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SYSTEMS ENGINEERING IN SPACE EXPLORATION

SEMINAR PROCEEDINGS

MAY 1—JUNE 5, 1963

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA

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FOREWORD

Presented here are the proceedings of a series of lectures given at Stanford University in the spring quarter of 1963 by personnel of the Systems Division of the Jet Propulsion Laboratory. The lectures were part of the course work in the Space Technology Seminar, AE 298, conducted by Professor Howard Seifert of Stanford's Department of Aeronautics and Astronautics, and were given on consecutive Wednesdays, starting May 1, 1963 and finishing June 5, 1963.

The purpose of the JPL presentation was to describe systems engineering in space exploration to university graduate students, provide a technical series of lectures not normally given at universities, indicate some of the problems and the systems approach to these problems, and convey what systems engineering means to the mechanical engineer, electrical engineer, aeronautical engineer, chemical engineer, physicist, chemist, etc. Throughout the series, various examples of spacecraft and associated problems were discussed, including related experiences of the lecturers. The intent or philosophy behind the JPL seminar series was to provide a continuous integrated technical program (not just a collection of heterogeneous technical lectures) which would describe the activities of one of seven technical divisions at JPL.

The lecture series was sponsored by the National Aeronautics and Space Administration (NASA) at the suggestion of John Porter, Chief, JPL Support Office to the California Universities Council on Space Sciences (CUCOSS). The overall technical editing of these proceedings and technical continuity in the seminar series were under the direction of Dr. C. R. Gates, Chief, and John G. Small, Deputy Chief, of the Systems Division at JPL.

N66-13843

Systems Engineering in Space Exploration

JOHN SMALL

Deputy Chief, Systems Division

The first discussion in this series presents an introduction to systems engineering as applied to planetary mission design. The various elements of the system will be described and related problems discussed.

In general, systems engineering can be defined as the engineering approach used in design and development efforts of a complexity requiring the involvement of several basic engineering disciplines. "Engineering" implies the analysis, design, or test of hardware or operations to accomplish a given function. "Systems engineering" implies the coordination of several engineering disciplines in a single complex effort.

In various projects, the systems engineer will be called cognizant engineer, project engineer, program engineer, or test engineer. He will be faced with problems of schedules and money allocation, and he will find it necessary to accomplish his task in spite of arbitrarily imposed and possibly unappreciated boundary conditions. For example, planetary spaceflight schedules are based upon planetary orbits; there cannot be any schedule slippage. Also, in order to avoid planet contamination in some missions, it may be necessary to sterilize equipment at temperatures well above those of standard operations. Each engineer, in designing a piece of hardware, is faced with many systems problems; and the systems engineer, the man who is charged with putting the various subsystems together, is faced with even more difficult problems. He should understand at least the interfaces between the subsystems (the signals that flow from one piece of hardware to another), so that when the equipment is assembled, either mechanically or electrically, it operates properly because the people who designed the subsystems used the correct inputs and produced the proper outputs.

In this seminar we are going to attempt to define and describe systems engineering within the framework of a series of discussions on the following subjects:

1. Systems engineering in space exploration
2. Systems studies and functional design
3. Systems analysis and optimization
4. Spacecraft design and development*
5. Launch and spaceflight operations
6. Program engineering and project problems.

*This material does not appear herein, but will be published later as an addendum to the present report.

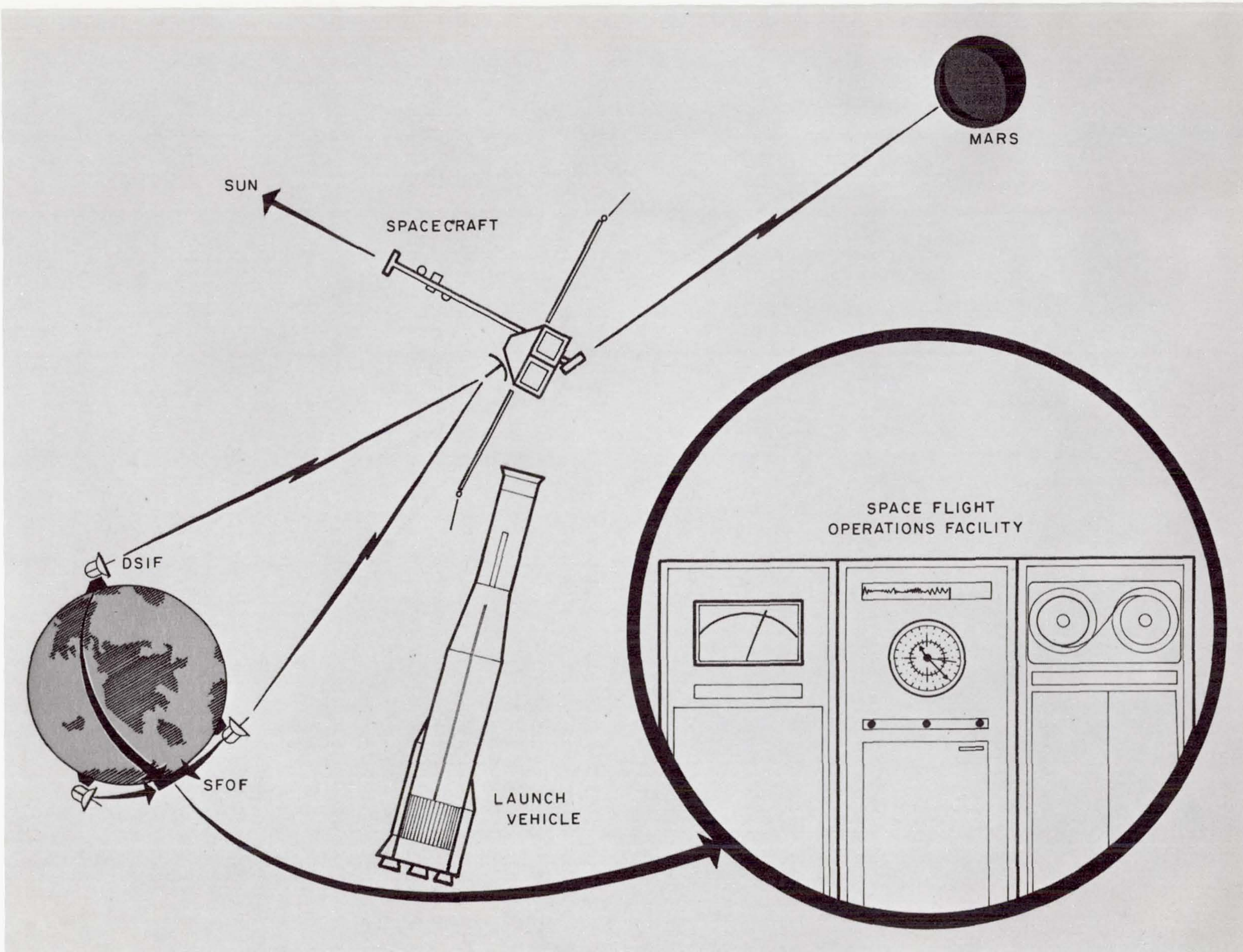

Fig. 1. Major systems for space exploration

In this, the first discussion of the series, I will describe some of the elements that we consider in a space system and some of the objectives that we attempt to reach.

Figure 1 shows the major overall systems involved in space exploration—the Deep Space Instrumentation Facility (DSIF), the Space Flight Operations Facility (SFOF), the launch vehicle, and the spacecraft itself. The DSIF comprises three ground receiving stations. These stations are located so that, regardless of the relative positions of the Earth and the spacecraft, provided the spacecraft is in an equatorial or near-equatorial plane, we can always track the spacecraft and receive telemetry from it. The stations can receive communications with bit rates of about 4 or 5 bit/sec at a Mars–Earth distance, with the type of spacecraft now used.

The SFOF integrates this telemetry information in real time and gives us the capability of making command decisions. We can steer the spacecraft. We can update certain events in the spacecraft in order to achieve our mission objective.

The launch vehicle's role is to inject the spacecraft on its mission's trajectory.

Figure 2 is a picture of Mars and is included here only to dramatize our objective. I think the picture may help to point up the necessity of looking at the scientific as well as the engineering aspect of our mission. The mission of the spacecraft is, of course, to make scientific measurements.

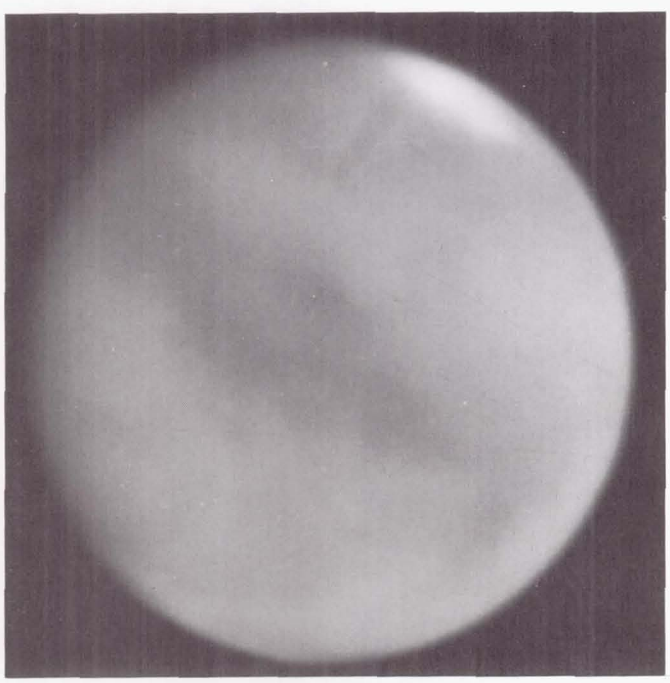

Fig. 2. Mars

A spacecraft design for the projected 1964 Mars mission is shown in Fig. 3. This particular design utilizes an octagonal base because we are using four solar panels as our power source. If we had designed a hexagonal base, we would probably have had three larger solar panels, and they would have been longer than those shown here; but this design looked to us to be a little easier to work with from a structural standpoint. Of course, this is a system tradeoff problem. The four-solar-panel design requires four opening mechanisms as against three for the other design, but, in this case, the structural problem was more difficult than the mechanism problem; so, on the basis of overall system reliability, we chose the four-panel model.

We have been using solar panels ever since we started building *Ranger* spacecraft. Although, hypothetically, a nuclear power source would work excellently, it would pose delivery problems and system integration problems; and we have been able to assure ourselves that solar panels are more practicable for these spacecraft.

On the tips of the solar panels are the solar sails. We expect that the effect of solar pressure on these sails will keep the center of pressure behind the center of gravity and result in spacecraft stability.

The high-gain antenna shown in Fig. 3 is a fixed antenna. In previous designs these antennas have been movable, but since in the last half of the Earth–Mars trajectory the Earth–probe–Sun angle remains almost unchanged, we could actually use a fixed antenna in the Mars spacecraft. From a systems point of view this means that we don't have to have bearings and equipment to operate the antenna in order to move it into different positions; therefore, we can eliminate that function. Near the Earth, the spacecraft pointing angle changes enough so that, in order to maintain telemetry, we utilize a low-gain and omnidirectional antenna.

The temperature-control louvers shown in Fig. 3 are operated by bimetallic strips. As the material under the strips is heated by the Sun, the strips expand and contract and open and close the louvers. It is a closed-loop circuit.

The equipment *Mariner* carries in order to make scientific measurements—the magnetometer, the cosmic dust

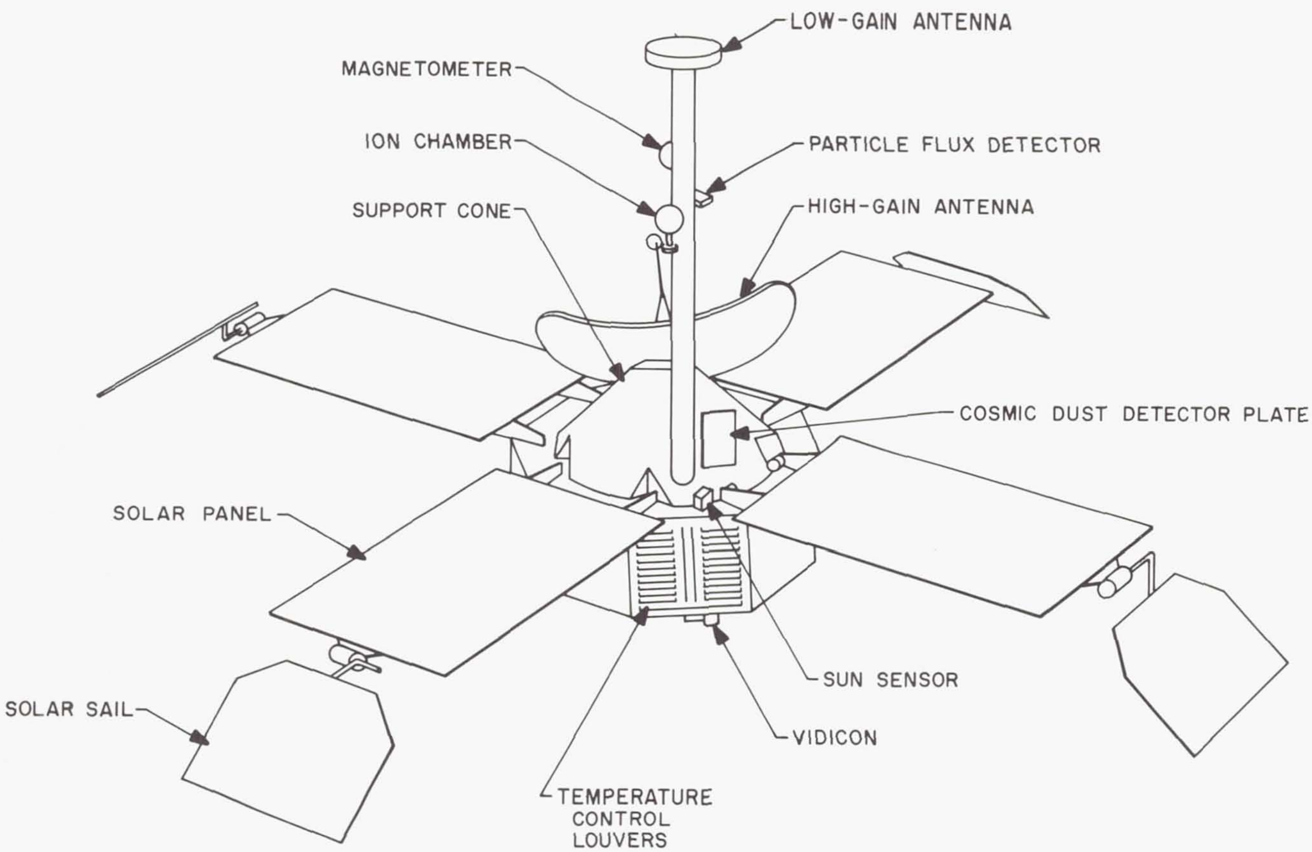

Fig. 3. *Mariner* spacecraft

detector, the ion chamber, and the vidicon—must be located as far as possible from the other equipment so as to avoid electronic and magnetic interactions. Thus, in effect, the science equipment and mission determine the spacecraft configuration, which basically must be kept as compact and rigid as possible.

Figure 4 shows the type of hardware that is packaged into the spacecraft. Of course, the packaging must be compact and light, which means that the container walls must be as thin as possible. This particular photograph, which shows one of the cases of electronic gear, was taken when the equipment was on a shake table, and so it is a little misleading. The light-colored wires go to the shake-test recording equipment; only the large black cables are the actual packaged wiring system. Everything must, of course, be connected by the cabling that runs through the box, and, because of induction problems, everything must be designed so that there is a minimum of cabling between items. There are many of these boxes on the spacecraft, and all must be integrated into the overall spacecraft operation.

Figure 5 shows the systems test layout that we use to test the *Mariner* spacecraft in the laboratory. Although at this point the various subsystems would have already been tested, we wouldn't yet have put them all together and run them in a systems test, which means a simulated in-flight operation of all the subsystems in their proper order.

Basically, the method we use here is that of spacecraft development. First we put the structure together. Next we put in the cabling and the power and check out the equipment. Then we slowly add the more complicated pieces of equipment to see whether they have interactions and whether they will work in their environment—and environment here means electronic environment; there may be electronic interference between subsystems, or the output of a given subsystem may not be at its mean value and may affect the input to the next subsystem so that the systems won't operate properly when connected in the system. Without a system test, this wouldn't be noticed.

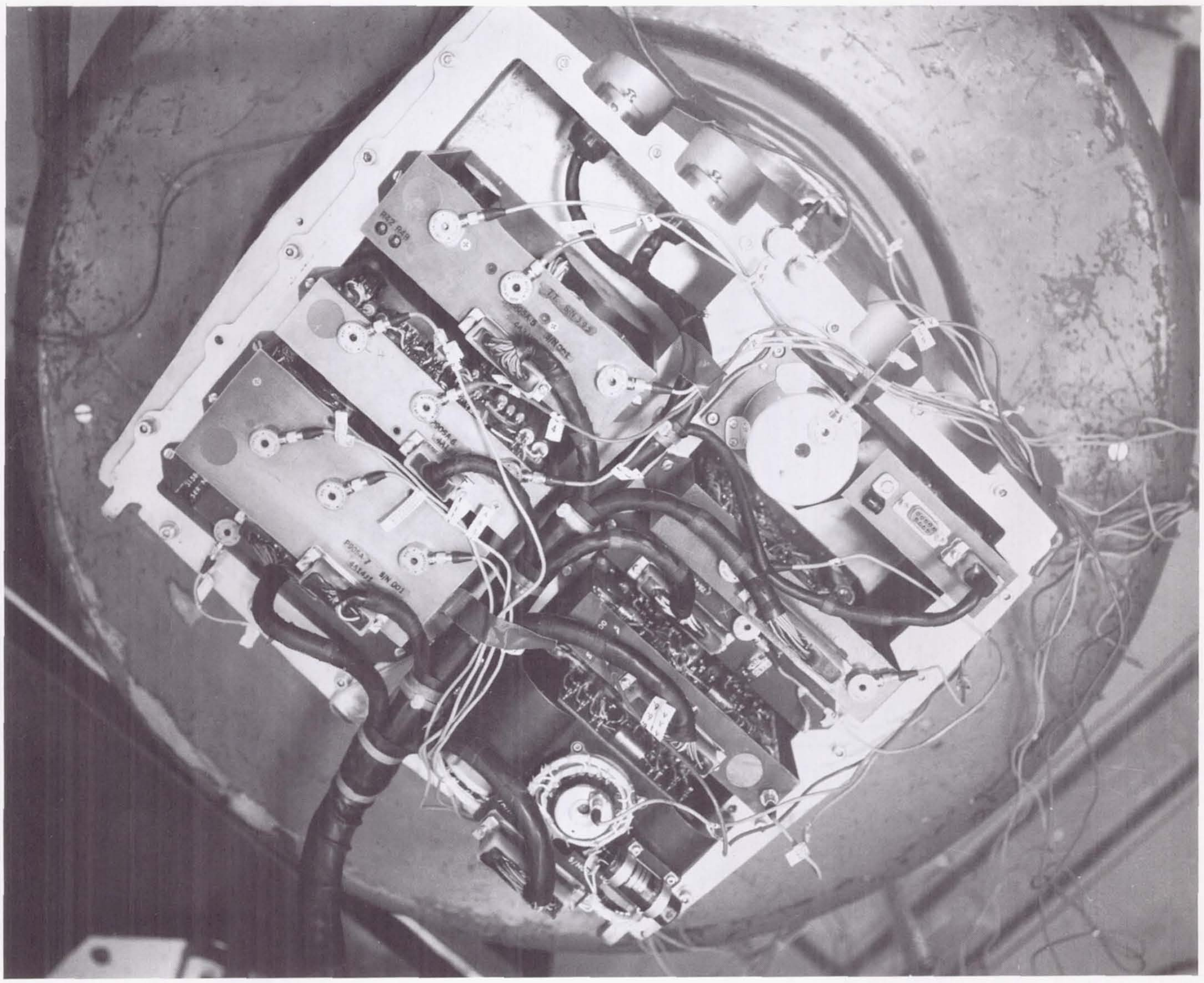

Fig. 4. Electronic gear packaging

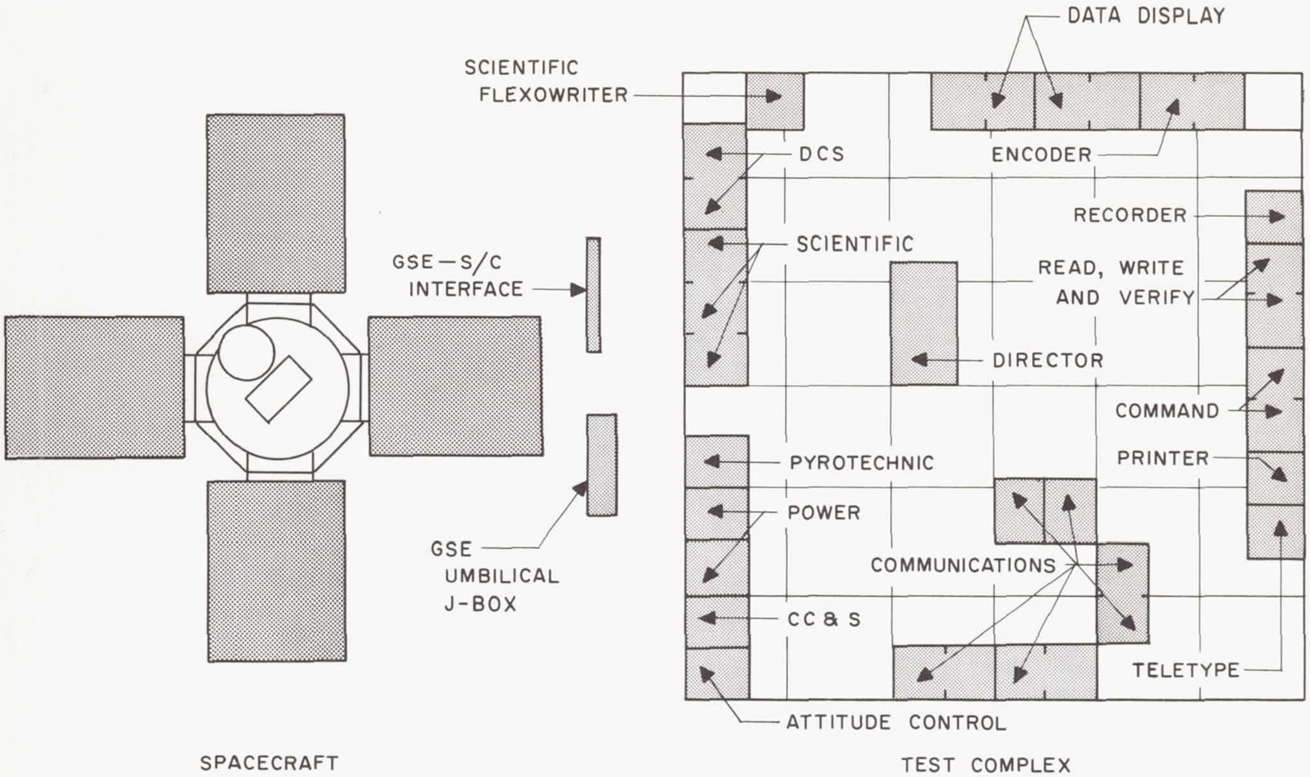

Fig. 5. *Mariner* systems test layout

Figure 5 shows the complex of ground support equipment which, through the cabling leads, operates the spacecraft. For a lunar shot test, simulated spacecraft operation for 70 or 80 hours would be required for all shake, temperature, and vacuum environments and the various combinations thereof. The resulting data are read out to ascertain whether the spacecraft is operating within the prescribed limits.

