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STUDY TO EVALUATE THE EFFECT OF EVA ON PAYLOAD SYSTEMS

FINAL REPORT

VOL. I. EXECUTIVE SUMMARY

NAS2-8429

NOVEMBER 25, 1975

Space Division
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FINAL REPORT, STUDY TO EVALUATE THE EFFECT OF EVA ON PAYLOAD SYSTEMS. VOL. I EXECUTIVE SUMMARY; VOL. II TECHNICAL ANALYSES	

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DESCRIPTIVE TERMS

PAYLOADS DESIGN & OPERATIONS ANALYSIS, EVA TASK ANALYSIS, COMPARATIVE COST ANALYSES, PROGRAM/PAYLOAD COST SAVINGS, PAYLOAD TRAFFIC MODELLING, EVA TIMELINES, CONTINGENCY ANALYSES, MAINTENANCE ANALYSES

ABSTRACT

THE OVERALL OBJECTIVE OF THE STUDY WAS TO ESTABLISH PROGRAMMATIC BENEFITS TO PAYLOADS WHICH CAN RESULT FROM THE ROUTINE USE OF EVA. THE STUDY COMPARED DESIGN AND OPERATIONS COSTS OF 13 REPRESENTATIVE BASELINE PAYLOADS TO THE COSTS OF THOSE PAYLOADS ADAPTED FOR EVA OPERATIONS. THE EVA-ORIENTED CONCEPTS DEVELOPED IN THE STUDY WERE DERIVED FROM THESE BASELINE CONCEPTS AND MAINTAINED MISSION AND PROGRAM OBJECTIVES AS WELL AS BASIC CONFIGURATIONS. THIS PERMITTED ISOLATION OF COST SAVING FACTORS ASSOCIATED SPECIFICALLY WITH INCORPORATION OF EVA IN A VARIETY OF PAYLOAD DESIGNS AND OPERATIONS. THE STUDY RESULTS WERE EXTRAPOLATED TO A TOTAL OF 74 PAYLOAD PROGRAMS REQUIRING 249 FLIGHT UNITS ON A PAYLOAD SCHEDULE COMPATIBLE WITH THE "572" FLIGHT MODEL. USING APPROPRIATE COMPLEXITY AND LEARNING FACTORS, NET EVA SAVINGS WERE EXTRAPOLATED TO OVER $551M FOR NASA AND U.S. CIVIL PAYLOADS FOR ROUTINE OPERATIONS. ADDING DoD AND ESRO PAYLOADS INCREASES THE NET ESTIMATED SAVINGS TO $776M. PLANNED MAINTENANCE BY EVA INDICATED AN ESTIMATED $168M SAVINGS DUE TO ELIMINATION OF AUTOMATED SERVICINC EQUIPMENT. CONTINGENCY PROBLEMS OF PAYLOADS WERE ALSO ANALYZED TO ESTABLISH EXPECTED FAILURE RATES FOR SHUTTLE PAYLOADS. THE FAILURE INFORMATION RESULTED IN AN ESTIMATED POTENTIAL FOR EVA SAVINGS OF $1.9 B.

FOREWORD

The "Study to Evaluate the Effect of EVA on Payload Systems" was conducted for the NASA Ames Research Center by Space Division of Rockwell International Corporation under Contract NAS2-8429. The Contract Technical Monitor for Ames was Larry R. Alton of the former Systems Studies Division. Mr. Alton was assisted in providing direction on the study by Ethel H. Bauer and by members of the Ames Life Sciences Directorate. Alfred M. Worden, Chief of the Systems Studies Division at Ames, and Stanley Deutch and Daniel Popma, NASA Headquarters Life Sciences provided special guidance and evaluation during the course of the study.

The final report of the "Study to Evaluate The Effect of EVA on Payload Systems", consists of three volumes as follows:

Volume I	Executive Summary
Volume II	Technical Analyses
Volume III	Cost Accounting Data and Methodology (Limited Distribution)

Volume II provides detailed descriptions of the technical analyses performed in the course of the study.

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TABLES

1. STUDY OBJECTIVES, APPROACH, AND PRELIMINARY ANALYSIS

1.1 STUDY OBJECTIVES

The overall objective of the study has been to establish programmatic benefits to payloads which result from the routine use of EVA. More detailed study objectives include:

Identify uses of EVA which significantly reduce payload costs.

Compare technical and economic characteristics of selected payloads which are automated, teleoperator, or EVA-design oriented.

Determine the amount of the cost savings attributable to EVA-oriented payload design and extrapolate to the NASA payload model.

Develop a costing methodology for future NASA use.

The study identified significant influences on payloads brought about by the application of a routine EVA capability and determined the associated cost benefits. These savings were projected to the entire NASA payload model; and NASA has been provided with the costing methodology employed in the study to permit computation of alternate results if desired.

1.2 STUDY SCOPE

The study compared costs of representative baseline payloads to the costs of those payloads adapted for EVA operations. The baseline payload definitions are those currently endorsed by the appropriate project offices or found in standard reference data.

The EVA-oriented concepts developed in this study derived from these baseline concepts and maintained mission and program objectives as well as basic configurations. This permited isolation of cost saving factors associated specifically with incorporation of EVA in a variety of payload designs.

1.3 BACKGROUND

EVA has been thoroughly demonstrated in Apollo and Skylab missions as a valuable tool and viable alternative to automated operations in routine mission operations, support to scientific experiments, and for planned or contingency maintenance and repair activities. Shuttle era payloads, including Spacelab payloads and automated spacecraft can take advantage of manned operations including EVA. The NASA space program has been directed toward lower cost development of payloads and operations via utilization of the Space Shuttle and low cost systems. Low cost criteria will increasingly be applied to future program developments, and should include cost savings derived from planned application of EVA. This study provides visibility on EVA advantages and will hopefully encourage adoption of EVA-oriented designs by present and future program managers.

1.4 STUDY SUMMARY

Study activity began with four stated objectives. Results of the study as reported in this final report met these objectives and provided other results in the following manner.

1. *Identify Uses of EVA Which Significantly Reduce Payload Costs.*

The study identified 61 potential EVA applications--44 of which were Routine Operations; i.e., applied at some point in the mission cycle of every payload. Detailed design and cost data on these applications resulted typically in Net EVA Savings of \$75K to \$150K for each such manual alternative. Conservatively, cost savings were only accumulated for 21 out of the total of 44 routine applications for which technical assurance and credible cost data could be provided.

2. *Compare Technical and Economic Characteristics of Selected Payloads--Automated, Teleoperator, or EVA Design Oriented*

Thirteen representative payloads were analyzed in the study. Baseline (automated) modes of operation were evaluated and compared to EVA modes. In all cases, EVA presented design simplification and lower costs. Net savings attributed to EVA for DDT&E and first unit costs averaged \$2.5 million for automated spacecraft and \$8.9 million for sortie payloads.

3. *Determine the Amount of These Savings and Extrapolate to The NASA Payload Model.*

The thirteen representative payload programs were extrapolated to a total of 74 programs compatible with EVA applications. These 74 programs require 249 flight units on a payload schedule compatible with the "572" flight model. Using appropriate complexity and learning factors, net EVA savings were extrapolated to over \$551M for NASA and U.S. civil payloads for routine operations. Adding DoD and ESRO payloads increases the net estimated savings to \$776M.

4. *Evaluate and Compare Automated Versus EVA Task Times.*

Credible task-time data were applied to the payload operations to derive integrated, comparative timelines. With EVA, routine preparation timelines were decreased in one case by 1.7 elapsed hours to a maximum increase of 1.3 hours--average 0.5 hour increase. EVA durations ranged from 1.5 hours to 6 hours--average 3.7. These activities require the following:

One-man EVA	11 payloads	One EVA cycle	9 payloads
Two-man EVA	2 payloads	Two EVA cycles	4 payloads
		Three EVA cycles	1 payload (on-orbit maintenance)

Planned maintenance for a projected 13 payload programs (out of a possible 51 payload programs) indicated an estimated \$168M savings due to elimination of automated servicing equipment. If all spacecraft designated "Reusable" (28 programs) are included, the potentially extrapolated cost savings of the EVA mode would be ∿\$316M. EVA savings for contingency problems of payloads were based on transport and equipment costs only. While the historical data do not necessarily establish expected failure rates for Shuttle payloads, the failure information was examined to select only credible analogs. The total estimated EVA savings were about \$1.9 billion.

1.5 STUDY TASKS AND REPORT STRUCTURE

A total of six tasks were conducted in the study. Figure 1 is a simplified study flow diagram. Phase I was reviewed at a briefing held at NASA Ames Research Center on 11 October 1974. The detailed analyses in Phase II served to develop the technical data regarding 13 representative payloads that permitted the comparative cost analyses which were then extrapolated to the NASA payload model.

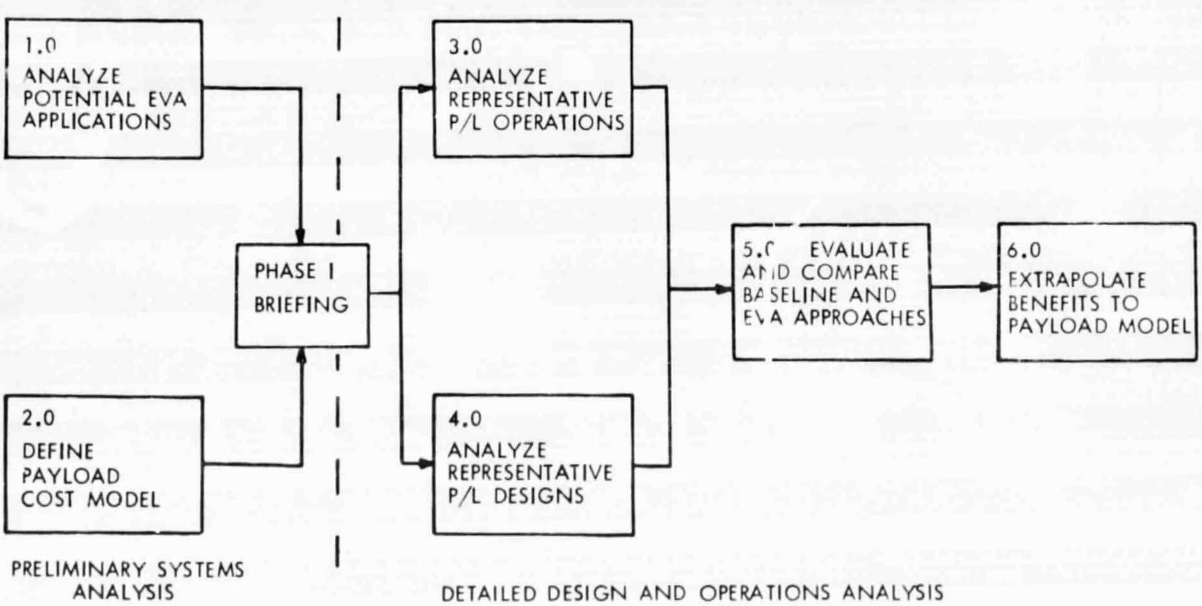


Figure 1. Study Task Logic

1.6 REPRESENTATIVE PAYLOAD SELECTION

The final grouping of the representative payloads reflects MSFC descriptions regarding design concept and reusability for staged and non-staged spacecraft. Planetary and lunar vehicles were grouped separately and four types of sortie payloads were defined. Table 1 lists the mission and design type of the 13 selected representative payloads.

Table 1. Representative Payloads

GROUP	SSPD NO.	NAME
		NO UPPER STS STAGE (TUG)
LCR	EO-08	EARTH OBSERVATORY SATELLITE (EOS)
LCE	AP-04	GRAVITY AND RELATIVITY SATELLITE (GRS)
CDR	AS-01	LARGE SPACE TELESCOPE (LST)
CDE	OP-03	MINILAGEOS (MIN)
		UPPER STAGE (TUG) REQUIRED
LCR	OP-06	MAGNETIC FIELD MONITOR SATELLITE (MFM)
LCE	AP-03	HIGH-ALTITUDE EXPLORER CLASS (HAE)
CDR	CN-58	U.S. DOMSAT "C" (DOM)
CDE	O?-01	GEOPAUSE (GEO)
		PLANETARY
	PL-12	MARINER JUPITER ORBITER (MJO)
		SORTIE
1	AS-01	1.5M IR TELESCOPE (SIRTF)
2	AP-06	ATMOSPHERIC, MAGNETOSPHERIC AND PLASMAS IN SPACE (AMPS)
3	ST-23	ADVANCED TECHNOLOGY LAB (ATL)
4	ST-04	PHYSICS AND CHEMISTRY FACILITY (PCF)

1.7 EVA APPLICATIONS PRELIMINARY ANALYSIS

The potential EVA applications were grouped into three categories: (1) routine operations, (2) contingency operations, and (3) planned maintenance, then evaluated for all classes of missions. The classes of missions cover all basic Shuttle-related operations: sortie, spacecraft delivery, maintenance, and retrieval. For sortie missions, the major on-orbit activities include preparation for experiments, the performance of experiments and, shutdown and storage in preparation for orbiter return. Contingency operations might be entered at any point during the mission and would exit to normal operations, as shown in Figure 2. Typical EVA applications for automated spacecraft are shown in Figure 3.

