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DEVELOPMENT AND UTILIZATION OF A SPACE STATION MISSION SIMULATION MODEL

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ABSTRACT

During the past year, a set of digital programs for the simulation of manned space station missions has been developed. These programs are analytical tools for design analysis and evaluation of such factors as subsystem capability, onboard experimental programs, crew size and skill-mix, logistics system capabilities, major system trade-offs and mission planning requirements.

This paper traces the program development and describes a simulation model designed for preliminary analysis of space station missions. A description of the model utilization and the areas in which it is proving to be of greatest value are included. Some results from the use of this model are also presented. The conclusion points out some considerations which have proven to be of importance in the construction of complex simulation models.

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INTRODUCTION

Over the past few years the growing complexity and costs of systems required to support space research and technology have generated a need for improving overall program management and concept evaluation techniques.

Some of the more recent areas of study in space research have been devoted to the conceptual design of orbiting, manned space stations capable of fulfilling basic, space related, research objectives. These system designs must reflect operational requirements for maximum utilization of available resources and identify important parameters for consideration in future plans.

One example of a space station system concept is the Manned Orbital Research Laboratory (MORL).[1] (See fig. 1.) This is an earth orbital experimental research facility for the study of space flight and man's capability to function effectively under the stresses of the space environment for long periods of time. This system includes provisions for logistics supply of the station, adequate recovery forces, communications support, and facility maintenance.

How does one go about designing and managing such large, complex systems? How is it possible to obtain the necessary information on cost, utilization, and efficiency of operation? How can the different design concepts be evaluated to find the more practical ones?

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One approach to providing answers to these questions on system design and analysis is through the use of detailed mathematical models constructed to represent the concepts under investigation and implemented by digital computers.

The use of mathematical models to simulate the various interrelated aspects of a complex system like the MORL must provide realistic measures of performance, cost effectiveness, and efficiency of operation as the system evolves from preliminary design to operational status. The flexibility and growth potential of mathematical models enable the designer-manager to vary the system and the research and development objectives as new concepts and approaches are formulated. Figure 2 depicts a space station simulation computer model.

A Space Station Mission Simulation Mathematical Model[2] based on the requirements of the Manned Orbital Research Laboratory concept has been constructed to encompass a large spectrum of space missions with the capability of adding detail and sophistication as required. The total model concept is one of sequential development of a mission simulation from a parametric study of basic mission requirements and alternatives to a detailed simulation of manned missions utilizing Monte Carlo techniques to process random events. The model consists of three separate submodels, each capable of independent study analysis. (See fig. 3.)

The first of the three submodels, the Preliminary Requirements Model (PRM), is tailored to solving problems related to conducting experimental work on a space station. Constraints on crew size, cross-training, and time available to conduct the experiments are applied in assignment of work loads. It is capable of scheduling experiments by geometrical techniques and of selecting the optimum crew skill mix to perform the experiments. The PRM is particularly applicable to a rapid evaluation of a large number of mission planning alternatives.

The Planning Model of the Space Station Simulation goes beyond the broad analysis made by the PRM. It proceeds to a detailed development of specific mission plans. This model employs parametric and deterministic analyses to provide a nominal mission plan for a specific mission with schedules for all tasks and logistics requirements for that mission.

The Mission Simulation Model, the third space station submodel, simulates the actual mission from the laboratory launch and unmanned checkout phase to the end of the mission. With the nominal plan from the Planning Model as input, and using a random event generator, an event controller and an overall control program, the random events and probabilistic effects are generated and processed as encountered. Mission modifications are made as the simulation proceeds until either an abort is called for or the end of the mission is reached. This model is a simulation in the true sense of the word. As nearly as possible, events happen as they would be expected to occur on an actual space station mission. Such phenomena as failures with attendant repairs and replacement of components, crew sickness, emergency procedures, rendezvous and recovery, and rescheduling due to unfinished tasks are encountered and the effects analyzed. Figure 4 illustrates the utilization sequence for the total space station simulation.

This paper will cover a detailed description of the first of the three submodels, the Preliminary Requirements Model (PRM). It will describe the PRM's utilization as a base for building and using the more sophisticated models to point out the value of a step-by-step concept of model construction.

The paper will also describe the application of the PRM as an analysis tool in its own right and include examples of studies made with this model.

PRELIMINARY REQUIREMENTS MODEL

One of the major difficulties in the construction of a mathematical model to represent any system as complex as a space station system lies in simplifying the problem to readily understandable dimensions without a corresponding deterioration in the value of the modeling technique. Decisions must be made, during the model design phase, as to what the simulation can reasonably be expected to cover. This allows the model builder to start with fairly broad, basic concepts and expand on this base to develop a detailed mathematical representation of the system under investigation.

The Preliminary Requirements Model is an example of a relatively noncomplex model constructed from a broad well-defined base. Using this base, further expansion and sophistication produces a more detailed and complex model without destroying the user's understanding of the concept under analysis. At the same time, the PRM is a useful analysis tool for the formulation of basic mission requirements and the evaluation of broad-base mission alternatives.

A primary function of the PRM is to produce outputs concerning the assignment of work to a given crew using an experiment scheduler to make work assignments more realistic, a skill optimization procedure to choose the crew for a given experiment plan, and a section for broad-base logistics analysis to ensure its compatibility with the Planning and Simulations Modes of the Space Station Model. This model provides a means for obtaining a rapid evaluation of the results of proposed missions and is particularly useful in cases where mission results are required on a gross basis only, and in the early stages of mission planning where exact input data are not available. The user must be aware of the types of analysis toward which the PRM is directed in order to understand the value of the results obtained from its use. Figure 5 shows, briefly, the scope and utilization possibilities for this model.

Following is a detailed discussion of the model logic and capabilities and some results obtained from the use of the Preliminary Requirements Model.

CREW SKILL OPTIMIZATION

Since many experiments require special skills the efficiency with which any crew is utilized during a space station mission is particularly sensitive to the skills available in the crew makeup.

One important capability of the Preliminary Requirements Model is the option which requires that the model logic choose a crew skill mix for a given experiment package.

The major difficulties in this area of analysis are in obtaining reliable predictions of man's capabilities in space and in developing a procedure for specifying a finite set of "types" of astronauts. Because of the limited amount of data describing the type and degree of cross-training a crewman may be expected to possess, as well as the subjective nature of this assessment, the procedure used to specify skill-mix types must permit flexibility in selecting these types.

The method employed in the PRM is to use a matrix of proficiency levels in which each row is a type of astronaut having a specified ability in each skill column. (See fig. 6.) Any alternate set of skills may be used. Proficiency levels ranging from highly proficient to no ability in the skill category may be specified, as indicated in figure 6 by the numbers 1 and 0, respectively. Since the results of this procedure are highly sensitive to the rules applied in the construction of this matrix, it is important that considerable care be taken in their development and application. In the construction of the matrix, recognition of the skill requirements of the experimental program and such individual constraints as cross-training between skills and skill types is essential. For instance, while a person with a full proficiency as a biochemist could reasonably be expected to possess a partial ability as a medical doctor, it may not be reasonable to expect him to also have a full proficiency as an electrical or mechanical engineer.

In order to obtain realistic inputs for exercising the model, a preliminary set of skill types and mixes compatible with the MORL baseline experiments were generated. Twenty skills were identified as representative of the needs of the experiments under consideration and an estimate was made of the proficiency at which an astronaut in a particular skill could be expected to perform. This proficiency level was delineated by using a code number of 0, 1, or 2 where a 0 indicates that a man with this particular skill mix can not perform tasks requiring the corresponding skill; the number 1 indicates the ability to perform tasks with full proficiency; and the code number 2 indicates the ability to perform tasks with a low level of proficiency. To apply these indices to the problem of selecting a crew, it was assumed that a crewman with a proficiency factor of 2 requires twice as much time to perform a given task as a crewman with a factor of 1 in that skill. Figure 7 is an example of a skill mix matrix showing the twenty skills used in this study.

After defining the set of possible skill types the next step, for skill optimization, is to determine the best skill-type assignment for each onboard crew member during each launch interval. The term "launch interval" refers to the number of days between successive resupply launches. The skill type assignments are made subject to the constraints imposed by available crew time and the crew rotation profile. This rotation profile is an input matrix specifying which astronauts, of those available for the mission, are onboard during each launch interval. A zero in the input for any astronaut indicates that he is not on the station for the interval. Figure 8 shows a typical rotation scheme for a six-man crew using a total of eleven men for the mission.

Associated with each astronaut available for the mission is the option to specify the skill type he possesses at the start of the mission. This capability allows the user, at his discretion, to identify mission dependent skills such as: Flight Commander, Deputy Flight Commander, Medical Officer, etc. that are associated with a particular duty station. Only those crewmen with no "fixed" skill type are free to be skill optimized during a mission and once a man is assigned a skill type number by the optimization procedure, he must retain that number for the remainder of the mission.

Before choosing the "best" crew, the PRM optimizer must find the feasible combinations from which the selection can be made. This is accomplished by a series of steps in which a trial crew is defined. By making a substitution of types in this crew, another combination is obtained to compare with the first. Each time, the better of the two is retained as the original. In order to proceed with this method, criteria for selecting one crew as better than another have been set up as follows:

1. Experiments are assigned in descending order with respect to man-hours required, to the crewman with a skill proficiency of 1 who has the maximum time available to do experimental work.

2. Experiments remaining from the first step are assigned, again in descending order of man-hours, to crewmen with a proficiency of 2 in the skill required.

3. The values of total hours worked by the crew (W) and total experiment hours completed (E) are computed for the crew evaluation indices

$$\text{Primary index} = E - \frac{W}{C}$$

$$\text{Secondary index} = \frac{W - E}{E}$$

where C is the maximum acceptable price of an experiment hour in working hours. The choice of the best crew is based on maximizing the Primary index (greatest amount of experiment hours completed in the least amount of time). The Secondary index (efficiency of the crew based on comparison of experiment hours versus actual working hours) is used as a tie breaker such that, of two crews with identical Primary indices, the one with the Smaller Secondary index will be chosen.

Using the above testing procedure to choose among them, the crews to be examined are set up in the following manner:

1. (a) Each skill type is assigned to the "open" man with the greatest number of available working hours.
   (b) For each such assignment, the resulting crew, sized by the number of men with fixed or previously assigned types plus 1, is examined.
   (c) The best of the smaller "test crews" from step (b) is retained and steps (a) through (c) are repeated until each man has been assigned a skill type.

2. The difference between available working hours and total experimental hours worked is checked for each crewman; this is an indication of the crewman's efficiency in working the experiments assigned to him.

3. Finding the crewman with the maximum difference from step 2 (crewman X), his skill type is exchanged with those of the other "open" crewmen and the

resulting best crew of this set is checked against the original (crew before first exchange) or current crew. If the new skill group is better, it is retained and recycled through steps 2 and 3.