In this type of test operation, the more data we gather, the more need we have for computers to store the data and to ring alarms relative to the measurements. For example, planetary shots involve mission times of a few hundred days, and to ensure reliability, we should operate this system a few hundred times. The resulting data output, which is enormous, is programmed into a computer and an alarm system is activated if any of the various subsystems give measurements outside the prescribed limits.

Figure 6 shows the inside of the JPL space simulator. The view is from the spacecraft toward the ceiling. The hexagonally-shaped pebble bed receives sunlight from the top; the chamber has cold walls, simulating the radiation of outer space. In our simulator we can't just beam light at the spacecraft; we must try to simulate sunlight, and we also must maintain the temperature and vacuum of the simulator as close to space conditions as possible.

This particular chamber was not ready when we made the Venus 1962 flight, and we had to proceed with very marginal simulation in a small chamber. As a result we made some engineering errors, and the spacecraft temperatures in the 1962 flight were higher than anticipated.

Figure 7 pictures a model of a future deep space instrumentation antenna, a 210-ft dish. At present we are using 85-ft dishes. With a 210-ft dish, which will be available in two or three years, we will be able to increase our reception capability about 5 times. A 210-ft dish will be installed at the Goldstone DSIF site.

An inside view of the original spaceflight operations facility is given in Fig. 8. (A much more comprehensive facility is being built for future flights.) It is basically a control center which converts raw telemetry data into

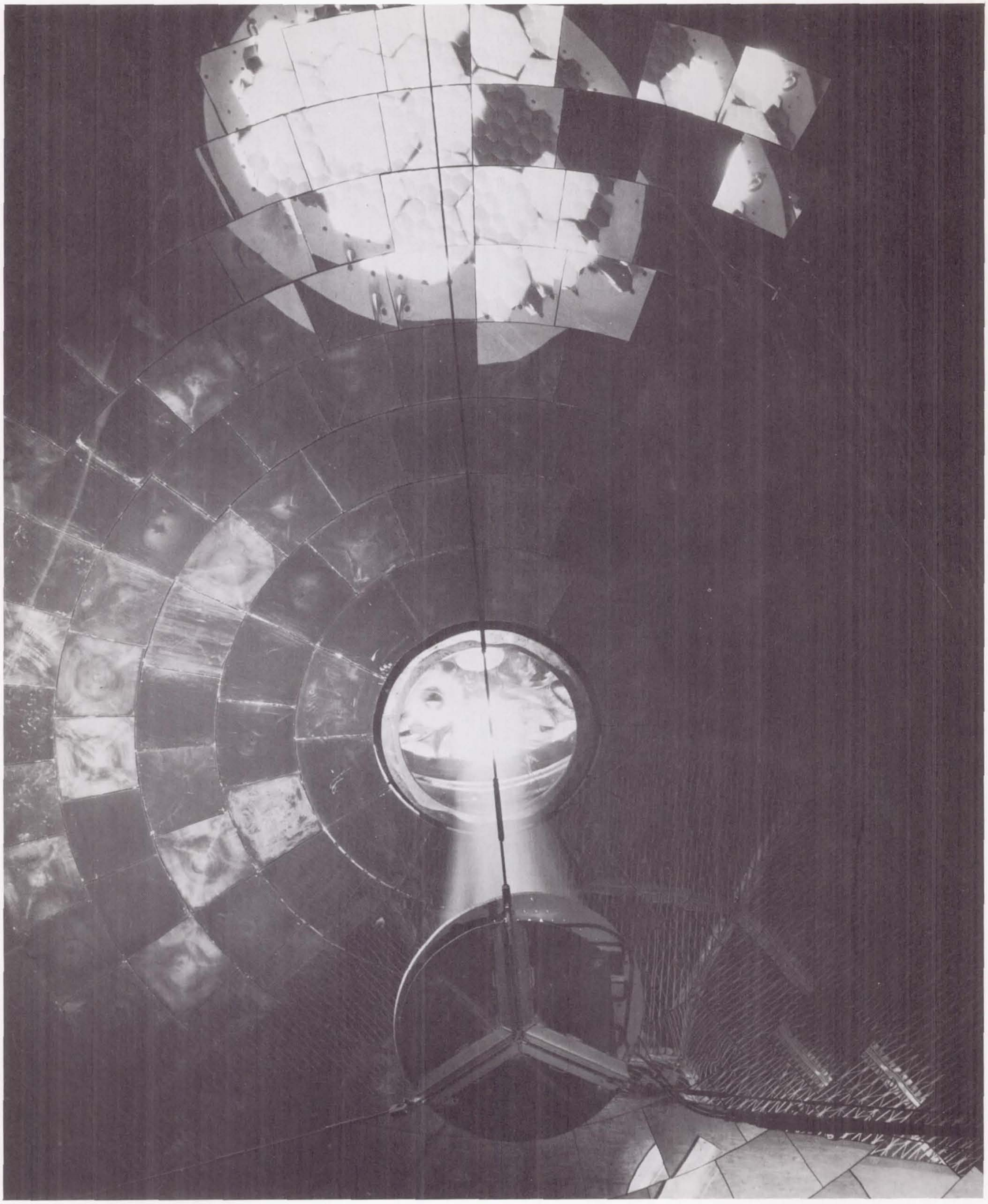

Fig. 6. JPL space simulator

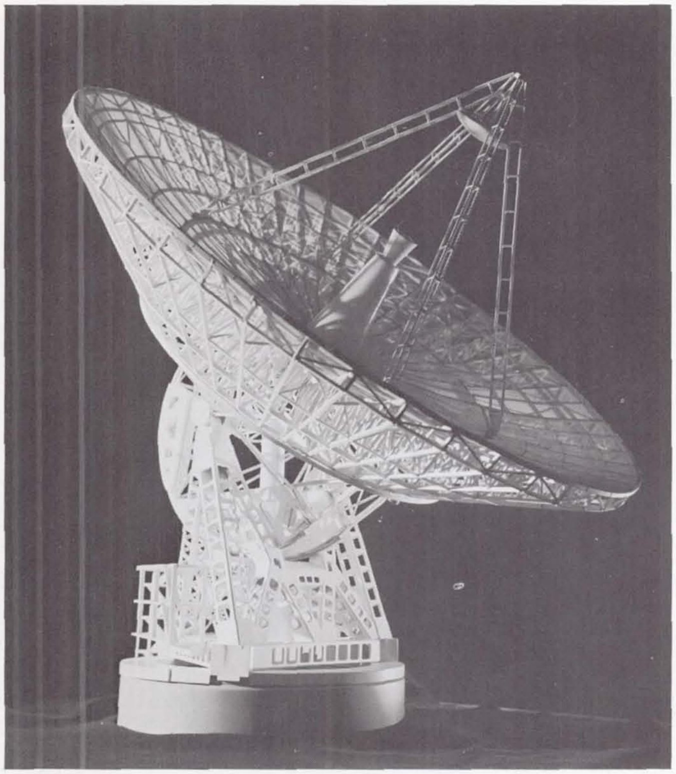

Fig. 7. DSIF antenna

actual physical measurements and then into actual physical parameters. The purpose is to keep track of the spacecraft in real time. The engineer must have data on temperatures, gas supply, signal levels, etc., in order to know the status of the spacecraft; this information is received from the SFOF.

Although all this telemetry information is available during a flight, man still has to make the decisions and act on the information, and must be very aware of time. The launch vehicle errors, for example, cannot be predicted and are significant enough so that we must do a midcourse maneuver for either lunar or planetary missions. We don't know what the vector velocity requirement is for the maneuver, and we have to wait until we have enough data. We want to make the maneuver as soon as possible, so that correction takes the least amount of energy, but we want to wait as long as possible, until we have the best information. We don't know what to do until we look at the data.

Up to this point I have been discussing the various parts of the system that are required to accomplish a deep space mission. Now I shall discuss one set of specific mission objectives—objectives which we would help

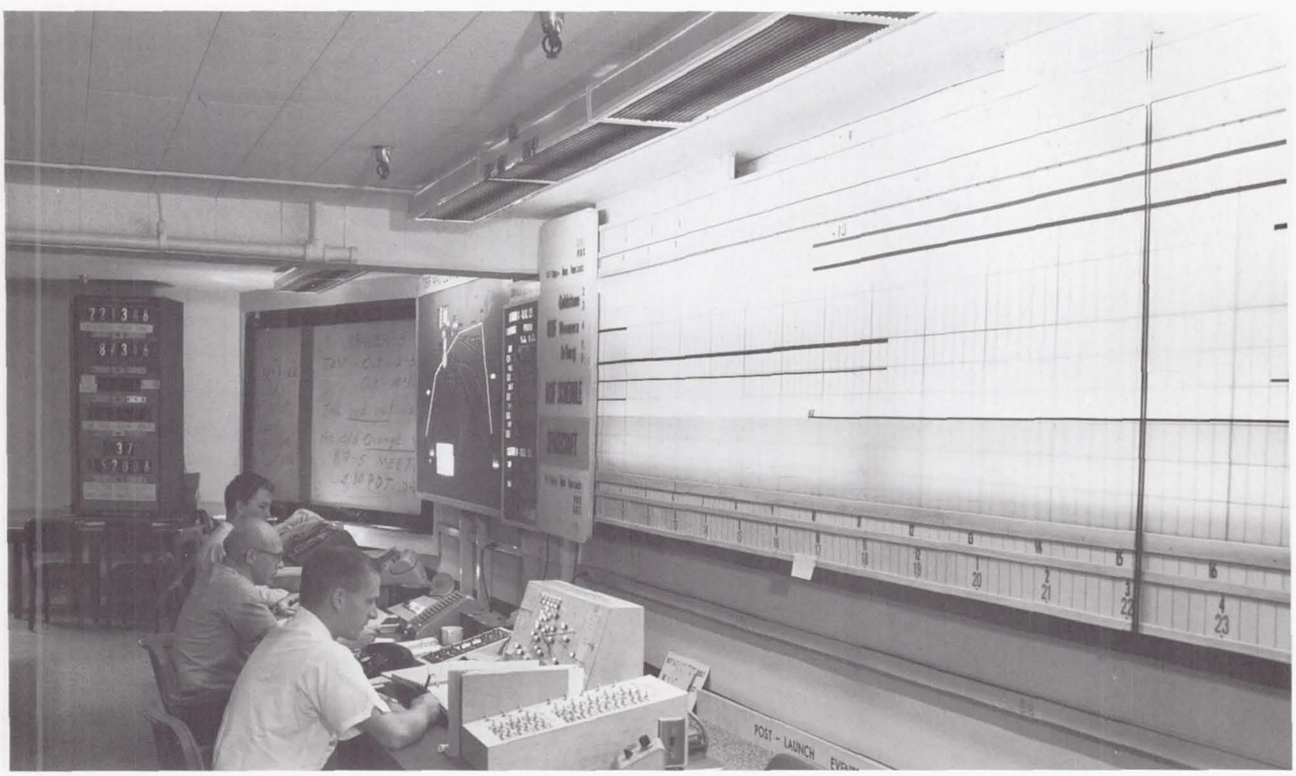

Fig. 8. Space Flight Operations Facility

generate, but which would be handed to us by management as requirements. It is at this point that the engineer can relate one set of requirements with another and make decisions as to system tradeoffs.

The following set of mission objectives, listed in order of priority, could be used for a Mars mission:

1. Conduct close-up (flyby) scientific observations of the planet Mars during the next opportunity and transmit the results of those observations back to Earth.
2. Provide, to the greatest possible extent, information bearing on the question of life on Mars. Either an IR grating spectrometer or a TV system, or both, will be carried solely for planetary measurements.
3. Provide experience and knowledge concerning the performance of the basic engineering equipment of an attitude-stabilized flyby spacecraft during a long-duration flight in space, farther from the Sun than is the Earth.
4. Perform certain field and/or particle measurements in interplanetary space during the trip and in the vicinity of Mars.

Fig. 9. Jet Propulsion Laboratory, 1963

5. Provide a design compatible with repeating the same or a very similar flyby mission to Mars during the following Mars opportunity with a minimum of modifications.

Now, having discussed system parts and mission objectives, I want to illustrate some of the other requirements of a complete system. Like everyone else in the space business, we at JPL are going through a complete building program in order to have the necessary facilities to accomplish our missions. Figure 9 is a mid-1963 photograph of the Jet Propulsion Laboratory. I think it is remarkable that, of the buildings shown, only one is used for spacecraft assembly; all the others are engaged in science and engineering efforts. This situation is pretty much the reverse of the old-fashioned airplane manufacturing operation.

Figure 10 illustrates another requirement of systems engineering—a chart that delineates functions and responsibilities. At JPL, at present, our organization chart sets out seven basic work areas—Systems, Space Sciences, Telecommunications, Guidance and Control, Engineering Mechanics, Engineering Facilities, and Propulsion. Notice that although the Laboratory is called a "propulsion" laboratory, propulsion accounts for only a small fraction of the work area. When you are told that five years ago it accounted for half the Laboratory's work, and that ten years ago it accounted for fully three-fourths of it, you can understand, I'm sure, the organizational difficulties involved in reorienting disciplines and shifting emphasis. Today, perhaps 70 percent of our work is in the field of electronics.

The work areas at the Laboratory have the following functions. Space Sciences is responsible for the procurement and manufacture of equipment for spacecraft and equipment for making scientific measurements. Space Sciences people review scientific objectives to see that we engage in projects that help to advance science. The Telecommunications Division is responsible for the Deep Space Instrumentation Facility, the spacecraft radio data encoder, and command subsystems. Guidance and Control, in addition to activities implied by its title, is responsible for spacecraft power and for the on-board computer. Engineering Mechanics is responsible for structures, mechanics, fluid dynamics, and temperature control. Engineering Facilities is a large division with responsibility for ground computers, environmental chambers, and wind tunnels. The work of the Propulsion Division

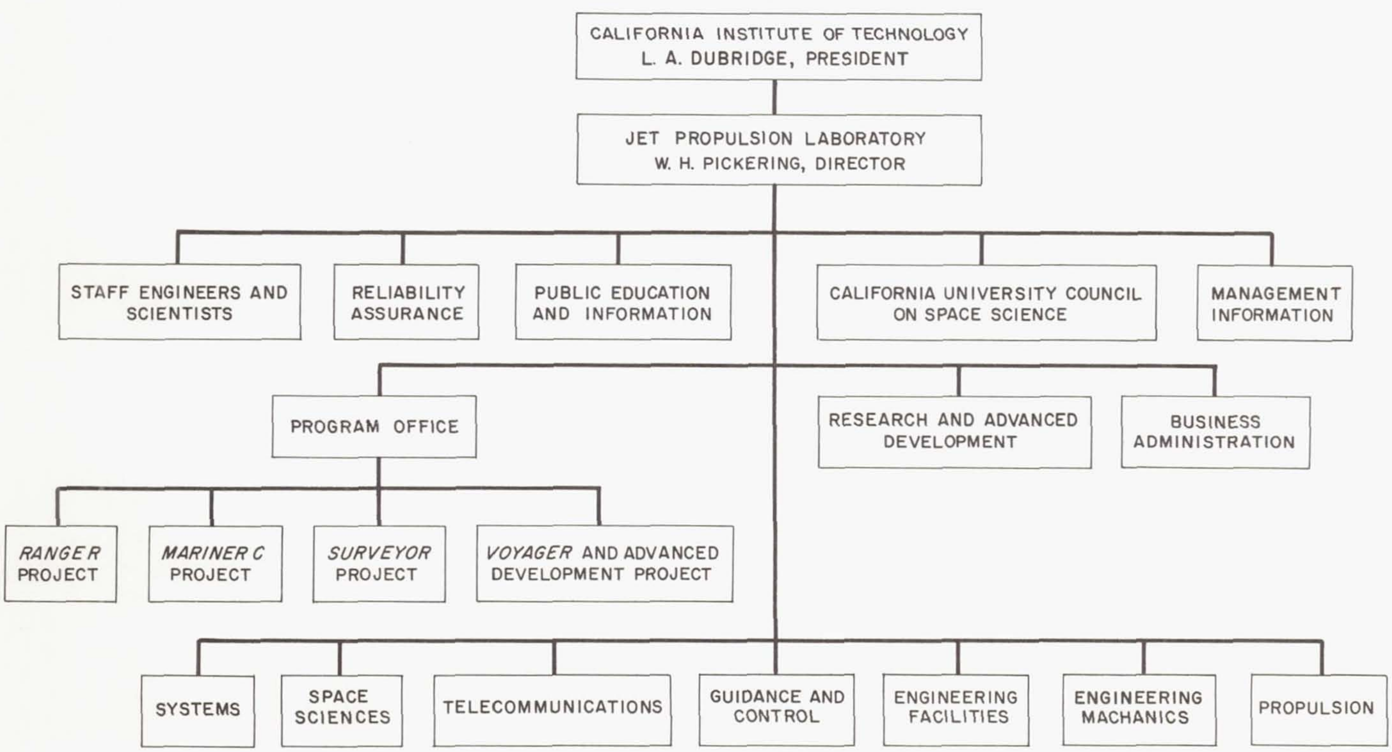

Fig. 10. JPL organization chart

involves both liquid- and solid-propellant spacecraft systems, such as the midcourse propulsion system.

The Systems Division is responsible for the overall spacecraft system—for tying all the various efforts together and delivering a complete system. The Systems Division also has responsibility for the Space Flight Operations Facility.

As shown in Fig. 10, JPL has subdivided its overall program into four main projects: *Ranger*, *Mariner C*, *Surveyor*, and *Voyager*. *Mariner R*, the successful 1962 Venus flight, is no longer shown on the chart. *Ranger* is a lunar mission. *Mariner C* is the 1964 Mars mission. *Surveyor* is a lunar soft-lander project which is being managed by JPL and built by Hughes Aircraft; it represents a new type of job, a management operation, for the engineers at the Laboratory. The *Voyager* Project involves future Mars or Venus missions and is only in the study phase.

Also shown by Fig. 10 are the other areas of support that the Laboratory requires. We have staff engineers and scientists. We have an Office of Reliability Assurance that is placed high in the organization so that it can be as effective as possible. We have a Public Information and Education Office and an office representing the California Universities Council on Space Sciences; NASA supports university research. We have offices of Management Information, Research and Advanced Development, and Business Administration.

As you can see, our organization is quite complex and requires a fairly large number of people in the various categories—scientific, engineering, administrative, technical, secretarial, etc. At present, we employ about 4000 people, of whom about 1500 are engineers or scientists.

Now I will discuss another of the boundary conditions that we must work with—the schedule. Figure 11 shows a typical schedule that we have used for overall control of the *Mariner* system. In some respects, schedule problems are simpler in *Mariner* than in other projects, since we know the time at which the planet will make its closest approach to Earth and we design for that.

You will notice that our scheduling is done in terms of time periods, milestones, that relate to completion dates of the various events.

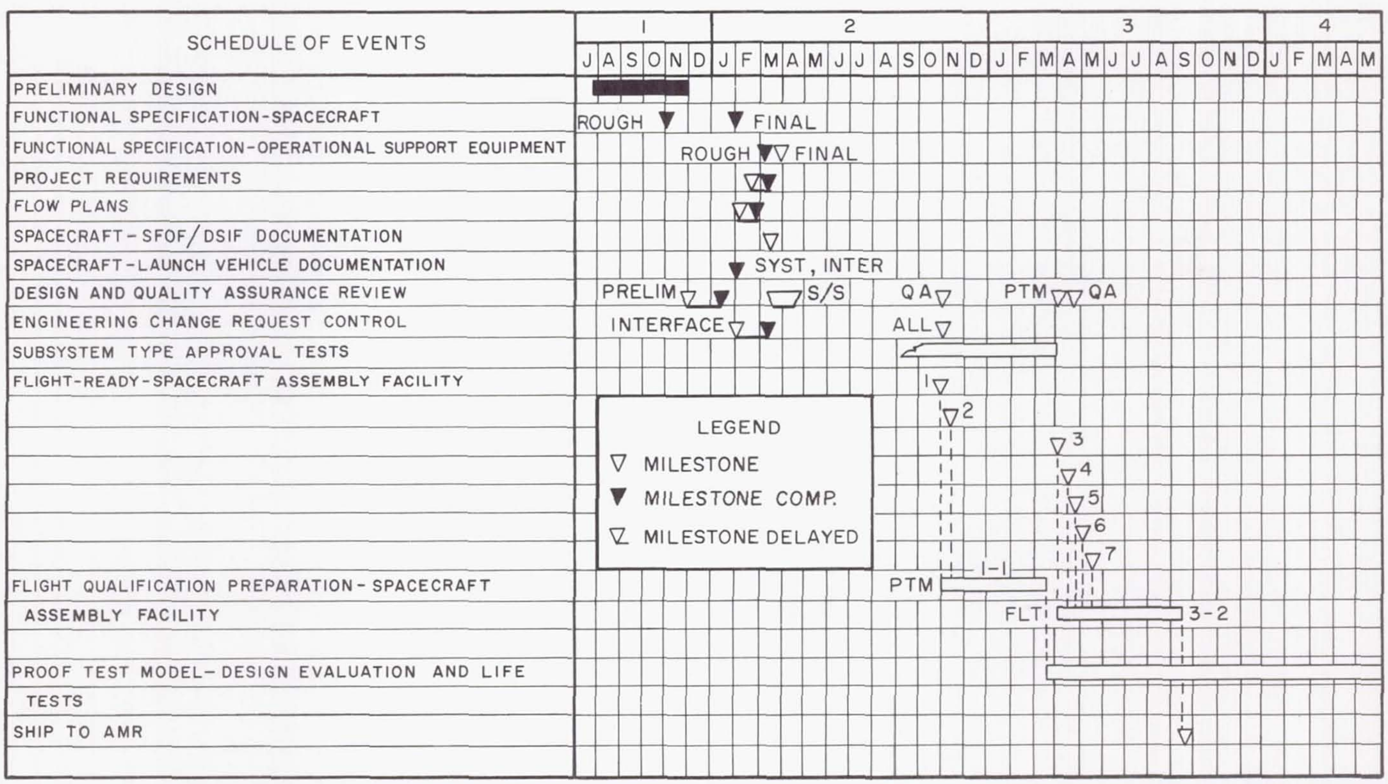

Fig. 11. ***Mariner*** **schedule**

In the preliminary design phase, the Systems Division calls together people from the various disciplines, and the engineering mission is discussed and analyzed. Projections are made as to what the spacecraft system must accomplish and how. Proposals for the substitution of new equipment for flight-tried equipment are heard and debated, and judgments are made on the basis of mission objectives. For example, someone may suggest the use of a new type of transmitter, while Systems people may want to stay with the type that has already flown and worked. Here, mission objectives and system requirements are the ruling criteria. Of course, on this point, everyone would like to have two transmitters and two receivers, and some method of switching, so that if one piece of equipment failed we would still get some data.

