Electro-propulsion system applications

As space missions grow more difficult, electrical propulsion shows progressively greater performance advantages over other propulsion systems and in some cases provides the only means for accomplishing the mission

By John W. Steams

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NASA has assigned responsibility for the development and employment of unmanned spacecraft to explore the planets and interplanetary space to JPL as part of its over-all mission. Through a study and evaluation of industrial efforts and progress in the field of electric propulsion, JPL has reached the conclusion that spacecraft with nuclear-electric propulsion can be used advantageously to perform planetary and interplanetary missions during the latter half of this decade. Preliminary design studies have indicated the performance potential of such spacecraft for these missions and have pointed out some of the requirements placed on the electric propulsion system by reason of its employment in the spacecraft.

John W. Stearns has since September, 1960, been a staff engineering specialist in the advanced propulsion engineering section of JPL, assisting the section chief in program planning and guidance and control with respect to proposed electric propulsion development. He joined JPL in 1954 after receiving his MSEE from MIT, starting as a research engineer with the inertial components and inertial systems groups of the Guidance and Control Div. In 1957, he was appointed engineering group supervisor for the inertial systems group in connection with the Sergeant program, and later served as project director for Vega inertial guidance. In 1960, as program engineer, he coordinated preliminary design of the guidance and control system for Ranger.

Prototype Stage Is Approaching

Until now, the use of electrically propelled spacecraft has had to await the development of sufficiently large boost vehicles and of lightweight nuclear power supplies. Development efforts are such that prototypes capable of meeting minimum requirements should become available within the next few years.

The electric propulsion system, an integral part of the spacecraft, is started after the spacecraft has been placed in earth orbit and separated from the launch vehicle. The thrust of the electric propulsion system is then used to provide for escape from the earth orbit and transit to the ultimate destination.

JPL studies have shown that the use of electric propulsion systems in spacecraft provides more than just an improvement in mission capability. In fact, certain highly desirable missions can be achieved only through the use of the electrical propulsion system. A second significant consideration is the fact that the power supply can serve a dual purpose. Upon arrival at destination, the power which was required for propulsion becomes totally available for experimentation, instrumentation, and communication.

The JPL Space Sciences Div. has examined the characteristics and mission capabilities of electric propulsion spacecraft in order to determine the most suitable system applications. Mars and Venus orbital missions, Jupiter spacecraft, and an out-of-the-ecliptic probe have been studied. A solar probe to within 20 solar radii (0.094 AU), though highly desirable from a space science view-point, must be deferred until spacecraft temperature control and other problems associated with the sun's hostile environment can be resolved.

The slow spiral of electrically propelled spacecraft into the selected Mars or Venus orbit can be useful for several reasons. For example, quantitative mapping of gravitational, magnetic, and radiation fields can be accomplished readily; temperature conditions as well as the composition and structure of the atmosphere may be carefully examined; and instrument packages might be landed at strategic spots (and times) to gain further knowledge of surface conditions.

Jupiter is the closest of the solar system's major planets—those planets whose composition and structure differ radically from the composition and struture of Earth, Mars, Venus, and Mercury. Scientists are particularly eager to investigate Jupiter, for information gained from such an investigation may bear upon the origin and history of the solar system.

It would be most instructive to investigate some of the satellites of Jupiter and compare them with our moon. We could then ascertain whether moons such as ours are common occurrences in the solar system or result from some unique incident. Further, the atmosphere of Jupiter is thought to be much like earth's at the time that life was forming here. A probe could determine whether life forms exist on Jupiter. Perhaps (CONTINUED ON PAGE 74)

Chemical Spacecraft Performance Estimates

Mission	Flight time, days	Approximate gross payload, lb		
		Booster I	Booster II	Booster III
Mercury probe	96	0	4,200	9,800
Venus				
Probe	112	1,600	12,700	16,900
Capture	—	—	1,950	—
Mars				
Probe	—	1,600	12,100	16,900
Capture	230	600	3,200	4,500
Jupiter				
Probe	750	0	1,100	6,000
Saturn				
Probe	1170	0	0	2,500
Out-of-ecliptic				
15 deg	—	—	2,800	9,000
22 deg	—	—	—	2,500