Major activities in normal mission operations are functions with potential EVA involvement for replacing or simplifying automated electromechanical devices which otherwise would be custom designed and manufactured.

Routine operations in Shuttle missions are defined as those which are normally planned to occur on delivery, retrieval, and sortie missions. It specifically excludes planned maintenance activities and activities performed to correct an unexpected anomaly (contingency). It does include activities which are done on a routine basis even if these are performed out of a normal sequence. For example, docking activities are routine, but are not normally required on a delivery mission. If, however, a spacecraft anomaly was detected subsequent to separation, the crew would likely perform a routine docking to retrieve the spacecraft to the ground.

Analyses of on-orbit maintenance considered both transportation costs and costs of servicing systems since such systems are considered to be part of the payload. By definition, contingency situations are those mission-interrupting or endangering situations for which no automated corrective techniques have been developed prior to flight. Therefore, use of EVA in contingency situations cannot be compared directly with automated approaches. Significant launch and payload cost benefits can be expected if EVA is used to reduce the probability of deployment and retrieval failures, either by eliminating potential failure modes through routine EVA usage or as a contingency option.

Table 2 summarizes EVA application categories and payload types affected.

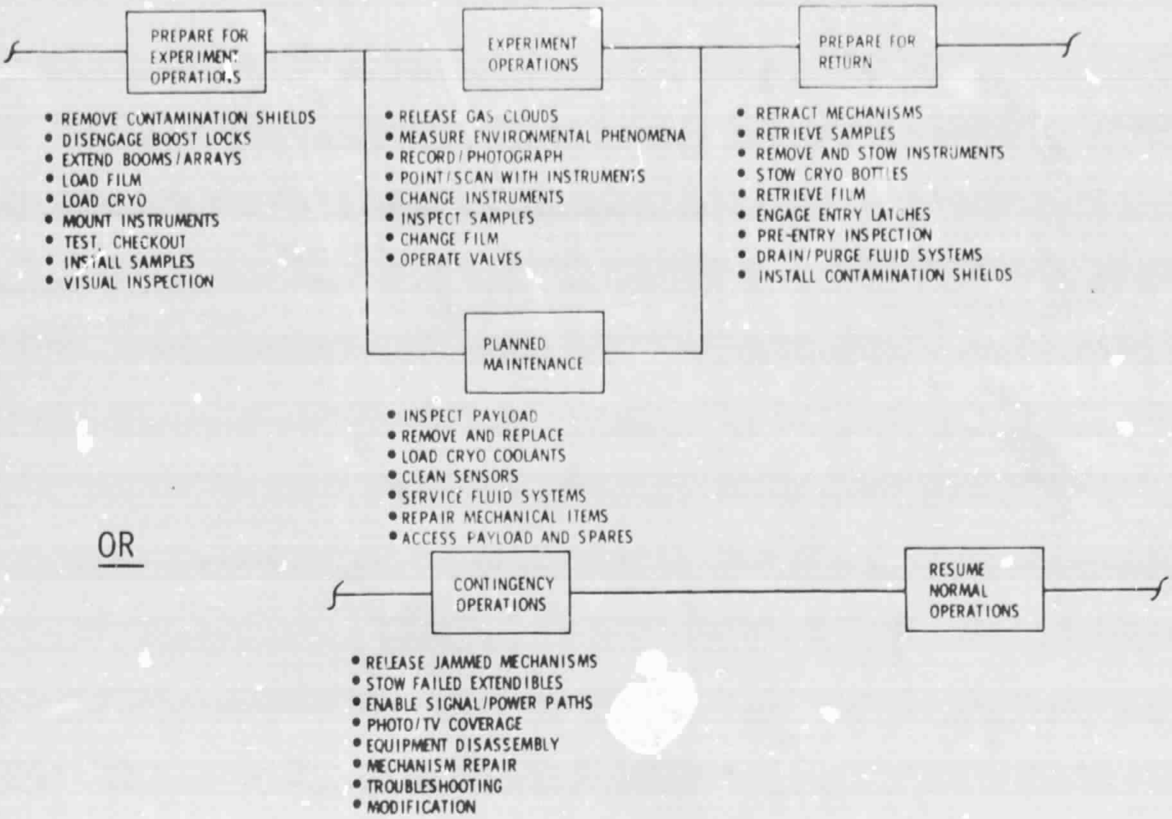


Figure 2. Typical Sortie Mission EVA Applications

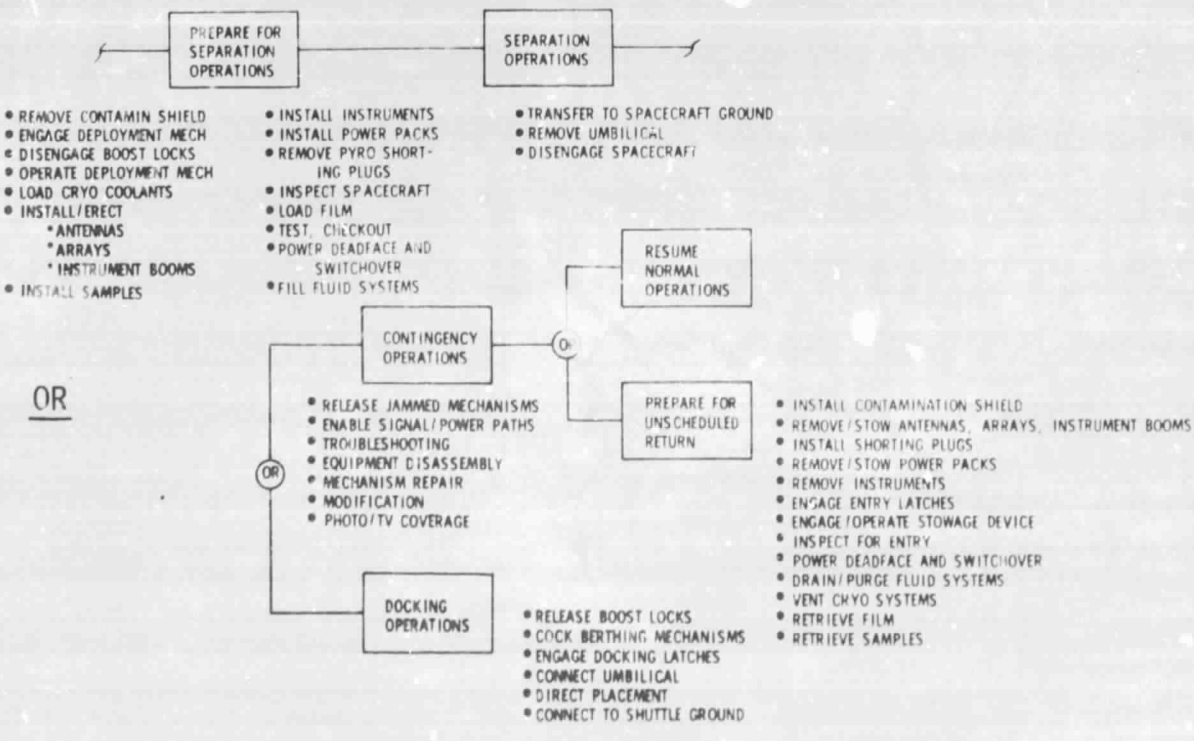


Figure 3. Typical Spacecraft Delivery Mission EVA Applications

Table 2. Summary of EVA Applications

Type of EVA Application	Type of Payload Affected		
	Automated Spacecraft		
	Reusable	Expendable	Sortie
ROUTINE OPERATIONS			
1. Pre-Operations	X	X	X
2. Experiment Operations			X
3. Spacecraft Separation	X	X	
4. Docking	X	(Unplanned)	
5. Preparation for Return	X	(Unplanned)	X
CONTINGENCY OPERATIONS	X	X	X
PLANNED MAINTENANCE	X		

II. PAYLOADS ANALYSIS

Prior to the integrated analyses on the 13 representative payloads, several preliminary activities were undertaken. This included baseline Orbiter provisions and a set of payload and EVA interface design criteria. An intensive review of mechanical elements common to most payloads was undertaken in order to preclude redundant analyses on each representative payload. Reference orbiter timelines were defined to establish common ground for representative payload timeline analysis. Timeline "building blocks" (detailed task segments) had the dual purpose of ensuring standardization and of adding credibility to overall integrated timelines.

2.1 SHUTTLE-PAYLOAD BASELINE CRITERIA AND REQUIREMENTS

Shuttle Orbiter characteristics and payload interface requirements affect the design of all payloads, with or without EVA applications. Payloads designed for EVA interface must meet additional design criteria. While the study was not concerned with all aspects of the payload design, a body of such requirements were necessary to ensure credibility of design solutions affecting study results.

2.1.1 EVA/RMS Provisions Evaluation

EVA. Provisions in the Shuttle include all basic equipment and consumables. Although various aspects of the provisions are currently under study, the Shuttle airlock is expected to have a pre-mission option of being installed inside or outside (in the cargo bay) the cabin envelope on the cabin bulkhead and equipment and consumables are planned to support up to three 2-man, 6-hour EVA's; one of which is reserved for Shuttle contingency.

Remote Manipulator System. The RMS is planned for use in zero-g handling of payloads. The mechanism will deploy and retrieve payloads and can be used for inspection. However, the current RMS concept has limitations on its capabilities. For example, no force feedback requirement has been established to date. Tip force is limited to 45 N (10 lb) and no rotation capability has been specified.

In considering operational uses of the RMS as an alternative to EVA, two areas were analyzed: crew direct viewing and RMS access. Figure 4 indicates the loss of direct viewing in the Shuttle cargo bay with a Spacelab installed. The figure also shows a large vertical cylinder positioned in the Orbiter bay. This could represent a large spacecraft, sortie telescope or other extendibles. The area forward of this volume is visible, but the entire aft area, including the vertical stabilizer, is obscured.

When automated spacecraft are parallel to the longitudinal axis of the Orbiter, as during the launch phase, only the forward end of the spacecraft and an arc over the upper surface are accessible to the RMS. When payloads

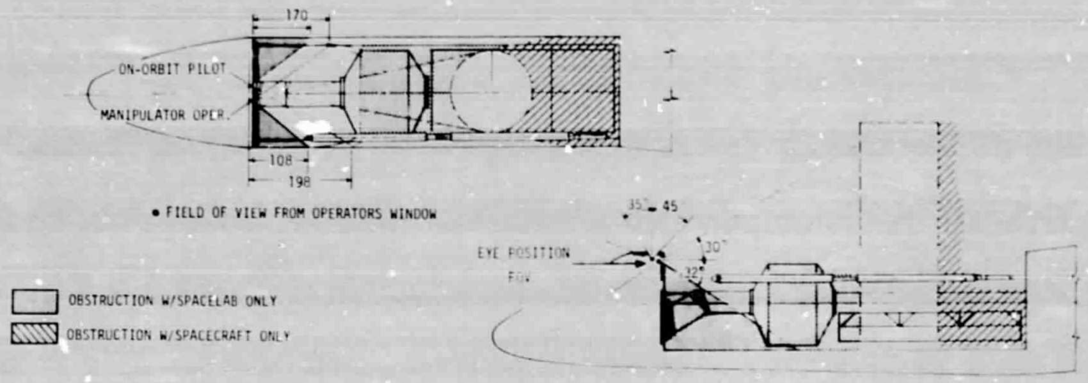


Figure 4. Constraints on Cargo Bay Viewing

are erected within the bay or have protuberances beyond the Orbiter moldline, they interfere further with the total effectivity of the RMS. The illustrated case, Figure 5, is of a spacecraft with a uniform maximum diameter equal to that of the bay width.

