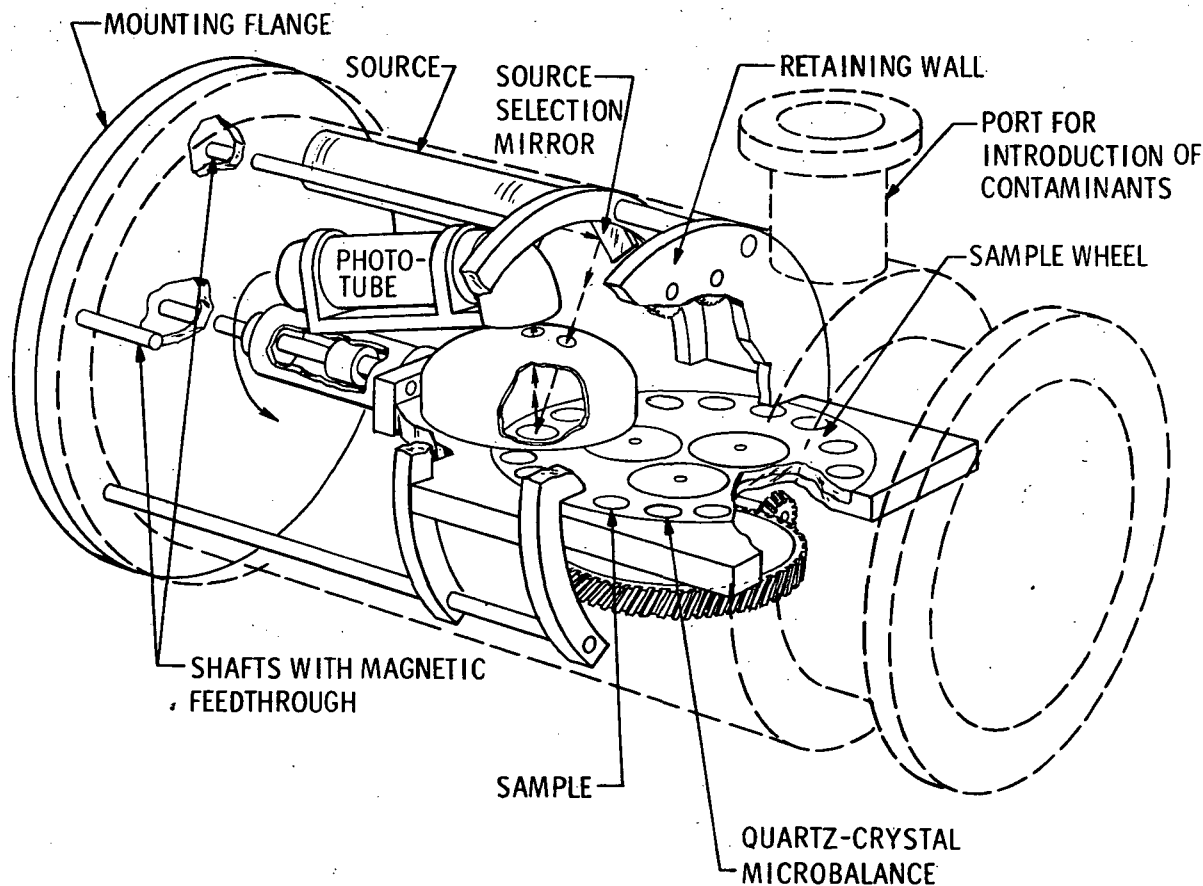


Figure 10. Integrated Real-Time Contamination Monitor (IRTCM)

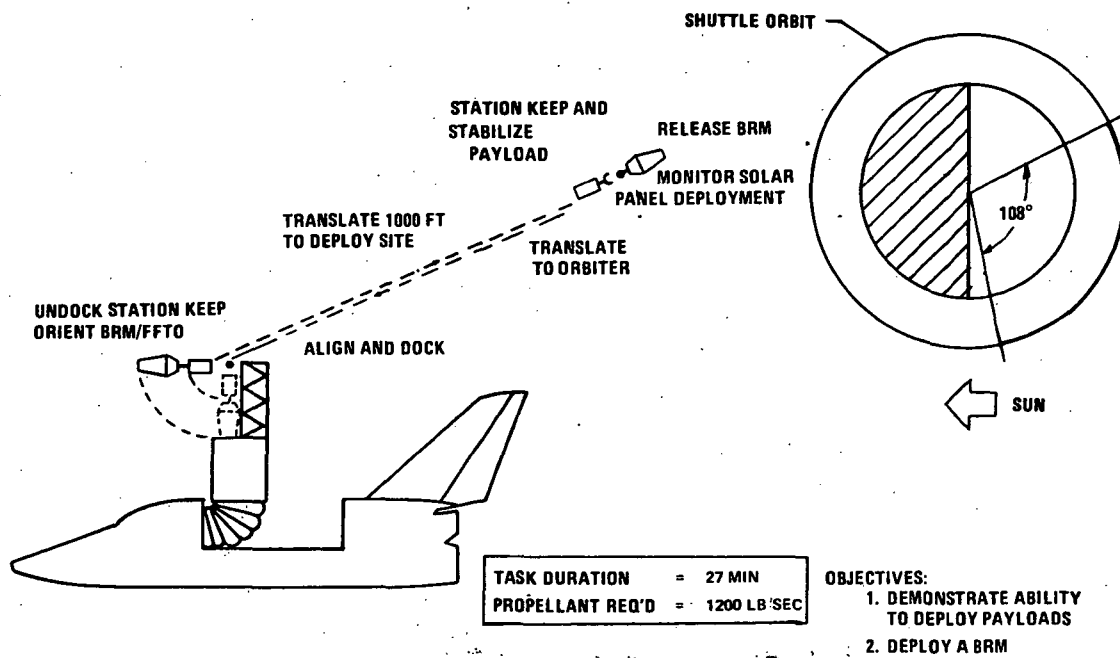


Figure 11. Deploy

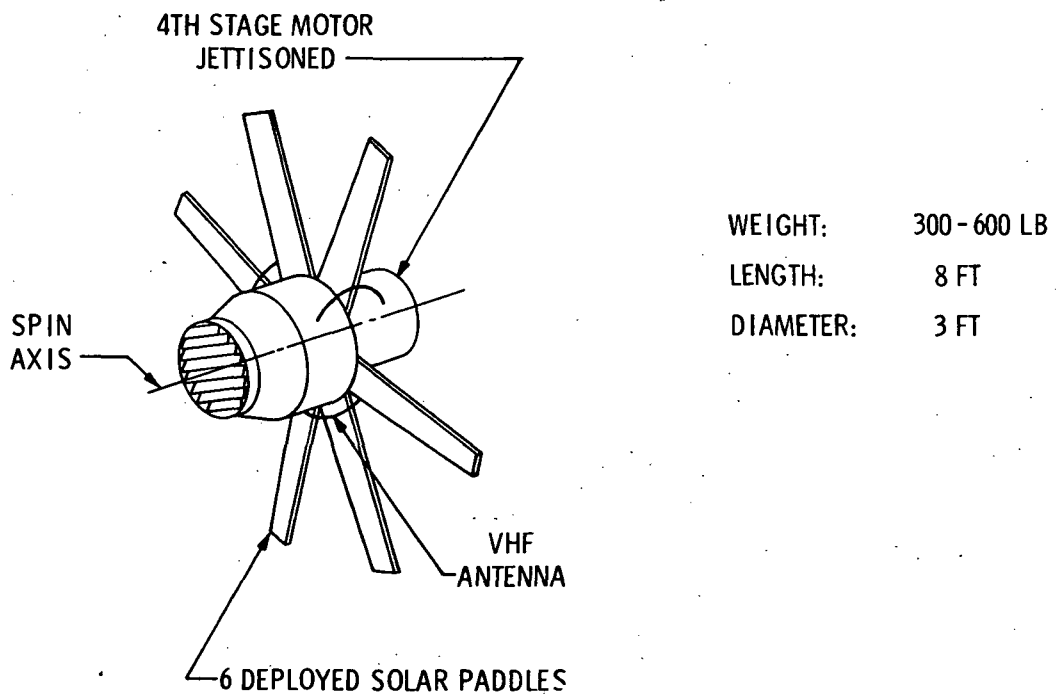


Figure 12. Bioresearch Module

the BRM is in a slightly higher orbit, there is no danger of collision between the BRM and the Shuttle due to the reduction of the Shuttle's velocity after retrofire. The teleoperator will point and stabilize the BRM with respect to the Shuttle orientation before releasing the BRM. After release, the teleoperator station-keeps near the BRM and measures BRM motions with respect to the Shuttle. The cameras also monitor the deployment of the solar panel before returning to the Shuttle. This activity requires 26.3 minutes and 1192 lb-sec of propellant.

5. Retrieve

The objective of this activity is to demonstrate the retrieval capability of the FFTO by retrieving a satellite such as a bioresearch module (BRM). The BRM to be retrieved could have modest dynamics (spin rate of 60 rpm). The capabilities within this activity which will be shown are:

- the motion matching and attachment capabilities of the FFTO with respect to the BRM, and
- the motion matching and docking capabilities of the FFTO/BRM with respect to the Shuttle.

The FFTO will leave the Shuttle and maneuver to the vicinity of the BRM where it will align itself with the spin axis of the BRM as shown in Figure 13. The grapple will then attach to the BRM and the FFTO will stabilize the payload. The combined FFTO/BRM is then flown to a position to dock with the Shuttle. The docking base pivots to position the BRM in its restraining cradle where it is latched for reentry.

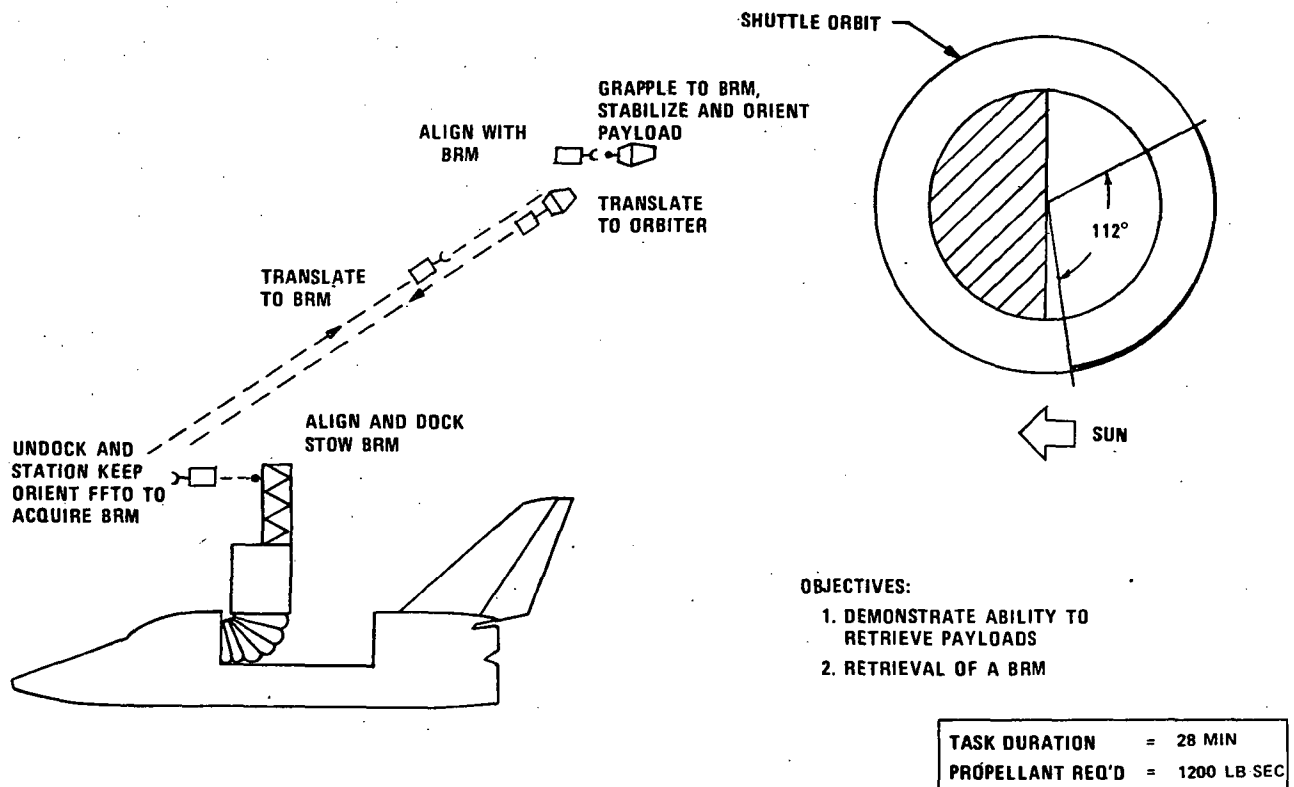


Figure 13. Retrieve

6. Satellite Service

The objective of the SATELLITE SERVICE activity is to show a capability for performing general servicing functions of a type representative of what would be required operationally. These were selected to be:

- module exchange,
- exchange of a film cartridge,
- connecting a fuel line having a quick-disconnect type fitting,
- measuring the contamination on a variety of surfaces, and
- cleaning surfaces.