Each division then writes a functional specification—a description of what that division's subsystem is going to accomplish. Functional specifications are written for both spacecraft equipment and operational support equipment or ground test equipment. There are also project requirements—requirements, for example, relating to the amount of testing that must be done and the type of quality control that must be applied.

Flow plans are then made to describe the method of equipment generation. For example, the structure for the directional antenna may be built by Engineering Mechanics, the electronics by Communications, the actuators by Guidance people, and flow plans are needed to describe the overall operation.

Documents are then written to explain the interfaces between the different major systems: between the spacecraft and the SFOF/DSIF and between the spacecraft and the launch vehicle. We can't build the spacecraft, the SFOF, the DSIF, and the launch vehicle without determining how the various pieces of hardware are going to interact. The spacecraft/launch vehicle interface involves problems of RF interference, cleanliness, sterilization, etc.

Then, as shown in Fig. 11, there are design and quality assurance reviews. Of course, each subsystem area has its own reviews, but Systems and Project also review to see that overall progress is what it should be. For example, in one project, in the last stage of the communications system preliminary design we couldn't decide whether to use an amplitron or standard cavity amplifier. Two months later, the design review revealed that the amplitron wasn't very stable, that it would not always do what it was supposed to do. We also learned that this type of cavity amplifier is made only in West Germany. If we had obtained that information earlier, maybe we could have gotten someone in the U.S. to obtain a patent and build the particular equipment.

On certain dates—differing, of course, from area to area—equipment design is frozen; after the freeze date any change must be approved. This control is called engineering change request control, and is applied in order to maintain system compatibility. It permits everyone to know what his inputs are and what outputs are required from him.

During type-approval testing the subsystems or parts of subsystems are subjected to levels of testing—shake, temperature, even possibly sterilization—of orders of magnitude 30 to 50 percent higher than those expected. Then, as shown in Fig. 11, we put together a proof-test model, which could actually fly, and we test it. We try to do a design evaluation of the PTM in a life test. For a Venus flight we would like to run the spacecraft in an environmental facility, with some of the ground support equipment, for at least as long a period as in an actual Venus flight.

Now, to review, I would like to list the major systems involved in a space mission, and then the major engineering efforts required.

The major systems are:

1. Launch vehicle and complex
2. Spacecraft
3. DSIF
4. SFOF
5. Mission analysis; performance, schedule, cost reliability.

The major engineering efforts are:

1. Mission objectives
2. Preliminary design
3. Design
4. Design verification
5. Test and operations
6. Flight operations
7. Data analysis

The primary input, mission objectives, dictates the competing characteristics of the mission: namely, the order of importance of such factors as performance, schedule, cost, reliability, types of telemetry data to be returned, etc.

In the preliminary design, the systems engineer attempts to tie together the various subsystems, to look at the interfaces and resolve problems so as to benefit the overall system and meet the mission objectives. For example, if we are short on power, we might want to increase the solar panel area or to add another battery; but doing this might mean a major change for the power people, and they would argue against it. A decision has to be made.

In the design phase, the Systems effort is to coordinate the overall operation; perhaps it would be necessary to disallow a change in one area that would adversely affect some other area.

In design verification, the spacecraft is connected with the ground support equipment so that we can make certain that it is performing as it was designed. Each part of the design, each part of the system, must be verified. Temperature control verification is carried out in the space simulator, and the transmitter function may be verified by operations with the DSIF to determine that the transmitter signal can be received and handled properly.

In the test and operations phase, the spacecraft undergoes such tests as are necessary to indicate that it is ready.

In the data analysis phase, a determination is made as to what measurements are to be made and how they are

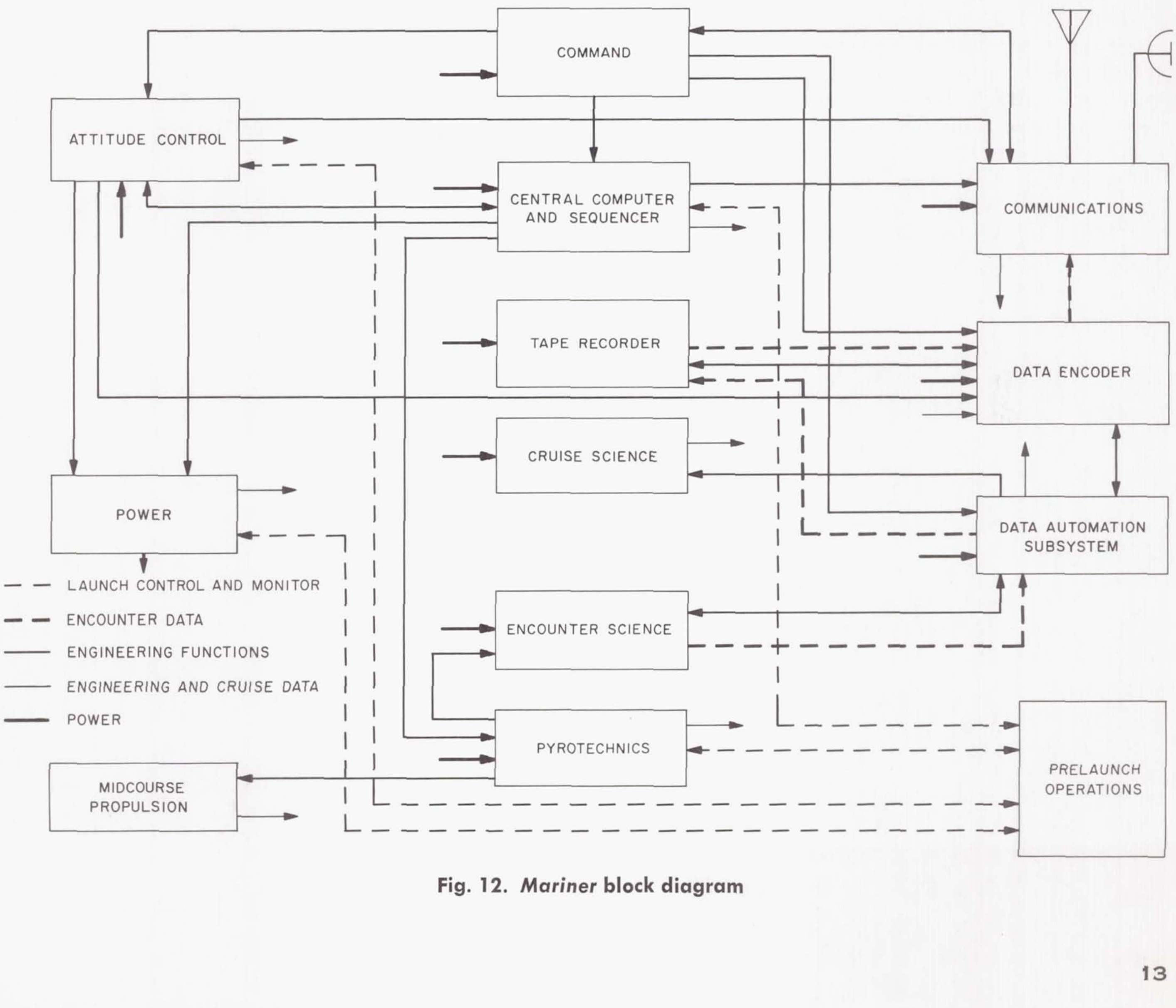

Fig. 12. *Mariner* block diagram

going to be measured. When the raw telemetry data is received, it is not in engineering units. The data must be converted into engineering units and then into physical parameters. For example, signals are received which indicate the pressure and temperature of the gas supply for attitude control. These signals are converted into lb/in.^{2} for the pressure and °F for the temperature, but this information won't directly indicate the mass of gas that is left. So the information is programmed into a computer and is read out as the mass of the gas. In a real-time sense in the critical areas, data must be read out in physical parameters, so that immediate action may be taken if indicated.

Figure 12 is a much simplified *Mariner*-type block diagram which illustrates the interactions of twelve spacecraft subsystems and prelaunch operations. The coded arrow system shows the interactions. For example, the encounter data, measured by encounter science, is fed into the data automation system (DAS). From the DAS it goes to the tape recorder, and from the tape recorder to the data encoder. The data encoder converts the data to the proper format for transmission and feeds it to the communications subsystem. The communications subsystem transmits the data to Earth over the high-gain or omnidirectional antenna.

When commands are sent to the spacecraft, they come in through the antennas to the command subsystem and are fed out from there. For example, to tell the attitude control system to move to a given position in order to do the midcourse maneuver, the command would go to the attitude control. The same command would also tell the power system to go on batteries, instead of on solar panels, because of loss of Sun attitude by the spacecraft. A command would also go to the CC&S to tell the pyrotechnics to fire so as to do the midcourse propulsion maneuver.

For each one of the subsystems, a block diagram of much more complexity than that shown in Fig. 12 is traced through by Systems engineers so that they can understand the various interactions and will be aware of where subsystem redundance can be used to give a maximum probability of success to the mission or where commands can be used to override a failed mode within a spacecraft.

An understanding of block diagrams is required of any engineer relative to either system or subsystem. Circuit data sheets are made which show the data flow between subsystems, and are detailed as to voltage and current and the variations thereof and can be interpreted as subsystem inputs and outputs.

The preceding discussion was an attempt to show the problems and procedures used in system engineering as applied to spacecraft missions.

N66-13844

Systems Design

W. DOWNHOWER
Chief, Systems Design Section

I would like to speak to you today on the topic of Systems Design and Systems Design Studies. I will attempt to explain what I mean by these terms by giving some definitions and some examples, and then try to show you how we use these activities in such major programs as *Ranger* and *Surveyor*.

Although it might be termed a truism, I believe it is important enough to state specifically: *the basic purpose of any study activity is to provide information for a decision.* It is extremely important to answer the question: What type of information is required by the decision maker and, hence, from the study activity?

There are four general categories of information a person would like to have available upon which to base a decision. This decision might be to begin a project, to continue a project, or to cancel a project. The types of information sought by an engineering study fall into four categories:

1. System performance and system description.
2. Schedule of accomplishment of mission objective.
3. Probability of mission accomplishment.
4. Cost of mission accomplishment.

I believe the first and second categories of information will be relatively familiar to you. The first category would be termed *Systems Performance and Description.* This is comprised of a technical description of the system design and a statement of what it can do in terms of mission accomplishment.

The second category answers the question: Consistent with the requisite level of systems performance, what is the *Probability of Mission Success*? That is, how many launches must you perform to have a successful mission? If the system will only work one time in five, this may be important to your program.

Once we felt we understood the problem of describing systems performance and determining the probability of mission accomplishment, we began to try to develop information in two additional categories as well. These are: Consistent with the levels of systems performance and probability of success; what is the *Schedule* upon which this mission could be performed? Fourthly, Consistent with systems performance, probability of accomplishment, and the schedule; what is the *Cost* of accomplishing this task? So, depending on the type of decision to be made, we are often asked to perform a study which will provide the information in categories one and two and quite often in categories three and four as well.

Since we are making decisions based upon the information from studies, we find it very important to be able to describe the depth of the study effort which we are about to carry out or have completed. An engineer is most familiar with what could be termed *practical* systems, i.e., systems which can be brought into being. Further, an engineer feels most at ease in working with systems or subsystems with which he is familiar so that he can feel quite confident in making statements about them, and stake his reputation on such statements. This would be termed a study of practical systems. Unfortunately, on a complicated system such as *Ranger* or *Surveyor* it would be very expensive in both time and resources to conduct a study activity of sufficient depth so that a responsible engineer could satisfy himself that it is a practical system. It often turns out that this depth of study may not or cannot be justified economically; studies of lesser depth may be needed to assess the "pros" and "cons" of the system and justify committing additional resources. This has caused us to develop study techniques of *practicable* systems. This distinction may at first appear to be simply a shade-of-grey difference from a *practical* system, and yet strictly speaking there is a black and white distinction between the terms *practical* and *practicable. Practicable systems are those systems which are thought to be capable of being brought into being.* Therefore, the result of *practicable system* study may be a description of the system and its performance but in addition there will be an attached list of problem areas which, in effect, describe the status of the system in terms of its evolution towards a *practical system.* In the case of a practical system, in addition to the systems description and its performance, one could go so far as to generate the detailed drawing from which the system could be built.

Now, to better understand this term *practicable*, I would like to define several different types of studies that one could undertake. They differ primarily in depth of effort. These definitions are my own. I believe they are a consistent set among themselves. The first of these I term *conceptual design.* The basic feature of a conceptual design is that it is a design of a *practicable* system. Its primary use is to provide information to those people who are planning programs. The information provided is usually an estimate of the capability of a system. This allows its utility in accomplishing overall program or project objectives to be assessed. For example: the first step performed in initiating the *Surveyor* project (the *Surveyor* is a lunar soft-landing spacecraft) was to conduct a conceptual design of the spacecraft. This was an effort of some six-weeks' duration which tried to find the pertinent performance factors of the system and to list the outstanding problem areas. With the completion of the study and listing of the information in these two categories (and although there were still a large number of problems to be solved) the Laboratory undertook the task of evaluating the utility of such a system in accomplishing the goals of the Lunar Program. Such a system might not be worth the investment to bring it into being. It might turn out to be unreliable or too costly. In the case of *Surveyor* the judgment was that it was neither of these.

Now, if we've gone through a conceptual design, and the result still makes sense—that is, we feel that the system under study is useful and we think the problems can be overcome—we then go on to the next level of study activity.

The next level of study is termed *design study.* The major difference between a design study and a conceptual design is that we are, by definition, constrained by the study to practical systems and subsystems. This may mean we will have to accept a lesser performance if we do not choose to advance the "state of the art"; or it may mean that to attain a specific level of performance, a considerably deeper "look," such that the result of the study can be termed practical, may be required. The problems uncovered in a conceptual design *must* be solved prior to or during the design study. To achieve this result, a design study is often a study of trade-offs between the various subsystems so that practicality for the subsystems and the system can be achieved.

To return to my *Surveyor* example, when we continued that effort beyond the conceptual design stage, we next looked at the alternate system concepts, all of which were *potentially* capable of performing the mission. However, these various alternates gave us different options in terms of the four major factors of performance, probability of success, cost, and schedule. Some systems had more performance, but were less reliable; or they were more expensive; or took twice as long to bring into being. In each case, however, the design was of a practical system. This spectrum of results allowed us to assess the utility of the *Surveyor* system, but with more confidence in the factors of performance, probability of accomplishment, schedule, and cost, which now had considerably more supporting material behind them.

At this point I would now like to define a more familiar type of study—*preliminary design.* Usually upon the completion of a design study and prior to the start of preliminary design, a major review of the design study has occurred and a decision has been made to go ahead with the project. That is, the project has been formally initiated. This means we are committed to a no-nonsense, detailed design effort to bring a flight system into being. Now we are dealing with very specific characteristics based on the design study work. We now have a definitive list of the different specific features that the preliminary design must detail in great depth.

In Fig. 1, I have tried to show the relationship of the three types of studies which I have just defined. To the left, we have the area of conceptual design, dealing in terms of feasibility with those systems which are *practicable.* Next we have the overlap of this conceptual design into design study. Usually in this overlap area there is a period of review wherein the results of the conceptual design are examined and a decision is made as to whether or not to continue and to increase the depth of the study activity. In general, there are only two ways we can go from a *practicable* system to a *practical* system. One, as I indicated earlier, is to reduce the goals of systems performance and reliability until the design lies within the realm of the state of the art. Or, as I've indicated in Fig. 1, to carry on a large amount of supporting advanced development effort directed toward solving the list of problem areas that are turned up in the conceptual design process.

Also, I should point out that one tends to narrow the range of topics under study as a function of time. Conceptual designs may cover a rather broad range of objectives.

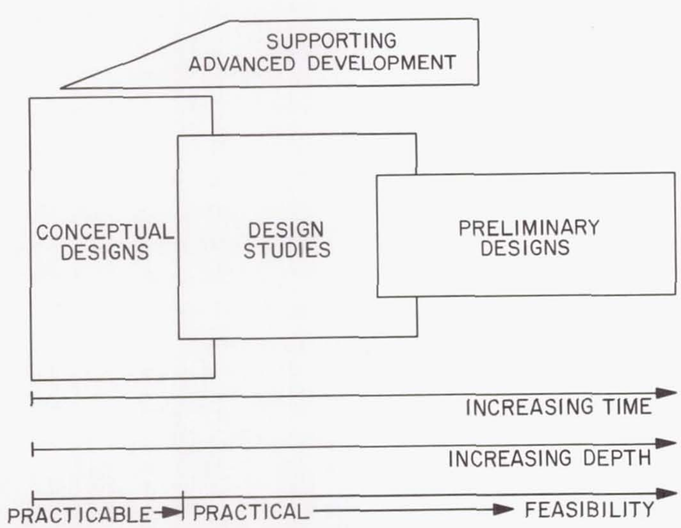

Fig. 1. Relationship of study activities

Design studies usually cover a more clearly and more tightly specified set of requirements assumptions. Finally, during the preliminary design study, we become very specific, and at its conclusion we will have a very detailed specific concept. And of course, as we have proceeded, we have invested an increasing amount of time and resources to increase the depth of effort.

So far I have talked only about the depth of study activity. As I have indicated, one can also discuss and describe the *breadth* or *range* over which such study activities can be done. I'll try to define a few of these areas for you. The term *component* is probably self-explanatory. A *module* is that collection of components required to perform a single *function.* A *subsystem* is then a grouping of modules which perform "like" functions. Good examples of such a subsystem would be a power subsystem, an attitude-control subsystem, a guidance subsystem, or a sequencing subsystem. A system then is the collection and combination of these subsystems integrated to perform a specific mission or to achieve a system objective. Typical examples of systems would be the entire spacecraft, the entire launch vehicle. We take the combinations of the systems such as launch vehicle, spacecraft, and ground tracking net, and with these we perform a *mission.* A *project* is a grouping of missions. This grouping is usually based upon some common feature such as the capability of accomplishing a unified goal or exploiting the use of a particular launch vehicle, etc. For example, the *Ranger* Project is that portion of the Lunar Program designed to return knowledge about the lunar surface by utilizing the capability of the *Atlas/Agena* launch vehicle. The individual *Ranger* spacecraft perform a variety of related missions in determining various facts about the lunar surface. The common denominator is the fact that they are all about the same weight. This weight limit is set by the injection-energy capability of the launch vehicle, the *Atlas/Agena.* In a similar manner, the *Surveyor* Project is composed of those lunar missions to be undertaken with the *Atlas/Centaur* launch vehicle. A *program* would be the combination of the various projects. A good example is the unmanned lunar exploration program conducted by JPL. This is currently comprised of two projects, the *Ranger* and the *Surveyor* projects, and a project in the study phase utilizing the *Saturn* launch vehicle, the *Prospector.*

It is actually possible to conduct studies over this entire regime. That is, all the way from a single component, clear through to a program. It is obvious that not all of these would be termed systems studies. In general, the study activity performed in an integrated systems sense does not go much below the subsystem level. However, studies have been performed of various systems, various missions, and various projects.

It is possible, by taking my definitions of depth and breadth of study effort, to create the matrix (Fig. 2) relating these various activities. We have done studies at one time or another for almost every one of the elements contained in this matrix.

BREADTH ↓	DEPTH →		
	PRACTICABLE	PRACTICAL	
	CONCEPTUAL DESIGN	DESIGN STUDY	PRELIMINARY DESIGN
COMPONENT			
MODULE			
SUB-SYSTEM			
SYSTEM			
FLIGHT			
PROJECT			
PROGRAM			

Fig. 2. Matrix of study

I would like to now go into the methodology of performing a systems study, and try to describe how one goes about performing a study such as I have referred to. These studies are actually simple to do. There is a lot of hard work, but the procedure is relatively straightforward.

Figure 3 (items 1–3) contains the basic information one needs to begin the study. This actually might be called a formal statement of the problem to be solved. We use these three subcategories to divide the problem statement. The first category is straightforward. It is a *definition of the study objectives*: that is, what problem is the study to explore? To go back to the example of spacecraft studies, the objective may be to perform a particular measurement on the lunar surface or on the surface of a planet. The second portion of the definition of the problem is the statement of the *constraints and boundary conditions* which must be observed during the study. By this I mean the practical limitations placed on the study. For example, this category would define the injection energy and accuracy capability of the launch vehicle. We do not design the launch vehicle at JPL but we acknowledge the fact that they are expensive, that they come in specific generations of vehicles, and hence only certain capabilities and accuracies are available within a specific time period. Thus, they provide a real constraint on the design. We have an *Atlas/Centaur*; it makes little sense to use an "*Atlas/Centaur* and a half." A similar limitation in a different technical area is the Deep Space Instrumentation Facility. This is the world-wide tracking network that NASA uses to track all spacecraft operating in deep space. It is designed to operate at certain specified frequencies, to have certain sensitivities in terms of reception capability, and to have certain transmission capabilities. In general, because of the expense and lead time involved in changing such characteristics of the Deep Space Instrumentation Facility, its capabilities at any specific time become a real constraint upon the study of a system which must operate in that same time period. Thirdly, in the areas where an engineer is asked to exercise judgment, there may be some preferential order of *competing characteristics*. For example, suppose I have a variety of ways to accomplish a specific mission. Some are more expensive, others less reliable, others may be better schedule-wise, still others may have more performance. It is obvious that in most cases we will not achieve an optimum solution, that is, the solution with the most performance, the quickest, the cheapest, the most reliable. In fact, it probably doesn't exist. So, in areas where trade-offs must be made, the ordering of these competing characteristics *in advance* helps set the philosophy underlying the entire study or design effort. If we can get a clear statement of the problem in terms of information in these three categories, then we are in pretty good shape in accomplishing the overall study itself.

1. DEFINITION OF THE OBJECTIVES
2. DETERMINATION OF THE CONSTRAINTS AND BOUNDARY CONDITIONS
3. IDENTIFICATION AND ORDERING OF COMPETING CHARACTERISTICS
4. ESTABLISH THE FUNCTIONAL REQUIREMENTS
5. DETERMINE THE ALTERNATE CONCEPTS SATISFYING THE REQUIREMENTS
6. STUDY THE INTERACTIONS AMONG THE ALTERNATES
7. IDENTIFY AND SELECT COMPATIBLE ALTERNATES
8. DOCUMENT THE FUNCTIONAL CHARACTERISTICS

Fig. 3. Methodology of study

The next step we carry out is to interpret the statement of mission objectives into a listing of those functional requirements which must be met to accomplish the mission. At this point we are still treating the system as "black box." That is, if you saw this spacecraft out in space, what would be its characteristics perceivable to you as an observer from the outside. We have not yet selected specific ways of carrying out the requisite functions.