Assumed Nuclear-Electric Powerplant Capabilities

Power	Output power, kw	Total wt, lb	Specific wt, lb/kw
A	60	3,000	50
B	300	3,000	10
C	1,000	10,000	10
D	10,000	10,000	1

Spacecraft Missions and Payloads Delivered

System		Mercury			Venus			Mars			Jupiter		
Booster	Power-plant	Time, days	Probe, lb	Orbit, lb	Time, days	Probe, lb	Orbit, lb	Time, days	Probe, lb	Orbit, lb	Time, days	Probe, lb	Orbit, lb
I	Chem		0		112	1,600		230	1,600		750	0	
	A		0		240	5,000[a]		300	4,200[a]		750	6,100	
					365		4,700	400		5,200			
	B				365		7,800	365		8,000	500	7,500	
											750	7,900	
IA	B	200	7,000[a]		240	10,500[a]		230		9,200	500	11,600	
		400	12,000[a]		200		9,000			12,500	800	12,500[a]	
II	Chem	96	4,200		112	12,700		230	12,100		750	1,100	
					112	3,200[a]		230	1,900[a]				
	B	400	23,000		240	24,000							
	C	260	34,000[a]		200	38,000	28,500	230		28,500	500	24,000[a]	
		200		23,500	365		37,400	365		37,500	750		13,600
		365		34,000									
III	Chem	96	9,800		112	16,900		230	4,500[a]		750	6,000	

[a] Planetary-capture spacecraft mission.

Continuous Solid-State Laser Operation Revealed by BTL

In recent months, Bell Telephone Laboratories has announced two major advances in laser technology—continuous operation of a solid-state laser and continuous emission of visible light by a ruby laser. These advances would appear to open the way to lasers of high beam intensity and low driving power.

The sketch below right illustrates Bell's experimental setup in achieving continuous emission in the infrared with a solid-state laser. A single-crystal rod of calcium tungstate containing trivalent neodymium ($CaWo_4$: Nd^3, radiating at 10,650 A) resides at one focus of an elliptical cavity. The light feed comes from a d.c. Mercury lamp. Laser action was obtained when power input to the lamp exceeded 900 watts. Output was in the milliwatt range. Stable emissions have been obtained for at least 5 min.

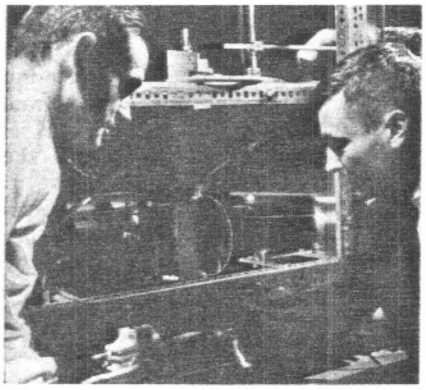
Experiments with the ruby crystal, which was prepared by the Linde Co., took the form depicted in the sketch opposite. Pure aluminum oxide (sapphire) in the shape of a cone forms the "receiving bell" of the ruby. The face of the bell, approximately 60 mils in diameter, receives the pumping arc.

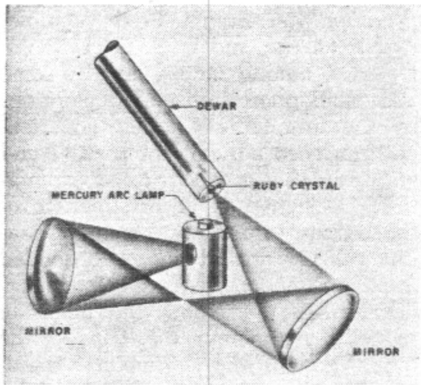
The bell tapers to meet a shank of chromium-doped aluminum oxide (ruby), which has a diameter of approximately 24 mils.