4. If the new crew is not an improvement over the current one, each skill type is assigned to crewman X and the best three of these new groups are checked against the current one. If one of these last crews shows an improvement, it is recycled through steps 2, 3, and 4; if not, steps 3 and 4 are repeated for a second open man.

The iterative improvement procedure is terminated when the iteration limit is reached or when the difference between crews is extremely small.

The crew chosen by the PRM optimization process is retained as the optimum crew for the launch interval, and work assignments are made to this crew.

EXPERIMENT ASSIGNMENT

In the section of the Preliminary Requirements Model devoted to work division, a given list of experiments is assigned to members of a selected crew (3 to 9 men) on the basis of the number of man-hours and the skill type necessary to complete each experiment. Experiments are assigned and scheduled for one launch interval (usually 90 to 180 days in length) at a time. These assignments are made subject to the constraints imposed by the crew time available for experiments and by the skills of the crewmen onboard during the interval.

The experiment assignment procedure used in this model may follow any of four methods. These are:

Method 1 - Equalize the total experimental man-hours of each crewman for the launch interval by assigning experiments with no associated priorities (the order in which the experiments are assigned is not specified).

Method 2 - Equalize the total experimental man-hours per day for each crewman in the launch interval by assigning experiments with no priorities.

Method 3 - Same as Method 1 except that the experiments must be assigned and scheduled in a specified order (priority method).

Method 4 - Same as Method 2 except that the experiments must be assigned and scheduled in a specified order.

The problem of assigning work to crewmen is handled by first checking an experiment for the skill it requires, then searching for the man most proficient in that skill. If more than one man has the top proficiency asked for, the assignment is made to the one with the minimum current load. The entire experiment package is handled in this manner with scheduling of experiments provided after the initial package assignment (non-priority case) or after each individual assignment (priority case). This procedure will set up unequal man-hour loads and prevent some experiments from being given to any crewman; therefore, it is necessary to employ an iterative process of reassignment among crewmen. The purpose of this is to use the entire crew in the most efficient way possible. The reassignments are made on the basis of minimum penalty. In other words, since assignments must be made to crewmen with proficiency ratings greater than 1 in some cases, this should be accomplished with as small an increase in man-hours as possible. (See fig. 9.) The ultimate result of this procedure should be an optimum balance of increased utilization of crew time and percent of experiments completed versus an increase in man-hours required to accomplish this.

The above process of work assignment must consider inherent constraints based on human capabilities and time allowances. These constraints are set up in the PRM in the following manner:

1. Each crew member is allowed a specific number of hours per day, his base load, which he can apply to experimental work. In addition to this, a crewman may be allowed to work on experiments for 2 or more hours a day over his base load for a number of successive days. However, as the number of successive days of overtime increases, the number of hours of overtime allowed in each day decreases proportionally. The figures used to specify this constraint are based on an allowable overtime curve showing duration versus hours per day. (See fig. 10.) At some number of successive days on the abscissa of this curve, a nominal load point is encountered. This is a line describing an area in which overtime for any specific day must be contained. As the number of successive days of overtime decreases and the nominal load point is reached, the allowable overtime per day increases and becomes a function of the slope of the curve.

2. In the equalization of workloads, as the number of experiments assigned increases and crewmen approach their maximum loads, assignments must be made to less efficient men, thus increasing the hours needed to work the experiment. A constraint is placed on this procedure, not only by maximum crew loads, but also by the specification of a maximum penalty for reassignment; that is, the maximum number of hours allowed to complete 1 hour of experimental work.

When all possible experiments have been assigned, the efficiency of the present crew can be measured by the relationship of the percentage of the total package completed and the actual man-hours required versus unpenalized man-hour totals.

Any experiments from the current supply interval which were not assigned, due to time shortage or requirements for a nonavailable skill, are carried over and given top priority for assignment in the next interval. Also retained for further assignment are the remaining man-hours for those tasks whose duration exceeded the launch interval duration. Both of the above carry-overs are shown in the interval summary along with a listing of each crewman, the experiments assigned to him, his total load and percent of utilization, and the percent of completion of the total experiment package. Figure 11 shows a typical output summary for one launch interval. The total hours worked is compared to the sum of experimental man-hours for a perfect assignment and result in a parameter, labeled inefficiency, which measures the composite effects of assignments to low proficiency personnel.

EXPERIMENT SCHEDULER

The experiment scheduler, which must be used with the assignment procedure, is basically a geometric technique for fitting several small rectangles into a larger constraining rectangle. Each experiment is defined as a rectangle; the length of which is the duration in days and the height being the average man-hours per day required to conduct the experiment. The Preliminary Requirements Model attempts to arrange (stack) these in an optimum manner in order to fit them within a larger rectangle; the width of which is the duration of the launch interval and the height representing the maximum hours per day that any crewman is allowed to work on experimental tasks.

The fitting process is carried out in three stages shown in figure 12. First, laying down a base of long experiments (those of duration longer than or equal to launch interval duration); then, adding the medium experiment (those of duration greater than half the launch interval duration); finally, the short experiments (duration less than or equal to half the launch interval duration) are fitted into the remaining area. At each stage, the experimental load is tested against the constraint of maximum hours allowed per day to see if the experiment being added will fit within the schedule. This load testing is performed by comparing the duration, hours/day, coordinate against an acceptable load curve for the onboard crew size. (See fig. 13.) The experiment is then accepted as scheduled or rejected until reassignment and/or rescheduling allow it to be accepted.

If a mission analysis is desired where the experiments are ranked by priority, the PRM will assign and schedule on a one-at-a-time basis. As each experiment is assigned it is scheduled along with those previously assigned to the same crewman. If constraints are violated the experiment is immediately reassigned and the same procedure followed until it is accepted for a crewman's work list or rejected by all crewmen.

In a nonpriority analysis all experiments for the launch interval are scanned and an initial assignment is made on the basis of optimum allocation of work load. The experiments are then scheduled and reassignments are made to balance work loads and to complete as many experiments as possible.

The preceding method of scheduling experiments is simple and not truly a schedule since it does not specify that an experiment must start on a particular date. This is, however, quite adequate for the analysis requirements in the PRM if the user remains aware of the fact that the purpose here is not to time-line a mission plan, but to optimize the total number of experiments which could be handled during a specific launch interval.

LOGISTICS

The logistics analysis section of the Preliminary Requirements Model is used to obtain the time between logistics launches (launch interval lengths) and to compute the excess capacity (weight and volume) of logistics carriers in order to determine the size of the experiment package for the launch interval.

PRM work assignments start at that point in the mission when the space station has been checked out, fully staffed, and is ready for the experimental program to begin. The initial laboratory and manning launches are considered only as an indication of the mission day on which the first assignments are to be made. Launch interval durations are determined from this point by the intervals between requirement days for equipment supply. Requirement days are specified by the user as a logistics library input.

Associated with each experiment is a specific weight and volume. These descriptors are totaled by the logistics analysis working down the experiment list. In sizing the payload for the logistics launches considered by this section, the PRM must first determine the excess capacity of the logistics carrier. This excess capacity is the weight and volume available for the experiment package. To find this carrier capacity, the amounts of carrier weight and volume specified for use by fixed equipment and expendables is computed for each launch. This value is then compared to the total capacity available in the multi-mission module type used for the launch and the difference, if any, is used to fix the experiment package size.

The PRM logistics analysis is thus used to give gross estimates on logistics requirements imposed by the experimental program.

One further option of the Preliminary Requirements Model should be mentioned in connection with its use as a screen for input data. This option allows the user to request four library data decks which may be used directly as input to the Planning Model to reduce the problems of input and case setup. The decks which may be produced are:

1. Logistics library deck consisting of various inputs for the Planning Model logistics routines.

2. Crew library deck containing data to specify the launch dates, stay times, skill types, and crew duty positions as well as the skill type arrays used in the PRM.

3. Experiment assignments library deck specifying the principal and alternate onboard crewman assigned to each experiment in each launch interval.

4. Task assignments library deck specifying the principal and alternate onboard crewman assigned to each of the station operations and maintenance tasks.

PRELIMINARY STUDIES

As previously mentioned, the Preliminary Requirements Model is a planning-type model for rapid evaluation of a large number of mission planning alternatives. Following are two typical examples of how this model can be applied to parametric analyses.

Problem I

The first analysis to be described here concerns the question of how an experiment program might best be accomplished.

The following experimental areas and their respective percentages of the total experiment package were considered:

Astronomy, percent	20
Earth resources, percent	13
Meteorology, percent	15
Biology, percent	20
Long-term flight, percent	18
Research and development, percent	14

In addition, the degree of skill participation assumed in each area is shown in figure 14.

The approach taken here was to examine the relative effectiveness of keeping up a constant level of effort in each of the above experimental areas in comparison with concentrating on one or more of the areas at the beginning of the mission and completing nearly all of the experiments for each of these before turning to another field of research. This approach resulted in three different program plans shown in figure 15. These three programs can be generalized as:

1. Continuous and constant level participation in all areas all the time.

2. Slight reordering of the above to concentrate on one or more of the areas in a given mission time frame.

3. A further reordering that concentrates a given area of activity in a time frame, followed by another area, etc. Some nominal level of effort for all areas is retained through the mission.

A second question investigated by this analysis is that of the effects of different levels of crew cross-training on experiment assignment and completion. For this aspect of the problem, three levels of cross-training were assumed.

The three levels represented here are: no cross-training (specialist in one skill only), medium cross-training, and a high level of cross-training. The proficiencies for each skill type were limited to either a 1 for full ability or a 0 for no ability. The 15 skills identified in figure 16 are distributed within the cross-training levels as shown in figure 14. The following list of assumptions are defined and maintained for all cases:

1. The mission duration was 5 years consisting of 10 launch intervals of 180 days each.

2. The onboard crew size was set at 6 men with a total of 30 astronauts in the program.

3. Crew rotation was 6, 2, 3, 2, 2, etc., new men each launch interval with the same scheme used for the number of men free to be optimized.

4. The crew was assumed to be available for experimental work a total of 42 man-hours each day. This was divided among crewmen 1 to 6 on the basis of 6, 7, 7, 6, 8, 8, hours/day, respectively.

5. The experimental program was sized to consume an average of 36 man-hours per day.

Results: Problem I

The results of this parametric study are shown graphically in figures 17, 18, and 19, and examination of these data leads to the following conclusions:

1. The results of the experimental program are relatively insensitive to the order in which the program is conducted. It should be pointed out here that this does not imply that the ordering of individual experiments will not affect the results. The PRM does not consider such things as resource demands and attitude requirements for experiments; therefore, the conclusion above is made only for the general ordering of experiment groups. In all three of the

program plans considered, the percent of experimental work accomplished is approximately equivalent at comparable degrees of cross-training. This will permit a high degree of freedom in program planning, since seemingly any order of conducting experiments will yield fairly good efficiencies.