1. MAKE SCIENTIFIC MEASUREMENTS
2. MAKE ENGINEERING MEASUREMENTS
3. PROVIDE DATA HANDLING FUNCTIONS
4. SUPPLY POWER
5. TRACK AND COMMUNICATE
6. CONTROL AND SEQUENCING
7. GUIDE
8. IMPART IMPULSE
9. CONTROL ATTITUDE
10. CONTROL ENVIRONMENT
11. EXTENSION
12. ARTICULATION

Fig. 4. Functional requirements

In Fig. 4, I have listed the functional requirement categories that we find appropriate to our work in the design of spacecraft. There are certainly other listings and definitions of functional requirements which are appropriate to other engineering fields. However, this particular list seems to be most useful in our area of spacecraft design. The first of these is rather obvious: that is, to *make scientific measurements.* Since the Jet Propulsion Laboratory is not directly engaged in the various manned spaceflight programs, this category is one of the foundations upon which we have built our entire organization. As is obvious, there is a large number of categories one could develop by dividing space up into various regions: interplanetary space, the surface of the Moon, the atmospheres of the various planets, the surfaces of the various planets. All of these fall under the Laboratory's general responsibility for the unmanned lunar and planetary exploration program.

The second category is to *make engineering measurements.* Typical of such measurements are those which allow us to understand the condition of the spacecraft itself: that is, monitor its performance, any abnormality in its performance, or potential problem or failure areas.

The next category is to *provide a data handling function.* This category encompasses the entire handling of the data from when it first originates in an instrument or sensor (such as categories 1 and 2) until it comes out as data at the DSIF.

The fourth category is to *supply power.* We may not know exactly what power source we may use, but it is possible to determine the power requirements as a function of flight time, and often the optimum power system will be determined by the character of this profile and the total demand placed upon the power system.

We then have the fifth category of *tracking and communications.* This is an obvious category: (1) to track the spacecraft so that we are aware of its position in space; (2) to communicate with the spacecraft, both to send commands to it and to receive data from it.

The next category is one of *control and sequencing.* Again, you may not know the exact mechanism you are talking of here, but you may find it necessary to shift among alternate data-taking modes, to provide timing pulses to other subsystems, or to perform a series of operations in some order or sequence.

Category seven is one of *guiding* the spacecraft. The term guide is used in a very general sense and means to control the flight path of the spacecraft. For example, a mission may require that the spacecraft pass within a certain distance of a prescribed object in space. This system provides such control of the trajectory of the spacecraft. In terms of providing guidance references, you may not know exactly the sensors to be used, but you are able to state the requirements on the overall system.

The next category is to *impart impulse.* By this, I mean to change the momentum of the spacecraft. The requirement in this category for a lunar landing spacecraft is obvious. On most trajectories you arrive at the vicinity of the Moon going approximately 8–9,000 ft per sec. If you wish to land you must impart impulse to the spacecraft system to slow it to some nominal speed at touchdown.

The next functional category is one of *controlling attitude.* This requirement may arise from the desire to be able to point an instrument in a particular direction. It may come from the requirement to point a rocket motor in a particular direction so as to control the flight path.

It might arise out of the area of tracking and communications. To provide adequate bandwidth to communicate it may be necessary to point a directional antenna towards the Earth.

The tenth category is one of *controlling the environment.* By this I mean, controlling the on-board environment within proper operating limits for the equipment in the spacecraft. For spacecraft operating primarily on near-miss and/or deep space missions, this becomes primarily a matter of thermal control. For spacecraft soft-landing on the lunar surface or on the surface of a planet, it may involve considerably more than that.

The next category is one of *extension.* By this I mean the simple extension or erection of devices from the main body of the spacecraft. A good example arises from the problem involved with carrying a magnetometer on a spacecraft. Because of the magnetic fields generated by a spacecraft, it is highly desirable to get physical separation between the main body of the spacecraft and the magnetometer itself. This may be accomplished by a telescoping boom which provides this physical separation.

The twelfth category is one of *articulation.* The requirement for articulation usually arises from the fact that an instrument will be required to observe a planet or other object as the spacecraft flies past it. We are then faced with the conflicting requirements of maintaining reference axes for stabilization to provide solar power, to provide directional communications back to the Earth, and now to point this instrument at a target body. Rather than relinquish the basic reference axes, the trade-off may indicate a boom, with the tracking instrument on the end, articulated relative to the rest of the spacecraft.

Once we have identified the functional requirements that the system should exhibit, the next step is to identify the various subsystem concepts and determine the various subsystem mechanizations available to provide the functions required. For example, within the time scale required, there may be several ways in which to provide power; or there may be several different possible attitude-reference systems, all of which satisfy the requirements of both guidance and attitude stabilization.

In addition to the various possible ways of meeting these functional requirements, the study leader will also ask the subsystem people who provide this information to also provide information as to subsystem cost, reliability, state of the art, and schedule. It is at this point that we start to collect the various pieces of information that we will eventually combine into statements as to the probability of mission success, the overall schedule, and the overall cost of the mission. These statements are built upon the base of subsystem information collected at this phase of the study process. What we are gathering is the parametric information on the various possible mechanizations at the subsystem level. With this base of information on the subsystem mechanizations, we then began to group these mechanizations in various combinations, generating, in the process, system concepts illustrating possible system philosophies. Once we have grouped these subsystems into systems concepts, we then go further and determine the interactions between respective subsystems. These interactions represent some of the problems which must be solved in the course of the design process.

A good example of a potential systems integration problem is posed by an RTG power supply, the radioactive-isotope thermal generator system. Basically, this form of power supply consists of a group of thermocouples inserted in a radioactive source which gives off heat. The thermocouples operate across the thermal difference which exists from within the radioactive source and the outside environment and convert the thermal energy to electrical energy. This is a highly desirable type of power supply in the sense, first, that the radioactive decay process is relatively immune to external disturbances, and second, that it does not demand any preferential pointing direction as a solar panel might. Unfortunately, RTG's have a number of major drawbacks which must be faced when they are integrated into a system. One is that they are not thermally efficient. For each unit of energy they convert into electricity, they give off a large number of units of waste thermal energy which must be dissipated. For example, an RTG power supply which produces perhaps 50 watts of electrical power may produce some 400–500 watts of thermal energy which must be dissipated. We are then faced with the question: If we use such a power supply, how do we dissipate this heat? By being aware of such potential integration problems as this we are able to go through the various system concepts and get a fairly good engineering "feel" for which ones are compatible and which are incompatible out of all the combinations that might be possible. Once we have found these compatible groupings and have identified such integration problems, the next very important, and often neglected, step is to properly document these pros and cons about each systems concept.

I do not mean to imply that every system studied will necessarily meet the original mission objectives. At this point I should state the responsibilities of the study leader. First of all, he has a responsibility to make sure that the people who have participated in this study have provided an unbiased report on the various alternate subsystems considered. By this I mean, he must be aware of the various margins in the design (performance margins, reliability margins, etc.) so that the study he has presented is a balanced result in terms of bringing the whole system up to the same point of development. But conversely, if this has been done, and the study leader finds that the mission objectives cannot be met, he then has an obligation and responsibility to these very same people. He must be prepared to go back to the originators of the study and frankly tell them that the mission that they have selected does not appear to be feasible, or at least not feasible within the constraints and boundary conditions that were placed upon the study. I think that both of these responsibilities are a matter of engineering integrity: first, to see that you get the best possible effort from the people who have initiated the study; second, to properly represent the results of the combined efforts of the participating people.

I would now like to give you several examples of different types of studies which we have performed at JPL.

My first example is of a study which we performed at the Laboratory about a year and a half ago. This is about as broad a study effort as one could imagine. Its title is: "Study of Several *Apollo*-Support Aspects of the Unmanned Lunar Program." What this means is: In what areas and in what way can the unmanned lunar program make a contribution to the Apollo (or manned lunar) effort?

We began this study quickly and came to the conclusion that there were three general areas in which the unmanned lunar program could potentially support the Apollo program. The first of these would be measuring environmental parameters which would aid in the design of the *Apollo* spacecraft and *Apollo* mission. The second major area of possible support would be the development and/or demonstration of techniques which may be required by the *Apollo* mission and spacecraft. And the third major area would be the actual flight test of Apollo equipment on unmanned lunar spacecraft. For the purposes of my example, I would just like to concentrate on the study technique and the result of our attempt to answer only the first question: What measurements of environmental parameters could be performed in support of the *Apollo* program?

The first task we found we had to do was to define the Apollo mission and mission profile so that we could better understand the particular requirements of the mission. I am sure that most of you are familiar with the mission profile/flight sequence (Fig. 5). The *Apollo* spacecraft will be launched from the Earth and placed into a coasting or parking orbit. This coasting period will allow an adjustment for any small deviations from the original launch conditions so that proper injection conditions may be achieved at the conclusion of the burning of the last stage. With the completion of this final burning of the booster rocket, the spacecraft would then be on a coasting trajectory to the vicinity of the Moon. Following injection, there would be a period of ground-based tracking to determine the actual trajectory of the spacecraft as compared to the desired trajectory. If required, a midcourse maneuver would be performed in transit to the Moon to correct for any deviations from the normal flight path. As the near vicinity of the Moon is approached, the astronauts will orient and fire a retro-rocket which brakes the spacecraft, slowing its velocity so that it will orbit about the Moon. Once in orbit, it may be necessary to perform a trim or corrective maneuver to adjust the orbit so that it passes over the desired landing point on the lunar surface. When proper orbit has been achieved, the astronauts will then separate the LEM (or Lunar Excursion Module), which is being built by Grumman. Two astronauts will then descend to the surface of the Moon in the LEM by firing a landing retrorocket and landing on the surface of the Moon. The third astronaut will remain behind in the orbiting portion of the spacecraft. With the completion of operations on the lunar surface and final checks on the LEM, the men will take off from the lunar surface under rocket power and rendezvous with the spacecraft, which will have remained in lunar orbit during this period. With the completion of the rendezvous operation, the men transfer back to the spacecraft. The empty LEM is then separated and left in lunar orbit. There is a period of rocket firing which puts the command module and the service module onto a trajectory which will return it to the near vicinity of the Earth. As was the case on the outbound flight, it may be again necessary, after a period of tracking, to perform another midcourse maneuver to correct for any errors associated with the departure from lunar orbit. The Earth's atmosphere will be entered on a grazing trajectory. The excess energy will be dissipated by use of atmospheric braking, and in a manner similar to Mercury's reentry, the spacecraft will return to the surface

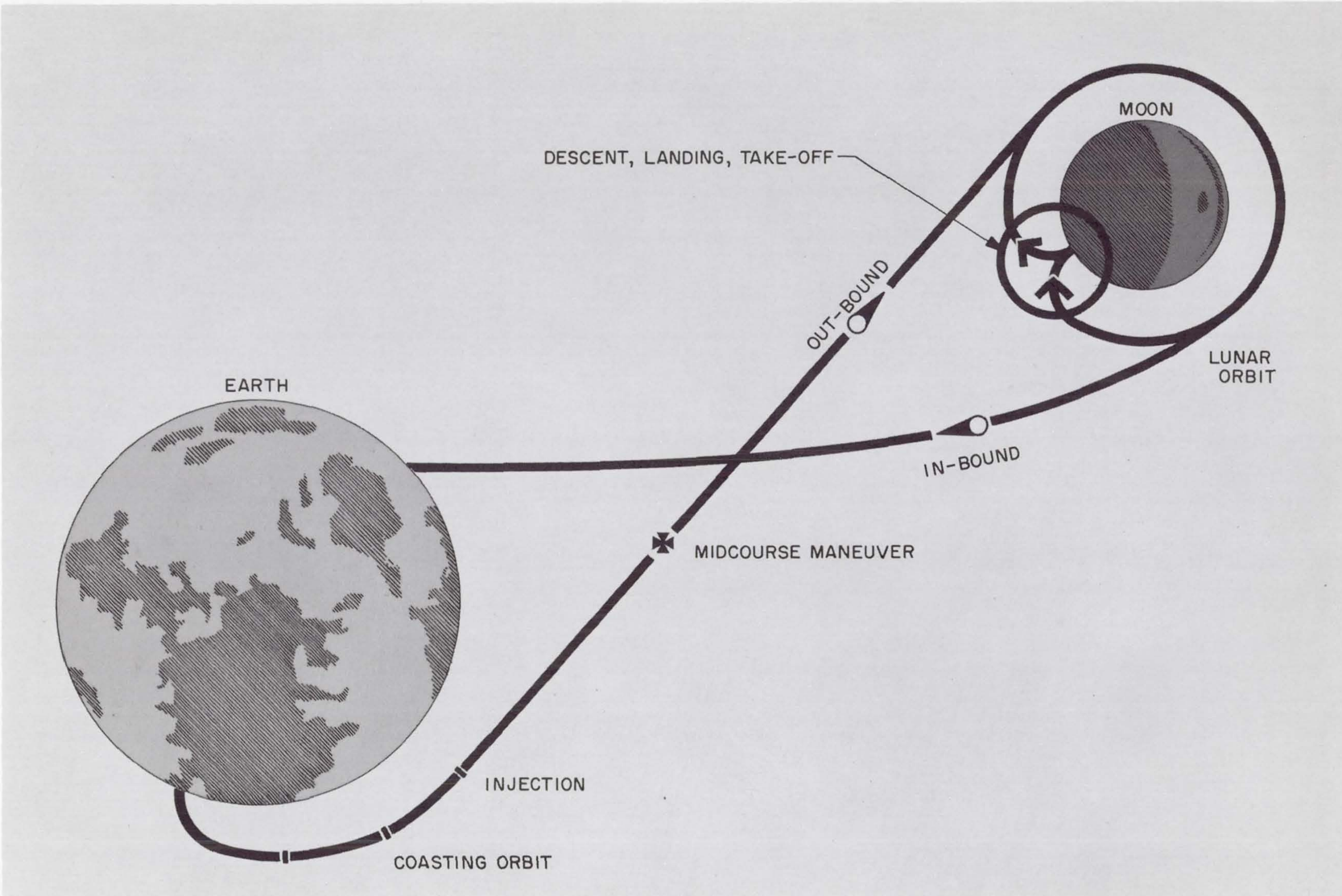

Fig. 5. *Apollo* mission profile

of the Earth. This, then, represents the nominal flight profile which *Apollo* will follow. The question is: how does one go about deciding, in a study sense, what kind of information on the various environments is needed, and how can these parameters be measured from unmanned spacecraft?

The first step of the study, as we performed it, was to generate a matrix as illustrated in Fig. 6. Down the left-hand column, as row headings, we listed the various steps in the Apollo mission profile as just discussed. In this listing, we went into considerably more detail than I have had time to discuss with you today. Then we listed across the top, as column headings, every environmental parameter that would be experienced. For convenience, we grouped these parameters into the various regimes shown here. That is, the near-Earth environment, the transit or translunar environment, the near-Moon environment such as would be experienced in lunar orbit, and the environmental parameters of the lunar surface. In so doing, we tried to list every known and potential environmental factor that might be experienced from near-Earth to the surface of the Moon and back. As you can imagine, this is a fairly long list, ranging all the way from Van Allen belt radiation near the Earth, to such details as whether or not there is dust on the surface of the Moon. Then, for every element in the matrix, we tried to answer the following three questions. First, is the particular environmental parameter in this column of consequence during a particular mission phase? We

		ENVIRONMENTAL PARAMETERS			
		NEAR-EARTH	TRANSIT	NEAR-MOON	LUNAR SURFACE
APOLLO MISSION PROFILE	1				
	2				
	3				
	⋮				
	N				

Fig. 6. Environmental parameters: *Apollo* mission profile

tried to limit answers to a simple "yes," "no," or "possibly." For those boxes in which the answer to question one was a "yes" or "possibly," we then asked a second question. That is, what is the nature of the interaction between the environmental parameter and the particular mission phase that raises this question as to the interaction between the two? Certainly one of the more obvious examples is the effect of Van Allen belt radiation, both on different elements of the system and upon man himself. During the lunar landing, the surface roughness and its hardness are both extremely critical parameters and strongly influence the design of the landing system. Finally, once this interaction has been stated as clearly as possible, we then attempted to answer the third question: What information is required to aid in the design? That is, is the current knowledge of the parameter sufficient to allow for design, or is additional or more accurate information required to properly carry out the design effort? By going through this type of questioning, we were able to sort out, from the many possible measurements which could be made, those which appeared to be the most important and critical to the *Apollo* mission. As you may well imagine, there were many areas where it appeared that the information was sparse, or not as detailed as the engineer would like. Outstanding among these were the following five parameters.

The first three I assume will be obvious; you could have probably written them down without going through all the work that we did. These are the parameters directly concerned with the physical characteristics of the surface of the Moon. They are extremely important because of their interaction with the landing system: the landing dynamics, the landing gear, etc. These parameters are: *the surface roughness, the surface slopes, and the surface hardness or bearing strength.* There are bounds placed on the ranges over which these parameters can vary. These bounds are, in general, based on the theories of the origin and evolution of the Moon. However, it was found that the extremes which these theories encompass present an extremely difficult engineering problem if one attempts to design for the entire range. Indeed, there is a definite engineering reward if any of these bounds can be markedly changed or reduced. This is particularly true when one considers the high degree of reliability required of manned spaceflight efforts.

The fourth parameter is *the presence or absence of lunar surface dust.* It appears on this list for two reasons: first, because of the landing problem, and, second, because if the surface is dusty one would expect that a rocket jet would kick up a large plume of dust which might obscure or hamper the use of visual or nonvisual sensors during landing, or, if the landing is successfully accomplished, the dust settling back on the spacecraft might cover such elements as sensors or solar panels.

The fifth category concerns the value of *the electromagnetic properties of the lunar surface*, particularly at microwave frequencies. Most of our concepts indicated that some sort of radar would be used both as an altimeter and as a velocity sensor during the landing and takeoff phases of the mission. Hence, it is important to know the scattering and absorptive properties of the surface in the radar frequencies in order to allow the proper design of such instrumentation. If, in the final *Apollo* design, one uses visual sensors to provide this same information, then the analogous category would be for a better definition of the surface properties in the visual portion of the spectrum.

There were actually two types of data sought for each of these five environmental parameters. The first of these might be called survey-type data; that is, information on these properties over a fairly wide area on the lunar surface. The purpose of such survey-type information would be to aid in the selection of the landing site. In performing a survey, it may not be necessary to obtain information in all five categories or to obtain it with the same detail or accuracy required to verify the final landing site. Rather, it may be adequate to take data at a sufficient resolution so that unacceptable landing sites are eliminated from further surveys. For example, photographic measurements, taken from such a spacecraft as a lunar orbiter, may be able to disqualify large portions of the lunar surface because of the extremes of surface roughness or surface slopes. Once we have weeded out the more obviously unacceptable sites, we must still gather detailed information on all five of the parameters at the selected landing site. This leads to the second type of data required to accomplish the Apollo mission; i.e., detailed landing site information.

The next phase of the study was to review the capabilities we had or could bring into being to make the measurements of these parameters. To determine this we formed the elements of the second matrix illustrated in Fig. 7. Across the top we used the five environmental parameters and the two different types of data required as the ten column headings of the matrix. Then, down the left-hand column, as row headings, we tried to list all of the instrument/spacecraft combinations that were available or could be built within the time scale of the *Apollo*

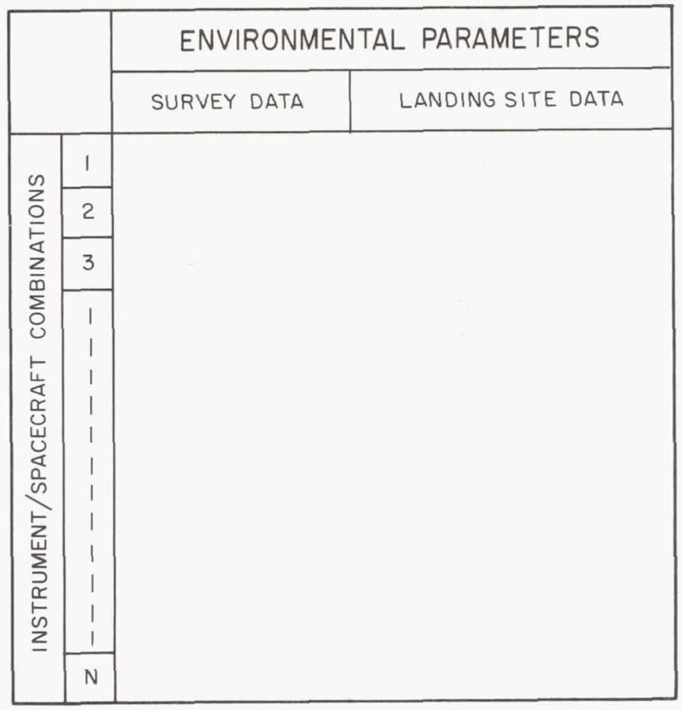

Fig. 7. Environmental parameters: instrument/spacecraft combinations

mission. This list ranged all the way from Earth-based measurements through measurements performed from sounding rockets, balloons, and Earth-orbiting spacecraft, lunar fly-by spacecraft, on to rough-landing spacecraft, orbiting spacecraft, soft-landing spacecraft, and down to roving vehicles placed on the lunar surface by a soft-landing spacecraft. Then, for each element in the matrix, we again asked several questions. The first of these was: can a measurement of the environmental parameter be performed with the particular combination of instrument and spacecraft? Again the answers were "yes," "no," and "possibly." As an example, a soft-landing spacecraft may not be able to perform an area survey. For those particular combinations for which we received an answer of yes, or possibly, we then asked the second question: with what accuracy can the measurement of the environmental parameter be performed, utilizing this instrument spacecraft combination? We may find that certain combinations eliminate themselves because they do not have sufficient resolution or the requisite accuracy to provide adequate information. We then took this list of possibly attainable measurements accuracies and compared it to the preceeding matrix listing the required accuracy. For those combinations that met the required accuracy, we then asked the third question: If there is more than one technique available to us, which is preferable? That is, one technique may measure a parameter directly, whereas the second technique may provide information on the same parameter, but do it in an indirect manner such that interpretation of the results is required. This interpretation of data may not be desired because of the uncertainty associated with it.

This, then, illustrates two phases of a study conducted at the project level to try to describe the utility of spacecraft systems in terms of measurements that could be performed. I don't have sufficient time here to go into further detail on this particular study; however, we did investigate the other several areas of possible support, and developed, in addition to the description of mission capability, descriptions of the spacecraft themselves, their estimated probability of mission success, the schedule upon which they could be developed, and the cost of the individual firings. This information was made available to the Lunar Program Office at JPL. As a result of that effort, we were asked to perform another study which I would like to describe to you now.