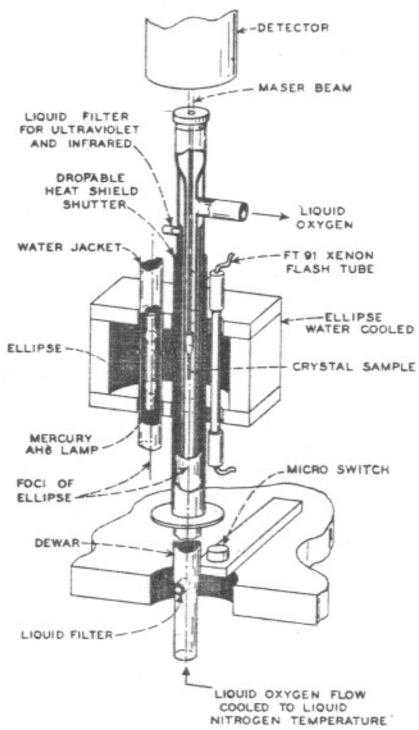
The image of the arc of the pumping lamp reaches the face of the bell at the same size and intensity as the arc itself. The cone of the bell acts as a "radiation condenser," making the arc light six times more intense as it enters the shank. The light then travels down the shank by a series of internal reflections. A silver coating at the end of the rod causes the pumping light to return and emerge at the original face. Since the pumping light travels a "double path," its intensity, already increased six times, is doubled, making it much greater than that in a conventional laser rod receiving light from the side. Consequently, the pumping lamp needs relatively low power.

Because the maser rod is not surrounded by the pumping source, it is physically available for a number of experiments. For example, slipping a coaxial magnet over the rod would permit studying magnetic splitting of emission lines. It may be possible to show changes in the basic frequency of a solid-state laser by applying mechanical stresses. Also, the cause of the "spiking" phenomena associated with solid-state maser action may be uncovered in the apparatus.

Initial results on continuous operation of the ruby laser, as well as a full description of the new pumping arrangement, will appear in the *Journal of Applied Optics*.







Donald F. Nelson, at the left, and Willard S. Boyle, BTL scientists who developed the continuously operating ruby laser, examine apparatus for conveying light to one end of bell-shaped crystal shown in the sketch (center) of the experimental setup. Right, diagram of BTL setup for achieving continuous laser action in the infrared with neodymium-containing crystal.

Electro-Propulsion

(CONTINUED FROM PAGE 23)

an explanation would be had for Jupiter's dimly seen, intriguing red spot.

Recent measurements of electromagnetic radiation from Jupiter show a decidedly nonthermal character which may be due to synchrotron radiation of electrons trapped in Jupiter's magnetic field. Field strength calculations indicate that this magnetic field must be of the order of kilogauss to produce such an effect, a finding difficult to explain in view of the fact that the planet is thought to be made up in large part of hydrogen and helium. In addition, particle and field measurements should be made during the trip to Jupiter to determine whether there is a substantial boundary to the solar atmosphere and magnetic field.

An out-of-the-ecliptic probe could assist in determining the three-dimensional rate of mass loss by the sun. A study of sunspot activity could be made, particularly with regard to the associated low-energy particle radiation and its interaction with magnetic fields at high solar latitudes. To study these effects, it would be extremely desirable to have space probes high out of the ecliptic plane at the maximum and minimum of solar activity. A probe high above the ecliptic plane would also be able to study the accumulation of gas and dust in the ecliptic and thus to determine whether it is a static accumulation or the result of continuing dynamic processes.

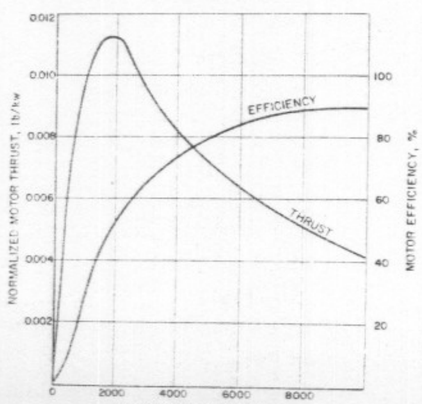
For all of these missions, the expanded weight capabilities of electric propulsion spacecraft are desirable. Until now, it has been necessary to select a few items for a scientific mission from among many equally important experiments. Carefully designed electro-propulsion spacecraft can provide really significant quantities of scientific instrumentation. In the parametric studies which follow, these benefits will be readily apparent.

A brief discussion of chemical propulsion vehicle capability is a convenient reference point for mission studies. Following that, a performance comparison with chemically-boosted nuclear-electric spacecraft should indicate where it is advantageous to concentrate on electric propulsion without trying to compete with chemical systems.