Since the unique features of this activity relate to the manipulation functions, a taskboard mounted to the pallet is suitable for demonstrating the maintain capability as shown in Figure 14. The procedure is to undock the teleoperator and maneuver to the taskboard as shown in Figure 15. The teleoperator attaches to the taskboard and performs the selected maintenance tasks. After completion of the tasks, the teleoperator returns to the docking station and docks.

The taskboard shown in Figure 14 will provide a suitable worksite to demonstrate the SATELLITE SERVICING capabilities and includes:

- Standard spacecraft module with features to allow it to be removed with special purpose or general purpose manipulators – and by an astronaut.
- Indexing holes which will demonstrate versatility of controlling module exchange mechanisms.
- A film cartridge which represents the removal and replacement of a nonstandard unit.
- An active Cleaning Technique (ACT) unit to clean – decontaminate – spacecraft surfaces.
- A TO31 device to measure surface properties which will allow an assessment of the contamination to be made.
- Specimens of spacecraft surfaces, and
- A quick-disconnect fuel line.

A separate subtask of SATELLITE SERVICE is defined to demonstrate the capability of an FFTO with a manipulator module to remove a failed module from a standardized spacecraft and replace the module with one in operating condition.

As with the general maintenance subtasks, the unique features of module exchange relate to the manipulative functions; and so, a taskboard mounted to the pallet is again suitable for demonstrating the subtask. The procedure is to undock the teleoperator and maneuver to a rack containing the replacement modules and load these onto the FFTO as shown in Figure 16. The loaded FFTO then maneuvers to the taskboard and exchanges the modules; next, it returns the failed modules to the rack, maneuvers to the docking station – and docks. A functional sequence analysis showed that 49.5 minutes and 828 lb-sec of propellant are required to accomplish this activity.

7. Experiment Plan and Schedules

Earth based simulation will precede the on-orbit experiment by about two years and the first horizontal Shuttle flight by about one year as shown in Figure 17. This gives time to rewrite experiment procedures and modify the FFTO – as might be required – to accommodate the new procedures or new