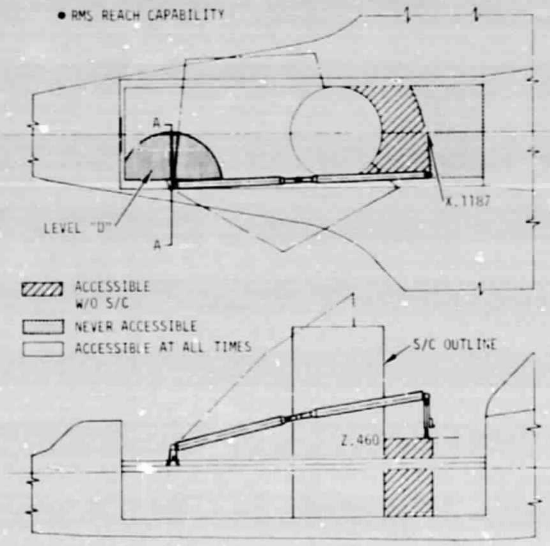


Figure 5. Spacecraft Constraints on Cargo Bay RMS Accessibility

EVA/RMS Task Evaluation. In considering various EVA/RMS task comparisons, RMS was evaluated with respect to access and flexibility for typical spacecraft delivery preparation and planned maintenance. One problem is that the RMS cannot reach side or underneath components, unless special erection and rotation provisions are provided (e.g., EOS-type of erection platform or a second payload-chargeable RMS). Another problem in using the RMS is the lack of positive indication feedback; i.e., "latch released", unless indicator circuits of the remote system are retained.

One of the beneficial uses identified in the study for the RMS was to assist EVA tasks by retaining the payload in a suitable work position. An example, shown in Figure 6, is based on maintaining two retention points on the pallet-mounted retention frame, while the RMS provides a third stability point. By raising the spacecraft to this position, the solar panels can be extended, thus allowing overall spacecraft checkout before umbilical separation. Extending the umbilical to the raised position as shown can readily be performed manually, but would require additional complexity in the automated umbilical concept.

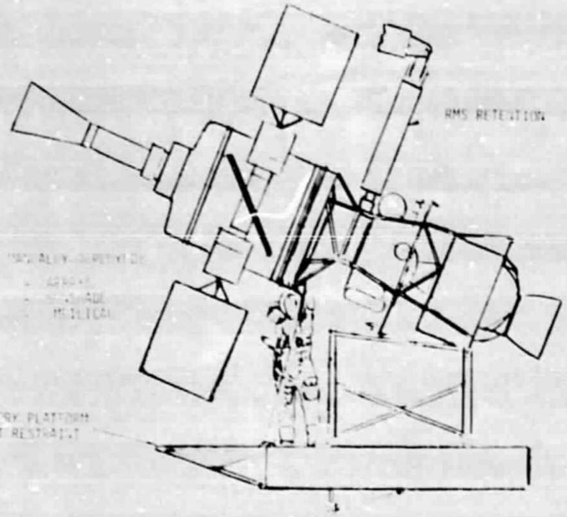
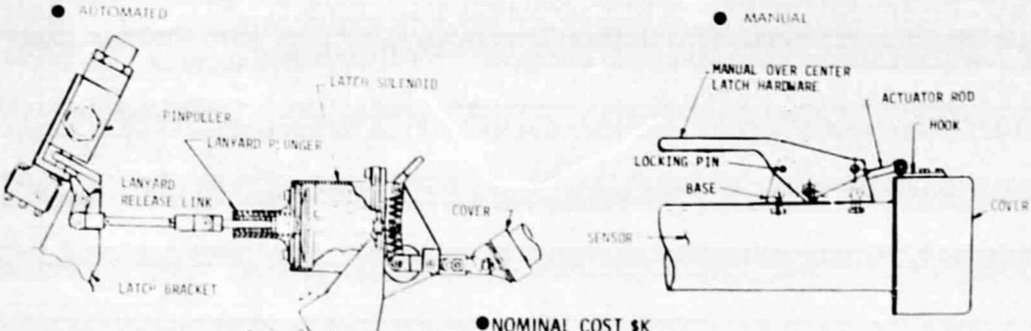


Figure 6. RMS Assist to EVA Activities

2.1.2 Payload Design Elements

Certain classes of mechanisms occur frequently in the baseline representative payloads. These include retention latches, deployment mechanisms, and umbilical make/break mechanisms. These mechanisms were studied in detail to derive EVA alternatives to perform the same functions. By examining these mechanisms it was only necessary to evaluate variations when analyzing the representative payloads. These design "building blocks" also add credibility to the representative payload design and cost analysis because data sources exist for actual flight hardware appropriate for Shuttle payloads. Manual designs were established to perform the same function, cost estimates were subsequently established on the basis of material, manufacturing technique, and relative complexity.

Retention latches are required for the payload itself as well as for every "movable" element which forms a part of an operational spacecraft or sortie payload. This requirement for "tie-down" applies to the Shuttle boost phase followed by on-orbit release. Subsequently, for retrieval of spacecraft or Spacelab payload stowage, latching is required for entry and landing. Figure 7 illustrates one of five latch designs evaluated in the study.



NOMINAL COST $K

	AUTO	EVA
DDT&E	26	1.0
UNIT	10	0.2

REF: JPL REPORT 32-832

Figure 7. Sensor Cover Latch Designs

Deployed mechanisms evaluation shows that the Shuttle cargo bay envelope, as with expendable boosters, tend to require stowed and latched solar panels and other devices during the launch phase. However, while one-way (or one-shot) mechanisms are acceptable in the expendable booster case, payloads planned for retrieval or payloads which could be returned to earth after on-orbit failures require two-way operation. Since overall Shuttle cost effectiveness is only achieved with retrievability, this case was postulated in this study. Figure 8 illustrates comparative automated and manual design concepts.

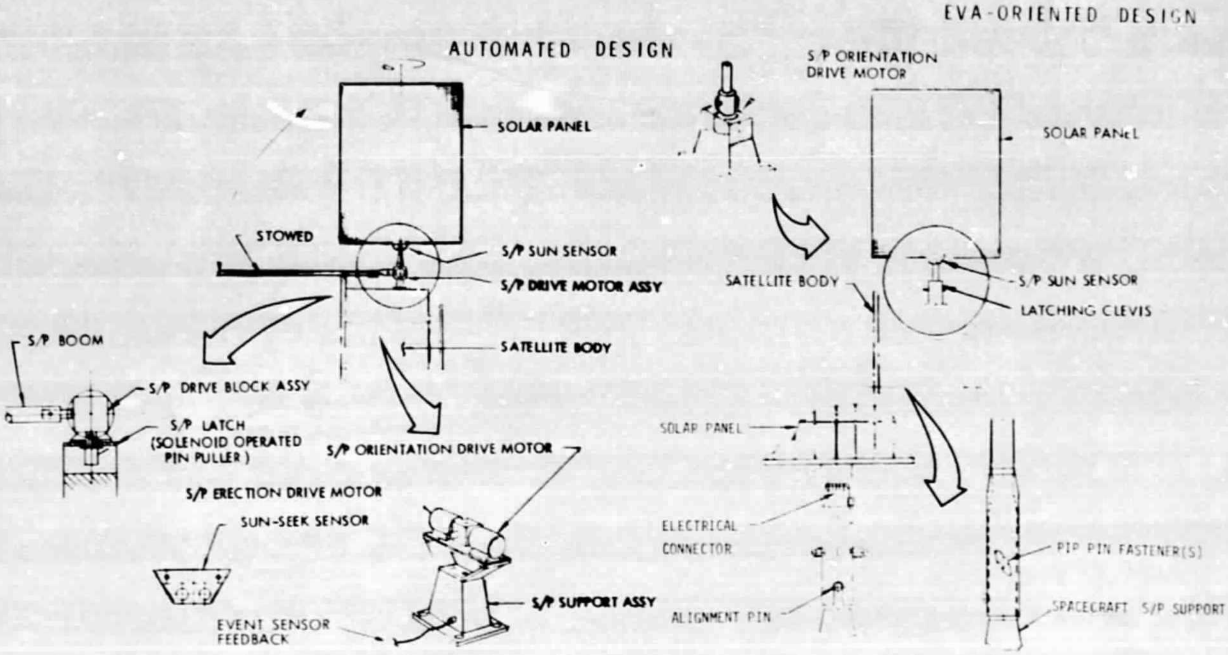


Figure 8. Solar Panel Deployment Design Concepts

Another class of mechanized elements consists of Shuttle-to-payload umbilicals. Requirements exist for Shuttle power to be provided to many spacecraft. In turn, the Shuttle requires safety monitoring of payload critical circuits plus potentially some control or checkout provisions. Many spacecraft required fluid venting or dumping via Shuttle plumbing. Two-way (break-remake) operations are required for retrieval capability. Comparative design and cost data for automated and EVA concepts are shown in Figure 9. Not illustrated are the additional automated complexities of operating the swing arm and latching it open as opposed to manual operation and latching.

One issue concerning deployable devices requires further NASA resolution in order to secure the benefits of an EVA design. Present Orbiter safety rules require cabin-operated (remote) stowage of all extendable devices, with either redundant capability or back-up jettison capability. If this rule is retained, it would preclude a significant portion of manual erection and stowage concepts.

2.2 TASK TIME SEGMENT ANALYSIS

Task-time data "building blocks" were developed for fundamental operations and used later in the analysis of representative payloads. Saving costs by designing for EVA activities would be of little use if the time required were to exceed Shuttle support capabilities or seriously impact payload flight schedule. The figure of importance is, of course, the delta time resulting from EVA compared to remote controlled operations.

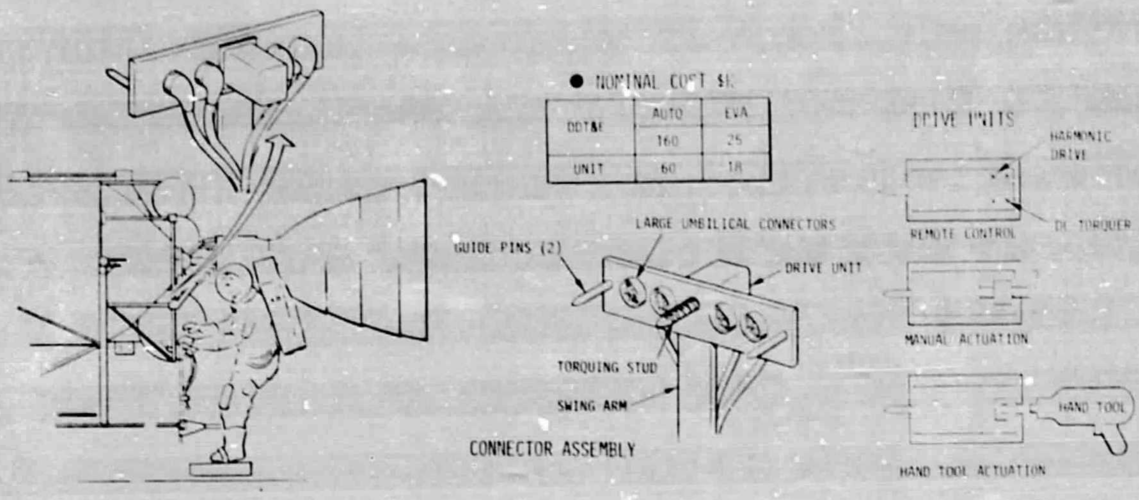


Figure 9. Large Umbilical Connector Concepts

2.2.1 Payload Operations Preparation Time

Both EVA and remote operations require preparatory activities before direct payload operations can begin. In the case of remote controlled operations, preparation consists primarily of PS panel checks and set-up of the payload and RMS control stations. In order to establish a reasonable level of accuracy, a variety of sources were reviewed. A consensus of data indicated that two crewmen working approximately one-half hour would be required in the remote (baseline) case.

For EVA preparation, the primary consideration is the time to don suits, prebreathe, and perform airlock operations. The prebreathing time is a variable as a function of suit pressure level subsequent to departure from the Orbiter 14.7 psi cabin. Figure 10 compares nominal time requirements for a 8 psi and 3.7 psi spacesuit. The use of the 8 psi suit is estimated to require approximately 1.5 hours less than the lower pressure garment for routine operations and could further reduce preparation time as confidence in the system is built up. The major influencing factor is that of the oxygen prebreathing. It should be noted that other crew activities can be performed during the early prebreathing period by use of portable oxygen masks. A 4 psi suit formed the baseline for the EVA operations because it represents current Orbiter/airlock design and EMU equipment concepts.