2. As the degree of skill cross-training is increased, the percent of experimental work accomplished is also increased. However, of particular interest is the amount of increase. A significant increase is realized in going from the 15 specialists to the 6 medium cross-trained types of men. The increase is not nearly as pronounced in going to 3 highly cross-trained skill types.

Problem II

The second of the two problems described here concerned the effects of crew size on experimental program accomplishment. Four cases with variations in the crew size and in the number of men optimized during each launch interval were investigated in making this analysis.

All cases were run under the following conditions:

1. The same basic mission plan and experiment package were used for all runs.

2. Mission duration was equal to 18 months (540 days) or 12 months (360 days) with launch intervals of 90 days' duration.

3. Three men were rotated each launch interval with the exception of one case of a nine-man crew where six men were rotated.

4. Ten possible skill mixes were available for the crew composition with proficiency ratings of 0, 1, and 2 allowed.

5. Crew size variations were for a three-, six-, or nine-man crew in which three men were skill optimized each launch interval with the exception of a nine-man crew in which six men were skill optimized.

6. Man-hours available for experimental work were allotted as follows:

Three-man crew - 3, 4, and 5 hours/day/man

Six-man crew - 5, 6, 6, 5, 7, 7 hours/day/man

Nine-man crew - 6, 6, 6, 6, 7, 7, 8, 8 hours/day/man

Results: Problem II

The results obtained from this analysis are shown in figures 20 and 21 from which the following conclusions were drawn:

1. The MORL system concept can, with six- to nine-man crew sizes, accomplish this experiment program. Figure 19 shows that the use of smaller crews would result in excessively long mission durations if a high percentage of experimental return is desired. The low experimental returns from a three-man crew is a result of two factors. First, the station-keeping and operations tasks (constant in the PRM), which have assignment priority, limit the time available for experimental work. Second, many experiments will remain unassigned due to the difficulty of getting the required skills onboard with so few men.

2. Rotating and optimizing six men instead of three each interval greatly improved the experimental return; approximately 25 percent for nine-man crews.

The curves, shown in figure 21, indicate the improvement which can be expected if up to six men are skill optimized each launch interval.

Significant in these results is the fact that optimization of crew skills can be highly effective and that a six-man crew for a station concept such as the MORL is very effective.

CONCLUSIONS

During the course of the study covered by this paper several conclusions were reached with respect to the simulation of large complex systems through the construction of mathematical models to represent these systems.

These conclusions can be stated as follows:

1. Modeling techniques and requirements for the system concepts should first be described as accurately as possible to establish a base. Once a broad base of requirements is defined, details and sophistication can be added as necessary.

2. The types of analyses which a simulation model and attendant computer programs can reasonably be expected to handle must be clearly defined. A common desire in building these models is for the model to cover all possible contingencies so that the user need only read the outcomes. Although it is important to simplify the use of these aids as much as possible, some responsibility must be left to the user to analyze the results and provide feedback through the model to improve these results.

3. Finally, it is important that the mathematical models be constructed in such a way that they are flexible both for use and modification. Space station system concepts are in a constant state of change as advances are made in research and technology. Management aids employed in the study of such system concepts must have the capability to change and grow in parallel with these advances.

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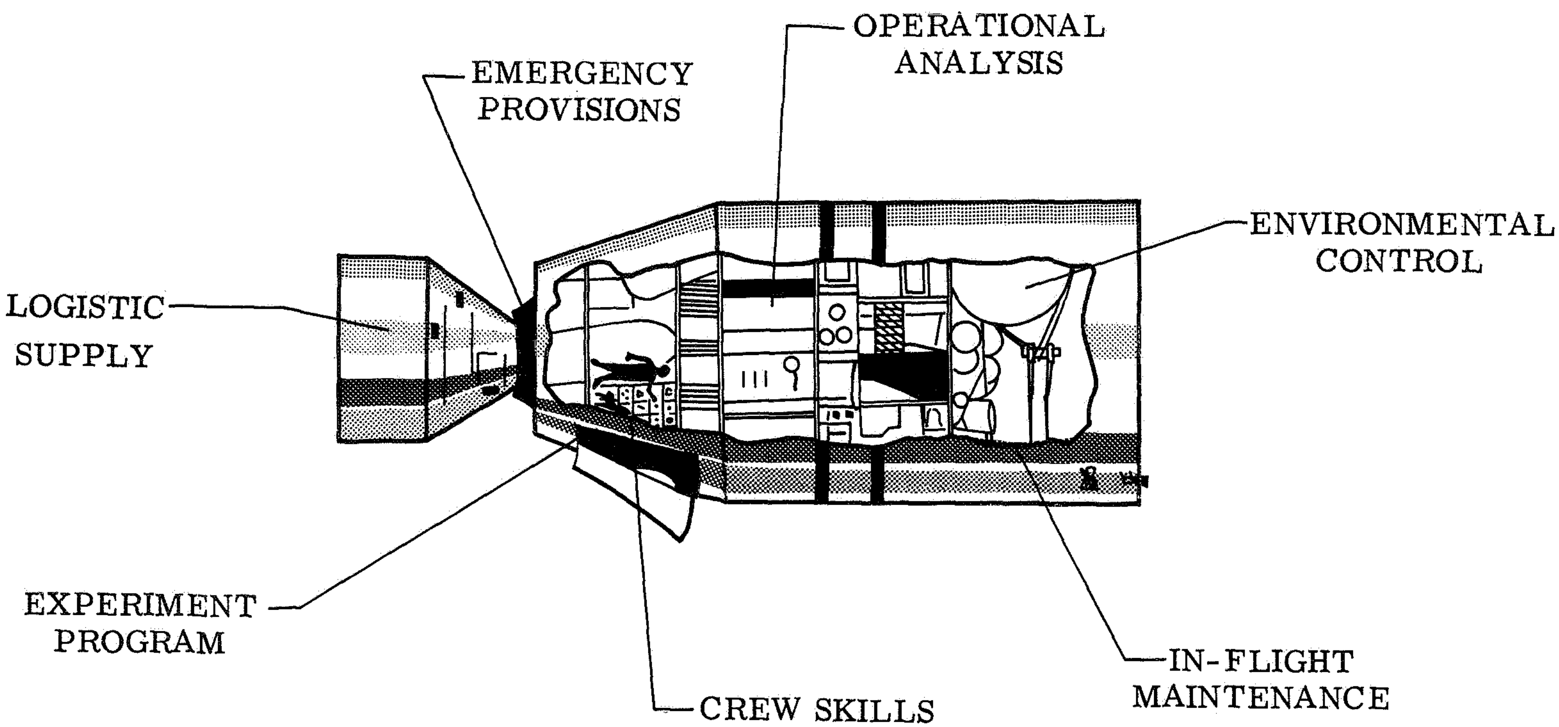


Figure 1.- MORL system concept.

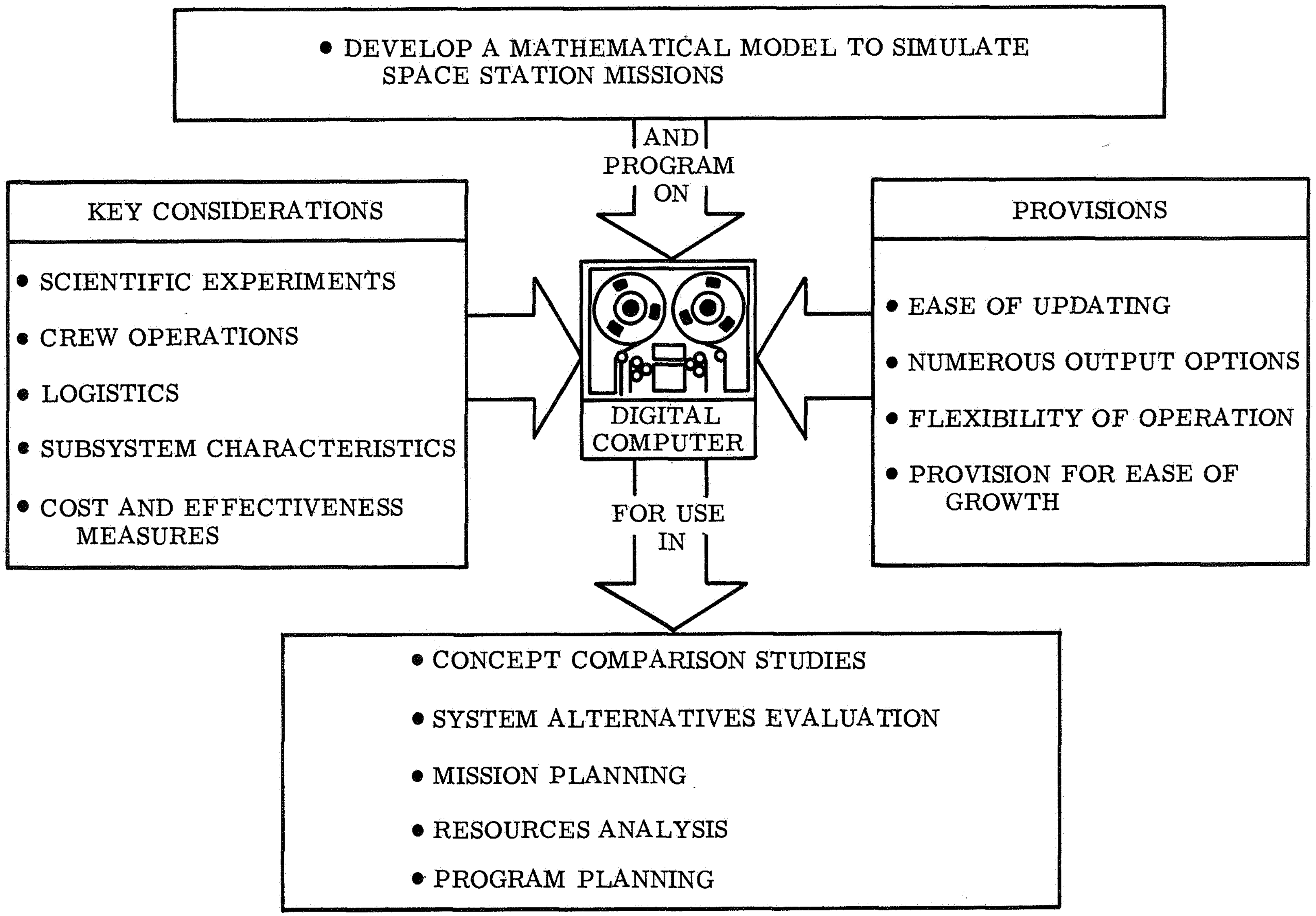


Figure 2.- Digital simulation for space station missions.