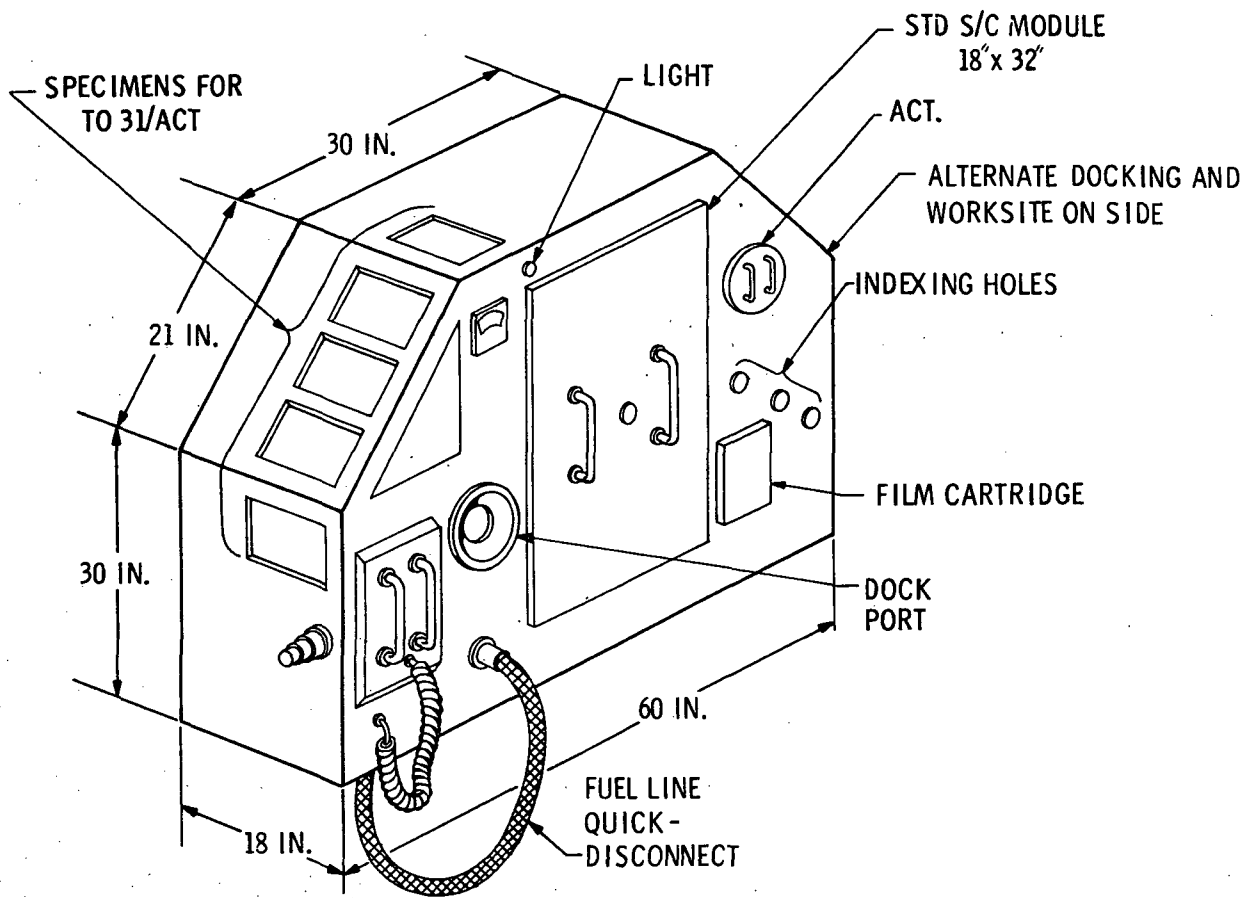


Figure 14. Taskboard Concept

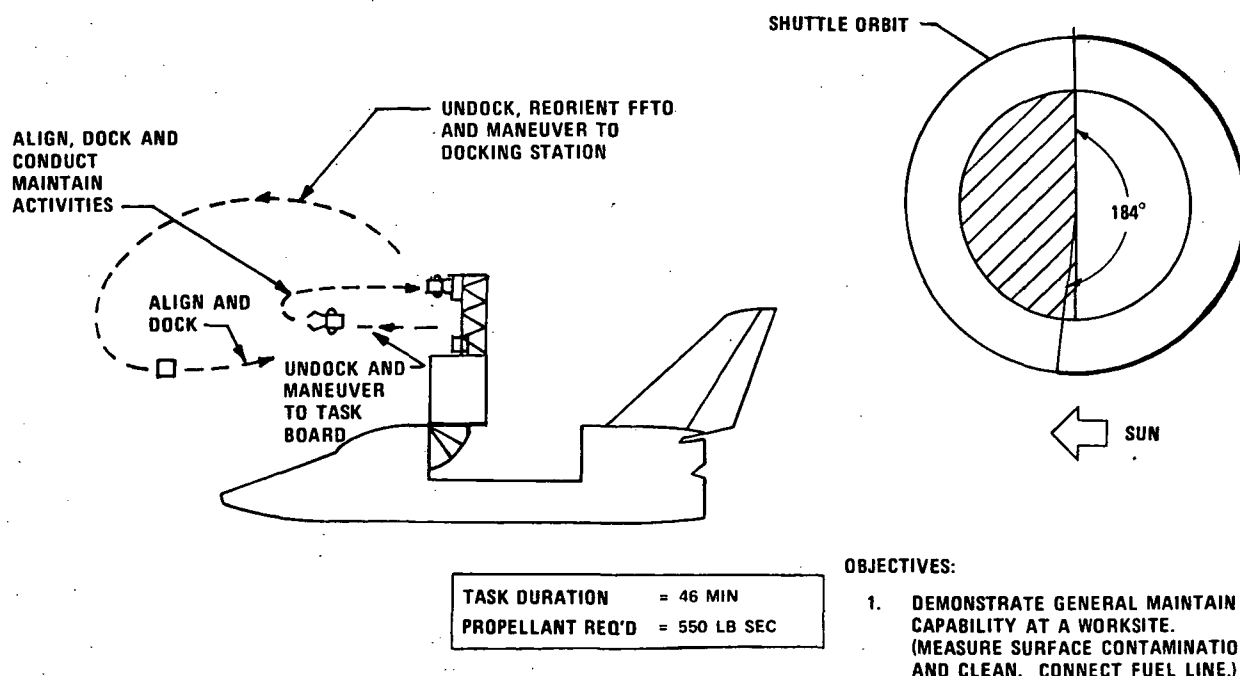


Figure 15. Satellite Service - Maintain Subtask

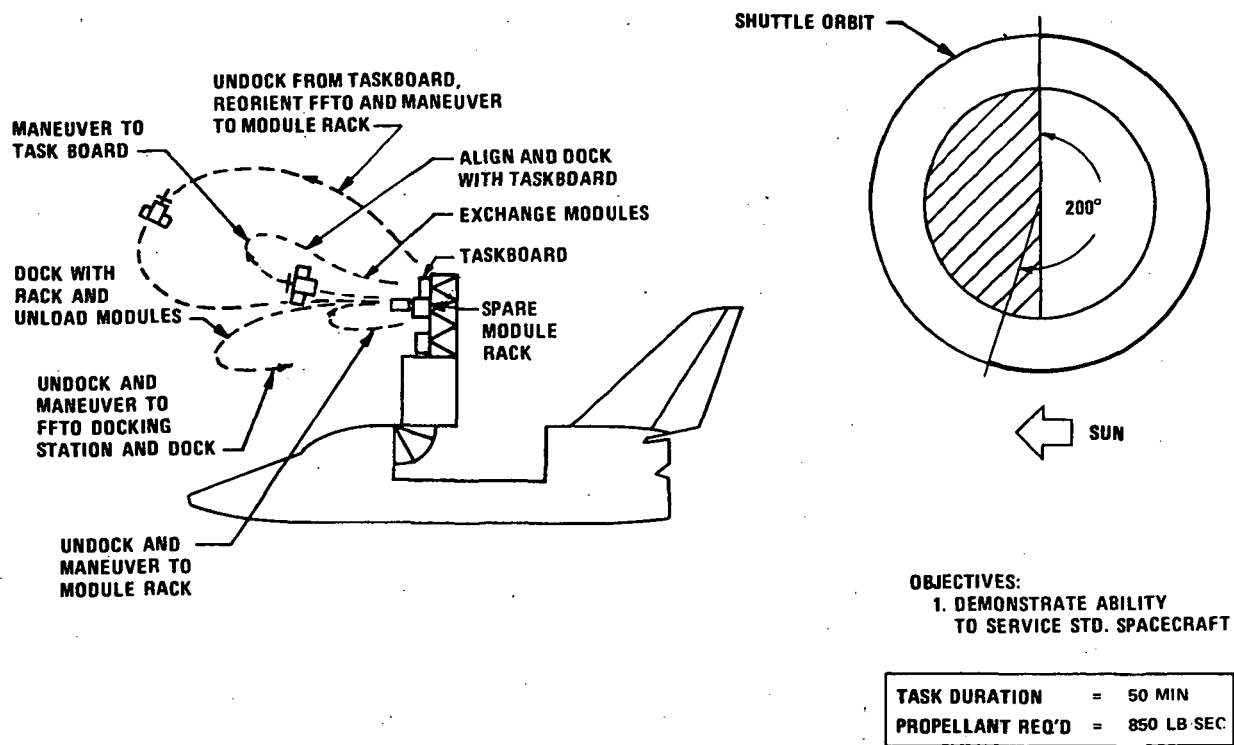


Figure 16. Satellite Service – Module Exchange Subtask

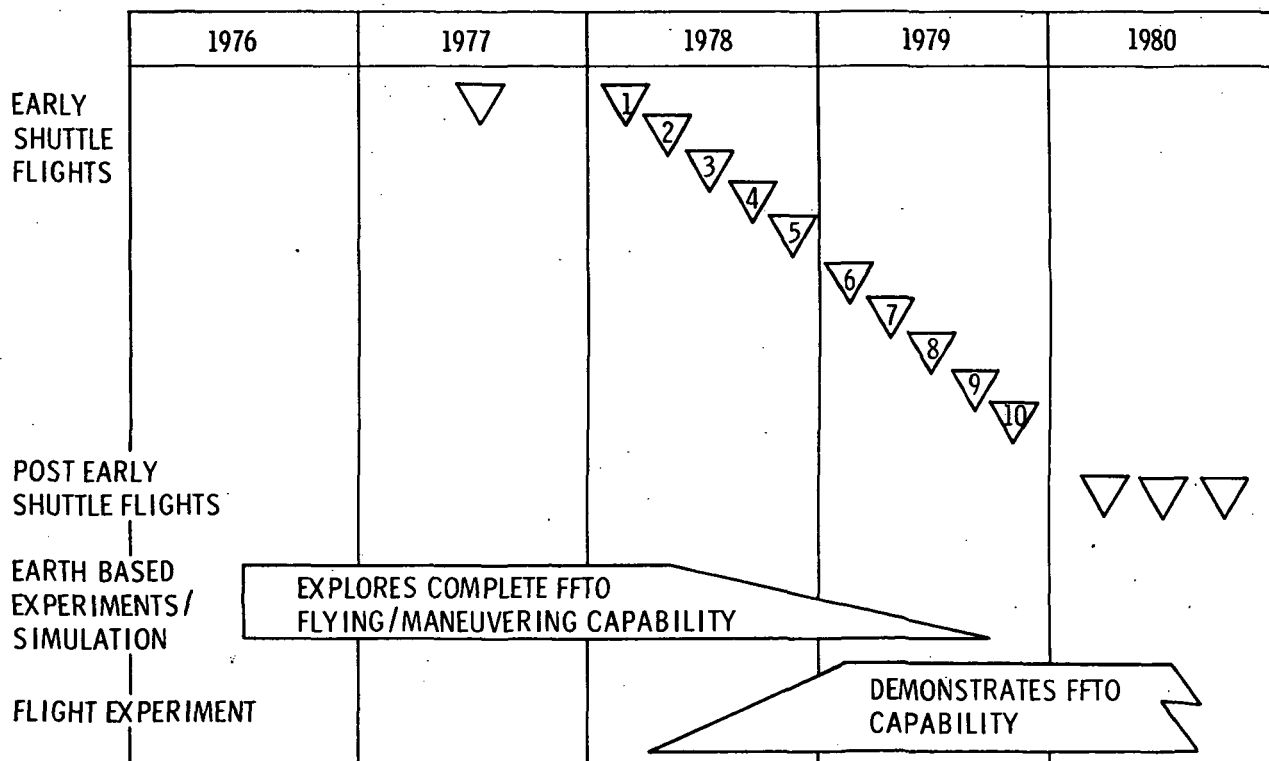


Figure 17. Flight Experiment Schedule

instrumentation and data requirements. It also gives time to generate the software required in terms of data processing or data handling. The flight experiment begins in early 1978 and proceeds into the 1980's when the SATELLITE SERVICING activities will be demonstrated.

8. Use of Experiment Results

Seven activities will be demonstrated in the teleoperator experiment to validate the FFTO design and to show its operational capability. The results gathered in the experiment will be in terms of engineering and operational data. These results will form a basis for design and redesign of the teleoperator, the Shuttle interface with the teleoperator, and Shuttle payloads. Further, they will be used to develop plans and procedures for teleoperator/Shuttle/payload operations. Finally, they will identify data gaps and limitations in performance capability which must be overcome.

B. CONCEPT DEFINITION AND EVALUATION

Seven system concepts were generated and evaluated. Of these one was selected as a baseline teleoperator for tailoring to meet the requirements of the flight experiment. The resulting concept is presented in Figure 18. To a large extent, the physical features are driven by the propellant tank arrangement and the docking cone.

The spacecraft occupies a volume of 48.5 in. x 36.8 in. x 32 in. excluding protuberances and weighs 401.6 lb. Table III presents a breakdown of the spacecraft weight according to subsystem.

TABLE III
FFTO SPACECRAFT WEIGHT SUMMARY

Guidance, Navigation and Control	57.8
Video	31.6
Communication	28.9
Structure	75.0
Electric Power	37.5
Manipulator/Grappler Module	25.0