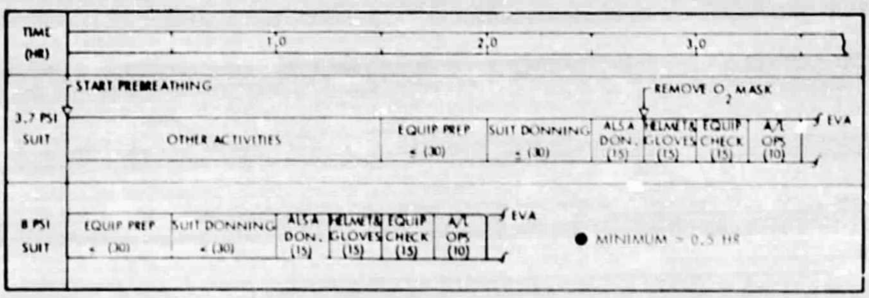


Figure 10. EVA Preparation Time Typical Routine Timelines

2.2.2 Shuttle Mission Timeline

For the purpose of this study, two timelines were defined for two reference Shuttle missions which can be described as Near Earth Orbit (NEO) and High Earth Orbit (HEO); i.e., >200 n mi. Starting time for payload operations is dependent on Shuttle events, as illustrated in Figure 11.

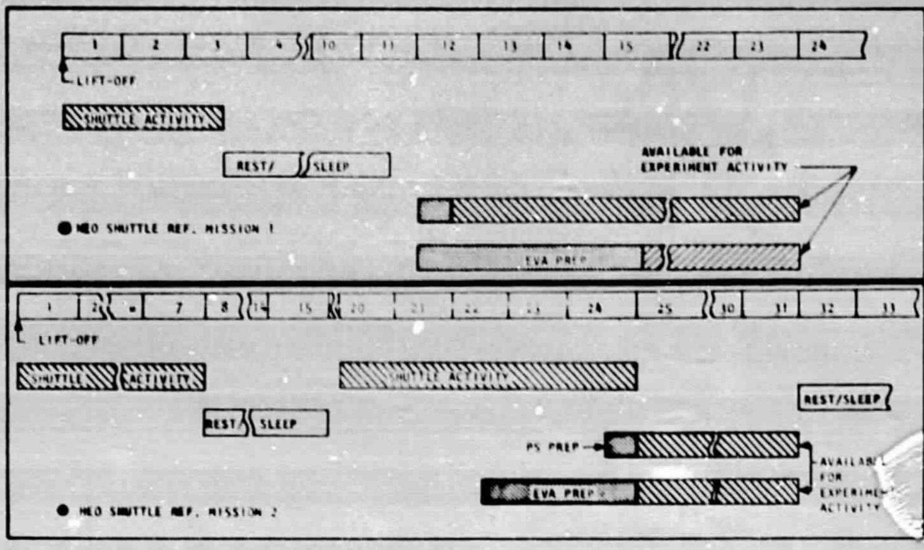


Figure 11. Basic Timelines, Shuttle Launch Phase

In the NEO case, the crew may not begin operations before the twelfth hour GET because of a scheduled off-duty period. Thus, in the automated mode, with less preparation time, more operations time is available.

For the HEO mission, experiment operations can begin starting with the 25th hour GET (possibly earlier for sorties not requiring deployment). Automated or EVA preparation can take place during a second Orbiter activity period. Activity is limited to preparation in that OMS firings and IMU alignments are required. In this case an equal period of payload operations is available. It is possible in this mode to initiate EVA as early as automated operations since EVA preparation can be concurrent with Shuttle operations.

2.2.3 Automated Device Basic Timelines

A key to development of baseline integrated timelines is the performance of automated deployment devices. Data for three such automated devices were used in the study. Movement rates are illustrated in Figure 12 for the following typical devices, Shuttle RMS, STEM(1) antenna, and ASTROMAST(2).

(1) SPAR Aerospace Products, Ltd., Ontario, Canada (re model A-463).

(2) ASTRO Research Corporation, Santa Barbara, California.

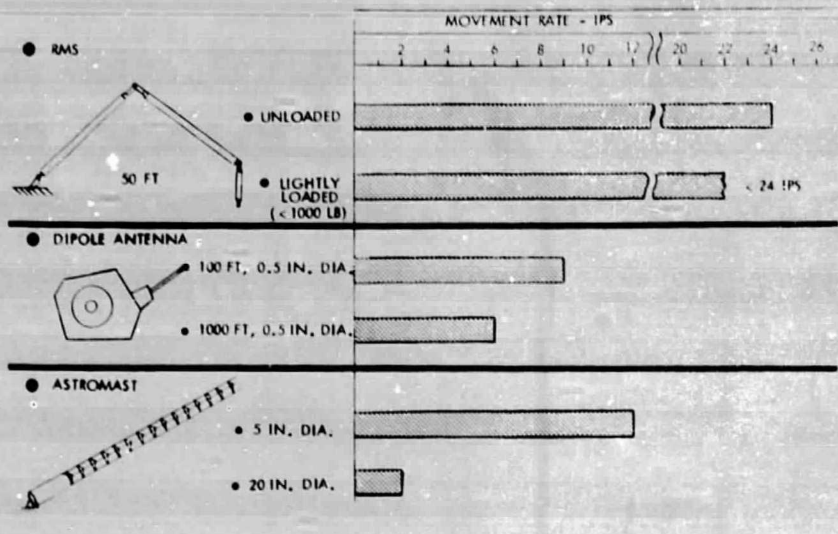


Figure 12. Automated Devices, Basic Movement Rates

2.2.4 Basic EVA Task Times

Examination of prior data was used to develop basic data for preparing integrated payload EVA timelines. To show examples of both preplanned and contingency activities that have been performed to date, reference is made to an EVA on Skylab, shown in Figure 13.

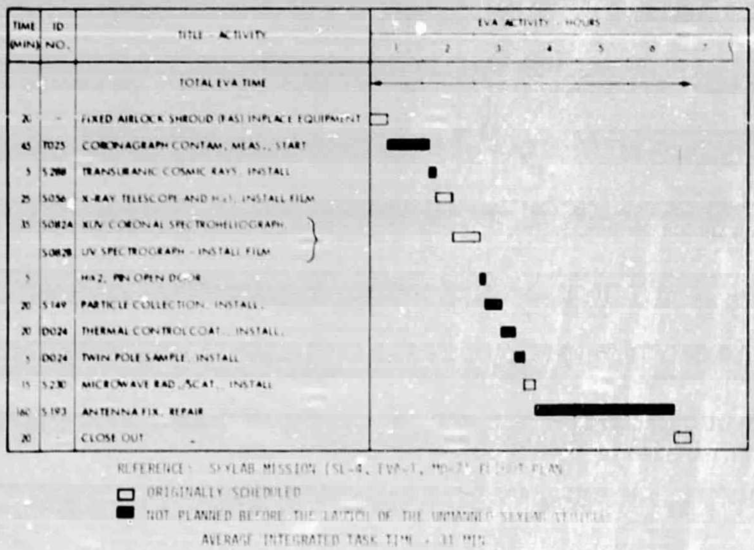


Figure 13. Skylab EVA Task Times

Less than two hours of EVA activities were planned. However, due to EVA to resolve failures or other contingencies, the EVA extended into the seventh hour. An important lesson learned from Skylab is that generally trained EVA crewmen can perform a variety of unplanned tasks with a minimum of special tools and training.

2.3 REPRESENTATIVE PAYLOAD DESIGN AND OPERATIONS ANALYSIS

The 13 representative payload design analyses were performed to develop the technical data needed to determine cost savings of EVA-oriented designs. Details were developed to bring all representative baseline payloads to the same level of definition. Then, EVA applications were identified and designs of the EVA-oriented payloads prepared.

2.3.1 Design Analysis

A complete WBS-oriented hardware listing was prepared for each payload to establish the basis for the subsequent costing and comparison. At least two levels of data were established with third or fourth levels being defined whenever there was significant difference between the baseline and EVA alternatives. Figure 14 illustrates a typical design analysis.

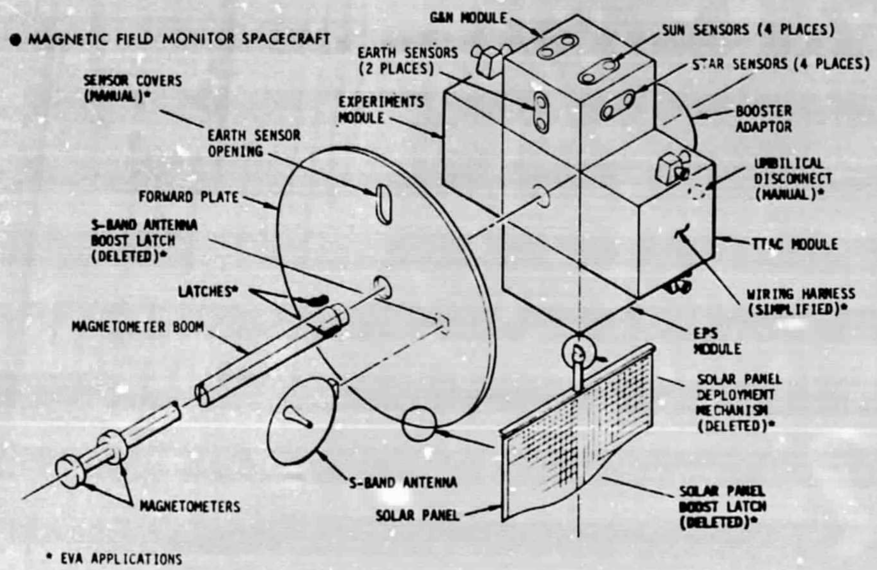


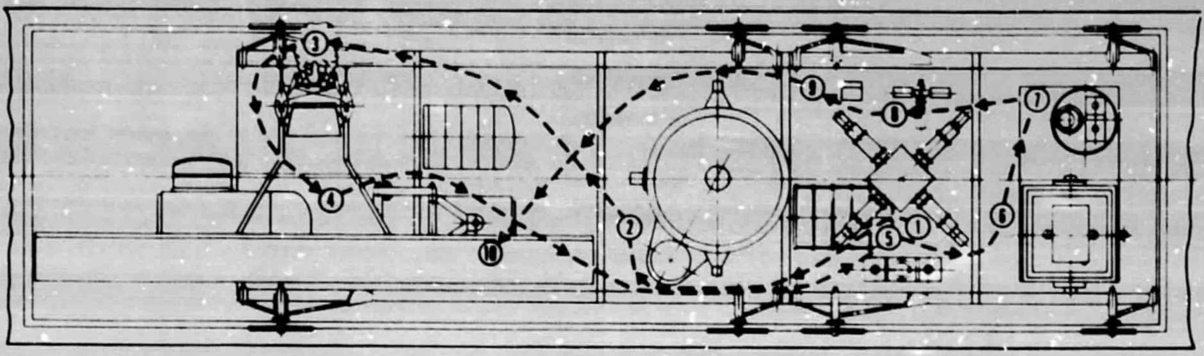
Figure 14. EVA Applications Identification

EVA applications were established for solar panel unlatching and deploying, sensor cover removal and antenna latch release. In addition, EVA was employed to install the magnetometer boom.

2.3.2 Operations Analysis

The operations analyses supported the design analyses by providing insight into payload functional requirements. Secondly, they led to baseline-to-EVA comparisons of the mission and crew timelines. In the preparation of representative payload timelines, all known factors were used, including the basic building blocks discussed earlier, baseline Orbiter and mission constraints, crew duty cycles, and payload source data. Each timeline was plotted as a function of the overall payload design configuration as typified by the analysis of the Advanced Technology Laboratory (ATL).

Figure 15 illustrates the activation sequence established for the EVA crew members--a sequence designed to minimize interference among payload instruments while ensuring clear translation paths for the crew. EVA work stations are numbered in sequence and correspond to the station numbers in the table included with Figure 15. Time estimates were made for the EVA mode of ATL activation and compared to the baseline activation. The task-time evaluation was carried out in this manner for all payloads.