We were asked to study in more detail how one could make a measure of lunar surface hardness, utilizing the particular capability of the *Ranger* spacecraft then under development at the JPL. For those of you who aren't familiar with the *Ranger* spacecraft, I would like to describe briefly what it looks like by using Fig. 8. It is an attitude-stabilized spacecraft, utilizing a three-axis reference system. To maintain stability it uses nitrogen gas jets, controlled by error signals from optical sensors, to provide torques about the reference axes. The power for the spacecraft is provided from two solar panels covered with photovoltaic cells. They have an area of approximately 20 sq ft. When the spacecraft has stabilized, after separation from the booster vehicle, the longitudinal axis (termed the roll axis), is pointed at the Sun by use of the board sensors, their on-board logic system, and gas jets. This action aligns the solar panels at right angles to the Sun so that they are fully illuminated and provide power. Once oriented towards the Sun, by using the degree of freedom provided by rolling the spacecraft about this roll axis, and by using the degree of freedom provided by the hinge in the high-gain antenna system, we are able to aim the directional high-gain antenna towards the Earth. Once we have attained two-way communication with Earth, we switch antennas and take advantage of the higher bandwidths attainable with such a directional antenna. This particular order of establishing the reference was chosen for several reasons. Since the Earth is not as bright an object in the sky as the Sun, we require a more sensitive seeker to determine its position. If this seeker would inadvertently "see" the Sun rather than the Earth, it would be permanently damaged. Secondly, by acquiring the Sun first, we are able to transfer from the on-board stored power (in the form of a battery) to the continuously available power from the solar panels themselves. Thus, we run into no risk of completely depleting our battery before the completion of the stabilization sequence. Throughout this period we are on a trajectory to the vicinity of the Moon. Underneath the spacecraft, at the end opposite the one we can see in Fig. 8, is the midcourse motor. After a period of tracking, we are able to determine the errors associated with the boost phase of the trajectory. Since we have on board three gyroscopic references, we are able to command turns about these reference axes. These turns align the thrust axis of the midcourse motor in the appropriate direction. We then fire the motor for a calculated period. By this technique, we can impart a known impulse, in a specified direction, to the mass of the spacecraft, thus placing it on a new trajectory. With the completion of this maneuver we go back through the acquisition of the Sun and Earth in the same manner described earlier and continue on the trajectory to the Moon.

The other systems of the spacecraft are contained in the hexagonal structure. There are six compartments available for the packaging of the various modules and subsystems required to form the entire system. This particular spacecraft had an additional design requirement, namely, that it should be capable of carrying a rough landing capsule, developed by Ford Aeronutronic Division, to the lunar surface. The capsule is shown in Fig 8.

As we approach the vicinity of the Moon, we again command the spacecraft to align itself to a precalculated attitude, performing turns about its reference axes. This precalculated attitude is such that the spacecraft approaches the Moon tail first, with its roll axis aligned to the velocity vector. In the case of this particular series of *Rangers*, the flight path chosen is such that the flight path and the velocity vector are coincident and vertical to the lunar surface at the point of impact; i.e., the spacecraft is on a vertical, impacting trajectory. At a preset altitude, the radar altimeter will provide an ignition signal to the retromotor inside this structure. With the ignition of this retromotor, the motor and the capsule separate from the spacecraft, which itself continues on to impact on the surface of the Moon. The capsule system, weighing some 330 lb at ignition, decelerates from the initial velocity of some 9,000 ft/sec to the burnout, at which time it has slowed to just over 100 ft/sec. With

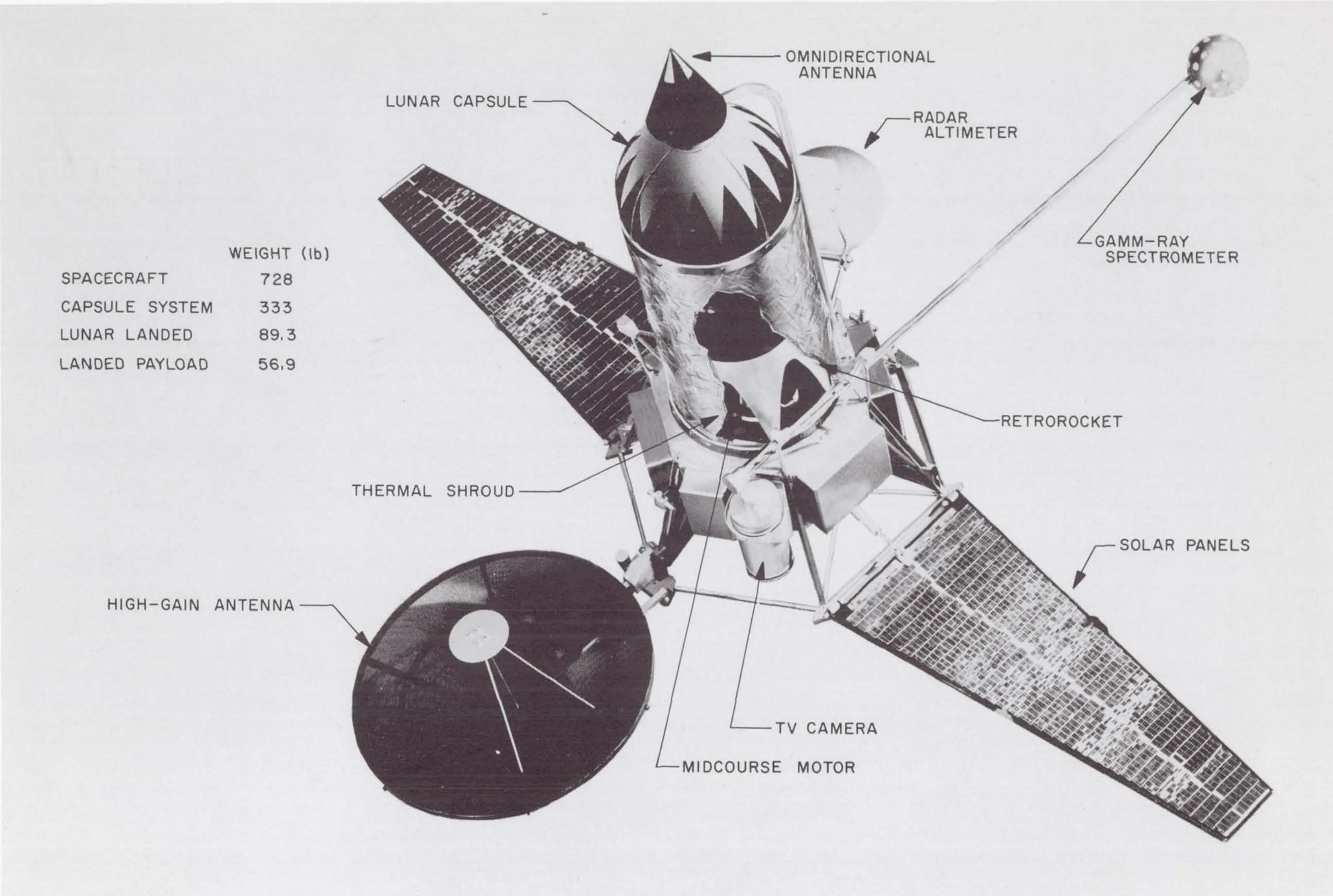

Fig. 8. ***Ranger*** **spacecraft**

burnout of the retromotor, the retromotor itself is separated from the capsule. The capsule, weighing some 89 lb, has a structure designed to absorb the residual kinetic and potential energy associated with the velocity and altitude at retromotor burnout. This structure is a sphere approximately 3 ft in diameter. The capsule has an outer balsa wood shell which is approximately 6 in. thick. This outer balsa wood shell protects the inner payload, which is about the size of a basketball and weighs 56–57 lb. Balsa wood was chosen as a protective shell, since during tests we found that on a unit-weight basis, balsa wood had the best energy-absorption characteristics of any substance that we could find.

The balsa-encased inner payload falls to the lunar surface. The velocity at impact is comprised of the residual velocity at burnout, plus any velocities attributable to angular errors, plus the velocities associated with the potential energy at the burnout altitude. The balsa crushes upon impact, absorbing part of the energy. The ball continues to bounce or may partially bury itself, coming to rest finally on the lunar surface. The shock associated with the impact is on the order of 3,000 G's. That is the peak loading which the inner sphere, which is the payload of the entire spacecraft, must be designed to withstand. This inner sphere consists of the measuring instrument, its associated data encoding devices, a transmitter, the associated power supplies, and the thermal control devices. These subsystems are all contained in this basketball-sized sphere, weighing just under 60 lb, which must successfully pass a shock test of some 3,000 G's.

To return to the question we were asked to study: Using as much as possible of this already developed system, how could we perform a measurement of lunar surface hardness? In the following illustrations I will show some of the supporting advanced development required to support the design study, which in this case was carried out by Aeronutronic for JPL.

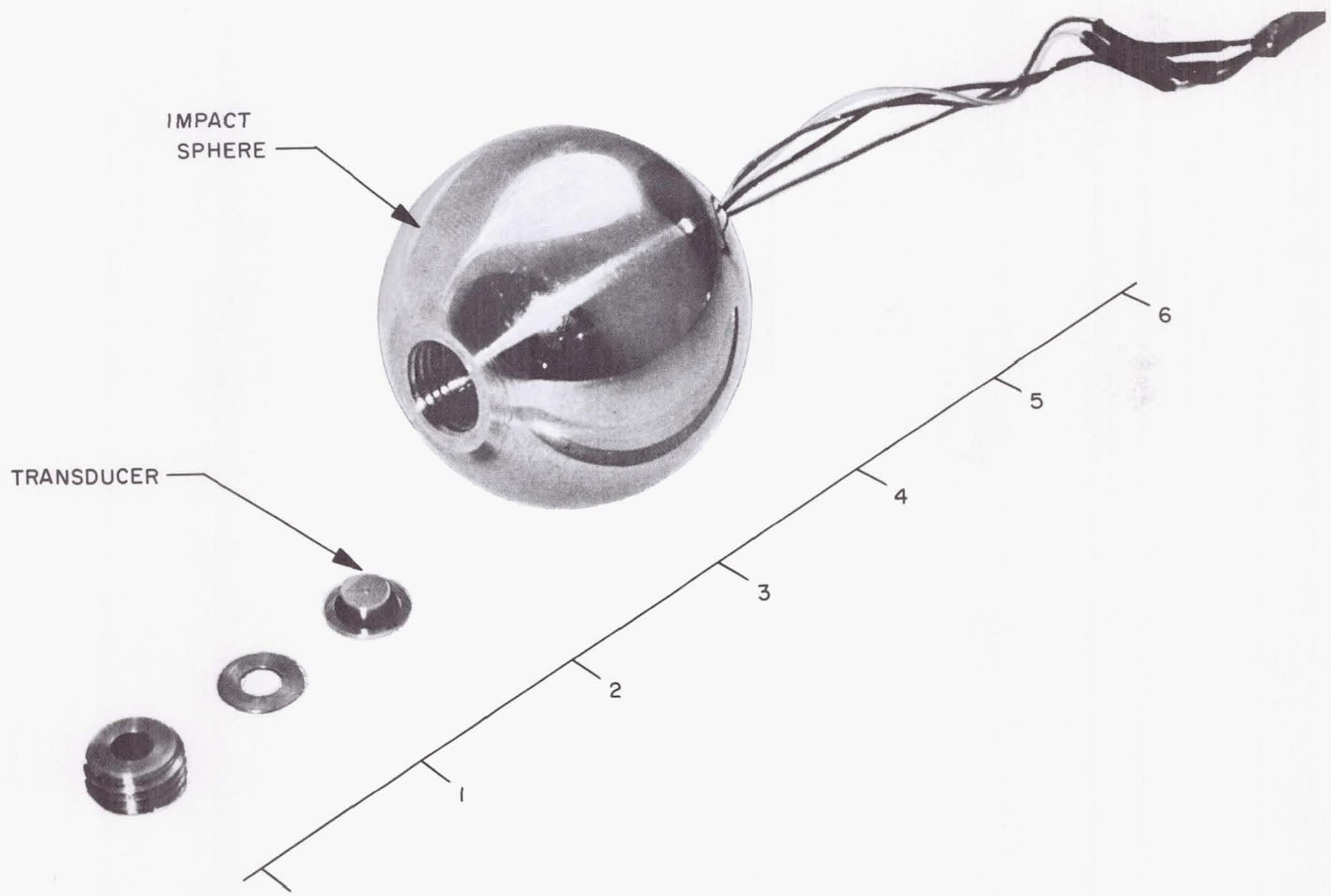

Fig. 9. Prototype accelerometer

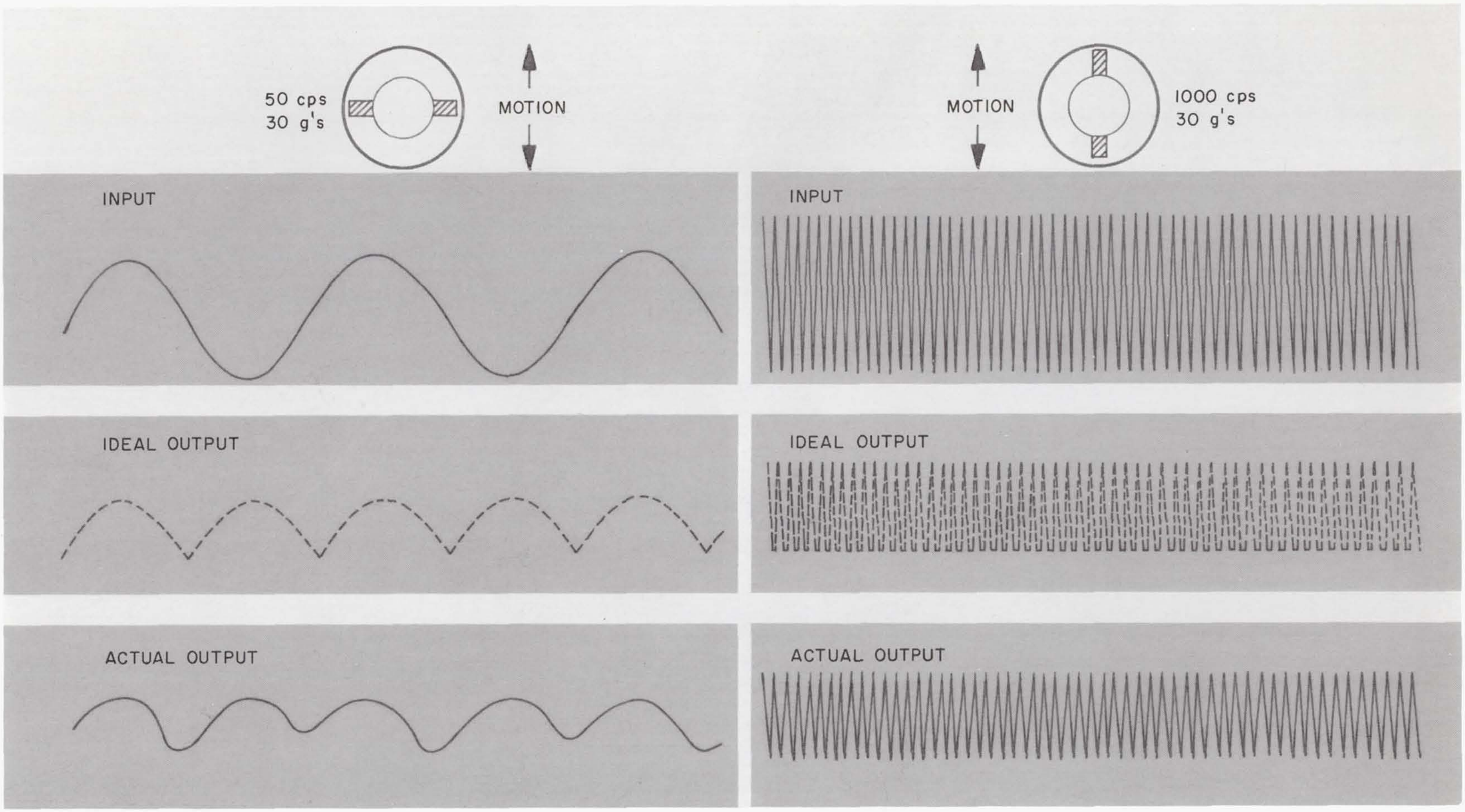

Fig. 10. Accelerometer test traces

Figure 9 illustrates an omnidirectional accelerometer. Actually, this device is about the size of a billiard ball. It consists of a hollow steel sphere, which is filled with fluid. We cap the ends of the cavity with pressure transducers. The readings that these two transducers sense will depend upon the deceleration load to which the sphere is subjected and also on the angle at which it strikes the surface. However, by simply summing the two readings and dividing by 2, we get the average pressure in the center of the sphere, which is dependent only upon the deceleration forces. Thus, with this device we are able to measure the peak deceleration without being required to know the impacting attitude of the device.

Figure 10 illustrates some test results obtained while qualifying this accelerometer. The column to the left shows the response when the system has the two transducers at right angles to the applied motion. The column to the right shows the response of the accelerometers when the pressure transducers are in line with the applied motion. Figure 10 illustrates the input, the ideal output, and the actual output as measured. As you can see, it performs well.

Figure 11 illustrates the design study in its final form. Illustrated is the new inner sphere resulting from the study. The sphere will replace that inner payload of some

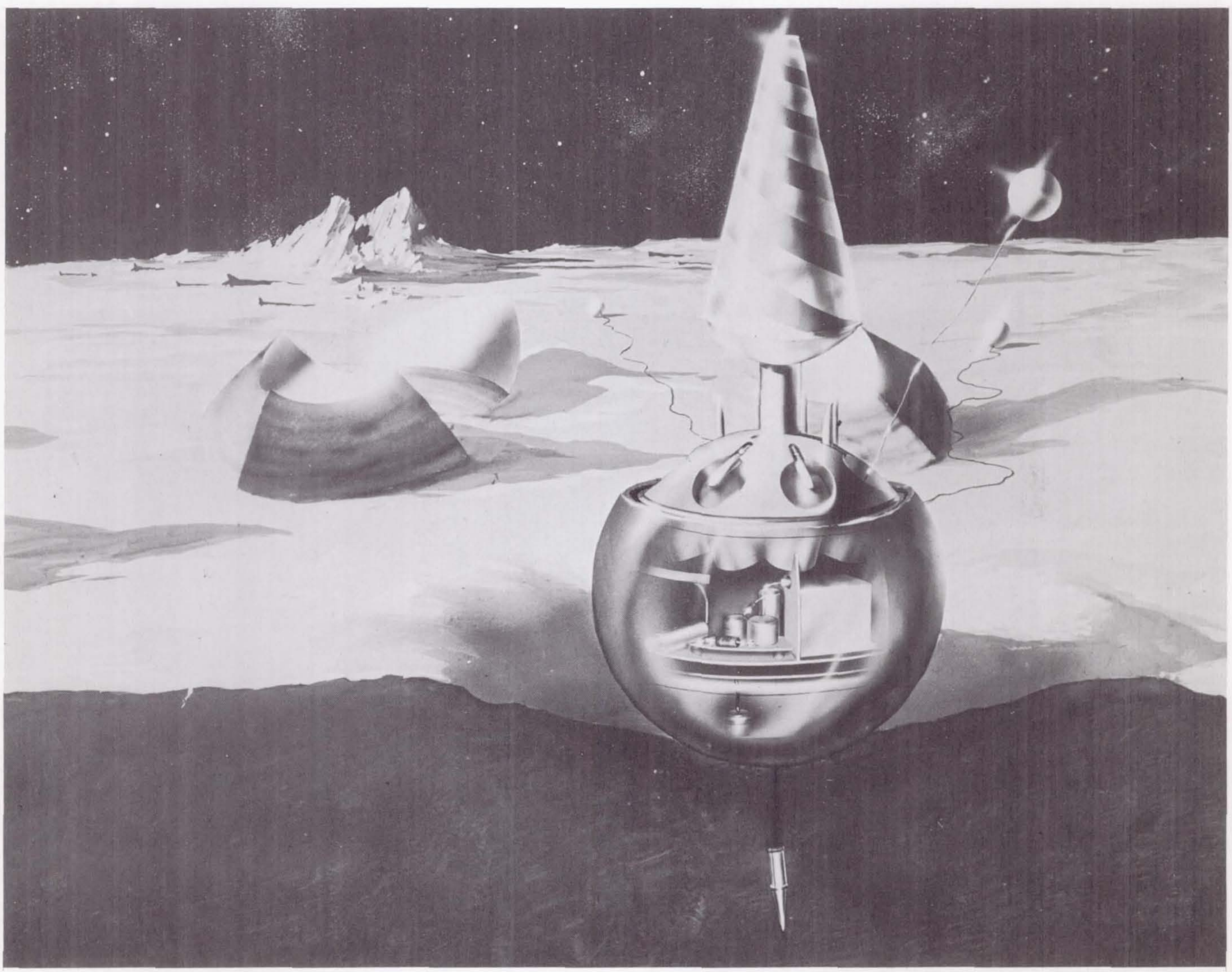

Fig. 11. SURMEC payload

60 lb we talked of earlier. It has been given the name of SURMEC, standing for Surface Measurement Capsule. It is shown here in an artist's conception as it would appear on the lunar surface. In the cavities shown, we carry a number of the omnidirectional accelerometers which I described earlier. To allow these spheres to be tossed by springs to the lunar surface, we developed a method to blow off the outer balsa wood shell. The shell is shown fragmented. When the outer shell is blown off, the accelerometer balls—trailing wires—are ejected by springs. These wires transmit back the information concerning the characteristics of the impact as sensed by the pressure transducers. We found, in the course of the study, that we could actually carry seven of the accelerometer spheres. It was found highly desirable to keep one of them active during the initial landing impact of 3,000 G's. We found that we were able to cover an area 1,000 ft in radius by using appropriately sized springs, 1,000 ft being attainable, of course, because of the reduced gravitational field of the Moon. Thus with seven measurements over a circle of a radius of 1,000 ft we could do a fairly good site survey with a single payload.