Propulsion	
Empty and Residuals	72.6
Usable Propellant	73.2
Gross Weight	401.6 lb

1. Propulsion

Figure 19 shows the propulsion system schematic. Two 7500 lb-sec impulse capacity propellant tanks are centered about the nominal c.g. Hydrazine propellant is expelled through the top of one tank and the bottom of the other by metallic bellows using a blow-down pressurization system. A total of 16 thrusters provides pure moment and axial thrust capability. The thrusters are arranged in two banks to provide partial redundancy. At maximum tank pressure, the nominal thrust of each thruster is 5 lb. This reduces to 2.5 lb when the propellant is depleted.

2. Guidance, Navigation and Control

A functional block diagram of the Guidance, Navigation and Control System (GNCS) is presented in Figure 20. This system was selected from among four candidate concepts as being most suitable for the free-flying teleoperator experiment system.

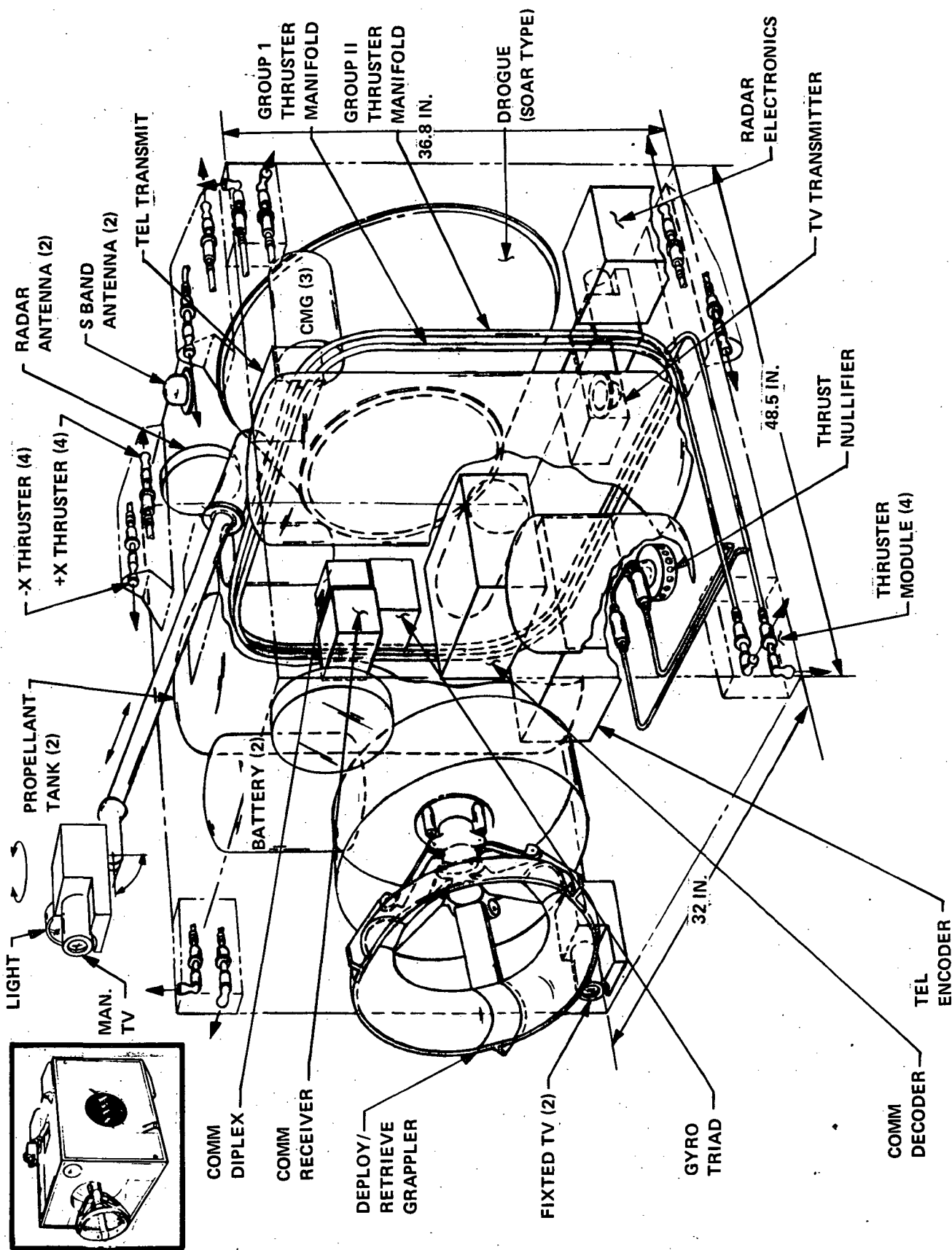
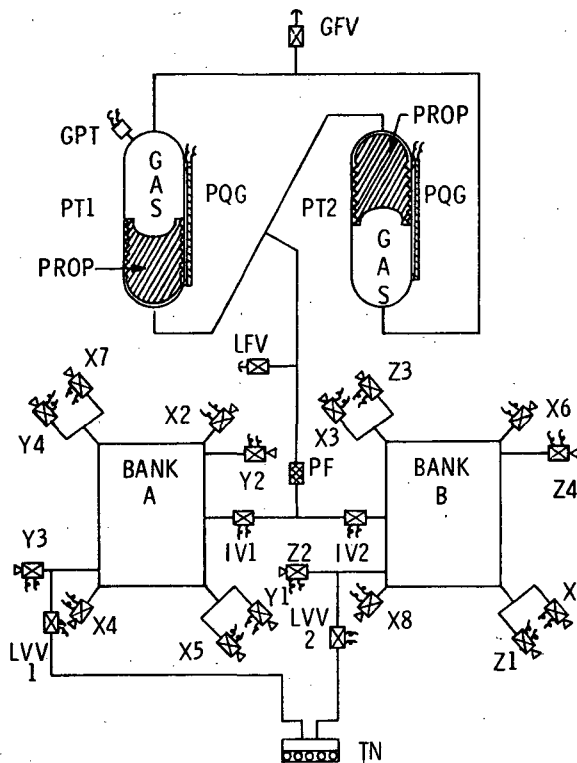


Figure 18. Experimental Teleoperator Spacecraft



TOTAL IMPULSE: 15,000 LB-SEC
 PROPELLANT: HYDRAZINE
 PRESSURIZATION: BLOWDOWN
 PROPELLANT ACQUISITION: METALLIC BELLOWS
 THRUST LEVEL: $T_{MAX} = 5 \text{ LB}$
 $T_{MIN} = 2.5 \text{ LB}$
 NUMBER OF THRUSTERS: 16

Figure 19. Propulsion System Characteristics

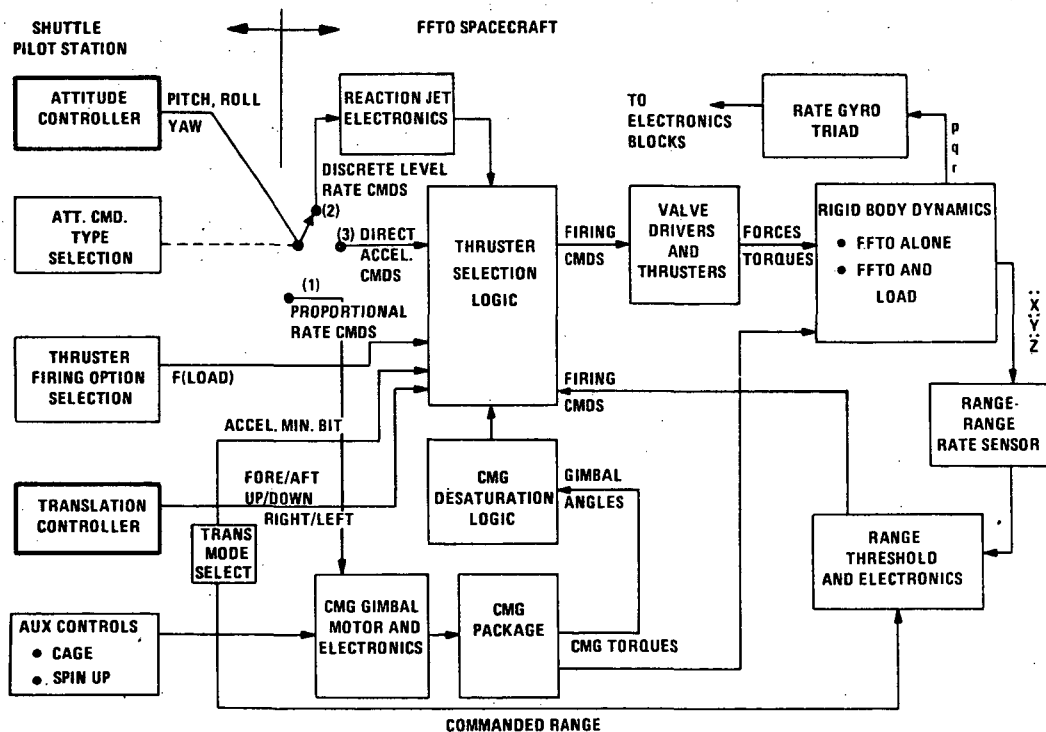


Figure 20. Overall Block Diagram of FFTO Attitude and Translational Control

The GNC concept employs a visual guidance method, using a TV camera to provide cues which allow navigation and guidance by a human operator. Range and range rate signals are also provided to aid in the guidance task. Translation is controlled by acceleration command inputs from the pilot. The attitude control system functions in a rate command mode with attitude hold about the latest commanded position. Control torques are generated by reaction jet thrusters located off the FFTO center of gravity.