①	MICROWAVE INTERFEROMETER	⑥	AUTONOMOUS NAVIGATION
②	MICROWAVE RADIOMETER	⑦	LIDAR MEASUREMENTS OF CIRRUS CLOUDS
③	SEARCH, RESCUE, AND IMAGING RADAR	⑧	NONMETALLIC MATERIALS EXPERIMENT
④	NEUTRAL GAS PARAMETER EXPERIMENT	⑨	CONTAMINATION MONITOR
⑤	UV METEOR SPECTROSCOPY	⑩	BARIUM PLASMA CLOUD EXPERIMENT

Figure 15. ATL Activation Sequence

Integrated timeline sequences as prepared for "delivery" of all automated spacecraft are summarized in Figure 16. The results show several cases with equal or nearly equal times, and for MJO, the EVA time is slightly less-if EVA preparation time were excluded. All time bars fit within mission constraints and crew duty cycles with a few exceptions. These exceptions are considered simple operational work arounds, or, in the case of the LST, a potential second shift. The term "normal shift" refers to the basic Shuttle timeline presented earlier.

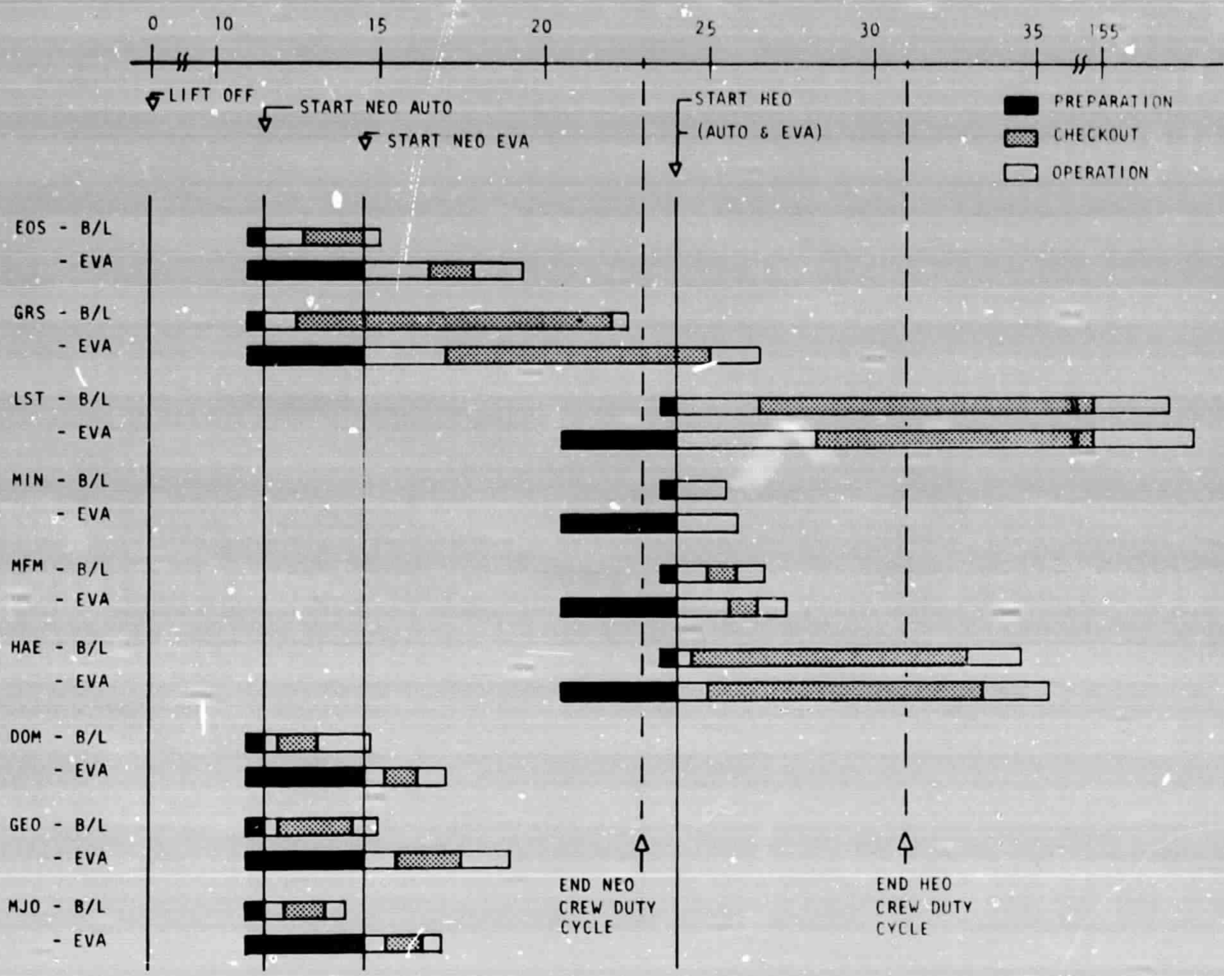


Figure 16. Summary of Automated Spacecraft Timelines

In one sortie payload case, Physics and Chemistry Facility, use of Spacelab Module airlocks impacts preparations such that EVA takes less total time than the baseline as shown in Figure 17.

In no case does a scheduled Orbiter sleep period interfere with use of EVA. The baseline and EVA timelines for preparation are within all Shuttle/mission constraints.

Table 3 tabulates the timeline data showing total elapsed time from start of operations (i.e., Time = 0) as well as net time for either automated or manual activities. The crew size data reflect task sequences for two men operating PS and RMS controls for the baseline concept--the same two men plus EVA crew for the manual concept. The crew size and number of EVA's are well within baseline Shuttle provisions on an individual payload basis.

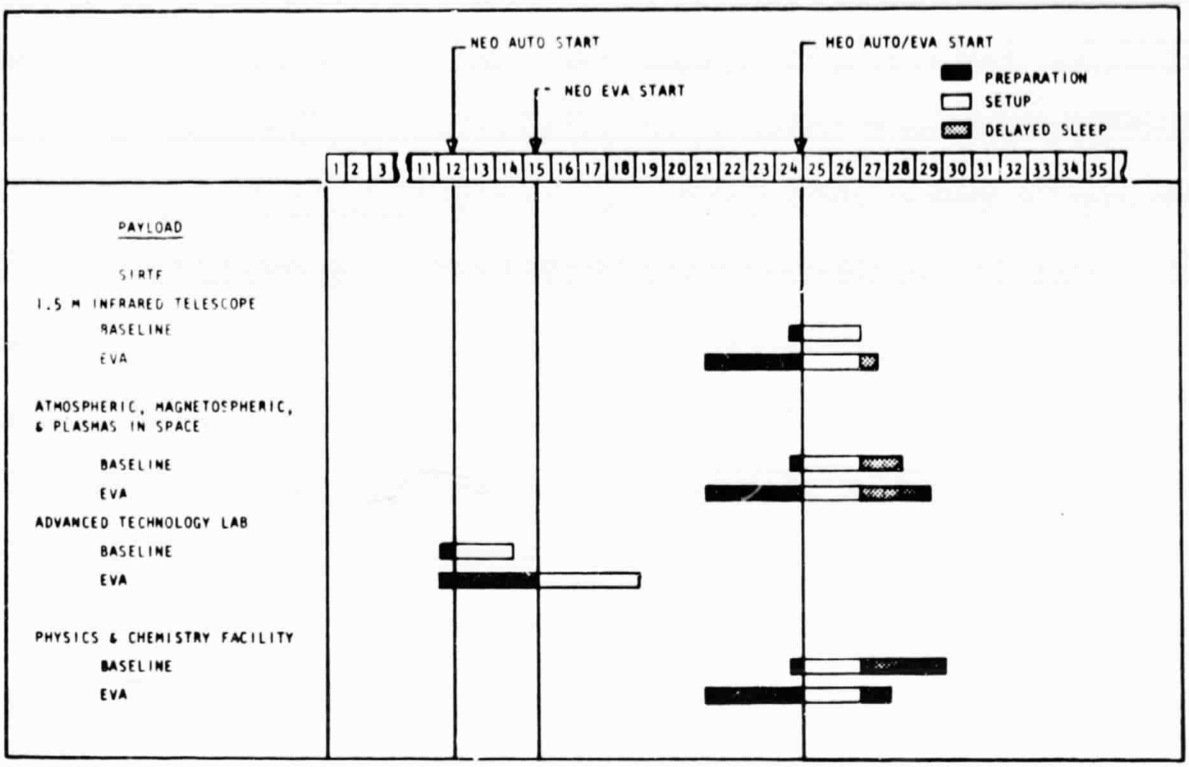


Figure 17. Summary of Sortie Payload Timelines

Table 3. Timeline Comparison Data

Item	9 Automated Spacecraft Preparation for Delivery		4 Sortie Payloads Preparation for Operation	
	Baseline	EVA Mode	Baseline	EVA Mode
Total pre-operations time - hours (avg. of all payloads)	18.8	19.4	--	--
Pre-operations time excluding checkout-hours	2.2	3.4	3.2	3.5
Average crew size	2.1	3.1	1.8	2.5
Average no. EVA's	--	1.3	--	1.0
Average no. men/EVA	--	1.0	--	1.5

III. COST ANALYSIS AND PROGRAM EXTRAPOLATION

3.1 REPRESENTATIVE PAYLOADS

The cost and technical analyses in the study were conducted as an integrated effort to achieve the objective of identifying program-wide EVA savings. Technical characteristics and their costs were studied in detail, as described earlier, and applied to representative payloads. Overall subsystems and equipment of representative payloads were examined technically and costed in both Baseline and EVA configurations. Finally, cost savings were extrapolated to all analogous spacecraft in a mission/payload model developed in this study.

3.1.1 Costing Analysis

Costs in the study were developed for flight hardware and related program costs associated with routine operations, planned maintenance, and contingencies. Shuttle transportation cost data were used only in comparing maintenance and contingency options. The ground rules and assumptions utilized in developing cost estimates were: (1) all costs are normalized to 1974 dollars, (2) profit or fee is excluded, (3) launch vehicle and launch costs are excluded, and (4) all costs would be accumulated to a standard Work Breakdown Structure (WBS) for baseline and EVA systems.

Flight hardware Cost Estimating Relationships (CER's) used for the representative payload cost estimates, were determined by analyzing the subsystems of six unmanned satellites or payloads. The methodology and basic data are the same as used for the Space Shuttle contract and recent military satellite firm price quotations.

3.1.2 Representative Payload Costing

Figure 18 presents an example indentured breakdown for a representative payload. The EVA alternatives to the baseline designs were assigned separate WBS numbers. The weight of each subsystem of the selected payloads was based on source data or estimated from the technical characteristics. This weight was compared to the CER generated for that system and the dollars per kilogram value noted.

A technical evaluation based on analogous historical payloads was applied to the result of the foregoing calculation to convert to a corrected dollars per kilogram and total cost for each line item of the WBS. The actual computation of the representative payload cost and final output was generated by a computer program referred to as CAM IV.

Output data from the CAM IV program was summed to recurring and nonrecurring baseline and EVA-oriented totals for each representative payload. Costs were printed out at all levels and summed at all intermediate levels as well as the totals listed above. Data for cost areas are independently available such as program management, flight hardware, orbital support unit (OSU), etc.

REPRESENTATIVE PAYLOAD NAME SHUTTLE INFRARED TELESCOPE FACILITY (SIRTF) WBS NO. 21.00.00.00.00

SIZE (m) 3 PALLET SECTIONS SOURCE DATA SIRTF ROCKWELL PROPOSAL, INITIAL STUDY DATA & SSPD 7/74 Page 1 of 2

WBS	NAME	TYPE/DESCRIPTOR	TOTAL WEIGHT (kg)	No. UNITS
02.0.0.0	Flight System			
02.09.0.0	Telescope Assembly 1.5 M Cryo Cooled 2d X 6	Baseline/EVA	3997/3824	-
02.09.01.0	Cylinder Housing	Baseline/EVA	1617/1611	-
.11	Thermal Isolators	Automated	9	6
.31	Thermal Isolators	Manual	6	6
.12	Sun Shade	Automated	9	1
.32	Sun Shade	Manual	6	1
.3	Structures		1599	-
03.02.02.01	EVA Work Aids		7	-
02.09.02.0	Front Cover Assembly Boost Protection and Calibration	Baseline/EVA	144/118	-
.11	Front Cover Latch Mechanism	Automated	25	6
.31	Front Cover Latch Mechanism	Manual	11	6
.12	Cover Swing Arm	Automated	34	1
.32	Cover Swing Arm	Manual	22	1
.03	Cover Structure		85	-
02.09.03.0	Rear Cover Assembly	Baseline/EVA	64/54	-
.11	Electrical Connector Assembly	Automated	11	

Figure 18. Typical Payload Detailed WBS

Table 4 presents the summary costing for the representative payloads. The data shows totals for baseline and EVA payloads, as well as gross and net savings.