A typical trajectory for chemical-propulsion planetary flights consists of initial launch into a low earth orbit, a period of coast to reach an appropriate point in space, and subsequent rapid firing of the remaining booster stages to inject the spacecraft into a heliocentric transfer orbit. After some period of guidance monitoring, errors from the injection guidance would be determined. Using the spacecraft guidance computations, a small, mid-course correction rocket aboard the spacecraft would be appropriately aimed and fired. Finally, at the ultimate destination, a terminal maneuver and retrorocket firing may be commanded as necessary to meet the terminal requirements of the scientific mission.

The table on page 23 summarizes the mission performance of chemical propulsion spacecraft, using three typical boosters. In this study, Booster I, *Atlas-Centaur,* is expected to place 8800 lb into a 300-n.mi. orbit about the earth. Booster II is a four-stage *Saturn* C-2, and Booster III is a five-stage *Saturn.* Both boosters will place 45,000 lb at the 300-n.mi. altitude. Booster III achieves a higher performance than Booster II because more-optimum use can be made of upper-stage propellants by increasing the number of orbital stages. The term gross payload signifies the total

Electro-Propulsion Performance Estimates



weight of the spacecraft at destination minus the weight of the booster and retrorocket propulsion. A probe or "flyby" mission involves a spacecraft which arrives at a given destination in space with no attempt made to control terminal velocity. A capture mission requires spacecraft arrival at the vicinity of a planet with a terminal velocity vector essentially equivalent to that of the planet; thus, an undefined elliptical orbit is achieved. An orbital mission (unless noted, all planetary orbits in the article are circular orbits, with a 500-mi altitude for the minor planets and a 2000-mi. altitude for the major planets) requires additional terminal control to accomplish a defined planetary orbit. The times for mission accomplishment and the terminal weights identified here cannot be considered optimum because many details of the systems have had to be assumed. The attempt here is to establish at least an order-of-magnitude capability of payload weight. A zero in the table on page 23 indicates that the mission cannot be accomplished in a satisfactory manner, and gaps in the chart represent generally undesirable missions.

Deep-space missions other than planetary may include an out-of-the-ecliptic shot. Booster III can place 2500 lb at a 22-deg inclination angle, or approximately 9000 lb at a 15-deg inclination angle. Despite the relatively large weight of its spacecraft (45,000 lb), it is incapable of performing a solar probe mission to within 20 solar radii (0.094 AU); its capability is limited to approximately 2500 lb of payload within 0.24 AU from the sun (just inside Mercury), with a flight time of roughly 40 days. For the scientist interested in a mission to Pluto, preliminary calculations indicate that not even an all-chemical vehicle as large as the proposed *Nova,* and with a flight time of 15 years, could deliver a payload to Pluto.

Mission Parameters

In a discussion of missions—even a discussion limited to planetary missions—there are great numbers of vital parameters to study. It would be impossible to study all possible optima for all possible trajectories. Because of this, performance figures included here are subject to challenge. The chemical systems evaluated are, however, typical of existing vehicle programs for this decade. Improved booster vehicles must be evaluated as they become available.

While uses for electric propulsion will undoubtedly include attitude control, correction for guidance deviations, spacecraft maneuvers, etc., these studies are still in process, and represent detail unnecessary to this discussion. We will concentrate specifically on the propulsion necessary to take a spacecraft from an initial earth orbit and perform a required planetary mission.

Electric propulsion spacecraft for these studies are assumed to have been placed in a 300-n.mi circular earth orbit by a chemical-propellant booster. This orbit is presently regarded as the minimum allowable for safe startup of a nuclear reactor in space. Studies indicate that there may be only small change of payload with a sizable change of orbital height. Hence, it is possible that, because of other more important criteria, different initial orbits might be selected as future studies are made.

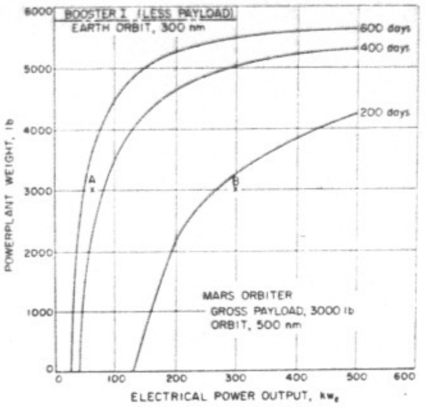
Performances given for electric spacecraft are based on calculations of L. D. Jaffe and others, trajectories described by J. H. Irving, and the program studies of W. Melbourne.