Figure 12 illustrates some other areas of supporting advanced development that were investigated. It shows the tests to remove the outer balsa wood covering. To the left, we have the hemisphere of balsa wood. To the right the balsa wood impact limiter has been removed, using primer cord laid right at the surface of the balsa shell and the inner sphere. I think that Figs. 9 and 12 indicate the point I tried to make earlier: that to take a study from the practicable phase to a practical phase, one must do supporting development work. In the earlier

SURMEC CAN RETURN LUNAR SURFACE CHARACTERISTICS

7 DISPERSED STRENGTH SAMPLES

SUBSURFACE STRUCTURE DATA FROM GEOPHONE

DUST LAYER DEPTH FROM PENETROMETER

FEASIBILITY OF TECHNIQUES DEMONSTRATED

FIRST FLIGHT IN 11 MONTHS

A HIGH-CONFIDENCE, MINIMUM-COST, AND TIMELY UTILIZATION OF RANGER TO SUPPORT *APOLLO* DESIGN

Fig. 13. SURMEC summary

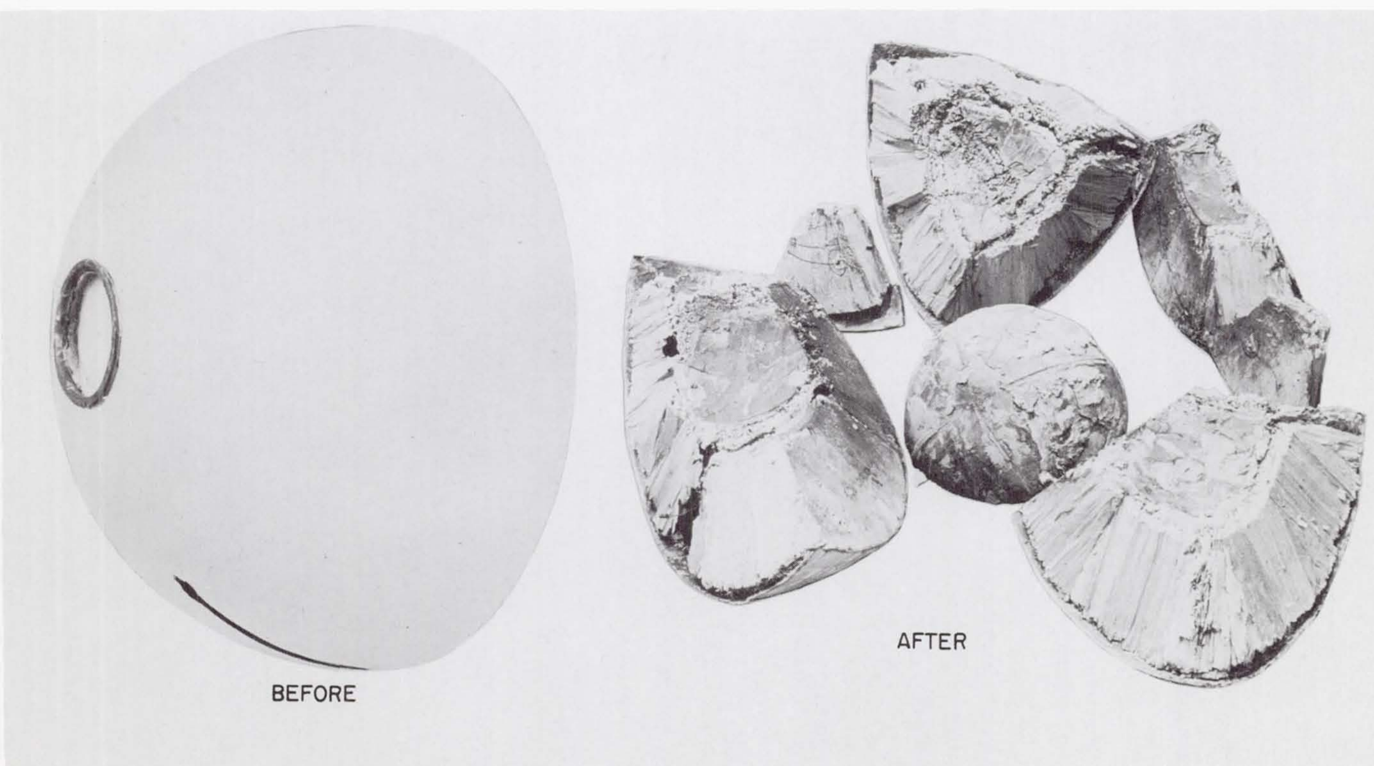

Fig. 12. Impact limiter segment removal test

study, the one concerning the support to *Apollo* by unmanned lunar spacecraft, we had classed this system as being potentially possible. I have shown only two of the areas where development work was done so that we could convert this initial concept into a practical design.

Figure 13 gives a rather terse summary of the study effort. I didn't discuss all of these factors. We found that in addition to surface hardness measurements it might be possible to carry a geophone which would, by listening to the impact of these spheres on the surface, give us some idea of the subsurface structure. We could also carry a penetrometer to attempt to measure the hardness by a completely different technique. As you see we felt that with the supporting development work we performed we had demonstrated the feasibility of the techniques involved. With these demonstrations and consideration of the rest of the system, we felt that it would be possible to attempt a first flight in just under a year, in about 11 months.

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N66-13845

Systems Analysis

C. R. GATES
Chief, Systems Division

The purpose of this discussion is to explain and describe the technology of systems analysis and to show how systems analysis contributes to the design and flight of lunar and planetary spacecraft. The discussion is in two parts: (1) a general definition, and (2) an explanation utilizing a specific example.

Modern spacecraft require that a diversity of technologies be synthesized into a completely integrated spacecraft (Fig. 1). Our modern technology requires specialists in the diverse areas who generally devote their entire professional lives to one of these disciplines. In order to yield a functioning spacecraft which will accomplish a desired mission, a new technology known as "systems engineering" has evolved. Thus, at JPL we have a Systems Division as well as a Guidance and Control Division, a Propulsion Division, etc.

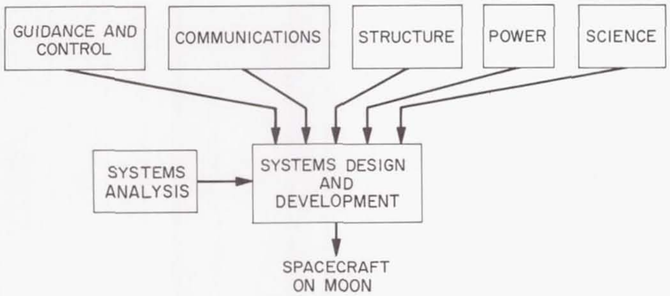

Fig. 1. Systems engineering

In Fig. 1, the box labeled "Systems Design and Development" shows the main stream of activity for a given spacecraft project. Most of the activities here involve balances and tradeoffs between the various subsystems. For example, how should weight and power be allocated among the various subsystems? A typical problem would be the choice of the gain of the spacecraft antenna; a higher gain antenna yields a stronger signal at the Earth, but it also requires a larger antenna and/or a higher frequency for the RF signal, and demands that the spacecraft be stabilized more accurately. Other tradeoffs would involve the allocation of weight and power to additional scientific instruments versus the use of that weight and power to accomplish other functions more reliably.

In order to accomplish these tradeoffs and balances, it is necessary that a mathematical model of the spacecraft be constructed and analyzed. In this activity, which is known as "systems analysis," the subsystems are usually considered as black boxes and are treated in terms of their input-output characteristics. The results of these analyses are fed into the systems design activity.

If we were designing a washing machine or a television set, the activity which I have called systems analysis, namely, the construction and analysis of mathematical models, would certainly take place; however, in these cases systems analysis would probably not be separated from the systems design and given a distinct identity. But for a spacecraft we have an additional problem, that of the selection and description of the flight path; and since each subsystem is highly sensitive to the characteristics of this flight path, a preponderance of our activities in systems analysis is concerned in some way or other with the trajectory.

A final point of interest in our discussion of systems engineering and systems analysis is to note the sharp demarcation which is usually made between project work —that is, work devoted to a specific spacecraft on a specific time scale for a specific mission—and technological work devoted to determining how to design spacecraft or to determining better methods for spacecraft design.

As noted earlier, the spacecraft and its subsystems are quite sensitive to the characteristics of the trajectory. For example, the distance of the spacecraft from Earth directly affects the communication system, and the distance of the spacecraft from the Sun (and whether it is in light or shadow) affects the temperature control system.

A typical spacecraft may use the Sun for one attitude reference as well as for gathering power; it may use a star for another attitude reference. It must communicate with the Earth and hence, generally, must point an antenna toward the Earth; and it must point scientific instruments at some other body of interest, e.g., the Moon or Mars. Consequently, the spacecraft sprouts hinges, gimbals, and other miscellaneous joints so as to point itself in a number of directions simultaneously, and since the relative geometry between these various bodies is dependent on a trajectory, the trajectory again is of great consequence.

In practice we may find that there exists a continuum of trajectories for a given mission, and our task is to select that trajectory or set of trajectories which does the best job. Trajectories may vary greatly in their sensitivity to guidance errors, and since for lunar and planetary spacecraft we wish to bring the spacecraft into some specific proximity in relationship to the target body, the accuracy with which the trajectory can be controlled by guidance is of great interest.

It should be noted here that systems analysis for space flight, with its heavy dependence on the trajectory, has developed as a field of technology in concurrence with the technology of modern high-speed digital computers. Most of the analyses which we do for our space missions would not be possible without the modern digital computer.

A brief comment on the relationship between space flight systems analysis and classical celestial mechanics might be of interest here. As you know, celestial mechanics is the oldest science (although not the oldest profession), dating back to the beginning of recorded history. The objective of classical celestial mechanics has been to describe accurately the motion of the planets—to give descriptions which would be good over large time intervals of the circular motion of the planets. The central problem in mathematical analysis in celestial mechanics has been to find approximate solutions to the "3-body" or "n-body" problem. For the Moon, say, the problem would be to describe the motion of the Moon in the presence of both the Sun and the Earth. Since no solution exists in close form, approximations, generally in the form of series, are used.

For lunar and planetary spacecraft flights, cyclical motion is generally not of interest. Also, the problem of controlling spacecraft flight by means of various maneuvers is present. Thus, while both classical celestial mechanics and space flight analysis use Newton's laws, the methods and procedures used tend to differ greatly.

We proceed to an example which illustrates the nature of the problems in systems and trajectory analysis. We will show the interrelationships between trajectory analysis and the various subsystems of the spacecraft—interrelationships involving subsystem transfer functions and input/output characteristics—and how they are gathered into a single technology with emphasis on trajectories.

The first example deals with the design of a trajectory for a lunar mission. (Here, design means selecting—out of the continuum of trajectories—that trajectory which best accomplishes what is desired. Design is often selection; in this case, it is wholly selection.) A partial list of constraints confronting the designer of lunar trajectory would contain the following:

1. Launch from Cape Canaveral.
2. Range safety.
3. Preinjection tracking.
4. Postinjection tracking.
5. Earth-probe-Sun angle, 90 $\pm$45 deg.
6. Vertical landing in lighted area.
7. High payload weight.
8. High accuracy.

The first item on the list is, of course, obvious, and it is a strong constraint. The second item is less obvious but just as real, because Range Safety prohibits flight over Cuba and Africa. This prohibition limits the trajectories out of the Cape to a narrow band down the middle of the Atlantic, between Africa and South America.

In the listed tracking constraints, "injection" simply means the time at which the boost vehicle drops away and the spacecraft is separated and coasting. During preinjection, in order to receive telemetry data from the boost vehicle and to track it, the flight path must be within range of various tracking stations. We must choose, then, a trajectory which can be tracked by existing stations of the Atlantic Missile Range. Similarly, during postinjection, tracking and telemetry considerations impose strong trajectory constraints.

For this hypothetical mission, the Earth–probe–Sun angle must be between 45 and 135 (90 $\pm$45) deg. The reason for this is that the Sun and the Earth will be used as attitude references. The angle subtended at the spacecraft between the two references must be in a 90-deg range in order to keep the servosystem stable.

Since this is a lunar flight we now must consider the motion of the Moon relative to the Earth. Figure 2 illustrates this motion. It is a view looking down on the top of a celestial sphere, in which the Z axis, pointing straight

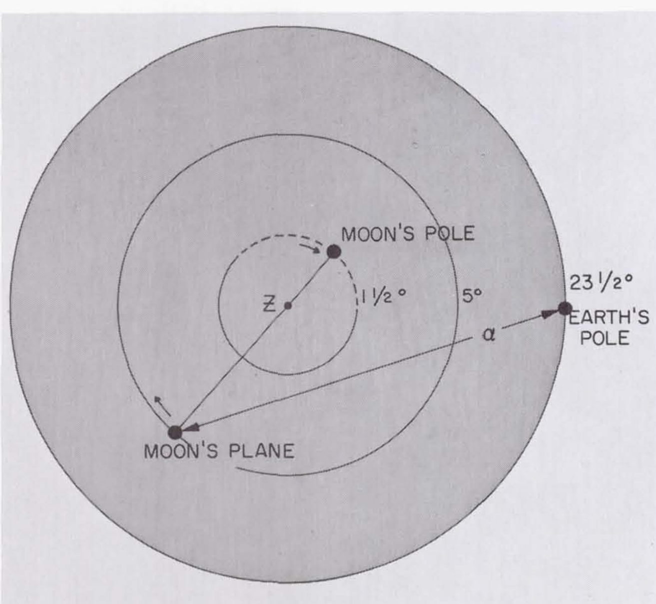

Fig. 2. Earth–Moon geometry

up, is the pole of the ecliptic; it is the vector which is normal to the ecliptic plane. The ecliptic plane is, of course, that plane which the Earth describes in its motion around the Sun. The reference system is the ecliptic plane. The pole of the Moon, that is to say the axis of rotation of the Moon, is inclined $1\frac{1}{2}$ deg with respect to the ecliptic pole. The pole of the Moon's plane—that is, the vector which is perpendicular to the plane of motion of the Moon—is 5 deg away from the ecliptic pole, and these two poles rotate so that they are the ends of a line which rotates around Z once approximately every 19 years. The reason for this is the simultaneous influence of the Sun on the Earth and on the Moon.

As we know, the Earth's pole is inclined approximately $23\frac{1}{2}$ deg from the ecliptic pole. For our purposes we can consider it to be fixed. The angle alpha between the normal to the Moon's plane and the Earth's pole is of importance to us; it fluctuates over the 19-year cycle. Now, the angle between the Earth's pole and the pole of the Moon's plane equals the angle between the equator of the Earth and the plane of motion of the Moon; if this angle is at its maximum—$28\frac{1}{2}$ deg—then the latitude of the Moon with respect to the Earth will fluctuate over a monthly cycle from $+28\frac{1}{2}$ deg to $-28\frac{1}{2}$ deg.

Figure 3, which shows how lighting constraints would affect the choice of trajectory, is a Earth-centered picture, looking down on the motion, with the Sun at the bottom. The Moon is shown in four different phases, and the four points of vertical impact of probes launched from the Earth are indicated by arrows. It can be seen that, for vertical trajectories, these points of impact tend to occur on the so-called leading edge of the Moon.

Figure 3 illustrates four possible lunar-impact situations. In Case 1, impact would occur in a lighted area, but the angle subtended at the spacecraft between the Earth and the Sun would be approximately zero, which is unsatisfactory. In Cases 2 and 3, impact would occur in darkness. So Case 4—impact during the Moon's third quarter—presents the only acceptable impact situation. Impact in Case 4 occurs in the light, and the angle subtended at the spacecraft between the Earth and the Sun is 90 deg. In practice, for a number of reasons, the arc shown represents the range of permissible phases of the Moon during which we can fire.

We find, then, that for any month we are constrained to a period of about four or five days during which we can launch to encounter the Moon.

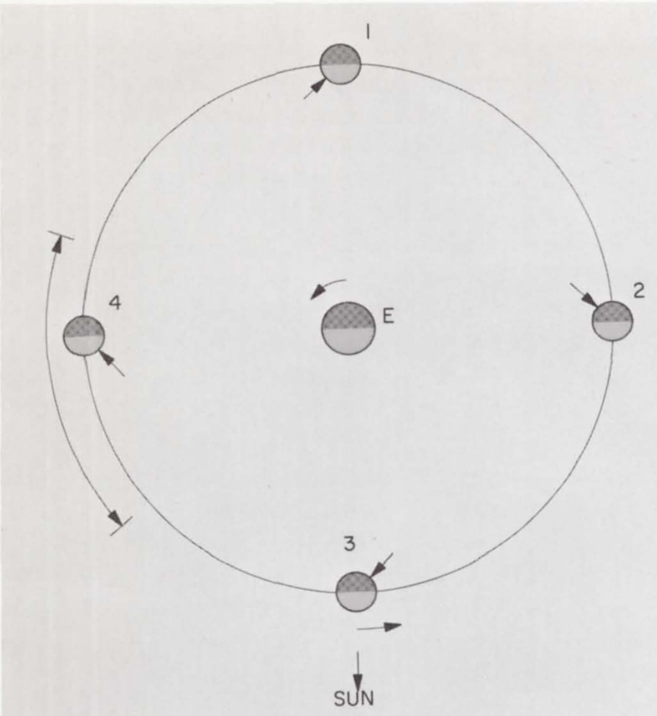

Fig. 3. Lighting constraints

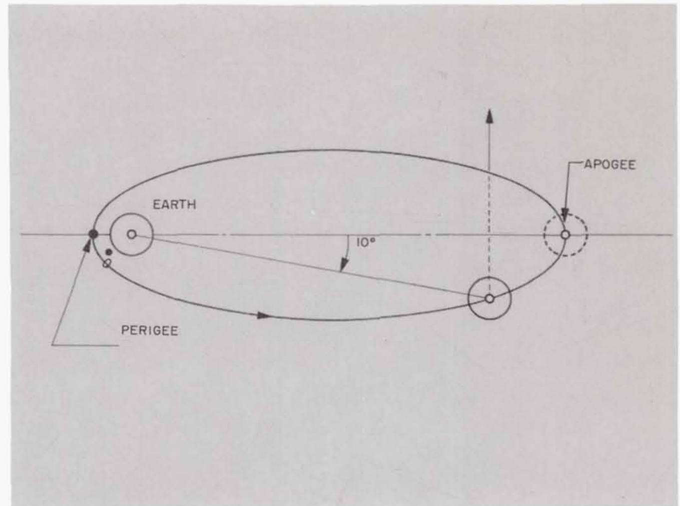

Fig. 4. Spacecraft trajectories

Figure 4, an Earth-centered picture, shows the trajectory in the place of motion of the spacecraft. Normally, for the type of trajectory which is of interest, we will encounter the Moon at an angle of about 10 deg, in reference to the Earth, prior to apogee. The attraction of the Moon is fairly weak relative to the Earth; and for the purposes of this discussion we will assume that the Moon has no mass.

It is apparent from Fig 4 that we have a range of possible injection points. However, if we inject at, say, point Q, the angle of injection, that is, the angle that the injection velocity vector makes with the local vertical, is steep. If we inject at perigee, the angle between the local vertical, the radius vector, and the velocity vector is 90 deg. It is desirable to inject at the perigee point rather than at some point where the velocity vector of the spacecraft would not be horizontal. If we inject either up or down from horizontal it requires more energy and we obtain less spacecraft weight.

Figure 5 is geocentric, nonrotating, showing the equator of the Earth, the North Pole of the Earth, Cape Canaveral, the latitude line pertaining to the Cape, and the latitude corresponding to the so-called sublunar point.

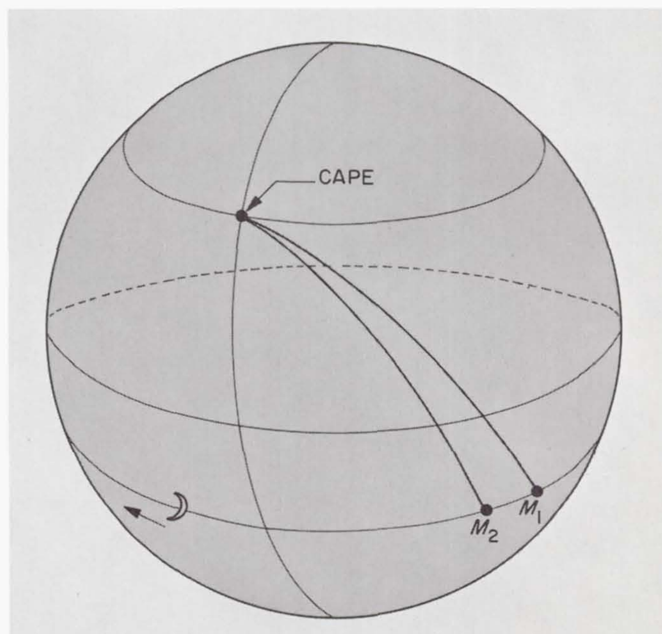

Fig. 5. Geocentric trajectories

The sublunar point is the other end of the line connecting the center of Earth and the Moon projected through the other side of the Earth.

Since this is a geocentric, nonrotating figure, the Moon will appear to the observer to be moving in the direction shown.

The flight path of the launch vehicle must be a great circle which connects the Cape and the sublunar point. If we launch at such a time that the Moon—or, more precisely, the sublunar point—is at M_1, and if injection occurs near perigee, then we will encounter the Moon satisfactorily. But if we launch at a certain time later, such that the Moon or the sublunar point has progressed, owing to the Earth's rotation, to M_2, our flight path then is totally different; we have to follow the Moon as it were. We therefore find that the trajectory is a function of the launch time. In practice, we are able to launch on azimuth—azimuth being the angle measured clockwise from north, between about 90 and 114 deg out of the Cape—and this will correspond to a time interval somewhere between 1 and 3 hours.

In summary, we find that we can launch during a period of about four to six days per month and during a certain phase of the Moon. Similarly, during any one given day, we will be able to launch during some launch window, which corresponds to the time that it takes for the Moon to traverse the distance which corresponds to launches between 90 and 114 deg. The launch window varies with launch date, since if the declination of the Moon is such that the sublunar point is north, then it will take the Moon a shorter time to traverse arc M_1 than it will to traverse arc M_2. Therefore, when the sublunar point is as far south as possible, the launch windows are long, and when the sublunar point is as far north as it ever gets, the launch windows are short.

The planetary spacecraft launch problem is very similar to the lunar spacecraft launch problem. For the planets, we obtain a launch opportunity every synodic period —the synodic period being the period corresponding to the beat frequency between the period of the Earth and the period of the target planet. Every 1.6 years we will be in the right geometric opportunity to launch to Venus, and for Mars it is about every 2.1 years. That means that we get an opportunity to launch to Mars in late 1964, but we do not get another opportunity until late 1966.

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N66-13846

Space Flight Operations

MARSHALL JOHNSON

Chief, Space Flight Operations Section

The category of functions known as space flight operations is a difficult subject to discuss and explain. It is a relatively new area, and the terminology associated with it is not widely understood. However, the following definition may be helpful:

> *Space flight operations are those operations necessary in order to obtain and process spacecraft information and commands required during that portion of flight from launch to mission accomplished.*

To draw an analogy, space flight operations can be described in terms of conventional airplane flight, in the sense that an airplane takes off and certain things happen to it while it is in flight; flight operations are those events that take place after the plane is airborne.

Although the analogy between flight operations and space flight operations is close, there are differences. For example, space vehicles are not yet very reliable, and in the sense that the related technologies are not fully developed, they are not well understood. This fact has been demonstrated by the difficulties that we have encountered in the *Ranger* mission series. Furthermore, spacecraft cost is substantial, and spacecraft manufacture involves a long lead time. We can't build 100 spacecraft, because the cost would be prohibitive. If we could afford 100 spacecraft, we couldn't launch them, because our present rate of manufacture and launch is about 1 spacecraft every 2 months. We are fund-limited with respect to the number of spacecraft we can build, and we are time-limited with respect to the rate at which we can build them.

The vehicles that we launch are unlike military ballistic missiles. They are not simply dead weights or containers for explosives. They are active devices. They react to the different environments through which they pass, and they react to commands from the Earth. These vehicles are sent off into space to accomplish scientific experiments; they are flying laboratories.

As noted, because of the state of our technology and the problems of funding, manufacturing and launching, we cannot afford to launch these space vehicles in rapid-fire fashion. Between shots we must analyze the results of each launch. We have to try to determine whether the vehicle functioned as it was designed to function. If it didn't, we have to find out why, so that we can make corrections in future flights. If we make mistakes, we have to try to discover what they are. The end object is to build vehicles that will do the scientific jobs with a minimum of error and a maximum of reliability.

In some cases, we have been successful at this; in others we haven't. The recent *Mariner* flight to Venus was successful. The spacecraft got there; it worked, but not exactly as designed. It could have worked better, and we are not certain why it didn't. In some of the missions in the *Ranger* lunar series the spacecraft functioned properly, but the launch vehicle didn't. In other missions, the spacecraft didn't function properly, and we don't know why. It is not possible to instrument a payload for every possible environmental problem on a system with more than 10^4 components. The questions and problems posed by these flights are central to our subject—space flight operations—the events that take place between spacecraft launch and mission accomplished. I will attempt to describe what these operations encompass, what they entail, the degree of effort we devote to them, and how and where they are conducted.