3.2 PROGRAM MISSION MODELING

An extensive systems analysis was conducted so as to attribute routine EVA cost savings to a total Shuttle traffic and mission model. In order to cost "represented" payloads, the appropriate "representative" payload DDT&E cost should be multiplied by the total number of programs. However, payload designators do not always correlate with programs. Since technical characteristics of Shuttle payloads are only consistently defined in the SSPD documents, the costing of all payloads by relationship to representative payload was based on these data.

The number of end item units and unique sets of mission equipment can only be derived from an examination of flight schedules. To determine final study flight schedules (and thus numbers of units and mission equipment), preliminary data which related the "572" flight schedule to the MSFC traffic model were used. The result is contained in total in Volume II with all payloads grouped with their representative payload. Pertinent data from this model are summarized in Table 5.

Table 4. *Representative Payload Summary Costing, $K*

PAYLOAD	BASELINE CONCEPT COST			EVA CONCEPT COST			GROSS SAVINGS	EVA INCR	NET SAVINGS
	NR + REC	NR	REC	NR + REC	NR	REC			
EOS	233.0	170.5	62.5	230.7	168.7	62.0	5.4	3.1	2.3
GRS	45.8	33.7	12.1	43.9	32.1	11.8	3.0	1.1	1.9
LST	180.0	124.3	55.7	166.5	115.6	50.9	16.9	3.4	13.5
MIN	2.4	1.9	0.5	2.2	1.8	0.4	0.2	0.0	0.2
MFM	16.4	11.9	4.5	15.3	11.1	4.2	1.7	0.6	1.1
HAE	25.1	19.1	6.0	24.7	18.7	6.0	1.4	1.0	0.4
DOMSAT	23.9	17.0	6.9	23.0	16.3	6.7	1.4	0.5	0.9
GEOPAUSE	41.0	29.6	11.4	39.9	28.8	11.1	1.8	0.7	1.1
MJO	46.8	32.1	14.7	45.6	31.1	14.5	3.6	2.3	1.3
SIRTF	72.8	58.9	13.9	66.0	53.1	12.9	11.3	4.5	6.8
AMPS	245.5	109.2	136.3	238.5	103.7	134.8	11.1	4.1	7.0
ATL	149.7	111.0	38.7	135.5	99.5	36.0	21.0	6.8	14.2
PHYS-CHEM	35.4	27.7	7.7	27.7	21.5	6.2	10.1	2.4	7.7
TOTAL	1117.8	746.9	370.9	1059.5	702.0	367.5	88.9	30.5	58.4

Table 5. *Study Payload Model Summary*

SPACECRAFT	NO. OF PROGRAMS	NO. OF NEW UNITS	EQUIVALENT SHUTTLE FLIGHTS	SPACECRAFT DELIVERY	SPACECRAFT RETRIEVAL	SPACECRAFT SERVICE
● LEO						
LOW-COST REUSABLE	5	19	38	51	40	4
LOW-COST EXPENDABLE	1	6	3	6	-	-
CURRENT DESIGN REUSABLE	8	19	34	38	25	24
CURRENT DESIGN EXPENDABLE	1	6	1	6	-	-
LEO TOTAL	15	50	76	101	65	28
● HEO						
LOW-COST REUSABLE	3	6	8	12	9	-
LOW-COST EXPENDABLE	5	24	12	24	-	-
CURRENT DESIGN REUSABLE	12	66	51	92	35	3
CURRENT DESIGN [illegible]DABLE	2	2	2	2	-	-
PLANETARY/LU[illegible]R	14	30	30	30	-	-
HEO TO[illegible]	36	128	103	160	44	3
AUTOMATED TOTAL	51	178	179	261	109	31
SORTIE PAYLOADS	23	71	181	235	MISSION DAYS 2193	
DOD FLIGHTS	N/A	N/A	155	N/A	N/A	N/A
NON-NASA/NON-DOD SORTIE	N/A	N/A	29	43		
TOTAL	74	249	544	639	109	31

3.3 COST EXTRAPOLATION

Detailed EVA cost savings data from the costing analysis performed on each representative payload was listed separately for the spacecraft, mission equipment, and orbital support unit. Each represented payload was then assigned a technical complexity factor based on engineering evaluation. Data on costing and results for each group are summarized in Table 6. The baseline (each) data are taken directly from the CAM IV output tab runs for representative payloads and rounded to the nearest $100,000. The quantities for non-recurring (program DDT&E) and recurring (number of flight units) are based on the study model. The equivalent quantities were determined by application of technical complexity factors and learning curves.

Table 6. Total Program Cost Summary (millions $)

Payload Group	Equivalent Units						Extrapolated Model					Total Savings ($M)	
	S/C Syst		M.E.		OSU		DDT&E		Recurring				
	NR	Rec	NR	Rec	NR	Rec	Each	Total	Each	Total	Total	Amt	%
EOS	5	14	5	15	5	5	$170.5	$ 852.5	$ 62.6	$ 858.2	$ 1710.7	$ 14.9	0.9
GRS	1	6	1	6	2	2	33.7	34.9	12.1	69.3	104.2	3.5	3.4
LST	8	14	8	14	9	9	124.4	1004.2	55.7	738.0	1742.2	121.1	7.0
Mini LAGEOS	-	-	1	6	1	1	2.0	2.0	0.4	0.9	2.9	0.2	6.9
MFM	3	6	3	8	3	3	11.9	35.7	4.5	22.9	58.6	4.0	6.8
HAE	5	24	5	24	7	7	19.1	97.9	5.9	132.8	230.7	3.3	1.4
DOMSAT	12	62	14	74	14	14	17.0	219.9	6.9	440.9	660.8	23.3	3.5
Geopause	2	2	2	2	2	2	29.6	59.2	11.4	22.3	81.5	2.5	3.1
MJO	14	30	14	30	16	16	32.0	454.0	14.7	417.7	871.7	20.2	2.3
AMPS	-	-	4	5	-	-	109.4	437.6	136.3	667.7	1105.3	29.2	2.6
SIRTF	-	-	10	35	-	-	58.9	589.0	13.9	476.1	1065.1	94.1	8.8
ATL	-	-	15	20	-	-	111.0	1665.0	38.7	758.6	2423.6	226.1	9.3
PCF	-	-	1	2	-	-	27.7	27.7	7.7	15.2	42.9	9.2	21.4
Total							$747.2	$5479.6	$370.8	$4620.6	$10099.8	$551.6	5.5

Overall savings for the study payload model totaled $551 million, a net savings out of a total of $10.1 billion established by extrapolation from the representative payloads. To identify additional savings, estimates were made for DoD spacecraft and non-NASA sorties by a simple ratio of flights, and do not reflect detailed technical nor cost analysis. These data are shown in Table 7.

3.4 SPECIAL EVA ISSUES

In the process of analyzing EVA design orientation, several issues were presented which, while not in the mainstream activity of the study, potentially could impact the validity of the study results. These are: man-rating requirements, EVA contamination, availability of equipment, and trained personnel.

These analyses were based on concerns frequently expressed in the payload community regarding the use of EVA as expressed in two generalized questions: (1) what are the impacts on the payload (costs, design complexity)? and (2) what are the costs of acquiring and using an EVA capability?

Table 7. Routine EVA Net Cost Savings Summary

Group	Auto S/C Qty.			Sortie P/L Qty.			Savings Total $M
	Prog.	Units	$M	Prog.	Units	$M	
EVA study Traffic/ Payload Model (NASA & Non-NASA)	51	178	192	23	71	359	551
DoD Spacecraft	44	154	166	-	-	-	166
Non-NASA Sortie (ESRO & Space Manufacturing)	-	-	-	4	11	59	59
TOTALS	95	332	358	27	82	418	776

3.4.1 Man-Rating

A totally objective evaluation of vehicle man-rating requirements and costs would require determining two alternate designs to meet mission objectives--manned or unmanned. In fact, of course, unmanned projects have only considered automated/mechanized functional performance. Manned programs were also single-minded from the start in major concepts, but did frequently involve lower level trades. Historical data furnished sources for defining man-rating cost elements.

Vehicles developed exclusively for manned flight, are analogous to the Shuttle Orbiter. These vehicles were also involved in dynamic flight operations including atmospheric flight, entry, landing, and potentially pad abort. None of these requirements apply to Shuttle payloads. The Lunar Module (LM) and the International Docking Module (IDM) have some analogy to the Spacelab module in that they are (partially at least) dependent upon another manned vehicle. The Apollo Telescope Mount (ATM) is comparable to Spacelab pallets and to automated spacecraft while they are installed in the Shuttle cargo bay.

A summary of cost elements associated with man-rating is presented in Table 8. Most man-rating requirements (life support, protection, refuge, and rescue) are provided by the Shuttle or Spacelab systems. The only EVA chargeable cost element for payloads is provision of a safe work station.

Table 8. Man-Rating Requirements

FACTORS/PROGRAMS	MAN-RATING COST ELEMENTS					
	LIFE SUPPORT	VACUUM & RADIATION PROTECTION	THERMAL & METEOR PROTECTION	CREW REFUGE	RESCUE PROVISIONS	SAFE WORK STATIONS
PAST PROGRAMS						
APOLLO CSM	X	X	X	X	X	X
LEM	X	X	X	X	X	X
SKYLAB	X	X	X	X	X	X
CURRENT PROGRAMS						
INTERNATIONAL DOCKING MODULE	X	X	X	X		X
SHUTTLE	X	X	X	X	X	X
SPACELAB MODULE & P L	X	X	X	X		X
SPACELAB PALLET & P L						X
AUTOMATED SPACECRAFT						X
EVA PRESSURE SUIT	X	X	X			

In order to be accommodated on Shuttle or Spacelab missions, payloads must comply with a variety of safety rules, whether EVA is performed or not. These include flight safety provisions and ground crew personnel considerations equivalent to EVA provisions. Delta provisions required for EVA include consideration of load-bearing provisions for the EVA astronaut during zero-g activities and additional protection for delicate equipment or the pressure-suited crewman. Secondary power (ac) systems may require additional protection for EVA interface when not connected to the Shuttle common ground; however, primary power systems will be provided with a return non-structural ground.

3.4.2 EVA Provisions and Training

Shuttle baseline provisions ensure a capability to utilize EVA on any payload mission. The provisions include the airlock, suits, backpacks, and life support consumables necessary for two 2-man, 6-hour EVA's. This includes the provision of two trained EVA crewmen on each Shuttle flight. If one considers the current flight schedule planning and the crew necessary to support it, a total of about 120 crew members will be trained in EVA and available to payloads. While this is a generalized training, it should be noted that the Skylab astronauts performed alsmost as many unplanned EVA tasks as planned. The routine operations defined in this study also are particularly amenable to such generalized training. Even payload-unique training may not be a significant expense. Preliminary planning data for Shuttle indicate that the cost to a payload for crew procedures, use of water immersion and simulator facilities, and EMU/equipment would only be about $5000 (one man for 75 hours).

Additional EMU's, consumables, and trained crewmen can be carried to orbit, weight chargeable to payloads. Costs, if any, have not been established by the Shuttle program. Baseline provisions will include a manned maneuvering unit (MMU) for EVA free-flight operations. Some potential exists for advanced technology equipment allowing "quick-reaction" time, primarily relating to higher pressure EMU which could be used to preclude prebreathing. This quick-reaction time would permit action on contingency situations, not feasible otherwise. It would also significantly reduce the crew preparation time for EVA. Based upon analyses performed in this study, routine application of EVA can largely be accomplished within the level provided by the STS, with no known cost assessed against the payloads.

3.4.3 Contamination Issues

Another issue of concern among payload personnel is contamination caused by EVA crew. Various in-depth studies have been performed on sources and effects of contamination on payload sensors or equipment. EVA, as a source, has not been as thoroughly evaluated, and it was beyond the scope of this study to do so. However, it was decided to examine some aspects of this issue.

First of all, it must be realized that EVA is one of many sources, all of which are amenable to control techniques. Combustion products are emitted at a rate of 40 grams per second from a single vernier thruster when it is firing. For deadbands of 0.1 degree and larger, the average fuel consumption is 0.4 gram/second. Vented materials include gaseous hydrogen and oxygen and water vapor from fuel cell reactant tanks which are purged periodically. The emission rate shown for the EVA crewman is 0.004 for suit leakage only; water vapor from the suit thermal control system would be about 0.22 gram/second.