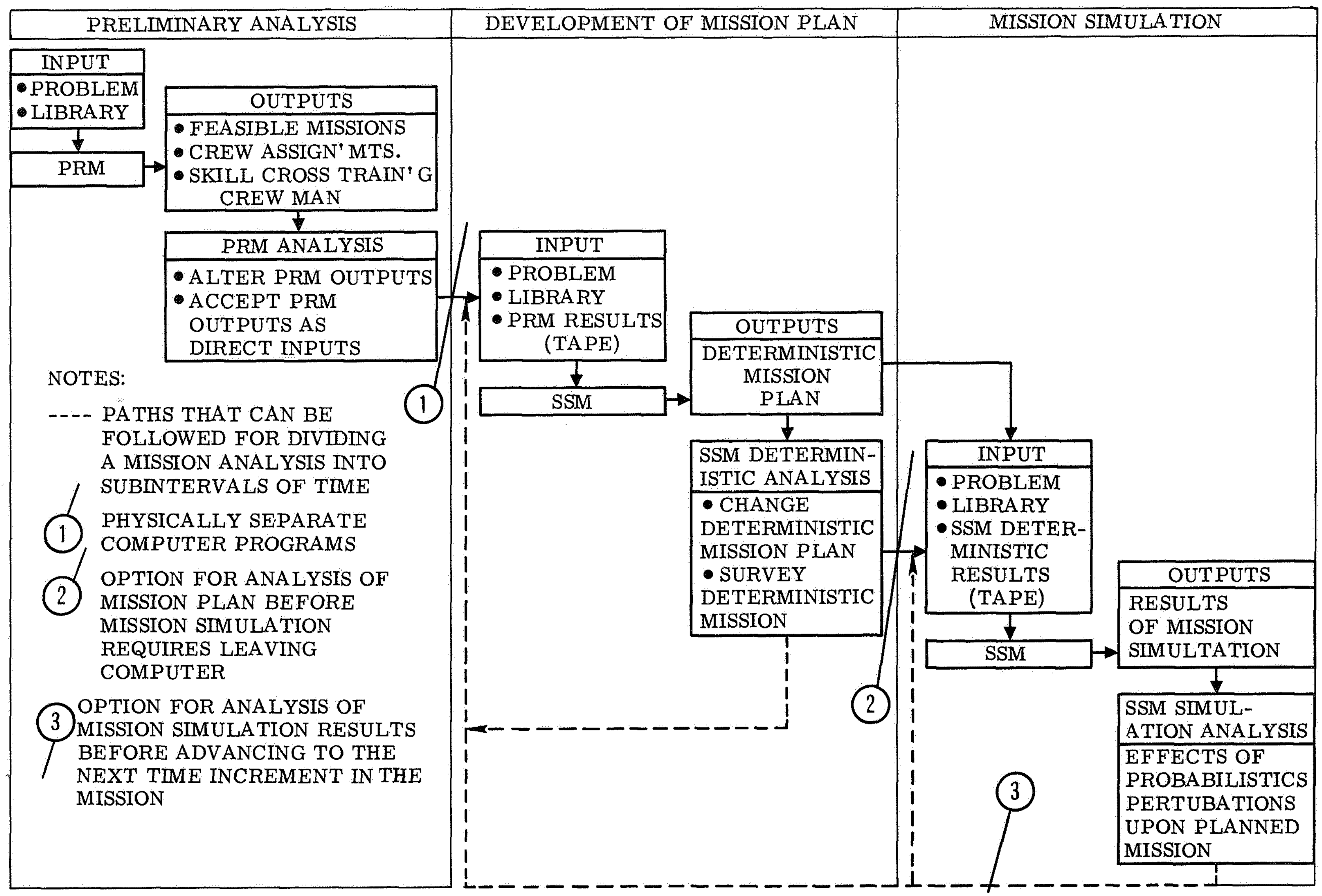


Figure 3.- Space station model (SSM) integration.

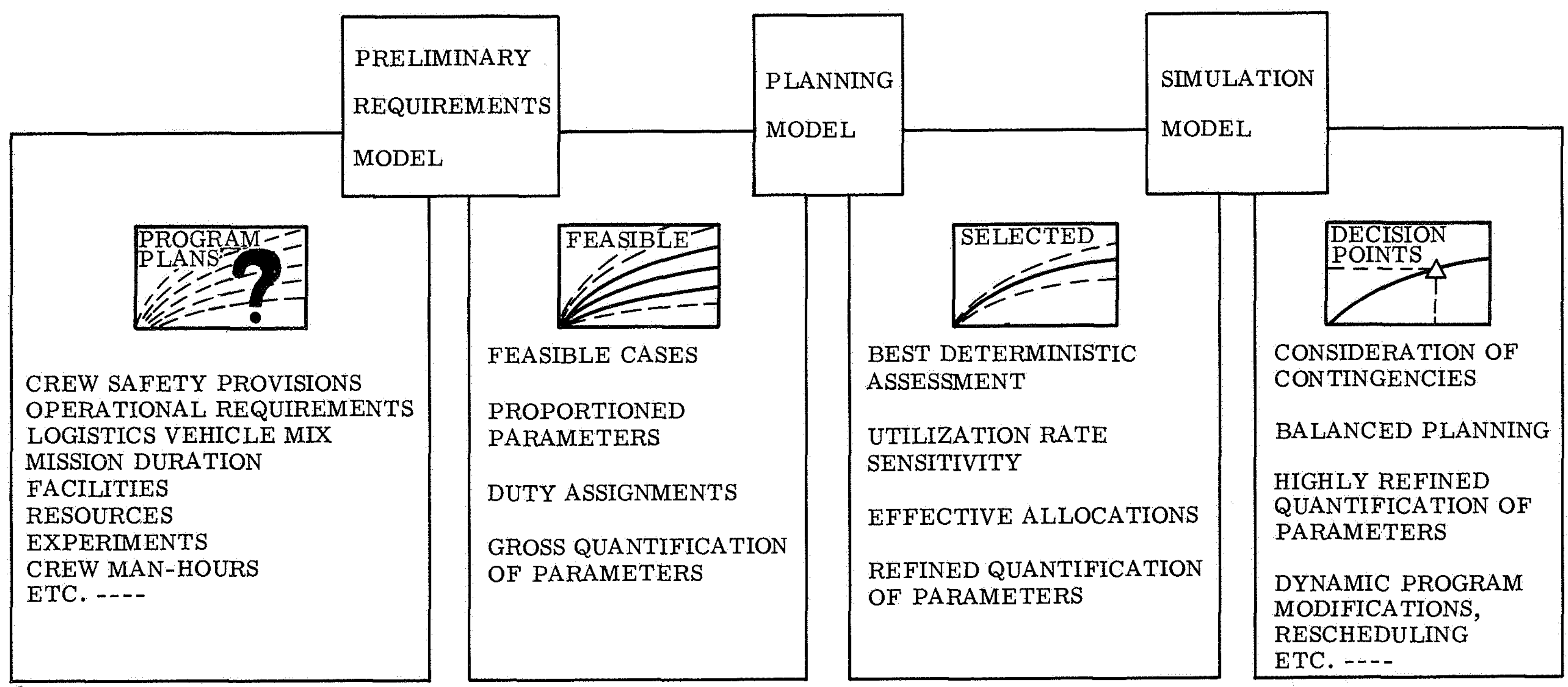


Figure 4.- Model utilization sequence.

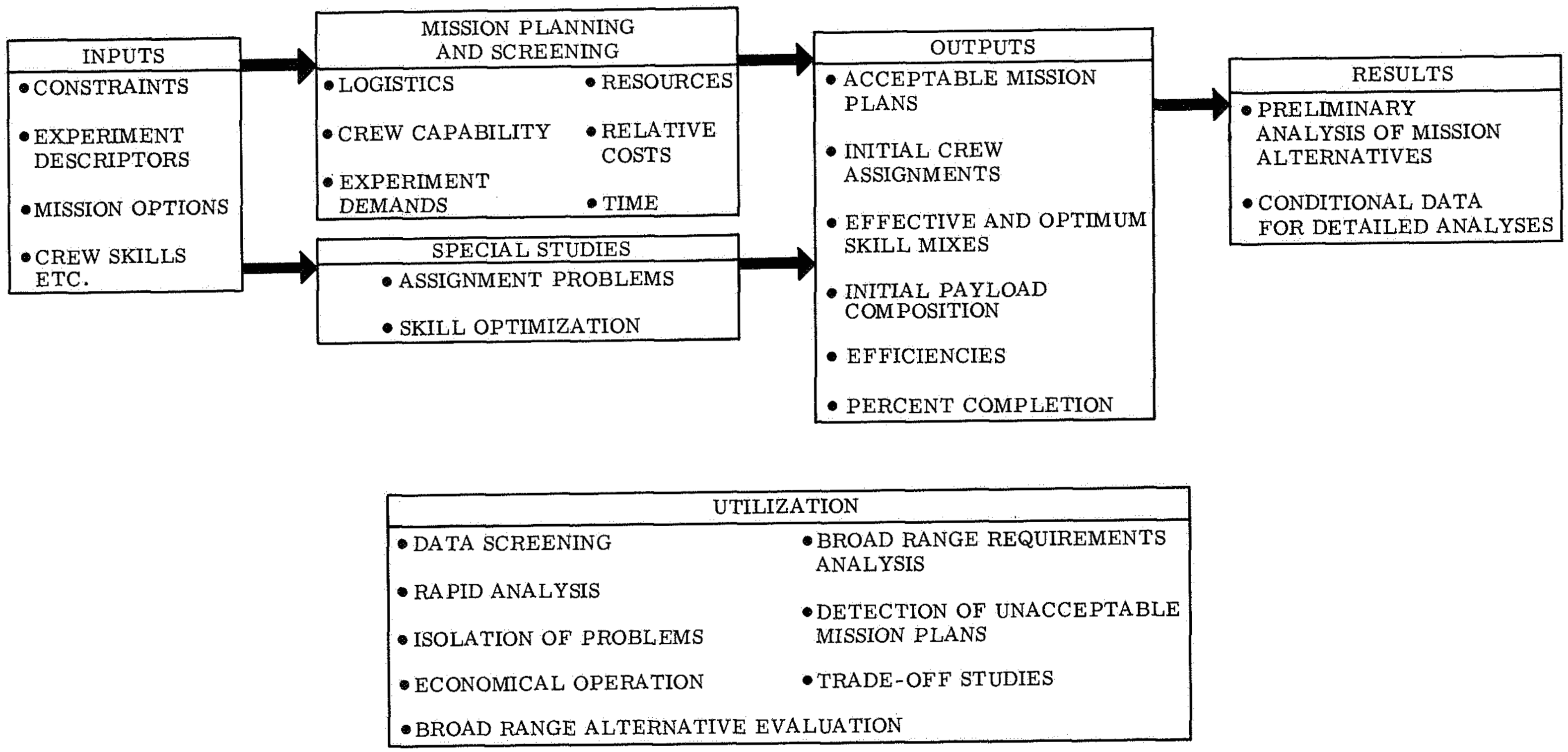


Figure 5.- Preliminary requirements model.