It is necessary, here, to point out that there is a lack of technology relative to space flight operations. There are no archives or libraries of technical information upon which to draw; there are no textbooks. No degrees are given in this area. Here, there is no way to learn other than through experience, thought, and planning. The technology is being developed as we go along. Although we have made mistakes and will make more, we are trying to keep the cost of development minimal.

As with all new technologies or new areas of investigation there is a problem of semantics. You have experienced this in your academic studies. The various disciplines employ different terminologies to describe common subject matter. At this point, I want to introduce and define some space flight operations terminology.

To begin with, in our work the Space Flight Operations Complex is a real world; it is the physical plant in which space flight operations are conducted. The Space Flight Operations Complex includes a number of tracking sites upon which are located large radio antennas designed to communicate with our spacecraft at extremely long distances—on the order of 100,000,000 miles. Collectively, these sites are called the Deep Space Instrumentation Facility, DSIF.

The primary function of the DSIF tracking sites is data acquisition. They do only a minimal amount of data reduction, interpretation, and analysis required for their own operation.

From the spacecraft, the tracking sites obtain two general types of data—telemetry data and tracking data. The telemetry data is generated in space by spacecraft instrumentation. It originates in the spacecraft and is transmitted through a spacecraft communications system back to Earth, the DSIF tracking sites being Earth-based receivers for the acquisition of the data. Telemetry data yields information about the spacecraft and the environment through which it is passing.

Tracking data, on the other hand, is used to measure spacecraft direction, velocity, and range and is derived from a spacecraft-mounted transmitter or an Earth-based transmitter. There are two general types of radio frequency tracking data—one-way doppler and two-way doppler. One-way doppler consists of a signal transmitted from the spacecraft to Earth, where it is received and measured. Two-way doppler, which is highly accurate and generally more useful than one-way doppler, consists of an Earth-generated signal which is transmitted to the spacecraft, received by the spacecraft, converted by a transponder, and retransmitted back to Earth.

The Space Flight Operations Facility is another element of the Complex. It is a building which serves as the focal point of the Complex. As such it serves as the gathering point for the data acquired by the tracking sites, as the physical plant in which this data is processed and reduced, and as a laboratory in which engineers and scientists can analyze, evaluate, and interpret the data in order to determine what the spacecraft is doing (in the sense of performance), what the scientific experiments are measuring, and where the spacecraft is going.

During the launch phase of any mission, the space vehicle is subjected to what may be the most severe environment of the flight. The launch site and launch site facilities constitute a critically important third element of the Space Flight Operations Complex. Our vehicles are launched from the Atlantic Missile Range, although there are other launching sites—the Pacific Missile Range, for example, and White Sands, New Mexico.

The various operations and functions of launch site, Space Flight Operations Facility, and Deep Space Instrumentation Facility are, of course, interrelated and complementary.

There is no single point on Earth from which a spacecraft can be monitored and controlled directly. The nature of planetary and spacecraft orbits and trajectories precludes this possibility. Therefore, our tracking sites, the prime points of data acquisition, are strategically located around the globe—at Johannesburg, South Africa;

Woomera, Australia; and Goldstone, California. Because of the locations of the tracking sites and the various other parts of the Complex are so widely divergent, the services of a fourth vital element of the Complex are required—namely, communications facilities, which link the parts together and integrate and unify the over-all operation.

Another element of the Complex—Spacecraft Checkout Facilities—is responsible for checking out the spacecraft and for determining, before the start of operations, that there is a good probability that the craft will perform as designed. Here, also, personnel are trained; they are familiarized with mission details, with specific spacecraft capabilities, with the types of data to be obtained, and so forth.

In order to explain more clearly the function of the Space Flight Operations Complex it is helpful to make a more or less arbitrary yet realistic distinction in order to categorize the various duties and tasks and functions that support the over-all operation. This distinction is between mission-independent, facility-oriented (or operational), functions and mission-dependent, project-oriented (or technical), functions.

And the distinction is a natural one to make. Some facilities or functions can be utilized in any type of space mission—not just in lunar missions, or planetary missions, or manned space missions, but in any type of mission. For example, a tracking antenna can track any kind of space vehicle that carries a transponder. A computer can process any kind of data. It doesn't make any difference whether it is data acquired from a spacecraft or derived from accounting information or paychecks. On the other hand, the analysis of the data (to get the meaning out of it), and the interpretation of the data (to understand it), and the evaluation of the data (to determine what the spacecraft is doing) are functions that vary with each spacecraft. The people who analyze, interpret, and evaluate data are performing mission-dependent functions, whereas the people who operate antennas, computers, communications facilities and other such elements of the Complex are performing mission-independent functions. Mission-dependent functions we call technical functions; mission-independent functions we call operational functions.

In the prelaunch period, both technical personnel and operational personnel are trained. In Spacecraft Checkout Facilities we have a spacecraft. It can be used to simulate data that is expected to be obtained during flight. The data can then be passed through the ground-based facilities that will handle it after launch in order to ensure data-facility compatibility. This can be done irrespective of the content of the data. It doesn't make any difference what the data means so long as a simulation is made of what is to be expected after launch.

Technical personnel, on the other hand, are concerned with data content, with data meaning. In the early days of our space effort—before we had access to such refinements as a Spacecraft Checkout Facility—our engineers and scientists were faced with problems based on unavailable empirical information. That is, the people who were asked to describe the performance of the spacecraft—where it was going and what the experiments were doing—were not able to see the sort of data they had to deal with until after vehicle launch. As a result we spent most of our time determining what the data meant rather than what the content of the data was.

To sum up, then, the principal elements of the Space Flight Operations Complex—DSIF, SFOF, Launch Site, Communications Facilities, Spacecraft Checkout Facilities—are ground based and, except for Spacecraft Checkout Facilities, are mainly employed after launch of the spacecraft. The basic functions—technical and operational—are performed in all the various elements of the Complex: technical functions being those associated with such relatively mission-dependent activities as analysis and evaluation of data acquired from a particular spacecraft; operational functions being those associated with such mission-independent activities as servicing spacecraft and operating the equipment used in acquiring and processing data.

At this point, in order to relate the activities of the Space Flight Operations Complex to the actual spacecraft flight, it will be instructive to explain—in an elementary fashion—some of the mechanics of our space effort. To begin with, at JPL we are primarily concerned with two classes of unmanned missions—lunar and planetary. These two classes of missions have opposing characteristics and common characteritics. The distinctions between the missions are most apparent, of course, in the area of spacecraft design, which has been discussed previously in this seminar. But common to both classes of missions is the basic two-stage vehicle—consisting of a booster and a second stage—which propels our spacecraft into orbit.

Figure 1 illustrates the sequential elements of spacecraft vehicle flight. During the first phase—the booster burn phase—the vehicle is picking up velocity, moving off the surface of the Earth. When the booster burns out,

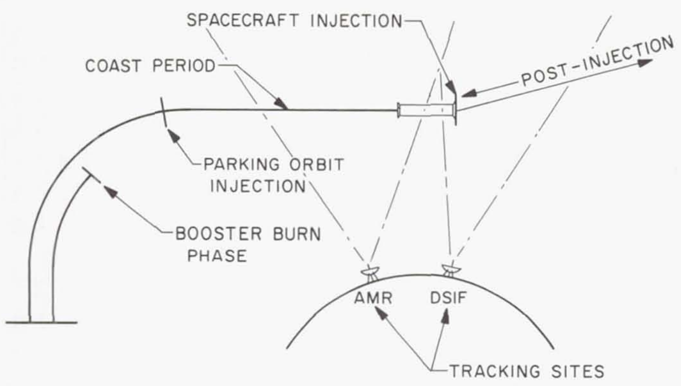

Fig. 1. Spacecraft flight sequence

the vehicle is still not in orbit—satellite orbit or space orbit. Before orbit can be achieved, the vehicle needs additional velocity or energy, and this it gets from the second stage.

Conceptually, there are two types of trajectories—parking-orbit trajectories and direct-ascent trajectories. The distinction between them is very simple. The parking-orbit trajectory is one in which the second stage and the spacecraft are put into an Earth–satellite orbit before the spacecraft is injected into a transfer orbit toward the target body. The direct-ascent trajectory does not utilize a parking orbit; the spacecraft is injected directly into the transfer orbit. Since we are shooting from a moving platform toward a moving target, we can aim at more points on the target if we can vary the point from which we are shooting, and consequently we usually use parking-orbit trajectories. A direct-ascent trajectory is the special case of no coasting time for a parking orbit, and does not require a restart of the propulsion system.

After the vehicle goes through the booster burn phase, the second stage lights up once. It burns for a given period of time, about 3 minutes. When it is shut off, the vehicle is in Earth–satellite orbit. This point, the point at which the engine is cut off, is called parking-orbit insertion or parking-orbit injection or satellite injection. Here, the vehicle is in a satellite orbit about the Earth. It remains there for a week or two weeks; then the orbit decays enough for the vehicle to re-enter the Earth's atmosphere. However, our objective is to get the vehicle off into a space trajectory, so we let it coast in this satellite orbit until it gets to the geocentric latitude and longitude from which it is to be launched at the target body. Just prior to the end of the coast period, at a known point calculable from theory, we allow sufficient time for the motor burning, and then reignite the second-stage. The second-stage motor has ignited twice now—first, to get the vehicle into satellite orbit; second to get it out of satellite orbit. At the conclusion of the second burn, the spacecraft is injected into a transfer trajectory which carries it toward the target body. This point is called spacecraft injection or simply injection.

Since the second stage is attached to the spacecraft all this time, it obviously is going to follow the spacecraft unless something is done to change its course. At some time after injection, a maneuver or a retarding thrust is applied so that the second stage does not follow the spacecraft or bump it or affect some part of the spacecraft system such as attitude control. Up to this point there is relatively little difference between a lunar and planetary mission or between a manned and an unmanned mission.

In order to relate the flight profile shown in Fig. 1 to the activities and functions of the ground-based Space Flight Operations Complex, it should be noted that the period from launch to injection is a most critical period of spacecraft flight. If it could always be negotiated successfully by both the vehicle and spacecraft, the probability of mission success would be high. For this reason the acquisition of spacecraft performance data during the launch-to-injection period is of considerable importance to a space mission. However, obtaining data during launch to injection presents difficult problems. For example, the coast period in the parking orbit covers from 2,000 to 10,000 miles of Earth surface; the parking orbit is at an altitude of only about 100 miles; and the spacecraft overflies ocean areas. Therefore, the tracking sites can see the trajectory of the spacecraft for only a short period of time—perhaps 5 minutes per site. During this period the Space Flight Operations Complex must obtain data from a fast moving vehicle in a short period of time, and it must process, evaluate, and interpret the data so as to give reasonable assurance that the vehicle is functioning.

After injection, space missions involve two additional critical phases. The first, the maneuver phase, is the period during which we are changing the course of the trajectory so that we can more precisely hit the point (planet or Moon) that we are aiming at. The second, the terminal phase, is the period just before the vehicle either passes or lands on the target body.

Correct planetary missions are not designed to land or impact; they are designed so that the spacecraft will fly

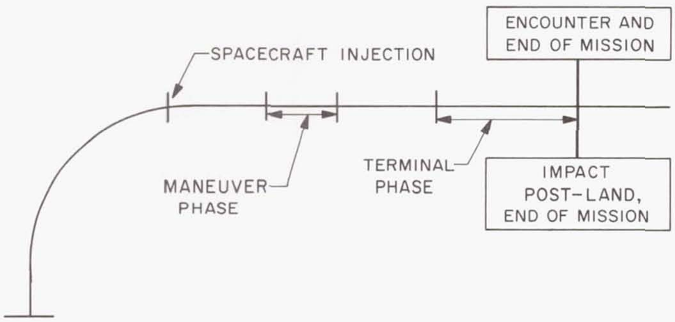

Fig. 2. Lunar mission phases

past, encounter, the target. Lunar missions are designed to impact the target: sometimes in a hard landing, as in the *Ranger* series; other times in a soft landing so that equipment can be operated in a further phase, a post-landing phase. Figure 2 depicts these phases.

In both lunar and planetary efforts, there is, of course, a time at which the mission is completed. But the spacecraft is not worn out; it is not turned off; it is still functioning. The *Mariner* mission to Venus, for example, was terminated at the beginning of this year, 1963. But last night, six months after mission termination, the spacecraft was coming back close to Earth, and we were listening for it.

There is a marked difference in transit time, the time that it takes a spacecraft to go from injection point to destination, between lunar and planetary missions. Lunar missions take about 3 days and Venus and Mars planetary missions take from 5 to 9 months.

An important consideration here is implied in the fact that during all critical phases of a mission—launch, maneuver, and terminal—spacecraft monitoring must be carried out continuously by engineers and scientists; if a spacecraft fails, it is extremely important to pinpoint the cause and the exact time at which the failure occurs. Since planetary missions last for several months, a very real problem arises in creating an environment in which personnel can carry out this type of protracted monitoring. In general, spacecraft performance and the types of measurements obtained are fairly predictable. We are looking for deviations in the data.

A problem that we have run into in the past is that deviations are not always spotted. After watching the tedious sameness of undifferentiated data day after day for months, operator personnel can easily overlook a change when it does occur. When the event is finally noticed it may be too late to do anything about it. For remember, these operations are real-time operations, and our spacecraft are active mechanisms and are receptive to corrective action, if completed in time.

The real-time nature of the more critical phases of a mission can perhaps be pointed up by an example of a lunar trajectory which is going to impact the Moon. In such a mission we may want to perform an experiment during the last 30 minutes before impact. To do this we must tell the spacecraft what to do; we must calibrate the instruments before the experiment starts; and we must start the experiment. If we start the experiment too early, the instruments won't be calibrated properly, the life expectancy of the equipment may be exceeded, and the measurements may be lost. If we start too late, impact on the Moon will effectively end the problem.

In the case of a planetary mission, the same situation is present in the encounter phase. The instruments are calibrated so that they will operate in only a small area near the planet, and we will lose the ability to make measurements unless we start the experiment at the right time.

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Program Engineering and Project Problems

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A subject that has interested me for some time is the relationship that exists between mission objectives, resources (money, manpower, facilities), and boundary conditions (schedule, performance, reliability). It is often in this area that mission success or failure is determined. When missions fail or projects are cancelled, the blame can always be laid at the manager's door; but in my opinion, it often resides primarily with engineering personnel. Engineering personnel are responsible for failures when they don't point out inherent program problems or difficulties, or when they are concerned only with performance problems and ignore schedule, reliability and cost.

Recently, Harvard University published a book entitled *The Weapons Acquisition Process*[*] which sets forth some classical information bearing on this problem. The author's approach was to analyze a number of missile programs, including those of the Army, Navy, Air Force, and NASA, and to compare these selected programs on a performance basis. Since the study was financed by the Ford Foundation, the authors are not subject to any possible charges of favoritism. The study documents the history of the missile business, and some of the information presented is startling.

Table 1, which is reproduced from the above-mentioned book, gives the development cost factor and development time factor for twelve missile programs. It shows the relationship between estimated cost and actual cost and between estimated development time and actual development time Notice that the average actual cost was about three times as much as the estimated cost.

Although the disparities shown throughout Table 1 can be attributed to a number of causes, it is obvious that the various project engineers and managers sacrificed cost control in order to meet time schedules. Engineers are rather good at underestimating both cost and time requirements. And they are equally good at composing reasonable after-the-fact excuses blaming schedule dislocations on changed conditions and circumstances. However, effective preprogram analysis would decrease this sort of difficulty.

[*]Peck, M. J., and Scherer, F. M., *The Weapons Acquisition Process: An Economic Analysis*, Division of Research, Graduate School of Business, Harvard University, Boston, 1962.

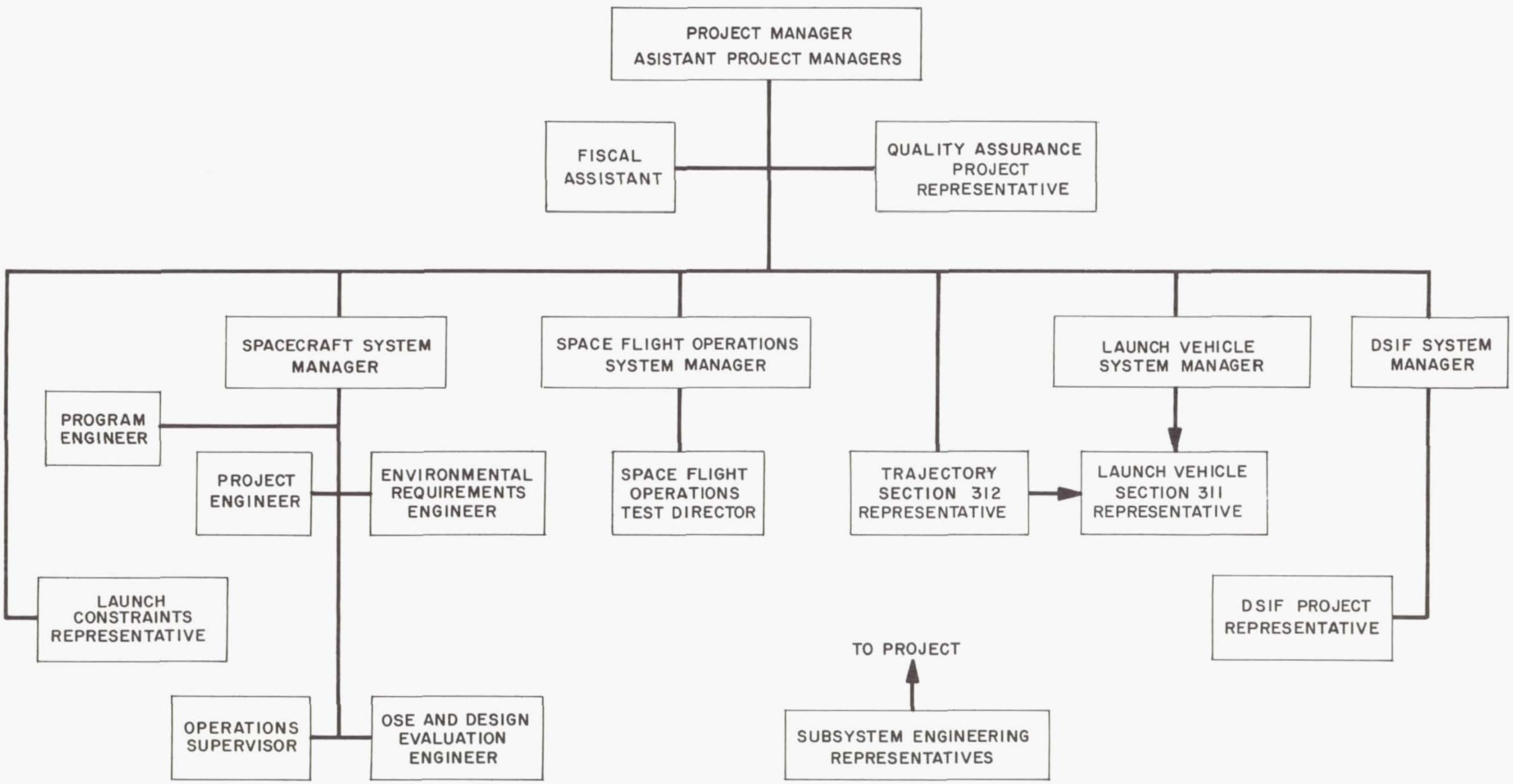

Fig. 1. Critical support areas

Table 1. Cost and time development factors for twelve missile programs

Program	Development cost factor	Development time factor
A	4.0	1.0
B	3.5	2.3
C	5.0	1.9
D	2.0	n.a.
E	n.a.	0.7
F	7.0	1.8
G	3.0	1.3
H	2.0	1.0
I	2.4	1.3
J	2.5	1.3
K	0.7	1.0
L	3.0	1.4
Average and standard development	3.2 ± 1.2	1.36 ± 0.35

A device showing the four elements that affect decision-making in this field might be called a parameter for project decisions and appear in equation form as:

$$P = \frac{\textit{value (or performance)} \times \textit{reliability}}{\textit{cost} \times \textit{time required}}$$

A decision could involve, for example, a choice between using a component which cannot quite meet performance requirements—in which case, the requirements would have to be lowered—or developing a new component which the vendor promises will meet the requirements.

It might be interesting at this point to look at a formula worked out by the Lockheed Aircraft Corporation as an aid in making decisions relative to bidding on proposals and contracts:

$$P = \frac{\begin{array}{l}\textit{probability of winning proposal}\\ \times\ \textit{probability of mission success}\\ \times\ \textit{probable profit}\end{array}}{\textit{cost of proposal}}$$

It is a simple formula, but it is a good one, and in this area there are no textbooks for guidance.

Figure 1 shows the various support areas that are of critical importance in over-all spacecraft systems operations and illustrates, from the standpoint of project management, the complex nature of a spacecraft systems project organization. Besides the areas of general support, such as spacecraft, space flight operations, launch vehicle, DSIF, there are specific jobs assigned to individuals. For example, the Program Engineer, who is responsible for schedules and schedule coordination, rules on the number of items the various groups are allowed to build. If one group has responsibility for a particularly complex subsystem, it may be necessary to build more units in order to allow for sufficient testing. The decision is made by the Program Engineer.

Spacecraft launch time is plotted versus energy capability in Fig. 2, which illustrates the sort of problems that might have to be handled by the Project Manager on the basis of logic, intuition, and experience. As shown in Fig. 2, two types of trajectories are available. Type I approaches a planet from the side nearest the Earth. Type

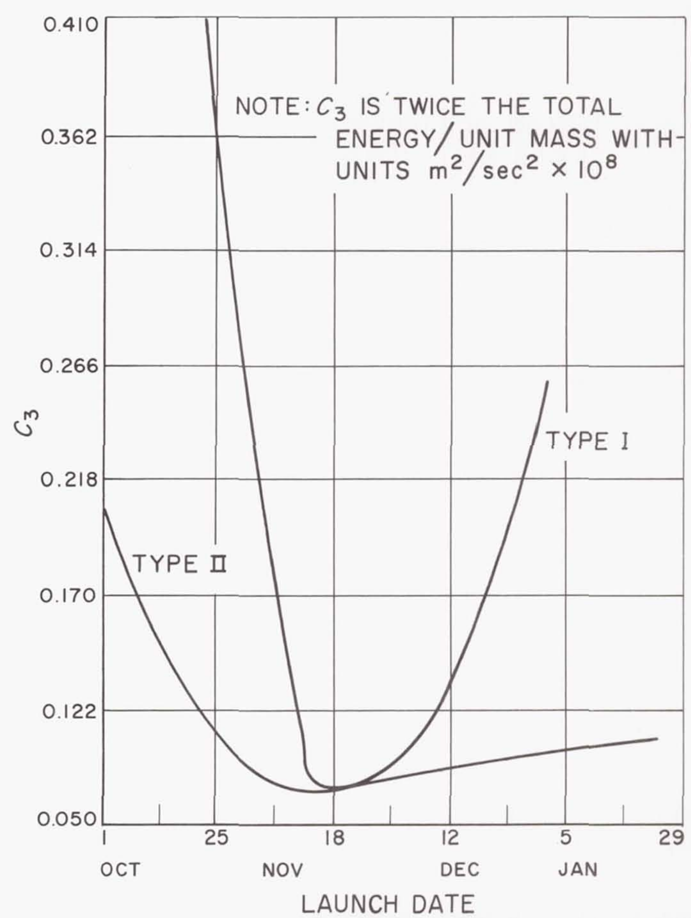

Fig. 2. Minimum injection energy vs launch date

II goes in and across the planet's orbit and then approaches the planet from the side away from the Earth. The two trajectories require different energy capabilities and flight times. The choice of trajectory and the choice of launch period are decisions that belong to the Project Manager; he has the data, and he makes his decisions on the basis of the data, and many people will disagree with him.