Thus, the EVA crewman introduces a very small increase in local contamination. But this source is localized in the cargo bay and, in some cases, protective measures should be taken. Advanced technology suits can potentially reduce the EMU levels well below that stated.

It was a general conclusion of the study that the EVA crewman produces a small and controllable contribution to the contamination level in the Shuttle, and that contamination covers can, selectively at least, be manually removed for on-orbit operations.

3.5 PROGRAMMATIC ISSUES

Two areas of EVA applications were studied programmatically in comparison to routine operations which were studied in detail. These are planned maintenance and contingency operations. The planned maintenance analyses were limited to comparing automated on-orbit maintenance to EVA maintenance, rather than evaluating all forms of on-orbit and ground maintenance or expendable spacecraft trades.

The contingency analysis was performed to establish the potential savings available by use of EVA based upon historical probability data. The use of the term "contingency" in this study is limited to Shuttle payloads and is defined as meaning any unexpected operations or equipment failure which impacts the normal course of the mission. By ground rule for Shuttle payloads, no such failure can occur which would endanger the crew or the Shuttle orbiter vehicle.

3.5.1 Study Contingency Analysis

The value of EVA for resolving contingencies has been strongly recognized since Skylab. On that program, EVA can be credited with saving the entire mission, in terms of restoring thermal control and electrical power, and with restoring a number of other functions/experiments. It was a major purpose of this study to quantify EVA savings in contingency situations.

Payload Model Contingencies. The spacecraft historical anomaly data examined in this contract were related to Shuttle-delivered spacecraft and sortie missions by analogy. These study efforts included interpreting and analyzing data for 20 U.S. space programs. The evaluation of historical spacecraft failures yielded information for application to the study traffic model for extrapolation purposes. Table 9 summarizes the contingency data and extrapolations to Shuttle payloads.

Table 9. Summary of Contingency Extrapolations

PRC SOURCE DATA:	PROGRAMS	PAYLOAD FLIGHTS	100% SUCCESS	100% LOST AT LAUNCH	OTHER PL'S WITH ANOMALIES	NUMBER OF ANOMALIES
SAMPLE GROUP	20	86	7	13	66	525
SHUTTLE PAYLOAD DATA:						
NASA AUTOMATED	51	261	21	39	200	1593
NASA SORTIE	23	235	19	35	180	1434
DOD AUTOMATED	N/A	155	13	23	127	946
NON-NASA SORTIE	N/A	43	3	6	33	262
STUDY TRAFFIC MODEL			EXTRAPOLATED FROM PRC TOTALS			

Potential EVA Savings. Savings can be derived from reduced transportation costs (orbiter flights) or experiment costs (loss of all or part of payload equipment). If an automated payload contingency occurred during or after delivery to Shuttle orbit, the contingency could require return of the spacecraft to earth for repair and a subsequent reflight.

If the contingency occurs on low earth orbit spacecraft after the orbiter has returned to earth, the repair and return of the spacecraft to operational status could require two flights of the orbiter; in either case, EVA could potentially save one orbiter mission (or ~$10M).

For sortie payloads the contingencies could be failure of a major experiment to function after the sortie flight arrives at the operational orbit. Analysis of representative payload groups shows an average cost penalty of \$3.5 million; i.e., about one-third Shuttle mission, for reflight. An EVA capability may allow immediate repair and completion of the experiment program so that a subsequent flight is not required. Average costs of sortie units extended beyond the Shuttle and jettisonable would result in hardware losses of \$1.7 million which might be prevented by EVA stowage.

By extrapolating from these data to the mission model and probability of failure, approximately \$1.9 billion savings exist as shown in Table 10.

Table 10. Contingency - Potential Cost Savings

			COST \$M
AUTOMATED SPACECRAFT TRANSPORTATION			
• NASA	39	UNSUCCESSFUL DELIVERIES	390
	39	LEO RETRIEVALS (≤ 50% LIFE)	390
• DoD	23	UNSUCCESSFUL DELIVERIES	230
	29	LEO RETRIEVALS (≤ 50% LIFE)	290
SORTIE PAYLOADS			
• NASA	35	UNSUCCESSFUL PAYLOAD EXPERIMENTS	125
	215	FAILED EXTENSION ELEMENTS JETTISONED	367
• NON-NASA	6	UNSUCCESSFUL PAYLOAD EXPERIMENTS	11
	39	FAILED EXTENSION ELEMENTS JETTISONED	67
• TOTAL POTENTIAL FOR EVA SAVINGS			\$1870 M

3.5.2 Analysis of Time-Critical Contingencies

A further analysis of this historical payload failure data was performed to identify failures whose consequence could be time-critical in terms of mission success or equipment losses. Failures in various subsystems were found to have time-critical results frequently in one or more categories. Time-critical categories are defined to include the following:

1. *Loss of consumables.* Leakage of spacecraft fluid supply causing mission abort and subsequent reflight if not halted.

2. *Loss of specimen.* Thermal and atmospheric environment failures time critically affecting bio-specimens.

3. *Missed launch window.* Sun-synchronous and geosynchronous spacecraft sensitive to the timing of their separation from Shuttle.

4. *Missed ground track or target.* Opportunities on a sortie mission limited due to look angles, field of view of changing phenomena.

5. *Off-nominal thermal condition.* Trends in payload thermal condition due to failures causing serious secondary effects.

A typical example of a time-critical contingency is the loss of consumables such as gaseous nitrogen. Assuming a given volume, temperature and isothermal expansion, the length of time for pressure to drop to a critical level was determined as shown in Figure 19. This point can be avoided if a successful repair can be effected. The rate at which the pressure drop occurs will determine the time available to prepare for EVA and perform a fix. Ability to locate the hole and perform a repair depends in part upon the reaction capability of the astronaut and the EVA equipment provided by the STS.

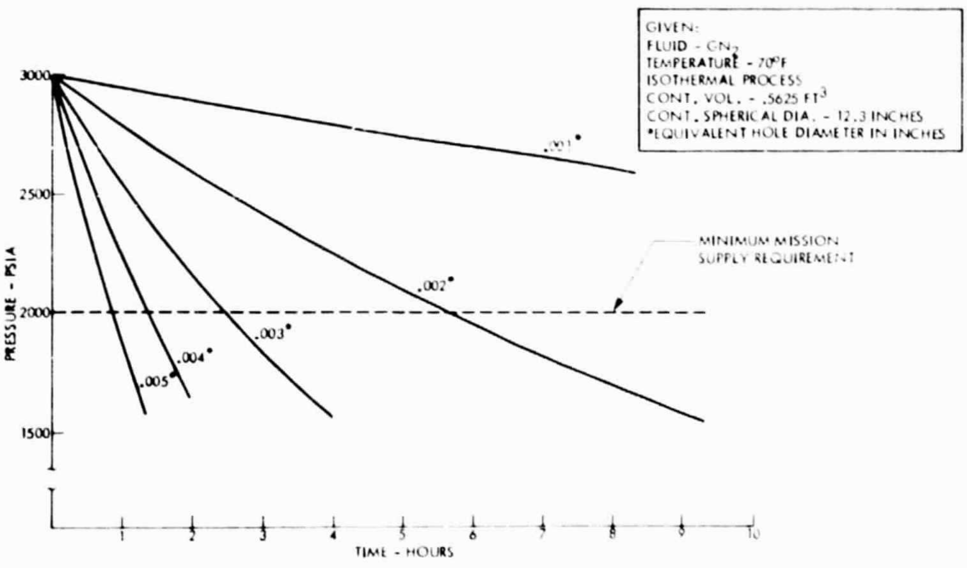


Figure 19. Typical Gas Leak Rates

Target opportunities on a sortie mission are limited due to look angles, fields of view or changing phenomena. Certain payloads have planned events, such as the ATL Barium Cloud Release experiment. This may be performed with a ground launch which requires that the on-board sensors be ready on a one orbit opportunity. Even where a mapping pass is repeated, planned mission activities may be impacted when the repeat mapping runs are required. Typical situations for sortie payloads are shown in Figure 20.

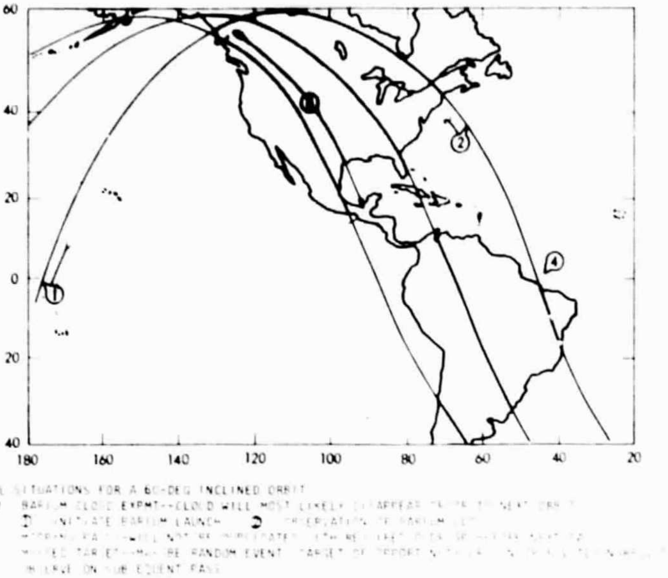


Figure 20. Loss of Ground Track or Target

Summary. Based on the number of anomalies in the data which resulted in time-critical consequences, percentages of total payload deliveries were calculated to apply to Shuttle payloads. An initial screening of the Shuttle payloads was made so that the percentage would only be applied to those payloads with a potential for the defined time-critical consequence. For example, only payloads with bio-specimens could have a potential loss of specimens. Further screening eliminated, where feasible, those anomalies where EVA response was precluded. The sum of all time-critical anomalies is about 15 percent of the total extrapolated number of potential anomalies.

Estimates were made of potential cost savings where there is a quick-reaction EVA capability to repair. The ratio of early failures is based on the overall contingency analysis presented earlier. The potential cost savings are tabulated in Table 11. This figure is conservative in comparison to the number of time-critical contingencies (15 percent) of all contingencies. By the same relationship, 15 percent of \$1870 million would equal \$281 million savings.

3.6 PLANNED MAINTENANCE ANALYSIS

The analysis of planned maintenance in the study was limited to comparing automated on-orbit maintenance to equivalent maintenance performed by EVA. The evaluation was programmatic in that it only compared equipment and transportation cost differences. The analysis was enhanced by the study of two representative payloads which have baselined alternate modes: EOS, automated maintenance; and LST, EVA maintenance.

There are several mission options for performing maintenance on both low earth orbit (LEO) and high earth orbit (HEO) spacecraft (low earth orbit spacecraft are those which are operating at altitudes and inclinations which allow the Shuttle orbiter direct rendezvous).

Table 11. Potential EVA Savings in Time-Critical Contingencies

POTENTIAL CONDITION	POTENTIAL SPACECRAFT W/ANOMALIES		NO. EARLY FAILURES(.024) S/C LOST/ANOM.		$M POTENTIAL COST/ANOM.		$M POTENTIAL SAVINGS	
	AUTO S/C + DoD	SORTIE P/L + NON-NASA	AUTO S/C	SORTIE P/L	AUTO S/C	SORTIE P/L	AUTO S/C	SORTIE P/L's
LOSS OF CONSUMABLES	64+39=103	58+10=68	2.5	1.6	10	10	25	16
LOSS OF BIOSPECIMENS	2+0=2	4+1=5	0.05	0.1	10	10	1	1
THERMAL PROBLEMS	79+47=126	56+9=65	3.0	1.6	10	10	30	16
MISSED LAUNCH WINDOW	132+78=210	---	5.0	---	3.3	---	17	---
MISSED TRACK OR TARGET	---	60+6=66	---	1.5	---	3.5	---	5
TOTALS	441	204	10.55	4.8	---	---	73	38
					TOTAL		$111 M	

For the HEO spacecraft, two alternatives were considered: (1) using an upper stage for delivering either an automated or a manned servicing module to the orbit of the spacecraft being maintained, and (2) using the upper stage to retrieve the spacecraft and bring it to the Shuttle orbit. The spacecraft maintenance would then be performed while attached to the Shuttle, either with an automated or with an EVA approach.