At launch, the FFTO will be commanded to fly away from the launch boom and stationkeep momentarily with the Shuttle. This will give the FFTO operator a chance to get the "feel" of the controls and to determine the orientation of the FFTO with respect to the Shuttle. He will then command an open loop attitude maneuver about two axes in sequence, to acquire the target visually. With the target centered in the TV monitor, the operator will command X-thrust to establish the proper closing rate between the FFTO and the satellite. The closure rate will be controlled as a function of range.

Close-in trajectory control will be accomplished through cues obtained from the TV scene.

Translational motion normal to the LOS will be noted by a movement of the image away from the center of the monitor as well as a change in the aspect of the image (assuming the target to be stabilized). These motions will be reduced to zero by commanding Y or Z thrust as required.

Operator attitude command inputs are in the form of either discrete or variable angular rate commands in the pitch, roll and yaw axes. These telemetered command signals are combined with the body rate gyro outputs and provide thruster firing signals dependent on the threshold values and the thruster firing logic. In the absence of an operator command input, the rate gyro outputs are inputted to an integrator which develops incremental attitude angle control signals and fires the reaction jets so as to maintain the FFTO body attitude angles about the last commanded position.

3. Video

An investigation was conducted to determine the number of cameras and their arrangement for providing good viewing of the grapples operation as well as the navigation/guidance function. Figure 21 presents these arrangements. A three-camera system was selected to provide guidance redundancy and viewing flexibility. One camera is mounted on an extendable boom. The camera mount itself gives pan and tilt capability. The other two cameras are fixed, one on each end of the teleoperator. All cameras have zoom and focus features. The selected camera is being developed under the auspices of the Manned Spacecraft Center. Its major characteristics are:

Maximum Field of View	35° x 47°
Zoom Ratio	8:1
Frame Rate	30 per sec
Scanning Format	2:1 Interlace
Bandwidth	4.5 MHz
Weight	6.2 lb
Power	12 watts
Size	3.25 x 5.2 x 9.5 inches

Several video communication link systems were considered and are presented in Table IV. Separate dual channels, each with 5-MHz bandwidth, were selected to give redundant high quality television using standard equipment.

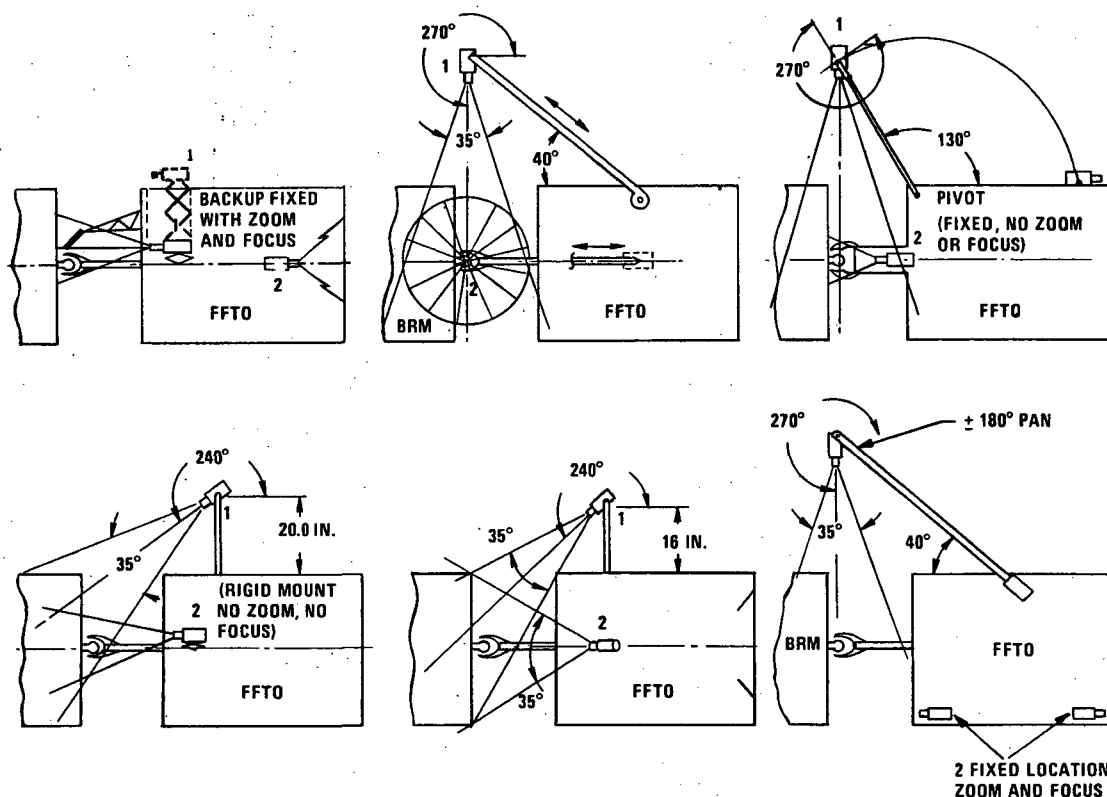


Figure 21. Video Camera Arrangement Geometry/Location/Maneuverability

TABLE IV
VIDEO COMMUNICATION LINK SYSTEMS

Link Types		Typical Major Parameters		Advantages	Disadvantages
1.	Extra Wide Band Dual Channel Video Data Link	Bandwidth	10 MHz	Dual TV in One Link Simultaneous Dual	Nonstandard equip. More difficult electronic No redundancy
2.	Separate Dual Channels, Wide Band Link	Bandwidth Ea.	5 MHz	Dual Equipment Redundant Links Standard Equipment	Greater weight total More total primary power
3.	Sequential Shared Wide Band Video Link	Bandwidth	5 MHz	Dual TV in One Link Standard Link Equip.	Lower frame rate per picture, flicker extra switching equip.
4.	Slow Frame Rate Median Bandwidth Video Link	Bandwidth	1.2 MHz	Minimum Weight Extended Range Potential	Scan conversion Required at receiver Limited motion response
		Power RF	6.0 watt		
		Weight	7 lb		
		Power RF	3.0 watt		
		Weight Total	10 lb		
		Power RF	3.0 watt		
		Weight Total	5 lb		
		Power RF	0.8 watt		
		Weight Total	4 lb		

4. Communications

An analysis of telemetered parameters, scale and resolution required resulted in the telemetry system characteristics shown in Table V. The analysis anticipated future needs as well as extensive monitoring of parameters required in an experimental program.

5. Manipulator/Grapppler

The free-flying teleoperator spacecraft design is arranged to accommodate any of a number of possible manipulator/grapppler module concepts through the use of a common interface. These have been categorized into two groups: (1) DEPLOY/RETRIEVE grapppler modules, and (2) Worksite manipulator modules. The applicable functions, activities and requirements spectrum for these modules is illustrated in Figure 22.

The sketch in the upper lefthand corner of Figure 23 illustrates a technique for accommodating attachment to a nutating/spinning satellite. In this approach, arm spin and arm rotation are provided to synchronize the motion of the terminal grasping effector (in this case, the baseline grapppler design) with the satellite motion. A similar alternative approach is to let the spin and rotation joints be "free wheeling" so that the arm "takes on" the motion of the satellite. A torque limiting clutch at the spin and rotation joints is then actuated to "harden" the attachment of the FFTO spacecraft to the spinning/rotating satellite for subsequent despin and detumble action. The purpose of either approach is to slow the attachment process and reduce the attachment loads to an acceptable level.

In many instances spin/nutation accommodation will not be needed, and so only the terminal grasping effectors are illustrated in the remaining concepts. It is assumed that, if needed, a suitable spin/nutation mechanism can be applied to any of the grasping effector concepts illustrated.

Figure 24 illustrates a number of concepts which have been devised for performing the worksite manipulation function once the FFTO has been attached to the satellite to be serviced by an appropriate docking device or one of the techniques illustrated in the previous charts. The figure illustrates a variety of working arms which incorporate joints and motors for multiple degrees of freedom.

Also illustrated is an extension type manipulator arm which eliminates the elbow joint. It incorporates shoulder roll and pitch, arm linear extension, wrist pitch and roll and finger grasping action. A rectilinear x-y-z motion manipulator is also illustrated which may lend itself to versatility with a relatively simple control device. A manipulator that was designed specifically for automatic removal/replacement of standardized spacecraft modules is also illustrated. The modules would be specifically designed to mate or interface with this mechanism.

Figure 25 illustrates a DEPLOY/RETRIEVE grapppler module concept which was defined in more detail for deployment and retrieval of a BRM. The three fingers grasp a ball suitably located on the BRM. This is done by using three links driven by a common sliding ring. The mechanism is "free wheeling" to accommodate BRM spin. After finger attachment the unit is braked at a predetermined torque level below the capacity of the FFTO attitude control system.

6. Control Station

A general arrangement of the display and control console is shown in Figure 26. This arrangement resulted from an analysis conducted to define the sequence of activities required by the operator during each of the planned experiment tasks. A preliminary selection of CONTROL/DISPLAY hardware concepts from among alternatives was made by considering human factors, weight, volume, space qualification and cost. A "fome-core" mockup of the preliminary design was constructed. Figure 27 presents photograph of the mockup.

TABLE V
TELEMETRY SYSTEM CHARACTERISTICS

SYSTEM MODULATION FORM	PCM/NRZ LEVEL
NUMBER OF ANALOG/DIGITAL CHANNELS	112
NO. OF SPARE CHANNELS (INCLUDED IN TOTAL)	14
MAXIMUM WORD LENGTH (ONE ANALOG/DIGITAL CHANNEL)	12 BITS
NUMBER OF DISCRETE (ON-OFF) CONTROL FUNCTIONS	64
MESSAGE FRAME LENGTH	128 BITS
MESSAGE FORMAT:	
SYNCHRONIZATION (FORWARD AND INVERSE 11 BIT BARKER CODE)	22 BITS
ADDRESS (8 POSSIBLE TERMINALS)	3 BITS
LABEL (8 POSSIBLE MESSAGE TYPES)	3 BITS
INFORMATION CHANNELS, UP TO 7 ANALOG OR 7 DIGITAL CHANNELS OF 12 BITS EACH OR A LARGER NUMBER OF LESSER BIT CHANNELS	84 BITS
DISCRETE FUNCTION GROUP	8 BITS
PARITY ERROR CHECKS (ONE FOR EACH 16 BIT SECTOR OF THE MESSAGE)	7 BITS
END OF MESSAGE SIGNAL	1 BIT
MESSAGE RATE PER SECOND	30
BIT RATE (FOR PROJECTED DATA REQUIREMENTS)	3840 BITS/SEC
BANDWIDTH, INFORMATION, TOTAL	12,000 kHz
MODULATION, RF LINK	FM-FSK
DEVIATION FOR BINARY "ONES AND ZEROS"	±20 kHz
SELECTED FREQUENCY BAND (FOR MIN. WEIGHT)	250 to 300 MHz
ALTERNATE FREQUENCY BAND (FOR SPACE BAND)	2000 to 2300 MHz
RF POWER AT SELECTED FREQUENCY	0.1 WATT
PRIMARY POWER FOR TELEMETRY SYSTEM	6.0 WATTS
ANTENNA TYPE AT 280 MHz NOMINAL	TURNSTILE, CROSSED DIPOLE
ANTENNA SIZE, MAXIMUM ELEMENT SPAN	18 INCHES
EQUIPMENT WEIGHT TOTAL	9.5 LB
INCLUDES 2 ANTENNAS, SWITCH, POWER CONVERTER, TRANSMITTER, SIGNAL CONDITIONER, MULTIPLEXER, A TOD CONVERTER AND SAMPLE HOLD	