Figure 3 shows, quite simply, the relationship between project cost and time. More particularly, it establishes the minimum time and minimum cost factors involved in this relationship. At present, most people in the space business try to accomplish their projects in minimum time because of competition from other contractors. But, of course, in order to obtain optimum reliability, it is often necessary to spend more time on a project.

Figure 4, spacecraft costs versus spacecraft weight, presents data that I have been collecting for four or five years. Note that the ordinate represents flying pounds, the weight of the actual launched spacecraft exclusive of the cost of any redundant or backup craft.

Explorer 1958, the first Earth satellite orbited by the United States, weighed 20 pounds and cost on the order of $30,000 per pound. The first U.S. deep space probe, *Juno* 2, 1959, which went out in space about as far as the Moon, weighed only 14 pounds and cost about $60,000 per pound. Of course, the significance of the Fig. 4 curve

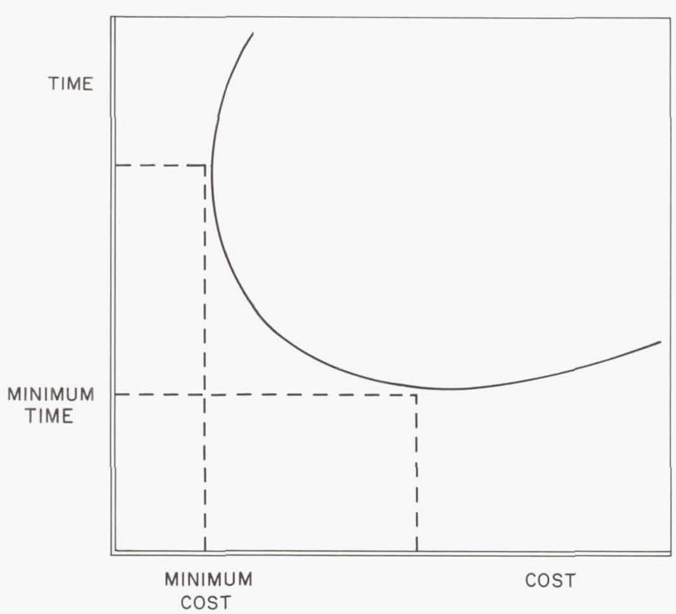

Fig. 3. Development possibility curve

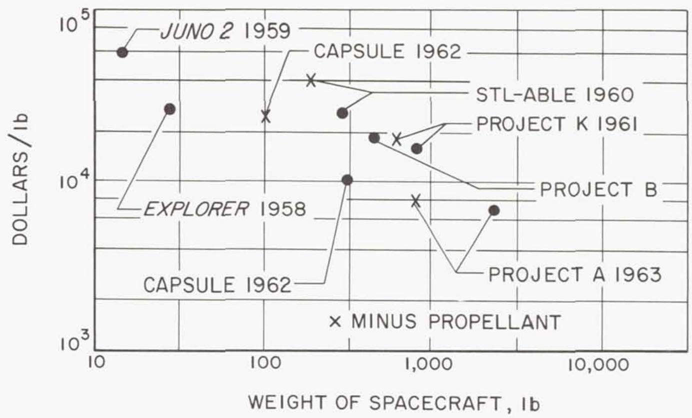

Fig. 4. Spacecraft costs vs weight

is that, as spacecraft weight goes up, cost per pound tends to go down. Increasing the reliability and probability of success of any spacecraft will tend to increase the costs.

Besides the problems involved in costs, schedules, and reliability, most facilities now have manpower problems; there is a shortage of engineers. Consequently, in order to utilize available manpower and money with maximum effectiveness, it is implied that agencies involved in the space effort—particularly prime contractors who subcontract—must be able to estimate accurately the number of people required to accomplish a given project, and to make a decision relative to subcontracting part, or perhaps all, of the project.

The curve in Fig. 5 was devised to illustrate the problem. The ordinate in Fig. 5 represents salaries, and the abscissa represents the ratio of procurement dollars to total funds. The zero point on the abscissa represents jobs that are carried out with no procurement support whatsoever; this is an unreal point today, as some supplies must be procured. The point at 1.0 is that point at which everything is done outside; the entire job is subcontracted. Normally, however, on a subcontracted job, the prime contractor maintains at least a monitoring control, and the prime contractor/subcontractor employee ratio would be perhaps 1 to 9. Relative to Fig. 5, that would mean operating in the area from 0.9 to 1.0.

We have reviewed some of our projects and have found that the steepest point we have reached on the curve is at about $300,000 per employee. And that, of course, means not just engineers and scientists and project managers; it means every employee at JPL. Most facilities engaged in the space effort have found, incidentally, that for every engineer or scientist, two employees are required in the supporting jobs.

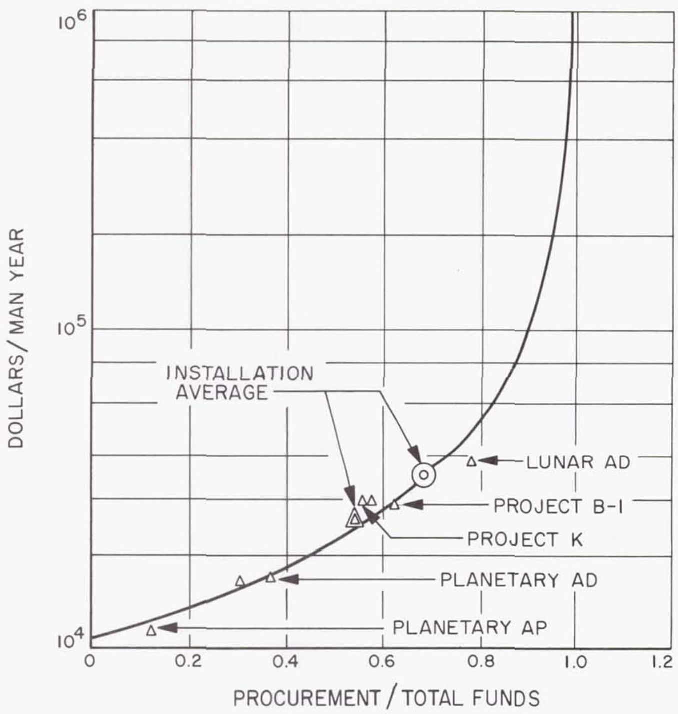

Fig. 5. Dollars/man year vs procurement dollars/total dollars

In order to relate some of this abstract material to space missions, it might be helpful to look at some mission scheduling. Table 2 presents a six-year and seven-mission schedule, which is a good approximation of the type of schedules that we are using. Notice that the planetary shots are in groups of two and three. The reason for this is that the planets are in favorable trajectory position only at the times shown, and we want to use the launch opportunities to best advantage. This means, of course, that a manpower problem occurs around launch time. For lunar shots, on the other hand, we can fire monthly, during the third-quarter phase of the Moon when lighting and other factors are favorable. Perhaps four or five lunar shots represent the optimum scheduling for any one year.

Table 3, which is based on the same scheduling given in Table 2, presents such related information as spacecraft weight, number of flights per mission, over-all mission costs, and costs broken down for several fiscal years. Normally, mission costs estimated over the project lifetime will assume a truncated pyramid shape, as can be seen in the second lunar mission in Table 3; over a three-year period, costs are highest the second year. Table 3 shows, in addition to scheduled mission costs, costs of supporting research and technology.

Having briefly discussed schedules and costs, I would like to continue on to the reliability factor. In this regard, Fig. 6 illustrates a much-argued subject, which is failure rate versus time. As shown in Fig. 6, design flaws appear early in testing; in temperature failures, for example, a component will work for a couple of hours and then exceed its temperature margin. On the other hand, wear-out failures, caused typically by simple erosion of material, generally occur much later. This shows the basic spacecraft problem; namely, how long should we test in order to eliminate the flaw failures but not get into the wear-out failures?

Table 2. Mission schedule

Mission	Calendar year					
	1	2	3	4	5	6
Lunar	1 2	3 4 5	6 7 8 9	10 11 12 13	14 15	
Lunar			1 2	3 4		
Lunar				1	2 3 4	5 6 7 8
Lunar						launches later than 1966
Planetary		1 2		3 4		
Planetary				1 2	3 4	5 6 7
Interplanetary					1	2

Table 3. Spacecraft costs vs spacecraft weight

Mission	Spacecraft weight, lb	No. of flights	Overall costs		Costs: fiscal years, $1,000,000				
			$/lb, $1,000	$1,000,000	1	2	3	4	5
Lunar	750	15	11¼	127	35	30	25	12	7
Lunar	1200	4	10	48		13	20	15	
Lunar	2400	12	7	202	10	30	35	35	30
Lunar	4500	8	6	216		1	3	10	30
Planetary	450	4	16	29		14	11	4	
Planetary	1400	9	11	139		17	30	35	30
Planetary	3000	8	9	216		1	5	20	40
Interplanetary	1400	6	12	101			1	10	20
Total		66		1078	45	106	130	141	157
Supporting research and technology					20	29	44	48	52
Total					65	135	174	189	209

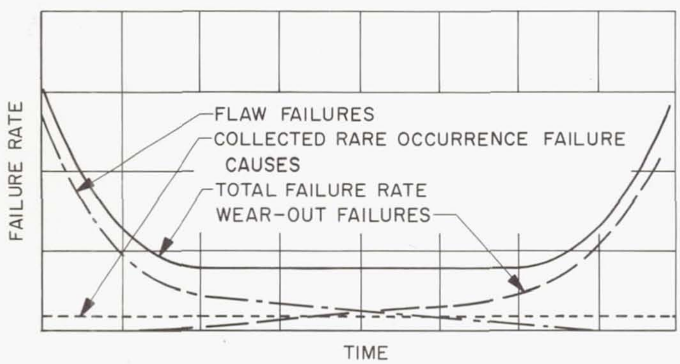

Fig. 6. Failure rate curve

To understand the over-all system from a reliability standpoint, it is necessary to understand the various subsystems and the interactions among them. Therefore, as an aid to spacecraft system reliability analysis we use a spacecraft system block diagram (Fig. 7) and trace the relationships of all the following subsystems:

Radio

Data encoder

Command

Attitude control

Power

Computer and sequencer

TV package

Midcourse propulsion

Thermal control and miscellaneous

Cabling

Pyrotechnics

We attempt to determine, as a function of flight time, the failure modes of each subsystem part and, further, the probability of failure in each subsystem. From these determinations, we then estimate the probability of over-all mission success. Changes can be made to increase reliability, and solutions to problems can be appraised as to their effect on reliability.

Figure 8 illustrates further the method that we employ in order to estimate subsystem reliability and to determine mission success probability. In the instance of the subsystem under investigation here—the power supply—it would first be necessary to determine the probability of acquiring the Sun, and that, of course, is dependent upon a properly functioning attitude control system. Having determined the probability of Sun acquisition, we would next need to determine the probability of having an operative solar array and battery

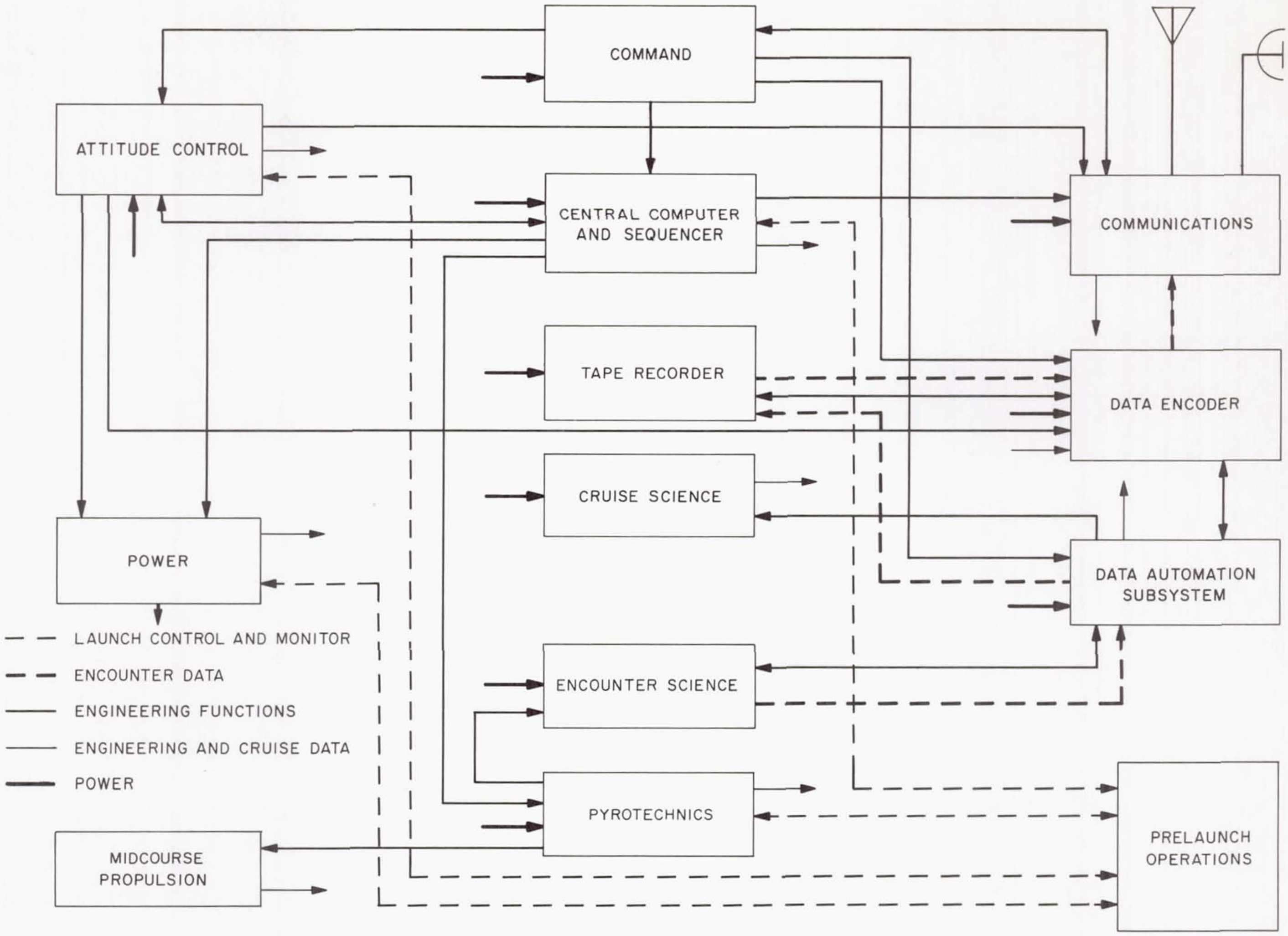

Fig. 7. *Mariner* block diagram

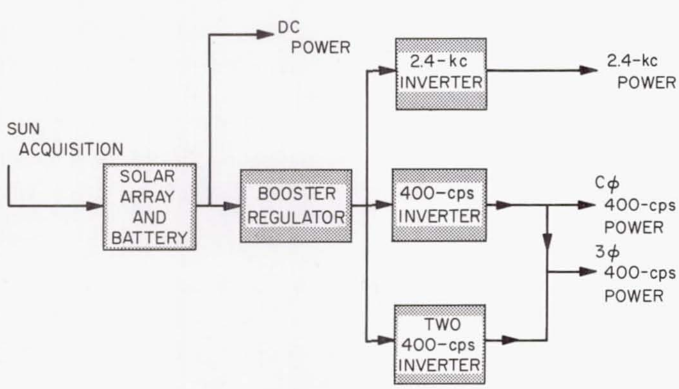

Fig. 8. Power supply

system to generate dc power; following that, booster regulator reliability would be determined. As shown in Fig. 8, there would then be two paths through which power could be obtained—the 2.4-kc inverter and the 400-cps inverters. The probability of finally delivering power would be determined by mathematically combining the reliability probabilities of all the various power supply subsystem components, the solar array and battery system, the booster regulator, and the 2.4-kc and 400-cps inverters.

In addition to studying subsystem reliability, we investigate such reliability variables as the various flight phases and the influence on success probability of omitting one or two of them. Figure 9, which illustrates this aspect of the reliability study, presents four possible flight paths or options. Path A includes both the midcourse and the terminal maneuver; path B omits the midcourse; path C omits the terminal; path D omits both.

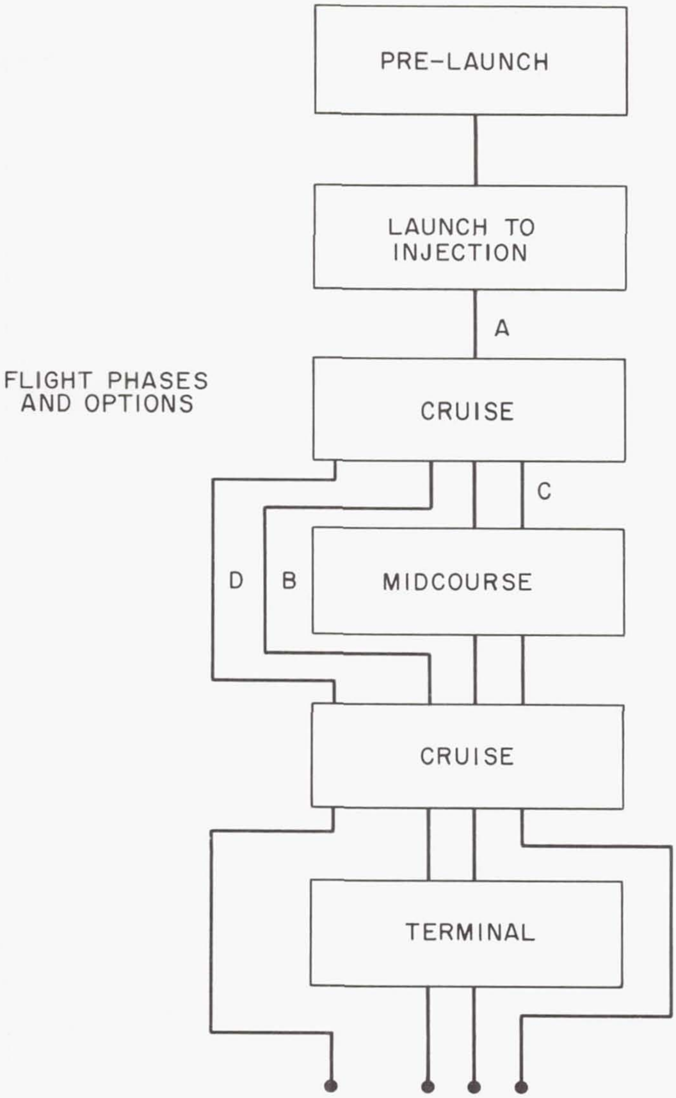

Fig. 9. Spacecraft reliability variables

The reasons for conducting this part of the study can be shown by presenting some facts relative to the terminal maneuver, its value to the mission, and its effect upon mission success probability. First, the reason for the terminal maneuver is to point the spacecraft along the velocity vector so that as the spacecraft approaches the Moon the TV-camera view is optimum; if we did not employ a terminal maneuver the spacecraft would not be pointed along the velocity vector and the resulting pictures would show a smear of the lunar surface. The chances for mission success, however, are considerably better if the terminal maneuver is omitted. And here, of course, the problem is stated: Is the hazard involved in the terminal maneuver sufficient to justify omitting it and settling for pictures of lesser quality?

It is a tough decision to make, and we feel that the data we have assembled, including the reliability studies we have made, are helpful in bringing about the best decision.

In this general area of reliability and success probability, it should be pointed out that mission success is not ordinarily an all-or-nothing matter. There are gradations of success (or failure). The following listing presents a few of them:

1. Complete success
2. Complete mission
3. Complete TV pictures
4. Some good TV pictures
5. Satisfactory spacecraft operation
6. Predictable failure
7. Failure

Notice that between failure and success there is a reasonable amount of variance.

During the course of these discussions, it has often been stated or implied that the space effort is a novel and unique undertaking. The area hasn't been charted, the books haven't been written, and the values haven't been assigned. In this latter regard, when *Mariner 2* was out about half-way to Venus, we made a preliminary and rather primitive attempt to find out what people were thinking relative to the value of this space mission. Table 4 presents a blank ballot that we used in a small sampling which attempted to assign kinds of value (political, scientific, etc.) to varying degrees of space mission success.

At the time, of course, we were particularly concerned with the possibility of a *Mariner* '64 flight. So we asked our voters to tell us what they thought the value of *Mariner 2* was and what they thought the value of *Mariner* '64 would be if (1) *Mariner 2* was successful or (2) *Mariner 2* failed. Tables 5 and 6 give results of this balloting. Numerical values obtained from the sample ballot and shown in Tables 5 and 6 are relative, not absolute, values.

Table 4. Value weightings for planetary missions (sample ballot)

	Political	Scientific	Engineering	Military	Future	Early failure recognition
Spacecraft operating correctly after launch						
Spacecraft through midcourse and in data mode						
Communications capability through t days						
Engineering data capability through t days						
Scientific data capability through t days						
Planetary distance reached						
Planetary data received						

Table 5. Value assignments for *Mariner* 2

Elements of mission	Minimum	Mean	Maximum
1. Launch	1.4	10.3	21.0
2. Midcourse	3.1	12.3	21.0
3. Communications	6.8	12.8	17.0
4. Engineering data	6.0	10.9	20.1
5. Science data	9.0	13.0	19.2
6. Planetary distance	9.9	15.4	28.1
7. Planet data	13.0	25.3	42.6

To repeat, this sampling was a first and wholly unrepresentative attempt. But it, like the reliability studies and the cost studies, was meant to be fitted into the over-all learning effort which must necessarily precede successful space exploration.

To solve project problems, there are many things to consider. In my opinion project managers should allow freedom of initiative, but must coordinate all efforts to accomplish goals and have the fortitude for decision after intelligent evaluation.

System engineering has not received adequate study, and with our large future in space, we must continue analytically and empirically to explore project problems.

Table 6. Value assignments for *Mariner* 2

Elements of mission	*Mariner* 2 '62	*Mariner* R '64	
		(*Mariner* 2 successful)	(*Mariner* 2 fails)
	Mean	Mean	Mean
1. Launch	10.3	7.3	8.4
2. Midcourse	12.3	8.7	10.3
3. Communications	12.8	9.7	11.9
4. Engineering data	10.9	9.4	10.8
5. Science data	13.0	10.0	13.7
6. Planetary distance	15.4	13.5	15.8
7. Planet data	25.3	23.3	24.4
Total	100.0	81.9	95.3
Categories			
A. Political	22.0	17.7	21.9
B. Scientific	26.7	21.9	28.0
C. Engineering	21.7	18.8	22.6
D. Military	6.6	5.9	6.8
E. Future	14.7	11.3	12.5
F. Early failure recognition	8.3	7.4	8.1
Total	100.0	83.0	99.9