The significant difference between LEO and HEO maintenance missions lies in the added costs of the upper stages and operations. Figure 21 illustrates that one Shuttle-Tug launch would be required to carry an automated servicing module to the geosynchronous orbit. Previous studies have shown that two high technology Tugs would be required to transport a manned servicing module from the Shuttle altitude to the geosynchronous altitude and return. Because of the size and mass of the required Tugs, this maintenance would require two Shuttle launches. Two Tugs and two Shuttles are also required for servicing the HEO spacecraft at the Shuttle orbiter orbit.

Comparative cost savings between automated methods and EVA were based only upon differences in transportation and equipment costs. Equipment costs were derived on two representative payloads (EOS and LST) and extrapolated to spacecraft programs in the study model.

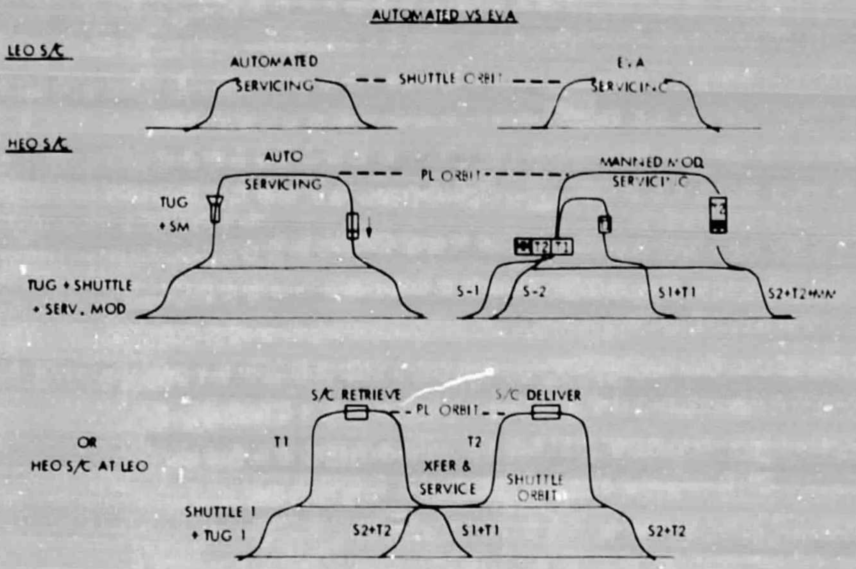


Figure 21. Maintenance Mission Options

The cost of automated maintenance units were established at $7.5 million DDT&E and $5 million first unit. The comparable EVA costs were $2.8 and $1.4 million, respectively. Table 12 summarizes the results.

Table 12. On-Orbit Planned Maintenance Savings

MISSION	MODE	COST $ M SUPPORT SYSTEM	COST $ M TRANSPORTATION
LEO	AUTO	248	
	EVA	80	
● EVA NET SAVINGS $ 168 M			
HEO	SHUTTLE ORBIT		
	AUTO	238	1128
	EVA	60	1128
	S/C ORBIT		
	AUTO	238	564
	EVA	235	1128
● EVA LESS ECONOMICAL THAN BEST CASE BASELINE.			

IV. STUDY CONCLUSIONS

4.1 STUDY ACCOMPLISHMENTS

This study activity began with four stated objectives. Results of the study as reported in this final report have met these objectives in the following manner.

1. *Identify uses of EVA which significantly reduce payload costs.*

The study identified 61 potential EVA Applications--44 of which were Routine Operations; i.e., applied at some point in the mission cycle of every payload. Detailed design and cost data on mechanized elements resulted typically in Net EVA Savings of $75 to $150K for each such manual alternative. Conservatively, cost savings were only accumulated for 21 out of the total of 44 routine applications for which technical assurance and credible cost data could be provided.

2. *Compare Technical and Economic Characteristics of Selected Payloads--Automated, Teleoperator, or EVA Design Oriented*

Thirteen representative payloads were analyzed in the study. Baseline (automated) modes of operation were evaluated and compared to teleoperator and EVA modes. In all cases, EVA presented design simplification and lower costs. While the teleoperator mode, as typified by the Shuttle RMS, could reduce costs from the baseline, it was more costly than the EVA mode, lacked flexibility and the capability of accessing task areas. Figure 22 summarizes the percentage of gross and net savings attributed to EVA for DDT&E and first unit costs for representative payloads.

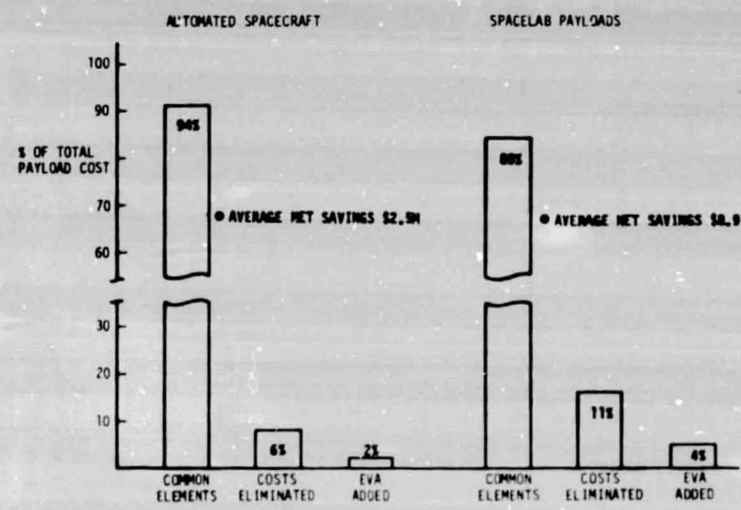


Figure 22. Typical Cost Ratios - Representative Payloads

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3. Determine the amount of these savings and extrapolate to the NASA payload model.

The thirteen representative payload programs were extrapolated to a total of 74 programs compatible with EVA applications. These 74 programs require 249 flight units on a payload schedule compatible with the "572" Flight Model. Using appropriate complexity and learning factors, net EVA savings were extrapolated to over \$551M for NASA and U.S. civil payloads for routine operations. Adding DoD and ESRO payloads increases the net estimated savings to \$776M.

4. Develop costing methodology for further NASA use.

The costing of representative payloads involved the examination of spacecraft analogs, development of CER's and expansion of previous computer models. These data have all been furnished to the study Technical Monitor, as well as the overall methodology applied.

4.2 MAJOR CONCLUSIONS

1. EVA design considerations must be applied to payloads during design development phase. While many advantages and cost savings can be achieved through application of EVA to conventionally designed spacecraft, best results can only accrue when EVA is "designed into" the payload--(1) to achieve maximum savings due to manual design, and (2) to ensure capability of manned interface in contingencies.

2. Payload programs will not be required to invest in EVA capability. Baseline Shuttle includes all investment costs associated with EVA--airlock, EMU, and life support tankage.

3. The Shuttle manipulator system is not a suitable alternative to EVA. The RMS lacks features for performance of small, varied tasks requiring access to a variety of locations in and around the payload. In addition, costs of special RMS interfaces would be greater than manual designs. The RMS provides valuable assistance to EVA.

4. Remotely-operated mechanical devices are complex and costly. Conventional payload electro-mechanical elements require sophisticated design and extensive development and qualification testing. EVA (manual) alternatives are current state-of-the-art, generic design, low-cost, and trouble-free.

5. Deployment and stowage functions are required for Shuttle payloads. Positioning of spacecraft and sortie experiment hardware within the Shuttle mold line is comparable to conventional boost shrouds. Consequently, typical boost lock and extension functions are required. Furthermore, in order to achieve full benefits from Shuttle retrieval capabilities (either scheduled or unscheduled), retraction and entry latch functions are required (i.e., two-way in lieu of conventional one-shot devices). Manual designs for these functions result in considerable cost savings and increased reliability.

6. *Shuttle safety rules currently preclude manual stowage.* A problem exists in ensuring EVA savings in that current Shuttle safety guidelines require remote control capability with two-way redundancy or jettison back-up.

7. *Umbilical requirements/concepts are an undeveloped technology.* Current plans call for multi-mission deliveries and retrievals of automated spacecraft. Operational needs and safety requirements dictate various signal, power, and fluid interfaces with the Shuttle. These interfaces must be broken and engaged to perform separation and retrieval operations. No development efforts in this field were observed in the course of this study. A conclusion of the study was that significant cost savings could be achieved with a manual design compared to remote electro-mechanical.

8. *Use of EVA does not contribute major operational costs to payload programs.* Concern about "man-rating" is generally over rated. Only minor delta design provisions, if any, are required over and above Shuttle safety rules, ground handling requirements or good design practice. EVA trained crewmen will be provided within the Shuttle cadre, and the generalized tasks for EVA described in this study should not warrant special payload-oriented training with perhaps few exceptions (e.g., unique maintenance).

9. *Contamination is not a prohibitive concern.* EVA contribution is small compared to other sources and is controllable--especially with technology improvements.

4.3 SUMMARY OF RESULTS AND RECOMMENDATIONS

4.3.1 EVA Operations

Credible task-time data from various sources were applied to the payload operations to derive integrated, comparative timelines. By the use of EVA, routine preparation timelines were decreased in one case by 1.7 elapsed hours to a maximum increase of 1.3 hours--average 0.5 hour increase. Actual EVA durations ranged from 1.5 hours to 5 hours--average 3.7 for routine operations. These activities require the following:

One-man EVA	11 payloads
Two-man EVA	2 payloads
One EVA cycle	9 payloads
Two EVA cycles	4 payloads

Maintenance timelines required up to 3 six-hour EVA's. It should be noted that retrieval operations would generally require the equivalent 1.5 to 5-hour one or two-man EVA's as discussed above for preparation. Thus, a worst case could involve 4 or 5 two-man EVA's, thus exceeding Shuttle-provided consumables.

4.3.2 Cost Summary

EVA was found to provide savings in the categories of routine operations, planned maintenance, and contingencies. Basic traffic model data indicated a net savings of about \$551M out of a total payload cost estimate of \$10.1B--or, about 5.5 percent. With additional extrapolation to DoD and some non-NASA payloads the total savings estimate was $776M. Planned maintenance for a projected 13 payload programs (out of a possible 51 payload programs) indicated an estimated $168M savings due to elimination of automated servicing equipment. If all spacecraft designated "Reusable" (28 programs) are included, the potentially extrapolated cost savings of the EVA mode would be ~ $316M. EVA savings for contingency problems of payloads were based on transport and equipment costs only. While the historical data do not necessarily establish expected failure rates for Shuttle payloads, the failure information was examined to select (conservatively) only credible analogs. The total estimated EVA savings were $1,950M. Table 13 presents a summary of gross savings by category. These data are not additive in total in that (1) automated maintenance has not necessarily been planned for the 13 programs on which the estimate was based--therefore, may not require any actual cost, and (2) many contingency savings are based on "automated" device failures which, if routinely replaced by EVA designs, would not occur.

Table 13. Program Cost Savings Summary

		$M TOTALS
ROUTINE OPERATIONS		
• AUTOMATED SPACECRAFT		358
• SORTIE PAYLOAD		418
		776
PLANNED MAINTENANCE		
• AUTOMATED SPACECRAFT - LEO	168	
• AUTOMATED SPACECRAFT - HEO	NO EVA BENEFIT	
		168
CONTINGENCY APPLICATIONS		
• AUTOMATED SPACECRAFT	1300	
• SORTIE PAYLOAD	570	
		1870

4.3.3 Recommendations

Recommended areas for further effort form the conclusion of this section. Some of these items are currently planned in follow-on contract activity with the Ames Research Center, in particular, interaction of study data with the payload community and advanced technology requirements. Full benefit of EVA applications can best be achieved in conjunction with appropriate Shuttle payload accommodation documentation.

Among the issues involved with EVA are technology issues associated with EVA equipment. Several of these issues relate to improved reaction time. Technology improvements could reduce prebreathing and suit donning times. Several analyses in the study indicated improved operations or increased cost savings could be attributed to quick-reaction; e.g., increased experiment time in an EVA mode and time-critical contingencies. Overall mobility was not evaluated in detail. However, in the process of examining the crew time sequences, especially for crewman translating through a maze of sortie payload experiments, his visibility and mobility should be the best possible to preclude damage to equipment or the FMU. Finally, EVA tool and interface developments are important to achieving the results defined in this study. A summary of recommendations includes:

- Interact results of study with payload community
- Review Shuttle payload specifications for compatibility
- Perform specific payload detailed designs
- Develop further EVA system requirements
- Perform selected simulations