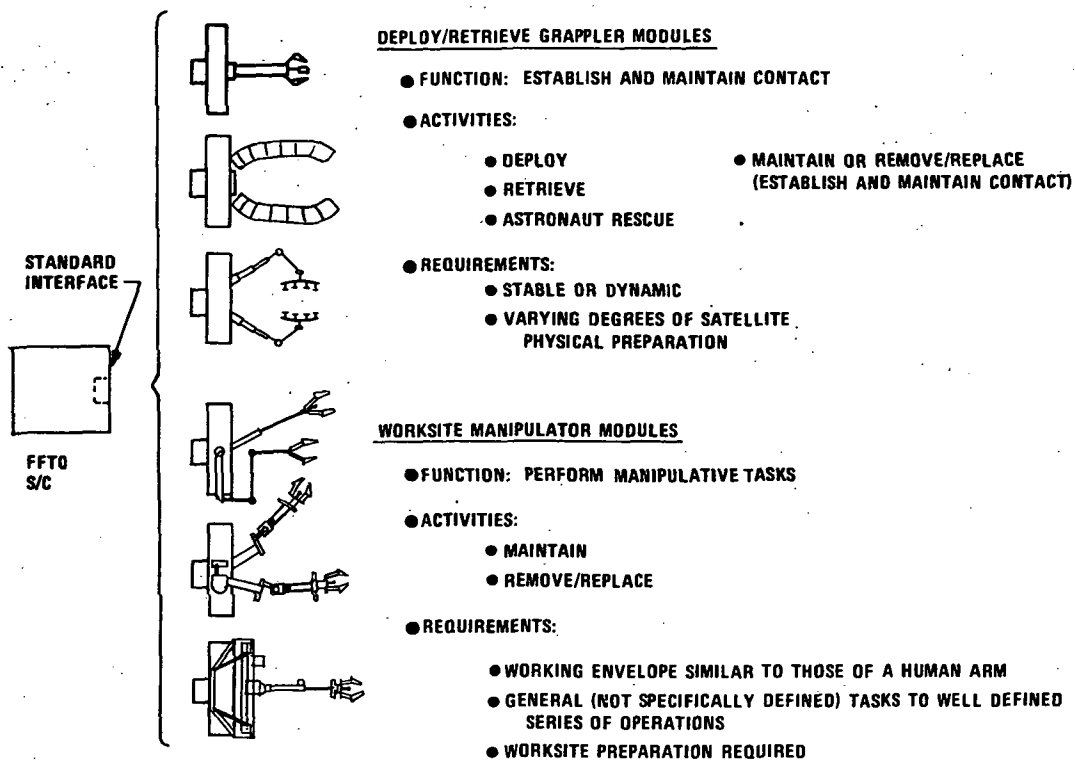


Figure 22. Manipulator/Grappler Module Concepts

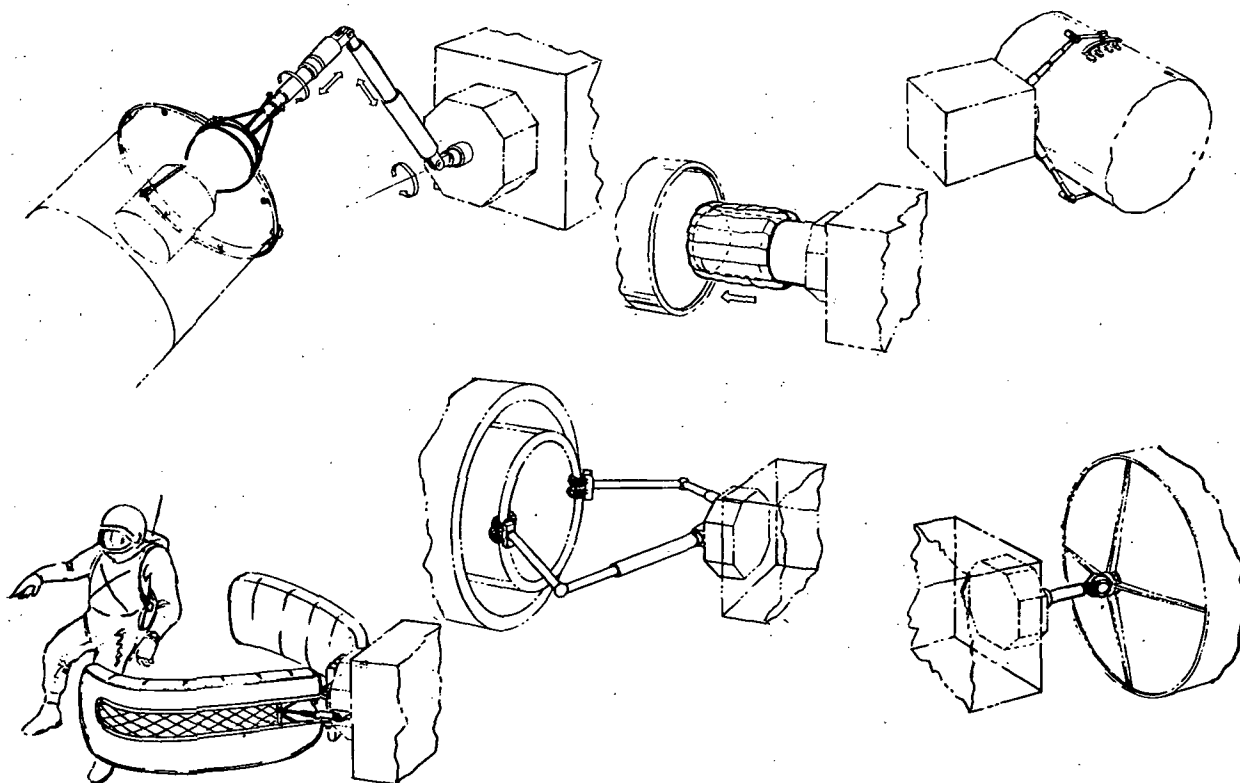


Figure 23. Deploy/Retrieve Grappler Module Concepts

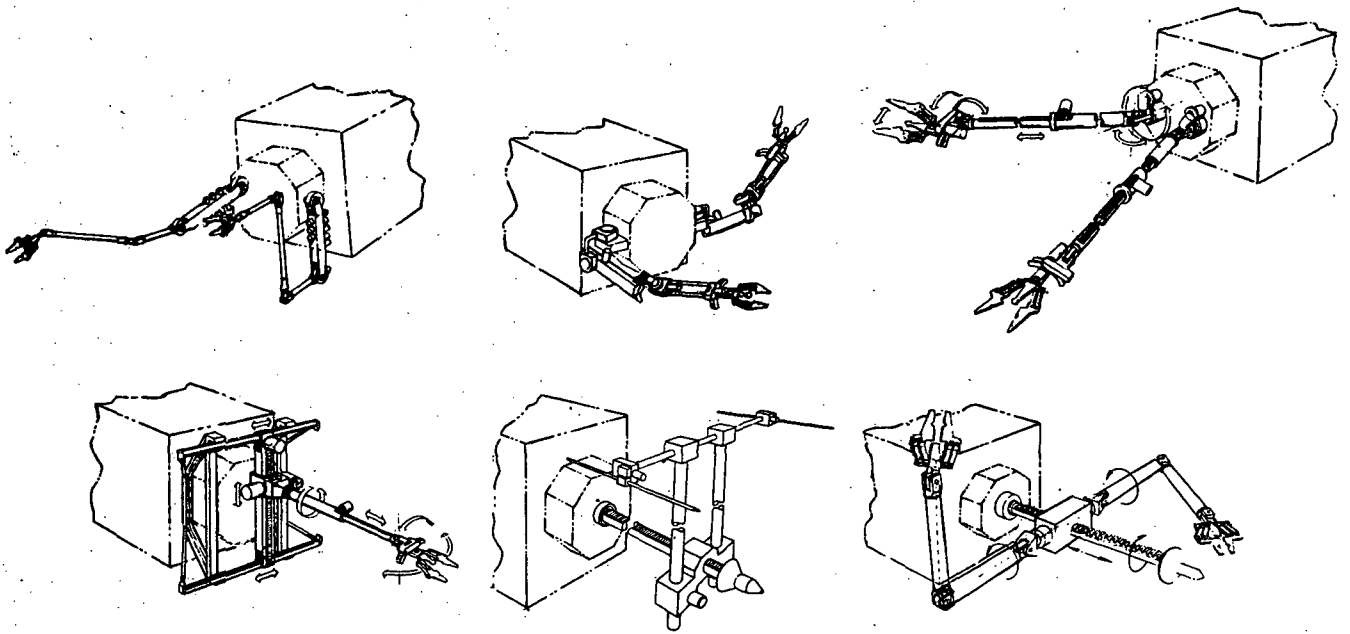


Figure 24. Worksite Manipulator Module Concepts

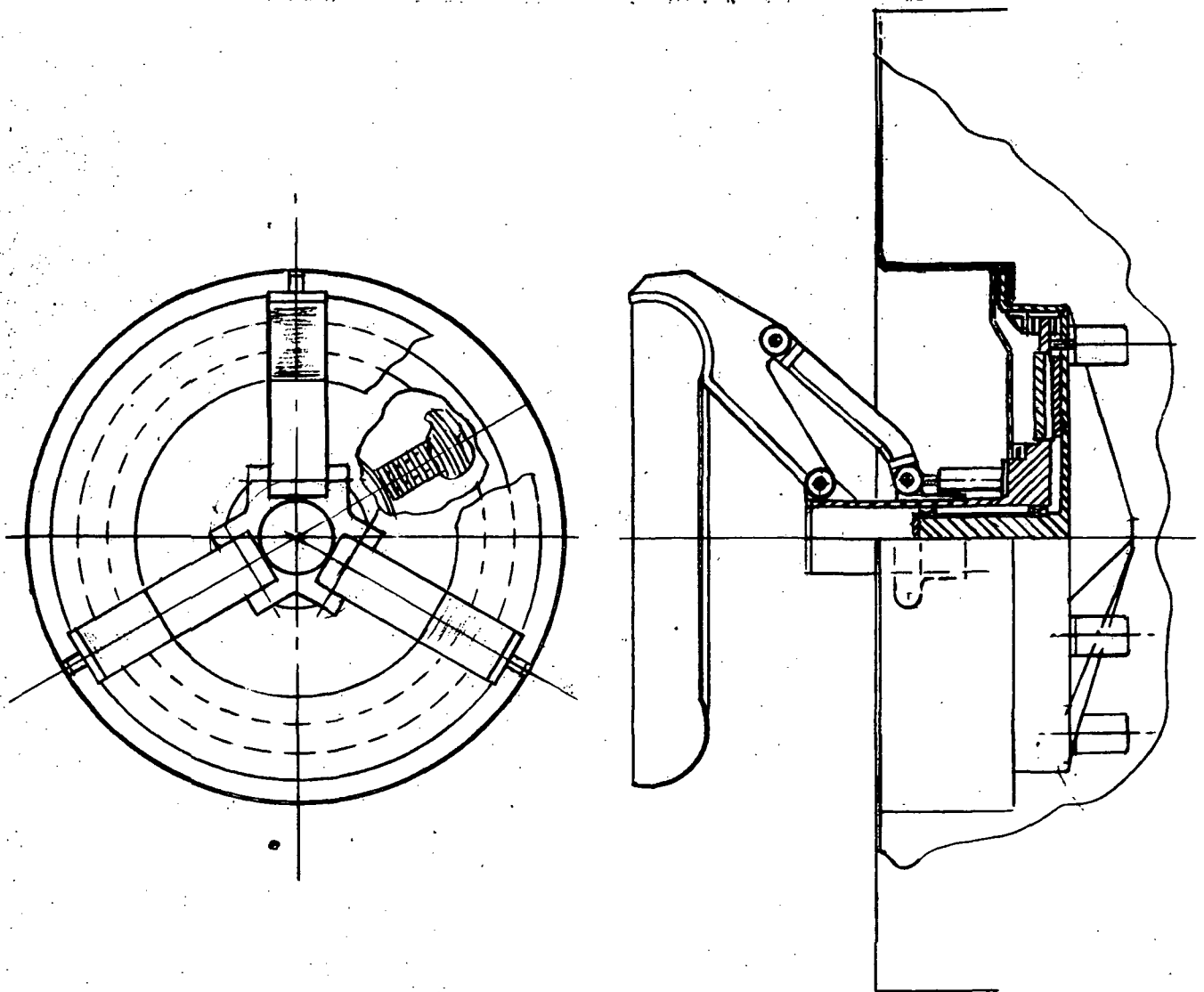


Figure 25. Early-Experiment Deploy/Retrieve Grappler Module

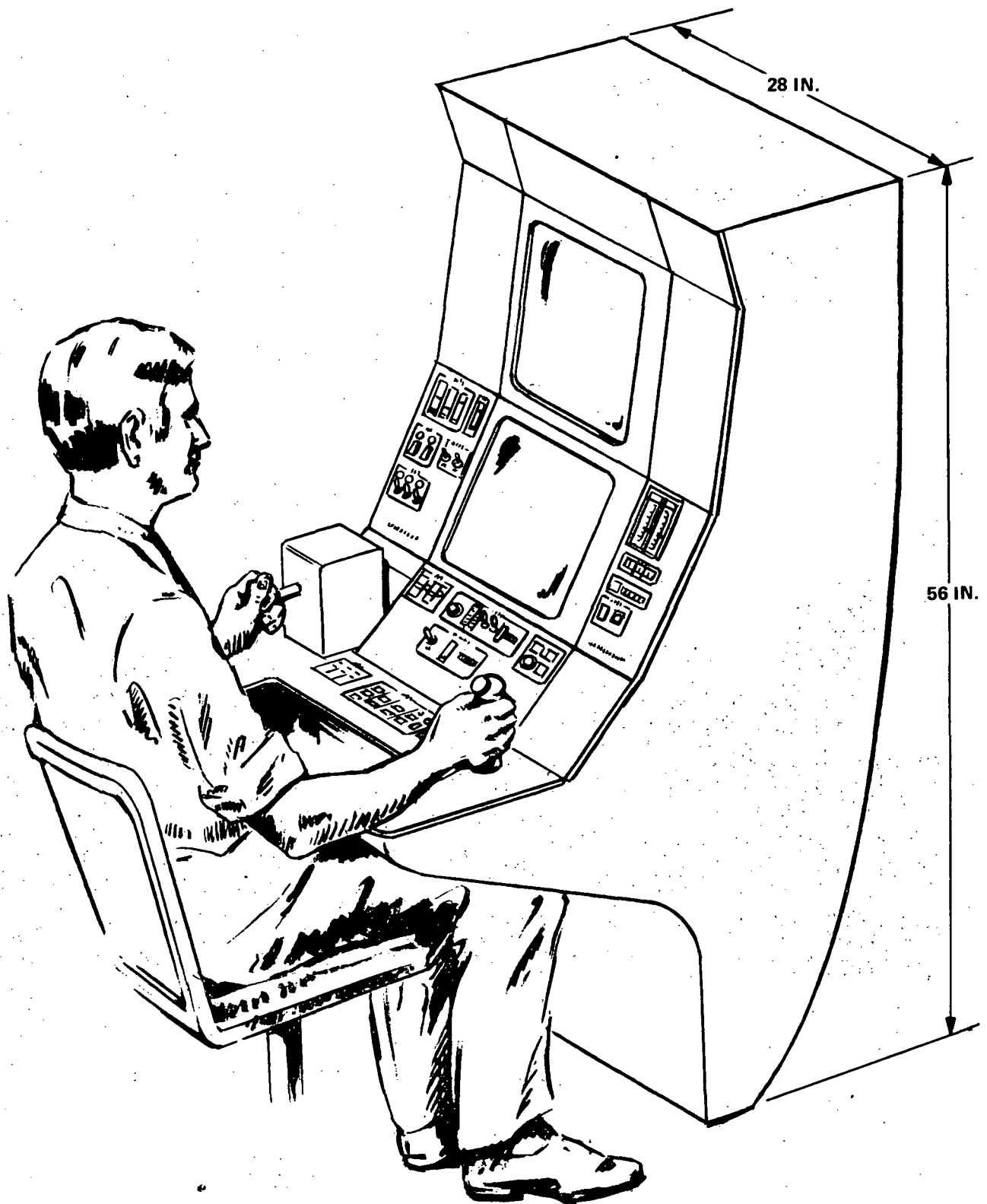
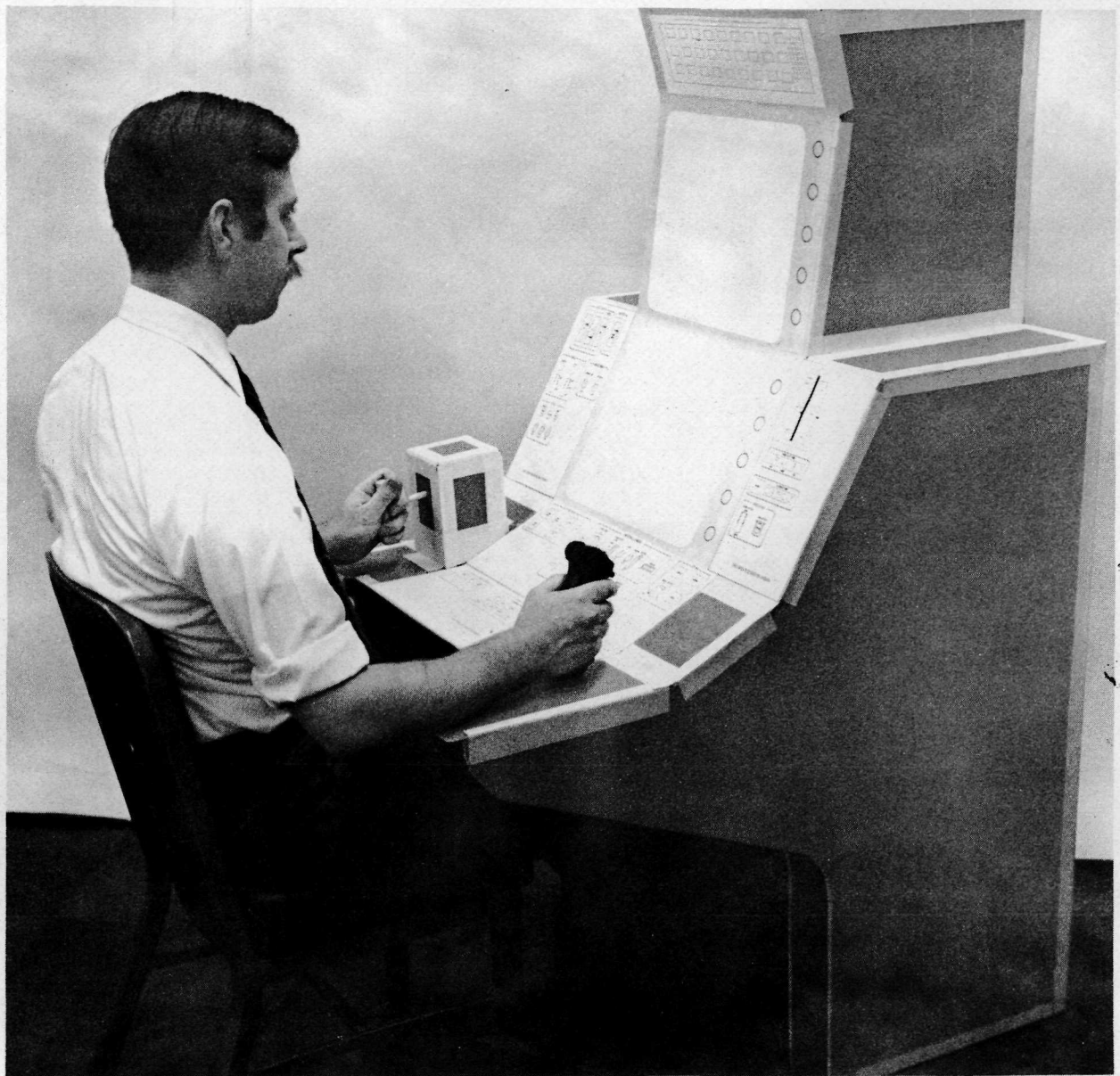


Figure 26. Display and Control Station General Arrangement



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Figure 27. Display and Control Station "Fome-Core" Mockup

A discontinuous task analysis was used to analyze operator performance requirements to assure that no work overloads were evident and to aid in the determination of a more nearly optimum console layout.

The final panel configuration is shown in Figure 28. Status displays and flight parameter displays border two television monitors. Primary power switches and various controls are suitably located for easy reach and proper handedness. Standard Apollo attitude and translation controllers are located on the right and left hand side of the console.

7. Teleoperator System Equipment Summary

Table VI lists the complete FFTO system elements, their weights and power penalty to the Shuttle.

TABLE VI
FFTO SYSTEM EQUIPMENT SUMMARY

System Element	Weight) (lb)	Shuttle Required Power (watts)	Shuttle Location
Teleoperator Spacecraft	402	—	Pallet
Control and Display System	106	266	Sortie Can
Dock/Deploy System	100	244	Pallet
Tie-Down Frame	20	—	Pallet
Communications Support	54	28	Sortie Can/Shuttle
Electrical Support	10	80	Pallet
Data Recording Equipment	288	151	Sortie Can
Totals	980	769	

C. PROJECT PLANS

This subsection summarizes the planning data for subsequent phases of a FFTO program and includes costs, schedules and supporting research and technology activities required to implement the free-flying teleoperator system and associated flight equipment.

The planning data describes two major program phases consisting of activities and events scheduled so as to effect integrated design, development, fabrication and operation of an FFTO system. Phase B, System Definition, will include preliminary design and supporting analysis of the FFTO, the Shuttle based equipment and ground support equipment. Phase C/D, Design, Development and Operations will include detail design of the operational FFTO, its integration into the Space Shuttle, hardware fabrication and testing, delivery of flight hardware and support of flight operations.

Emphasis is placed on the planning for Phases A and B so that it may be implemented immediately subsequent to the completion of the preliminary analysis phase. Phase C/D planning is more general and subject to refinement during the definition phase. The overall program is compatible with the Space Shuttle schedule — that is the experimental teleoperator system will be available by the end of 1977.