	SKILL CATEGORY							
	BIOLOGY	MICROBIOLOGY	CHEMISTRY	PHYSIOLOGY	ASTRONOMY	UTILITY	UTILITY	UTILITY
TYPE OF CREWMAN	1	2	3	4	5	27	28	29
1	0	2	2	1	0	1	0	0
2	1	0	0	2	1	0	0	1
3	2	2	0	0	2	0	1	0
4	0	0	1	0	0	1	0	0
5	0	1	0	2	2	0	0	1
6	2	0	2	1	0	0	1	0

Figure 6.- Skill factor matrix.

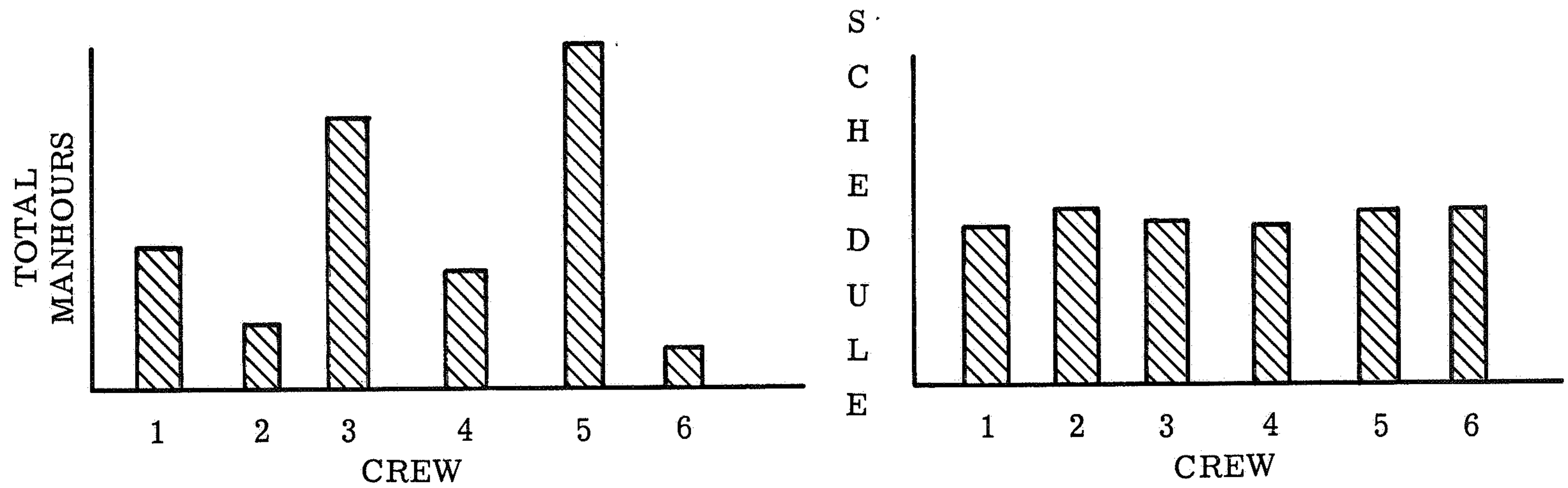
SKILL CATEGORY

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
BIOLOGICAL TECHNICIAN	1	1	1	2	2	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
MICROBIOLOGICAL TECHNICAN	2	1	1	2	2	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
BIOCHEMIST	3	1	1	1	1	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
PHYSIOLOGIST	4	1	1	1	1	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
ASTRONOMER/ASTROPHYSICIST	5	0	0	0	0	1	1	1	1	1	2	2	1	0	1	1	2	2	2	2	2
PHYSICIST	6	0	0	0	0	2	1	1	1	1	2	2	1	0	1	1	2	2	2	2	2
NUCLEAR PHYSICIST	7	0	0	0	0	2	1	1	1	1	2	2	1	0	1	1	2	2	2	2	2
PHOTO TECH/CARTOGRAPHER	8	0	0	0	0	0	0	0	1	0	0	0	2	0	2	0	0	0	0	0	0
THERMODYNAMICIST	9	0	0	0	0	2	1	1	1	1	2	2	1	0	1	1	2	2	2	2	2
ELECTRONIC ENGINEER	10	0	0	0	0	0	2	0	1	0	1	2	1	0	0	0	0	1	0	0	0
MECHANICAL ENGINEER	11	0	0	0	0	0	2	0	1	2	2	1	1	0	1	0	0	0	0	0	0
ELECTROMECHANICAL TECH	12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MEDICAL DOCTOR	13	1	1	1	1	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
OPTICAL TECHNICIAN	14	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
OPTICAL SCIENTIST	15	0	0	0	0	2	1	2	1	2	0	0	1	0	1	1	0	0	0	0	0
METEOROLOGIST	16	0	0	0	0	0	2	0	1	2	0	0	2	0	0	0	1	0	1	1	1
MICROWAVE SPECIALIST	17	0	0	0	0	0	2	0	1	0	1	2	1	0	0	0	0	1	0	0	0
OCEANOGRAPHER	18	0	0	0	0	0	2	0	1	2	0	0	1	0	0	0	1	0	1	1	1
PHYSICAL GEOLOGIST	19	0	0	0	0	0	2	0	1	2	0	0	1	0	0	0	1	0	1	1	1
PHOTO GEOLOGIST	20	0	0	0	0	0	2	0	1	2	0	0	1	0	1	0	1	0	1	1	1

Figure 7.- Skill mixes for input.

CREWMAN NUMBER	1	2	3	4	5	6	7	8	9	10	11
LAUNCH INTERVAL 1	1	2	3	4	5	6	0	0	0	0	0
LAUNCH INTERVAL 2	1	0	3	4	0	6	2	5	0	0	0
LAUNCH INTERVAL 3	0	0	0	4	0	0	2	5	1	3	6

Figure 8.- Crew rotation profile.



- ASSIGN TO MOST EFFICIENT MAN
- IF EQUALLY EFFICIENT ASSIGN TO ONE WITH MINIMUM CURRENT LOAD

- EQUALIZE LOADS BY ITERATIVE REASSIGNMENT ON THE BASIS OF MINIMUM PENALTY

ALTERNATIVES

- DAILY ASSIGNMENT
- ASSIGNMENT ON TOTAL HOURS
- EXPERIMENTS WITH PRIORITY
- EXPERIMENTS WITHOUT PRIORITY

Figure 9.- PRM assignment procedure.

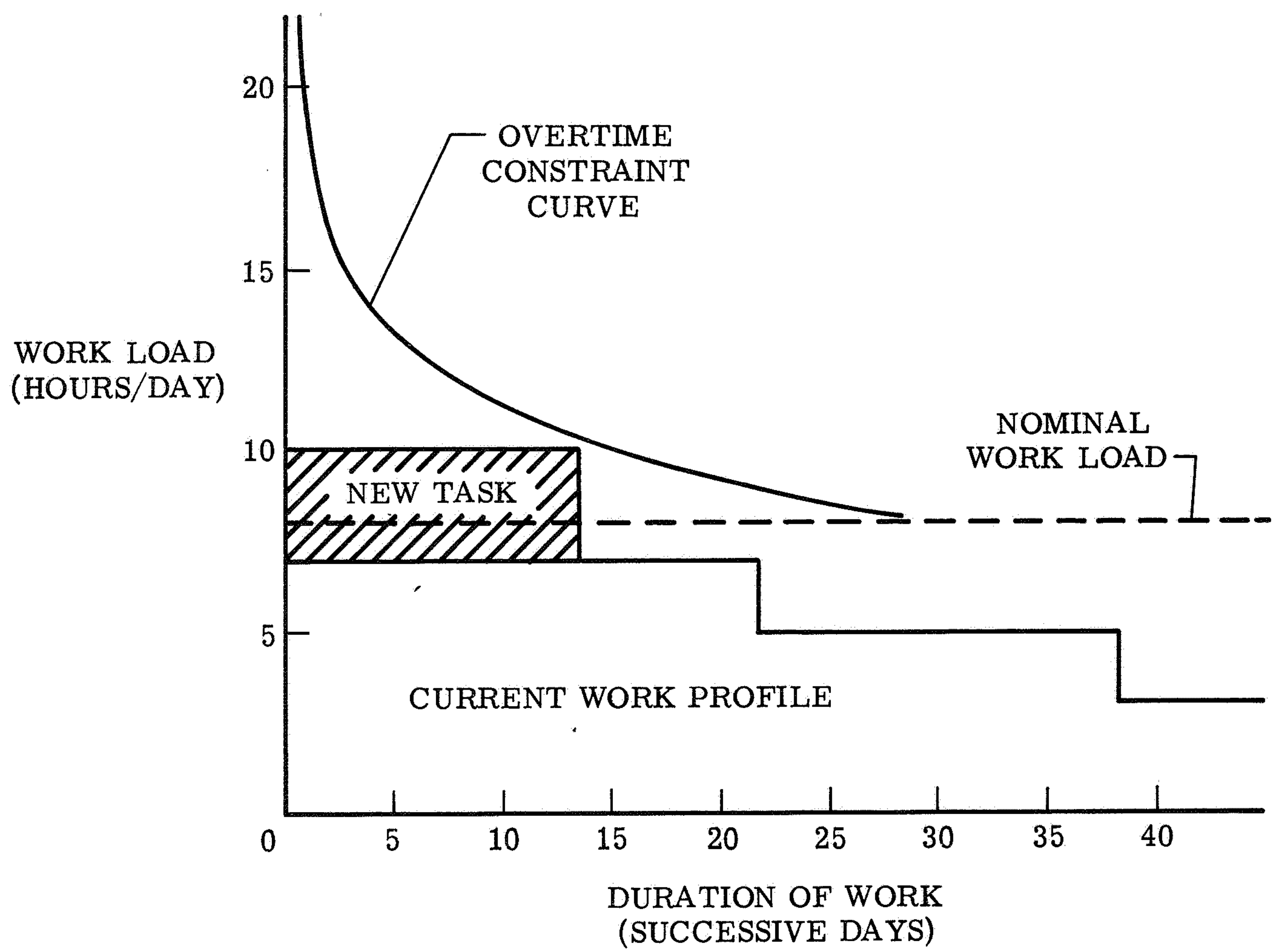


Figure 10.- Allowable overtime curve.

EXPERIMENTS AND TOTAL LOAD ASSIGNED TO EACH CREWMAN

CREWMEN	MAN	PERCENT (TOTAL)	PERCENT (UTIL.)	EXPERIMENT LIST
1	606.8	18.4	99.1	3 6 8 12 15 18 23 . .
2	611.7	18.6	95.9	22 30 35 36 37 . . .
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
7	569.6	17.3	93.0	1 2 5 9 10 38 . . .