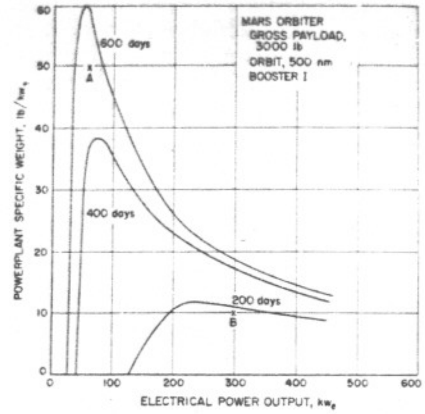
The electric-propulsion spacecraft would spiral out from earth over a period of 3 to 5 months under the effects of a constant low-level thrust at a high specific impulse. Escaping from earth, the spacecraft would then, in the case of a probe or flyby, be gradually and continually accelerated toward the destination planet (possibly with an interim coast period). In the case of a capture mission, it would be necessary at some point in the heliocentric trajectory to reverse the thrust in order to decelerate the spacecraft and subsequently match the planetary velocity. Obviously an orbital mission would require an additional maneuver, a slow spiral, into a specified final orbit.

For performance estimates in this section, the boosters studied for electric-propulsion spacecraft are the same as previously given, except that Booster IA has been inserted (either an advanced version of Booster I or a preliminary version of Booster II) and Booster III has value only as a reference. Booster IA will easily place 15,000 lb into a 300-n.mi orbit. Emphasis has been placed on smaller boosters to remove any doubts of validity of payload magnitudes, to illustrate further the potential versatility of electric propulsion spacecraft, and to remove doubts of the early availability of launch vehicles.

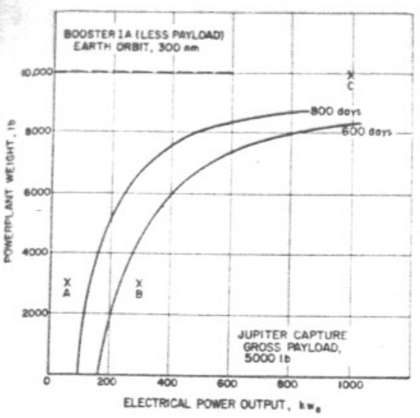
Thrust devices and nuclear-electric

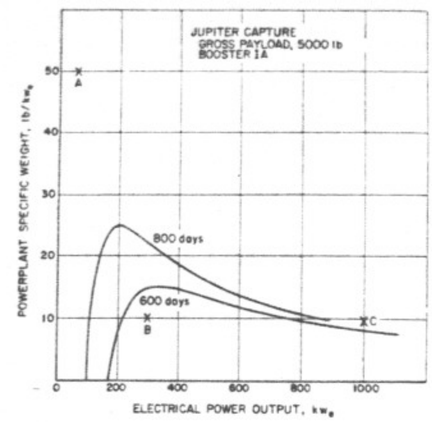
Powerplant Requirements for Mars Missions





Powerplant Requirements for Jupiter Missions





powerplant systems considered in this study represent an extrapolation of the state of engineering art. The thrust units follow the performance curves in the graph on page 76, which shows specific impulses and thrust levels reasonably sure of being attained during the latter half of this decade. In some cases, the performance is potentially achievable by more than one type of thrust device.

Powerplants used in the study are listed in the table on page 23 and assume a progressive powerplant development program. The last of these power supplies, Powerplant D, cannot currently be realized. Rather, it represents an extreme limit for the foreseeable future.

Significant missions using the many combinations of boosters and hypothetical spacecraft powerplants are summarized in the table on page 23 These have been selected for illustration from more extensive studies. Powerplant A was only considered for use with Booster I. With larger boosters, the much lower thrust-to-weight ratio associated with the larger spacecraft would result only in excessively long flight times for most missions. Powerplants C and D were considered only with Booster II because of the large powerplant weights. Also, Powerplant D does not fit a practical analysis at this point, and hence does not appear in the table. In this manner, we obtain a satisfactory balance between the proposed booster and spacecraft.