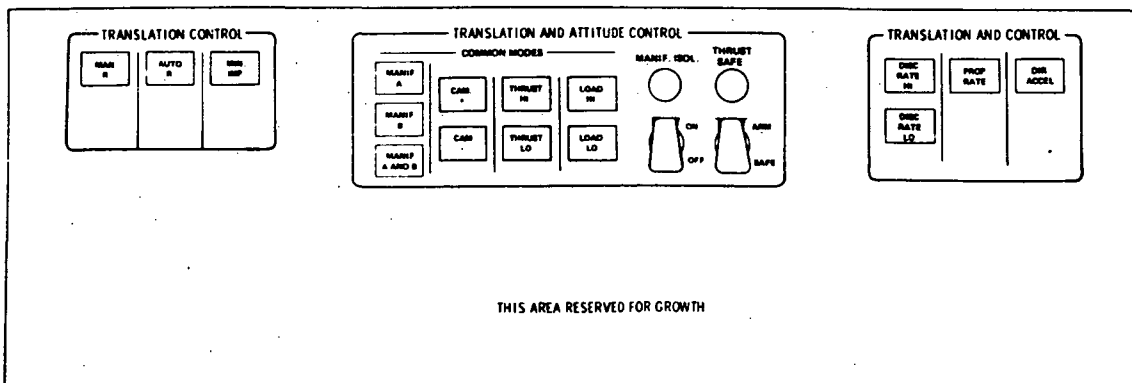
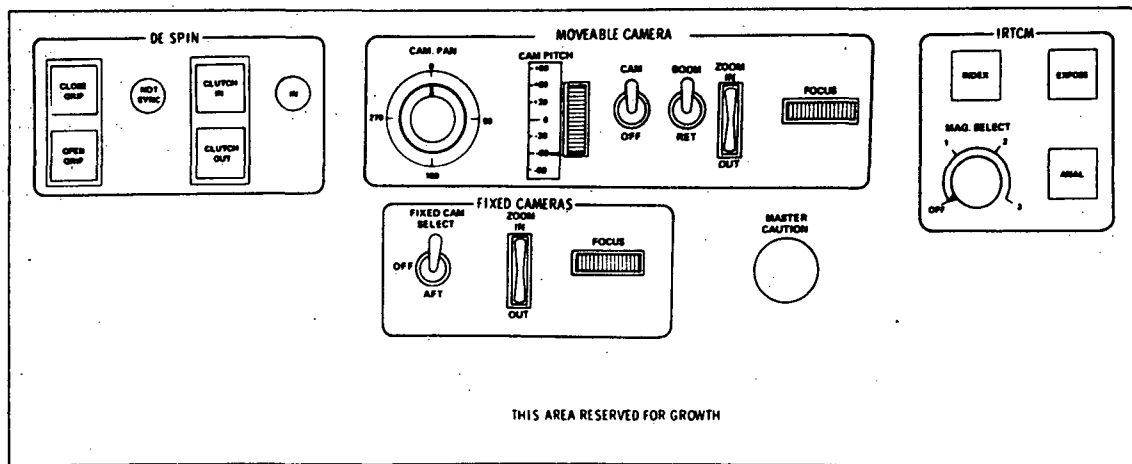
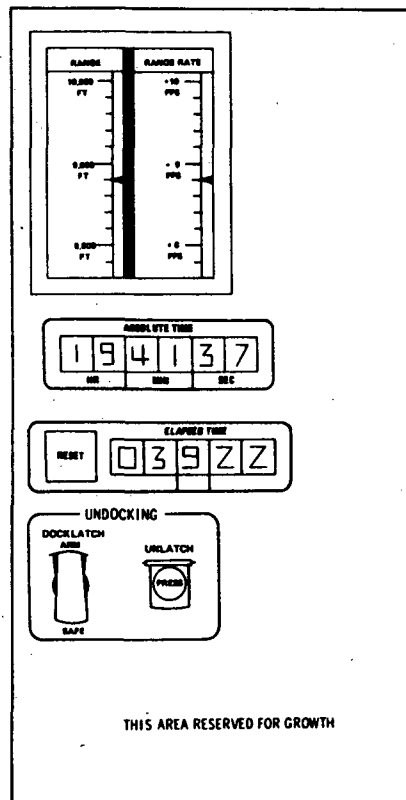
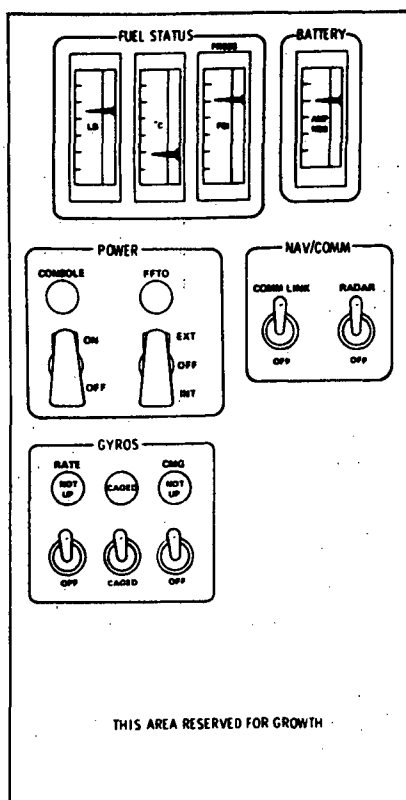


Figure 28. Display Arrangement

1. Schedule Summary

a. Phase A

Phase A is a six month study emphasizing FFTO concept generation and evaluation. Figure 29 shows the study schedule and the major activities. Table VII shows the cost summary for the Phase A effort.

b. Phase B

Phase B is planned as a 12-month program consisting of:

- System Engineering and Preliminary Design,
- Development of System Test Requirements,
- Preparation of Specifications,
- Preparation of Phase C/D Development Plan,
- Design and Fabrication of Mockups,
- Preparation of Contractual Documents.

c. Phase C/D

Phase C/D is tentatively planned as a program which, until delivery of the first flight system, will encompass 39 months. It will consist of:

- Design
- Development
- Qualification
- Fabrication of Flight Systems
- Training
- Operational Support

The overall schedules for the accomplishment of these two phases are illustrated in Figures 30 and 31. The output of Phase B will be:

- A preliminary design of all elements of the teleoperator experimental system,
- A set of system and subsystem specifications,
- A plan for the subsequent phase of the program,
- A soft mockup of the system.

To integrate the system into the shuttle in 1977, Phase A must begin early in 1973 and be followed immediately by Phase B. Furthermore, the key technology programs required must be initiated soon so that the results of such programs are available during the Phase B and C/D efforts.

Phase B and Phase C/D costs are summarized in Tables VIII and IX. Since emphasis in the planning effort has been placed on Phase B the cost indicated for this phase is reasonably accurate.

The cost for Phase C/D is a Rough Order of Magnitude (ROM) cost intended only as an initial planning figure.

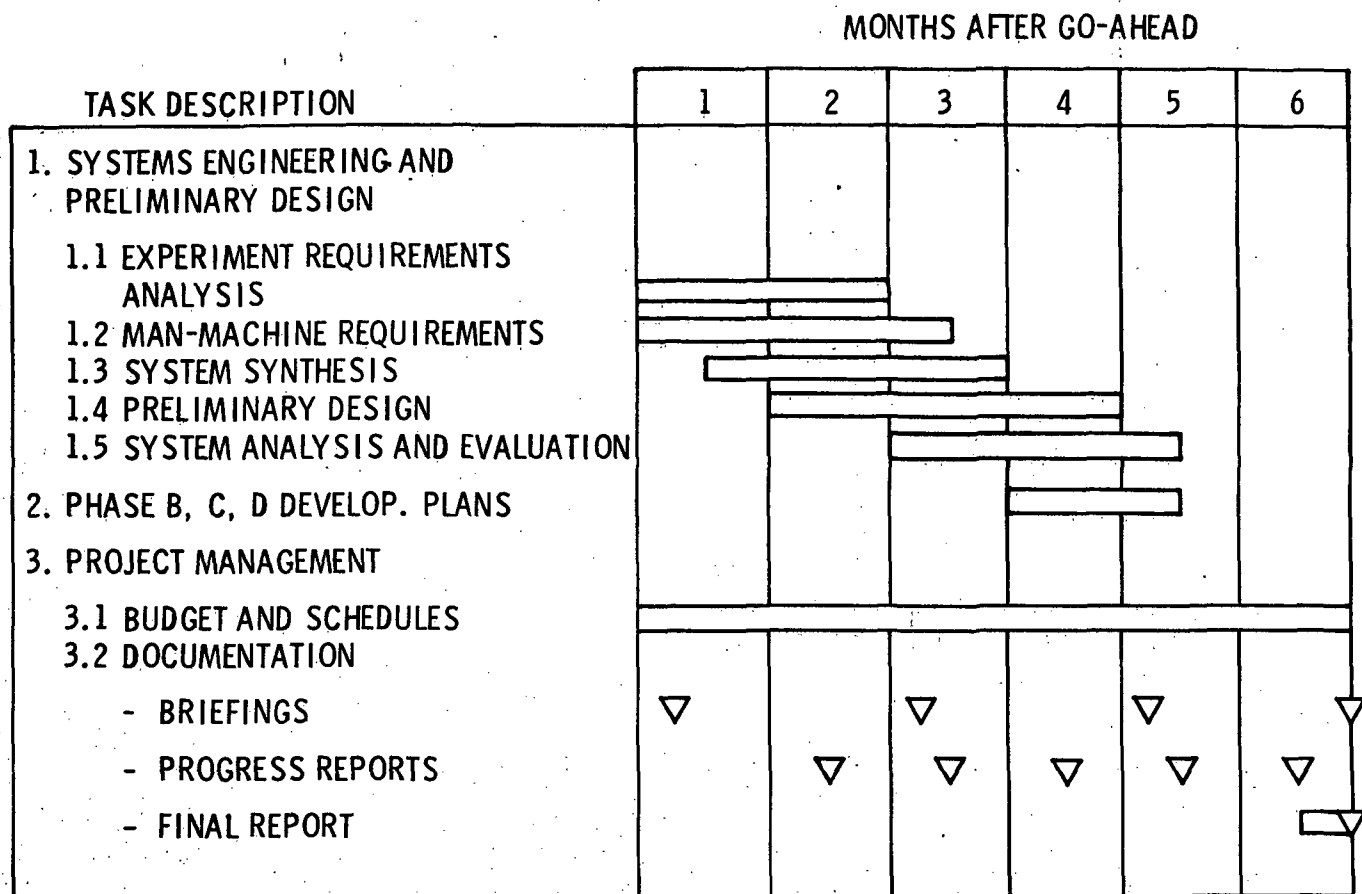


Figure 29. Summary Schedule, Phase A

TABLE VII
FFTO PHASE A COST SUMMARY

Phase A Task	Expect. Cost
Program Mgmt, Administration and Documentation	\$ 33,000
Systems Engineering and Preliminary Design	82,000
Phase B, C/D Development Plans	10,000
Total Program	\$125,000

TABLE VIII
FFTO PHASE B COST SUMMARY

Phase B Task	Expect. Cost
Program Mgmt, Administration and Documentation	\$ 117,262
System Engineering and Preliminary Design	384,570
System Test Requirements	15,015
Specifications	7,016
Phase C/D Develop. Plans	86,052
Mock-Up	32,915
Total Program	\$ 642,830

TABLE IX
FFTO PHASE C/D COST SUMMARY

Identification Number	WBS Identification	Expect. Cost
01-001-01	Project Management and Documentation	\$ 4,697,000
01-001-02	System Engineering of Preliminary Design	6,593,000
01-001-03	Teleoperator Spacecraft	3,093,000
01-001-04	Shuttle Based Equipment	1,819,000
01-001-05	Test Articles and Eval.	11,338,000
01-001-06	Ground Support Equipment	653,000
01-001-07	Mission Operations	1,275,000
	Total Program	\$29,468,000