TOTAL 3296.7 89.7 (AVERAGE)

SUM OF EXP MAN-HOURS 3115.2

INEFFICIENCY 5.8

LIST OF UNSCHEDULED EXPERIMENTS

32 4 11 13 14 17 31 33

TIME REMAINING ON CARRY OVER EXPERIMENTS

NEW COUNT	EXP	MAN-HOURS	DURATION
1	1	277.5	270.0
2	2	102.5	180.0
3	3	240.0	180.0
4	4	3.0	90.0

Figure 11.- Launch interval summary.

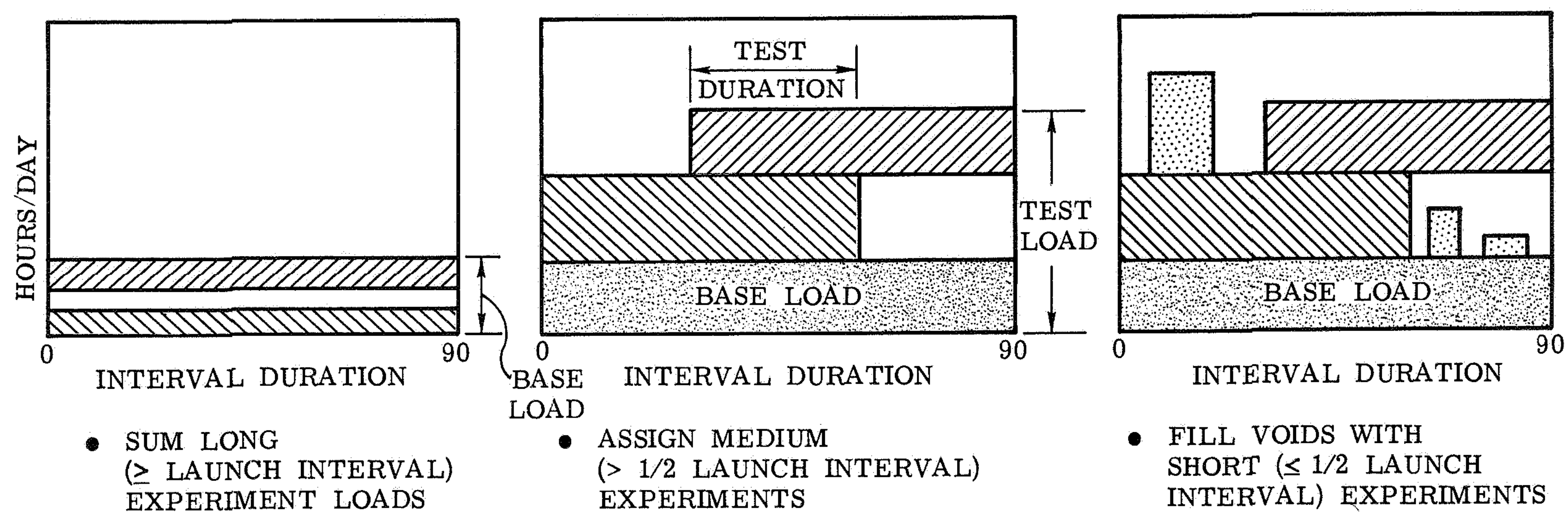


Figure 12.- Experiment scheduler.

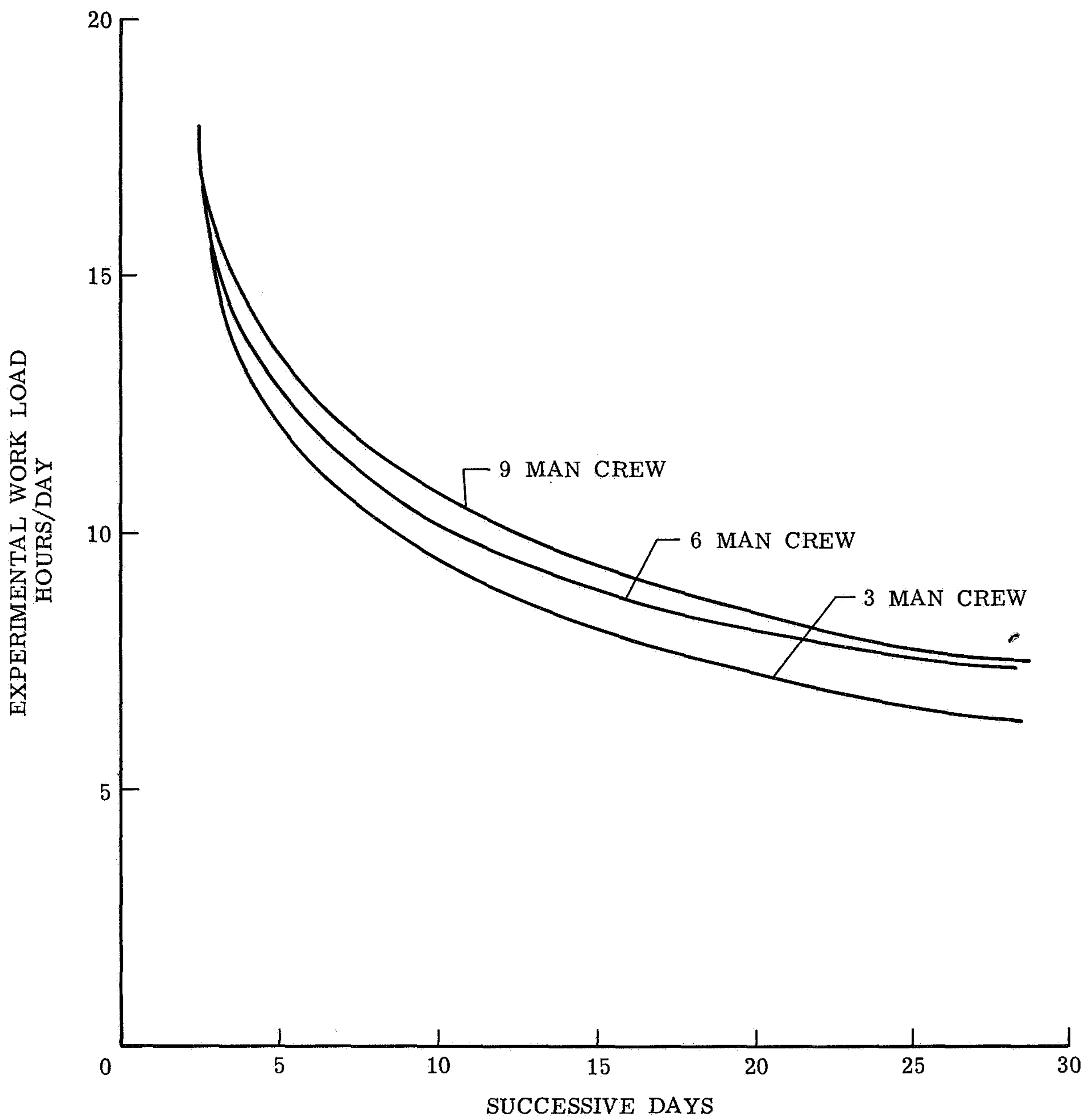


Figure 13.- Allowable peak loading curve.

PROGRAM AREA \ SKILL	ELECTRONICS TECH.	PHOTOGRAPHER/ OPTICAL TECH.	ELECTRICAL/MECH. TECHNICIAN	ELECTRONICS ENGINEER	MEDICAL DOCTOR	MECHANICAL ENGINEER	PHYSICIST/PHYSICAL SCIENTIST	ASTRONOMER	METEOROLOGIST	BIOLOGIST	AGRICULTURIST	OCEANOGRAPHER	GEOLOGIST	CHEMICAL ENGINEER	MEDICAL TECHNICIAN
ASTRONOMY	10%	10%		10%				70%							
EARTH RESOURCES	10%	15%									25%	25%	25%		
METEOROLOGY	15%	15%							70%						
BIOLOGY					30%					70%					
LONG-TERM FLIGHT			15%	15%	40%	10%								10%	10%
RESEARCH AND DEVELOPMENT	15%		15%	20%		20%	30%								

Figure 14.- Allocation of skill participation requirements.

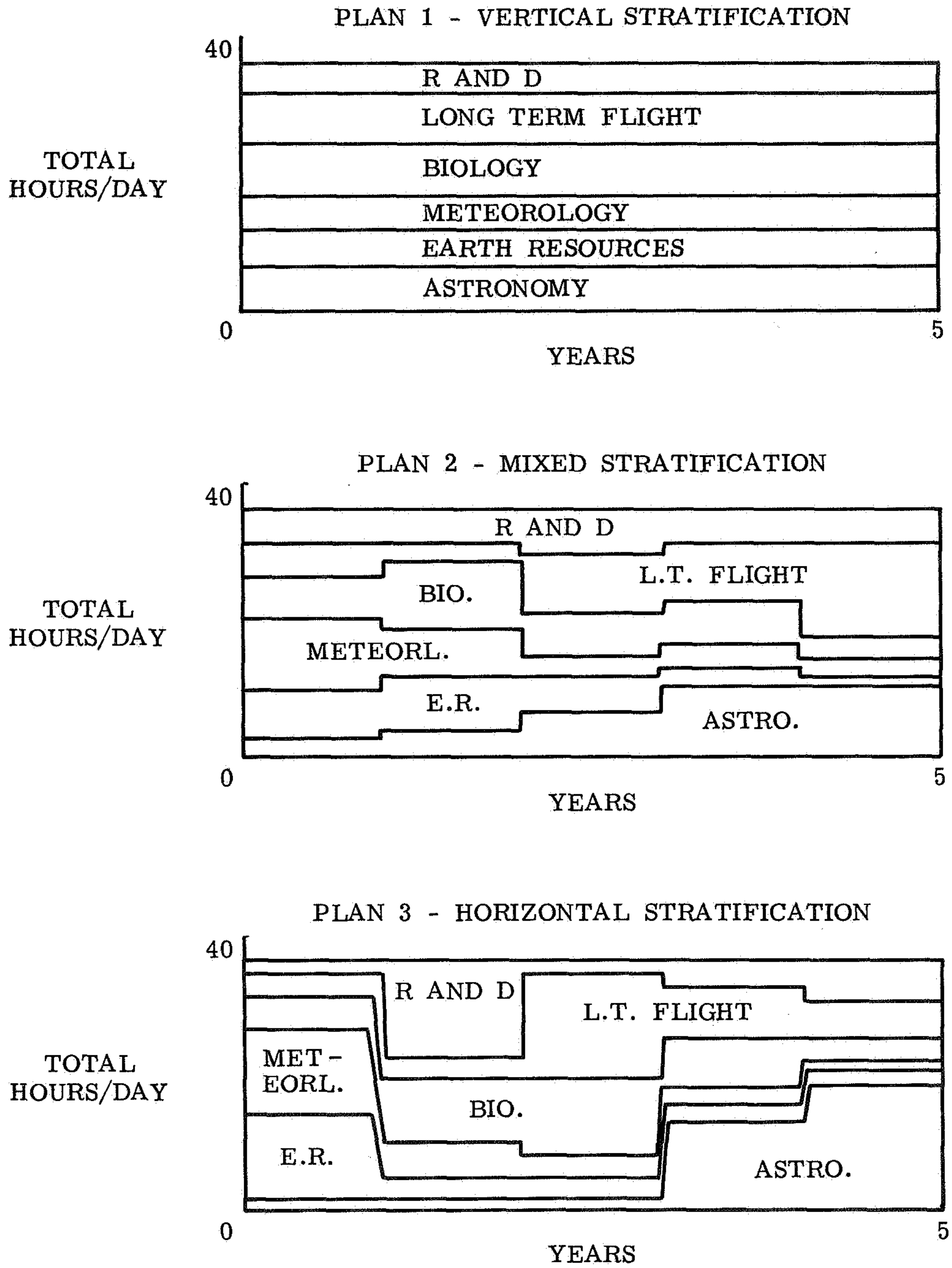


Figure 15.- Experimental plans studied.