For an out-of-the-ecliptic probe, Booster I with Powerplant A can place a gross payload of 1700 lb (terminal weight of 4700 lb) at approximately a 15-deg angle of inclination to the ecliptic plane. With Powerplant B, it becomes feasible to place substantial gross payloads (6300 and 4300 lb) into orbits inclined at 30 and 45 deg, respectively. Booster IA with Powerplant B can take several thousand pounds to Pluto in three years. With some reasonable assurance, we can say that electric propulsion systems become superior to chemical when flight times for planetary missions exceed approximately one year.

We can compare some of the system tradeoffs for electric propulsion if we look briefly at specific planetary missions. One of the representations most often used is that of the gross weight delivered at the destination as a function of the total flight time. Such curves, generated by E. W. Speiser of JPL, are the means by which we have arrived at the summary table on page 23. Such curves are obviously of considerable importance when mission criteria are being established.

Powerplant Tradeoffs

At this point, however, it is necessary to leave specific missions studies and to give consideration to powerplant tradeoffs. This is of particular importance because weight limitations of present vehicles lead to results that are different from those expected.

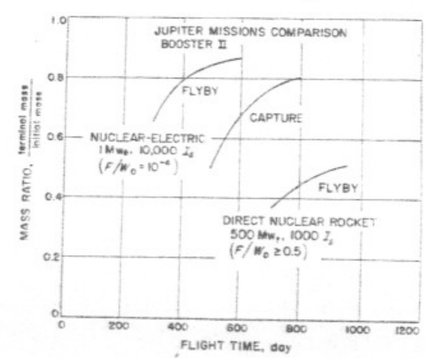
Consider first the Mars orbiter mission for an electric propulsion spacecraft using Booster I. This booster will place 8800 lb of initial spacecraft weight into a 300-n.mi earth orbit. We wish to terminate in a 500-n.mi Mars orbit with a terminal weight consisting of an operating powerplant (reactor and power conversion unit) plus an additional "gross payload" of 3000 lb. The latter is the weight necessary for empty propulsion elements, structures, guidance and control, telecommunications, instrumentation, and the scientific experiments. The higher the power available, the less fuel required and the more weight we can allot to the powerplant. Or, alternately, for the same fuel expenditure, a higher power level will allow accomplishment of mission in a shorter time or result in a higher terminal weight. This is illustrated in the graphs on page 78 the first showing maximum total weight allowable for powerplant, and the second the specific weight of the powerplant.

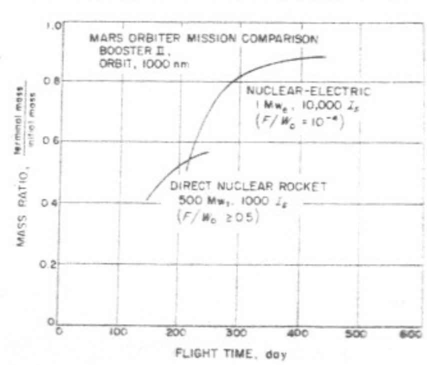
The minimum power point on these curves is that at which all the allowable weight is expended as fuel. Specific power, of course, would be infinite; the powerplant would weigh nothing. At high power levels, fuel expenditure tends asymptotically toward zero. For reasonable mission times, there is a relatively broad but definite knee to the curve of maximum power. In this area, the spacecraft design is most easily fulfilled. The figures display Powerplants A, B, and C of the previous section.

A Jupiter capture mission using Booster IA is shown in the graphs above. Here we have called for a gross payload weight of 5000 lb in addition to the operating nuclear-electric powerplant, leaving 10,000 lb for division between powerplant and propellant. Notice how Powerplant B offers excellent versatility of system design. Powerplant weight could be doubled, or the gross payload increased by 60%, with only a 25% degradation of mission time. In other words, 3000 lb can easily be made available for engineering contingencies.