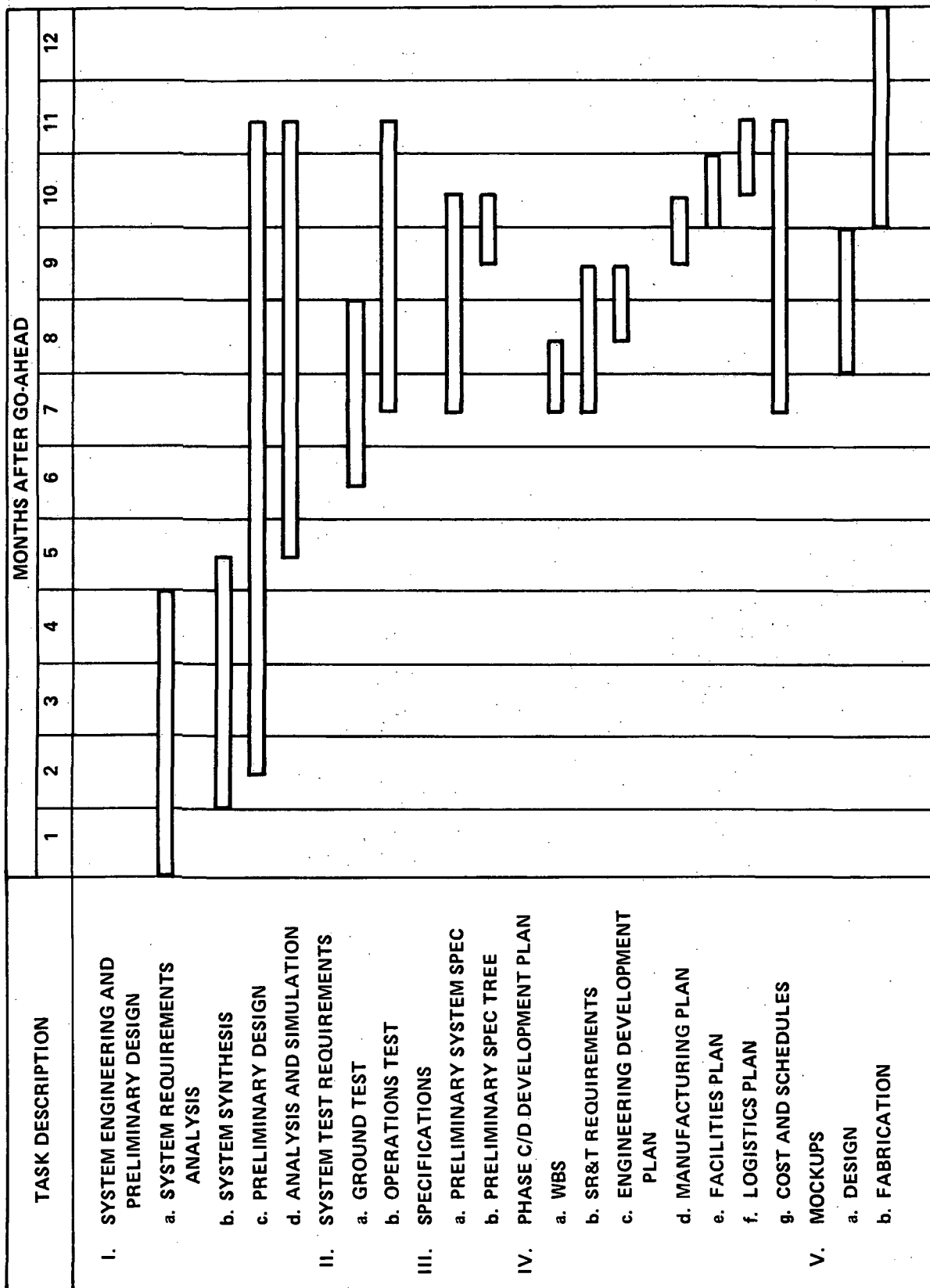


Figure 30. Summary Schedule — Phase B

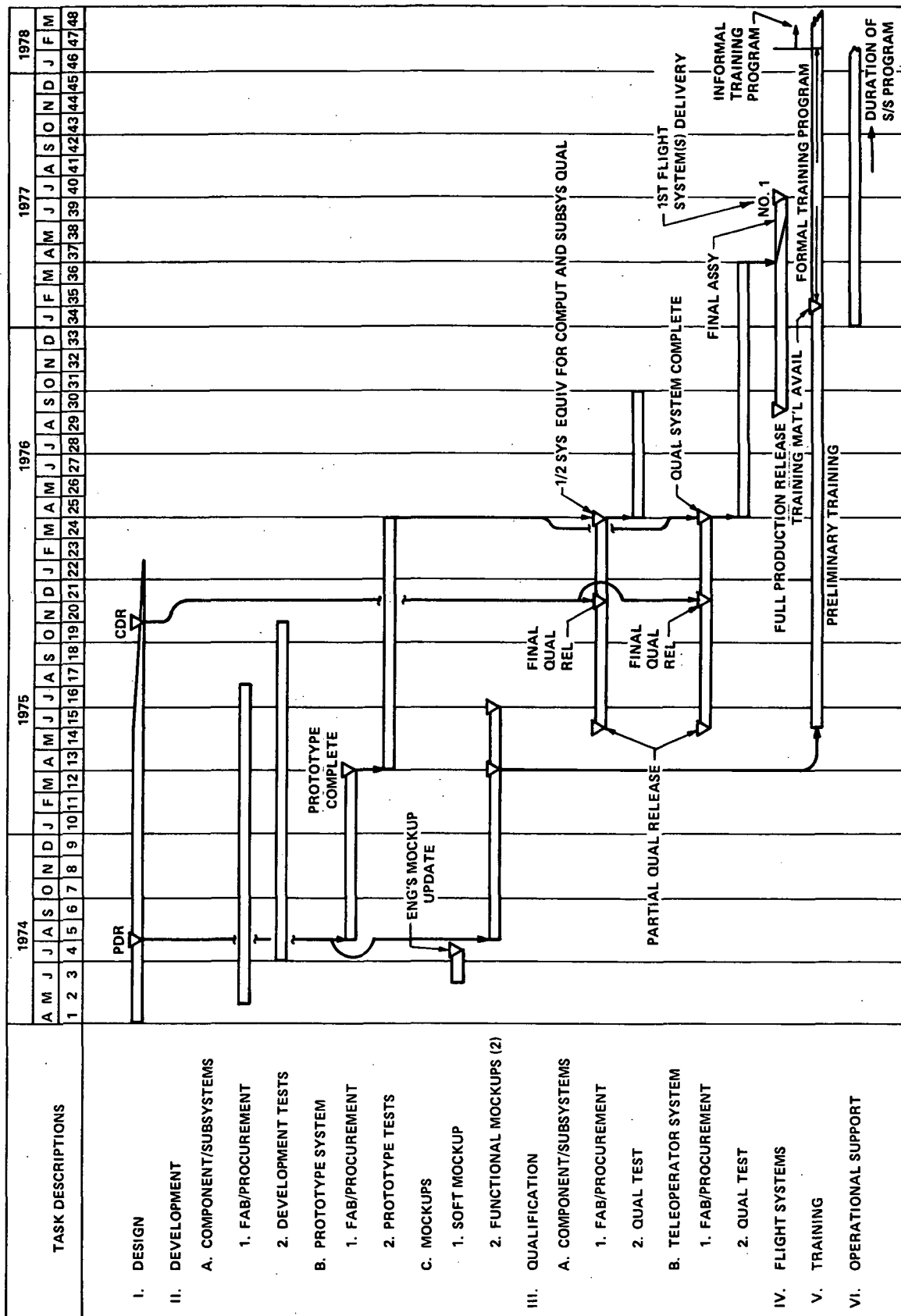


Figure 31. Summary Schedule - Phase C/D

D. CONCLUSIONS

1. A systems level free-flying teleoperator experiment/test is required to fully verify FFTO operational capabilities and to explore critical problem areas.
2. Critical problem areas which must be studied on-orbit are:
 - Retrieval of dynamic satellites. Problem areas are (i) the ability of the man to assess target satellite dynamics, (ii) the ability of the man to match motions between the FFTO and the target satellite, (iii) the grapples design and its control by man, to latch the FFTO to the target satellite, and (iv) the resulting dynamics of the combined system of masses after contact has been established.
 - Flying in the earth's shadow (night flying). The unknowns in this area relate to man's ability to navigate and control the trajectory of the FFTO in a low light level environment. What visual cues are needed? What procedural or operational constraints are required to assure safety? What sensors and augmentation aids are required by man in order to control the FFTO? What Shuttle aids should be provided?
 - Man-machine compatibility. The on-orbit experiment/test will explore (i) operator's workload related to operational procedures and maneuvers, (ii) the ability of man to maneuver the FFTO/payload under large c.g. variations, (iii) the handling qualities preferred by man under retrieval, servicing and FFTO-alone conditions, (iv) the man-machine interface between the operator and the FFTO and the operator and the Shuttle systems and crew.
3. To allow for the timely development of an operational FFTO, an on-orbit experiment/test of a teleoperator must be conducted very early in the Shuttle program.
4. An experimental Shuttle teleoperator can be developed by 1978.
5. The experimental FFTO need not be optimized to evaluate operational performance. Rather, it should be low weight/low cost to demonstrate critical capabilities.
6. FFTO capabilities most useful to the Shuttle missions are (i) retrieval of satellites having adverse dynamics, (ii) the monitoring and inspecting of Shuttle surfaces and operations, and (iii) servicing of Shuttle payloads including module replacement, decontaminating surfaces and fluid replenishment.
7. Astronaut rescue is an important capability of the FFTO, however, the need for this capability depends on the extent and type of EVA operations planned for Shuttle missions.
8. The experimental FFTO can gather valuable engineering and operational information such as the measurement of contamination fluxes in the vicinity of the Shuttle.
9. Teleoperator operations in support of the Shuttle are limited to short ranges, on the order of several thousand feet.
10. A useful FFTO capability can be provided with a 15,000 lb-sec total impulse capability.

11. A 15,000 lb-sec total impulse FFTO can retrieve a stabilized 20,000 lb satellite such as a HEAO.
12. Without EVA or with limited EVA, a remote manipulator system is required to perform payload servicing on-orbit.
13. Retrieval of dynamic satellites/payloads is the most demanding FFTO activity and drives the spacecraft design and man-machine interface requirements.
14. The manipulator subsystem should be of a modular design so that various types can be interchangeable on a basic teleoperator spacecraft.
15. Terrestrial manipulator systems have questionable application in space.
16. Until the functional requirements of manipulators and grapples are established, design and development cannot efficiently proceed.
17. Manipulator controller requirements and designs for multi-degree of freedom manipulators must be defined.
18. Future payloads and satellites to be retrieved or serviced on-orbit must be designed to accommodate retrieval or servicing by a remote manipulator system.
19. A deficiency of defined requirements exist in several important subsystems; (i) video, (ii) manipulator/grapples, and (iii) displays and controls for manipulators and video systems.
20. A safety, reliability and system qualification policy, regarding Shuttle payloads, must be established.

VI. STUDY LIMITATIONS

By its nature, this pre-Phase A study addressed the broad scope of the experimental teleoperator program. The approach is parametric, keeping most options open, and as such, the results are useful even though shuttle mission characteristics and system characteristics may vary in the future.

The mission analysis portion of this study identified general applications of an FFTO and specified functional requirements. Only in several areas were detailed requirements specified. A number of system concepts were generated within the configuration analysis portion of the study. Complying with a pre-Phase A scope of work philosophy, no detailed design effort was accomplished. Within the experiment definition effort, top-level procedures and time-lines were prepared. Details of these will be generated in subsequent studies.

VII. IMPLICATIONS FOR RESEARCH

The free-flying teleoperator system was constrained to use state-of-the-art hardware and technology where practical. In spite of that constraint, the following fundamental studies, aimed at exploring capabilities and requirements, were identified as areas of beneficial research.

- Investigate the effects of gross c.g. shifts of the magnitude associated with coupling a 5000-lb MEM to a 400-lb FFTO. The problem here is determining propulsion system design requirements and operational procedures to offer good trajectory control.
- Establish guidance and control capabilities and requirements of an FFTO flying in the vicinity of the Shuttle during the night portion of an orbit. The problem here is to explore the lighting limitations associated with "night-flying."
- Conduct a detailed manipulator study to establish requirements for servicing satellites on-orbit. Within this effort, the following study areas are:
 - maintenance/servicing task requirements
 - manipulator design requirements
 - payload design requirements
 - manipulator controller requirements
- Define operational and system design requirements to accomplish satellite retrieval. This effort will include the following factors:
 - satellite failure modes and the resulting dynamics
 - approach procedures for determining dynamics and positioning FFTO/grappler for retrieval
 - grappling dynamics resulting from attaching the FFTO to a satellite
 - grappler design requirements
- Determine video system requirements as regards camera mobility, worksite/target illumination, resolution and zoom/focus. In support of this effort, two trade studies should be conducted, (1) color versus black and white, and (2) stereo versus multiple 2D cameras.
- Establish man-machine procedural, operational and hardware requirements, specifically addressing the following work items:
 - one man versus two man control
 - maneuvering the FFTO with large c.g. offsets
 - handling qualities of FFTO's
 - motion matching for retrieval
 - berthing/docking at the Shuttle
 - communications between the FFTO operator and the Shuttle crew
 - manipulator viewing requirements
 - display requirements
- Define remote handling and servicing requirements in space to provide clear guidelines and techniques for supporting space vehicles, space station, space tugs, satellites, etc.

VIII. SUGGESTED ADDITIONAL EFFORT

This study has shown the feasibility of accomplishing useful work on-orbit with a teleoperator. Specific payoffs of such work to the early Shuttle program were identified. However, as a result of this study, several areas of additional effort have been suggested. These will refine the Shuttle FFTO System Experiment definition with emphasis on

- allocating experiment tasks between ground simulation and orbital demonstration
- experiment parameters, conditions, data and use of results
- man's role in terms of time-lines, workloads and man-machine-compatibility
- interface requirements between the FFTO/Shuttle and the FFTO and payloads

An important aspect of the flight experiment is satellite retrieval. The requirements of this activity drive the design of the teleoperator more than any other single activity. It is therefore critical that the gross characteristics of the payloads (satellites) to be retrieved be known and that the operational and dynamic problems of retrieval be explored.

The critical factors to be considered during the analysis are the physical characteristics of the payloads and the dynamic modes of operation. These factors will provide important inputs into the grapples design requirements, into the propulsion system requirements, and into retrieval procedures and operations.

Operational data influences the design of the FFTO and have a pronounced effect on the man-machine interface definition. These data are used to determine (1) whether or not a function should be manual or automatic, (2) supplementary systems which should be provided, and (3) display and control requirements. These data refer to the conditions imposed on the FFTO because of the task it must perform. Such factors as time constraints, lighting conditions, maneuver sequences, etc. fall into this data category.

Current justification for the Experimental FFTO has been qualitatively established. The need for the experiment is proffered in terms of providing increased confidence to the ultimate users of the FFTO. The experiment will demonstrate that the FFTO can indeed perform to the level specified. It is now timely to proceed to the next step in justifying the experiment; the establishment of a need in quantitative terms.