SKILL MIX / CROSS-TRAINING — SKILLS	ELECTRONICS TECHNICIAN	PHOTOGRAPHER/OPTICAL TECH.	ELECTRICAL/MECH. TECH.	ELECTRONICS ENG.	DOCTOR	MECHANICAL ENG.	PHYSICIST/PHYSICAL SCIENTIST	ASTRONOMER	METEOROLOGIST	BIOLOGIST	AGRICULTURALIST	OCEANOGRAPHER	GEOLOGIST	CHEMICAL ENG.	MEDICAL TECH.
NO CROSS-TRAINING															
SPECIALIST NO. 1	1														
SPECIALIST NO. 2		1													
NO. 3			1												
NO. 4				1											
NO. 5					1										
NO. 6						1									
NO. 7							1								
NO. 8								1							
NO. 9									1						
NO. 10										1					
NO. 11											1				
NO. 12												1			
NO. 13													1		
NO. 14														1	
SPECIALIST NO. 15															1

MEDIUM CROSS-TRAINING

1. ASTRON/OPTICAL TECH.		1						1							
2. BIOLOGIST										1					1
3. EARTH SCIENTIST									1		1	1	1		
4. M.E./CHEMIST/PHYSICIST						1	1							1	
5. E.E./E. MECH. TECH.	1		1	1											
6. DOCTOR					1										1

HIGH CROSS-TRAINING

1. ENGINEER	1		1	1		1									
2. BIO-CHEMIST					1					1				1	1
3. EARTH SCIENTIST		1					1	1	1		1	1	1		

Figure 16.- Assumed crew skill cross-training.

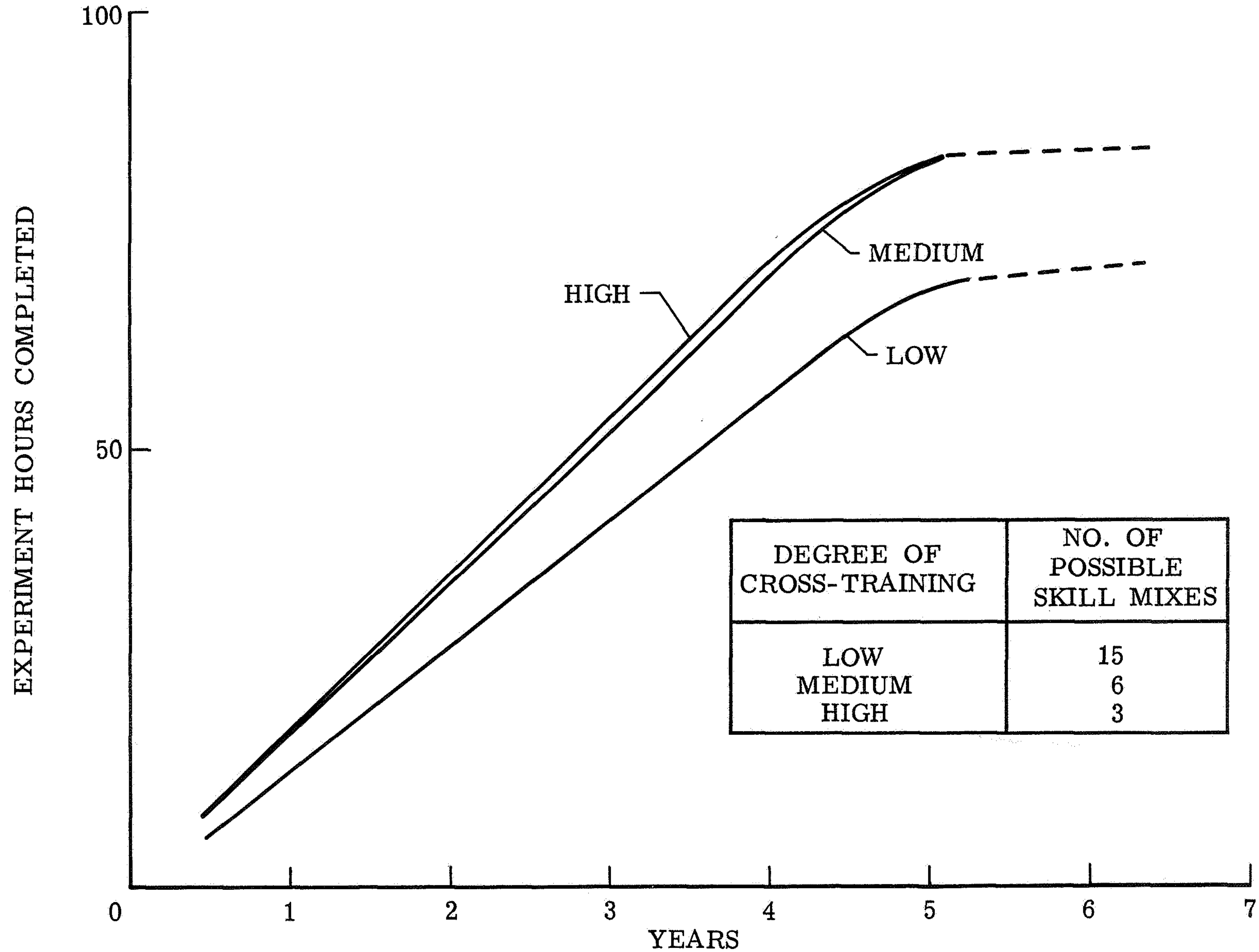


Figure 17.- Plan 1 vertical stratification.

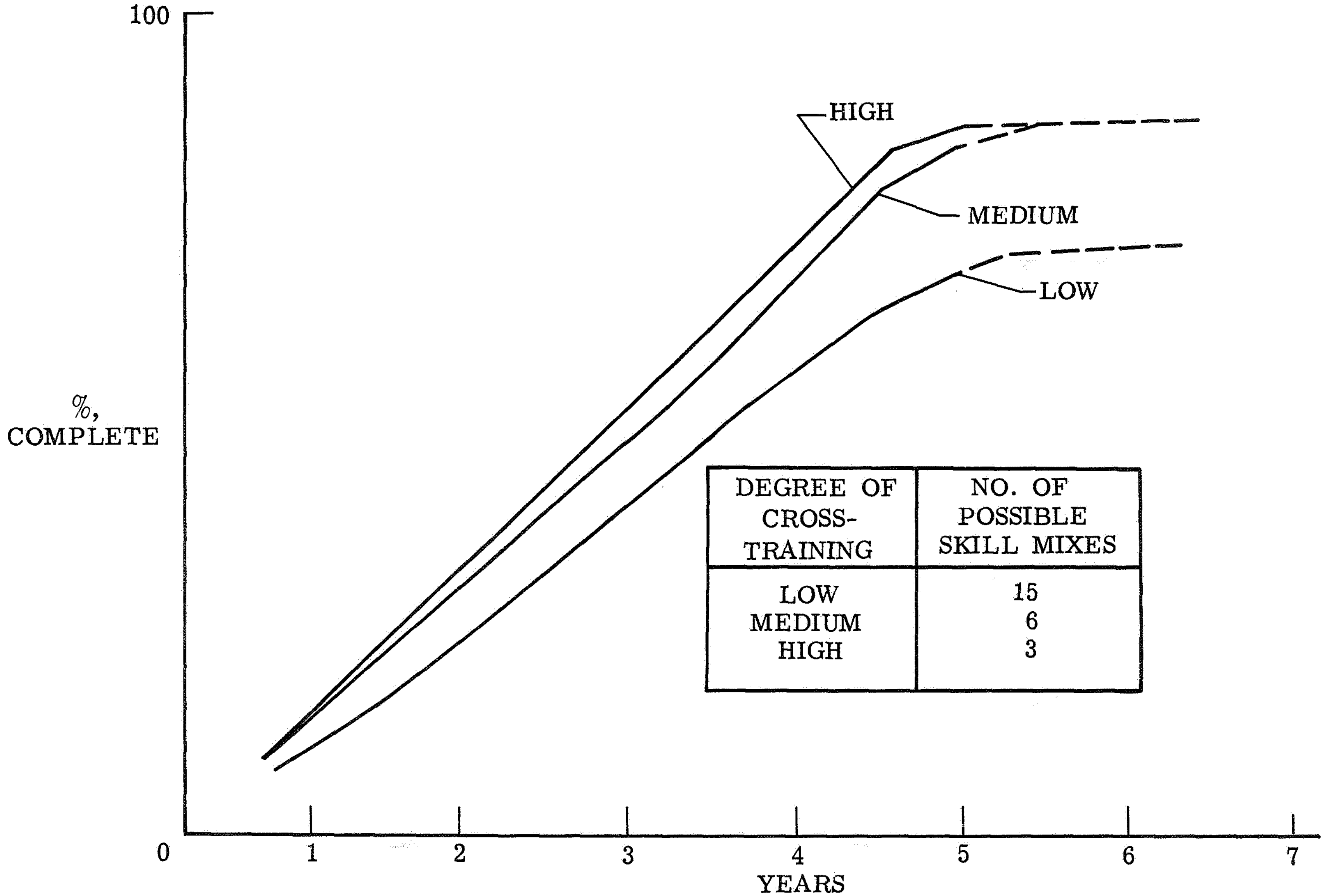


Figure 18.- Plan 2 mixed stratification.

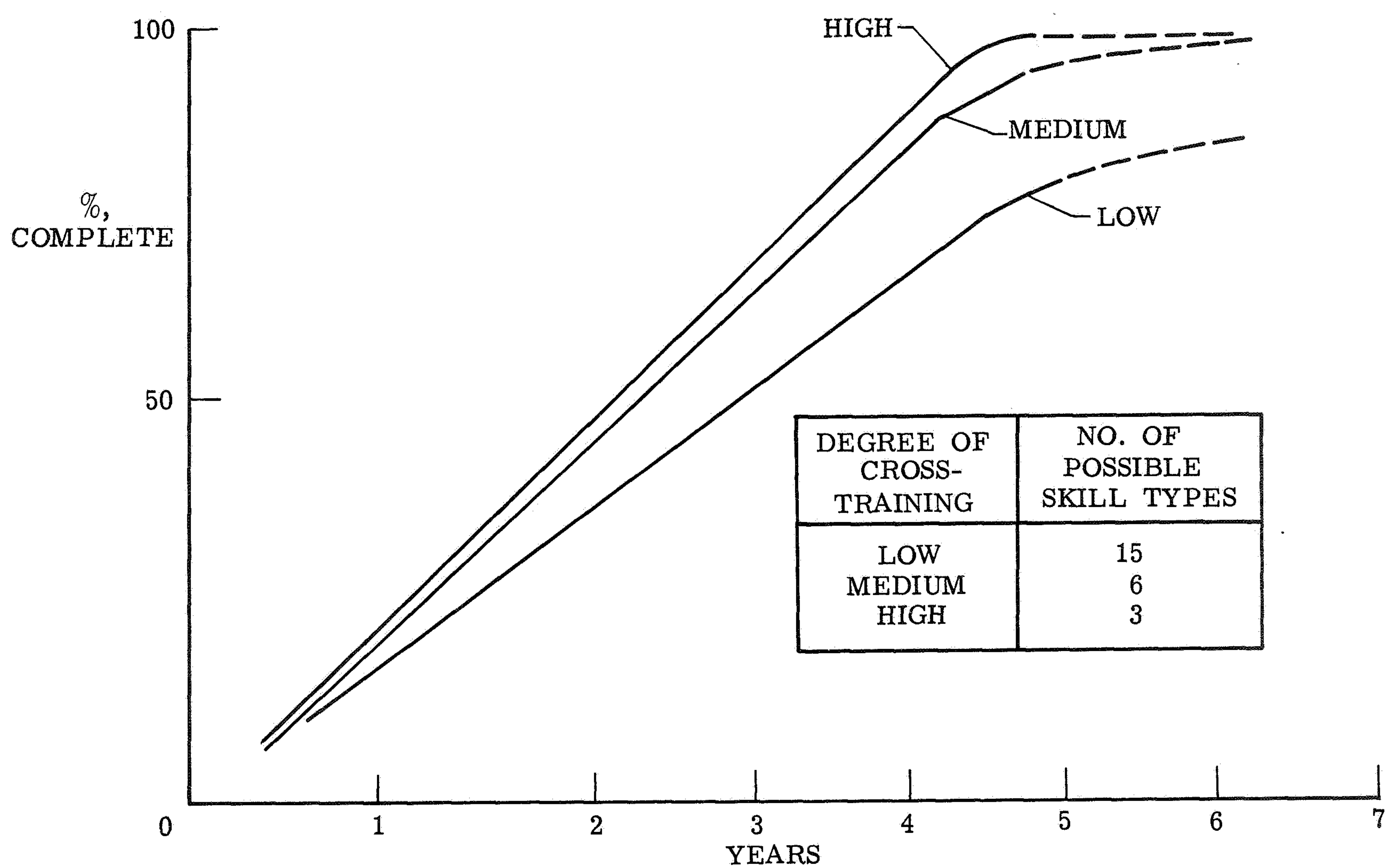


Figure 19.- Plan 3 horizontal stratification.

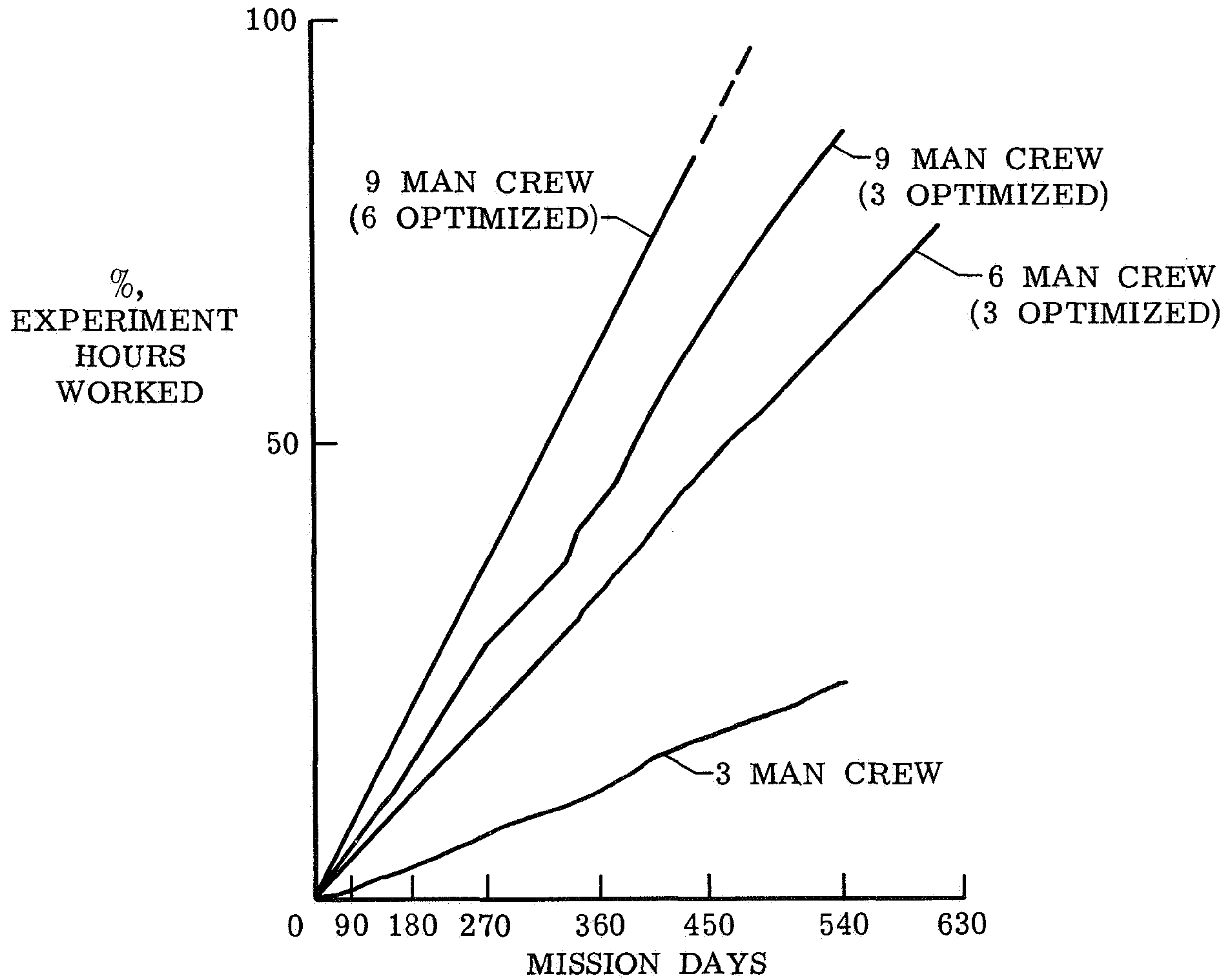


Figure 20.- Percent experiment hours completed versus mission days.

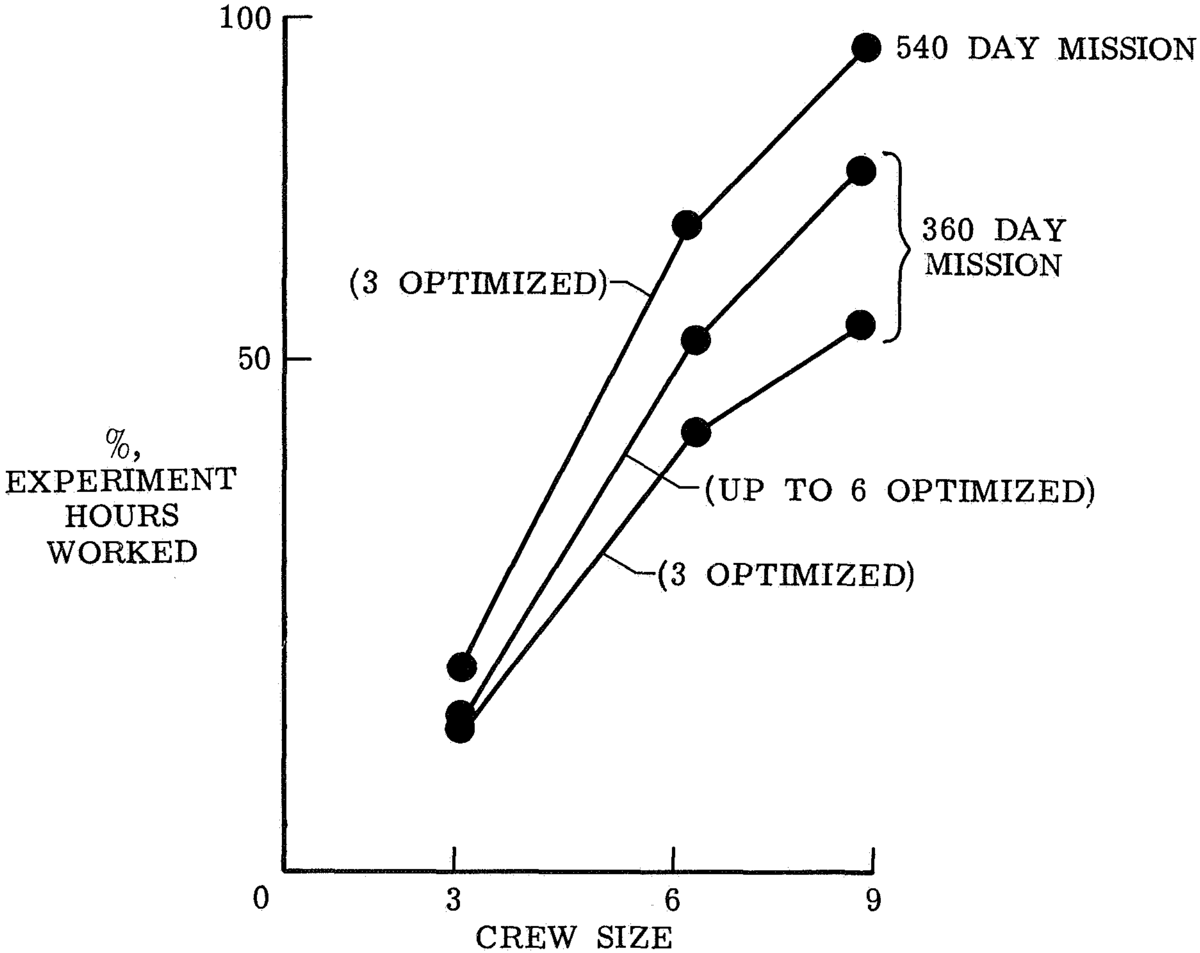


Figure 21.- Percent experiment hours completed versus crew size.

NASA-Langley, 1967