Other missions can be easily repre-

Nuclear and Electric Systems Compared for Mars and Jupiter Missions





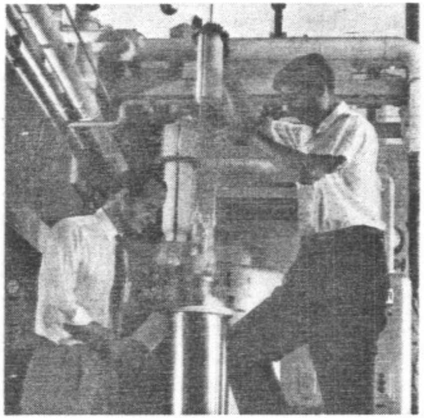
clear and electric spacecraft was made strictly on the basis of terminal weight delivered at the destination. The value of the electric powerplant in the latter, as a source of spacecraft secondary power, was ignored. The results are shown graphically on page 79 for typical Jupiter and Mars missions. For the Jupiter missions, the electric system is superior in both payload and flight time.

For planetary and interplanetary missions wherein the specific impulse is at a premium, nuclear-rocket systems presently offer less performance incentive than the nuclear-electric systems. But by this we cannot infer that there is no need for direct nuclear rockets with lower specific impulses. As upper-stage boosters, they should greatly enhance the capability of future launch vehicles to lift large spacecraft into orbit.

There is no point in dwelling on our need for nuclear power in space. It is increasingly obvious, however, that (1) our planetary and interplanetary ... heavier space-craft needed will become available.

As space missions become more difficult, electric propulsion shows a progressively greater performance advantage over other forms of propulsion. For many very difficult missions, it seems to provide the only means of reaching the spacecraft destination. This conclusion is of practical significance because flight missions with electro-propulsion spacecraft are now being planned for this decade. ◆◆

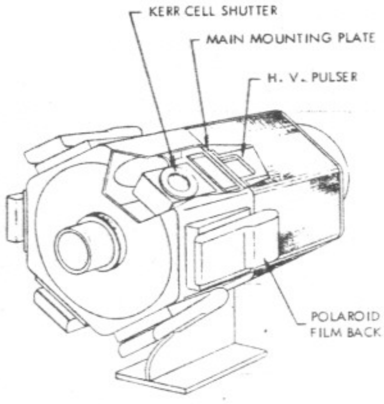
Card on page 85



Superconducting Magnet

A cryogenic magnet system is now commercially available that develops 50 kilogauss at −269 C. The superconducting system consists of coil and its support, a special power supply, gaussmeter, Dewar assembly, helium liquid-level ... columbium, in standard sizes from 20 to 7 1/2 mil diam, in several-thousand-foot lengths, bare or insulated. The solenoid, approximately 3 in. in diam and 3 in. long, produces the 50 kilogauss field within a 1/2-in. ID. A transistorized power supply furnishes constant-current, low-ripple d-c power for use with superconducting magnetic coils. The portable unit is designed for less than 0.1% regulation from no load to full load with an input voltage variation from 105 to 125 v AC. Unique protective features are incorporated to prevent damage to the power supply or to the superconducting magnet. Another feature is that the power supply is programmed to increase or decrease the output current linearly to any preselected current up to a 25-amp maximum in a finite time. Westinghouse Transformer Division, Sharon, Pa. (314)

mately 2 1/2 to 3 ft high by 2 1/2 by 2 ft. System accessories include a flux stabilizer and a field-homogeneity control system. The V-2500 Series power supply produces 7 kw of d-c power, continuously variable from 1 watt to 7 kw. Varian Associates, Instrument Division, Palo Alto, Calif. (313)



Kerr-Cell Multiframe Camera

This multiple-frame ultrahigh-speed Kerr-Cell framing camera system, the first available commercially, permits observation from one line of sight and meets stringent shuttering-speed and optical resolution requirements. ... same aspect and through the same set of optics are thus possible. Using established triggering techniques, framing rates to 100-million per second are achieved at exposure times in the range of 5 to 10,000 billionths of a second. Exposure time and resolution are independent of framing rate. The KFC-600 was primarily developed to provide instrumentation for areas of technology not adequately served before. These involve research in extremely high energy density phenomena, as well as normal-energy densities viewed on a microscopic scale. Such studies include hydrodynamic explosives, exploding wires, etc. Provisions have been made to permit recording on Polaroid film, where rapid evaluation is desired, and on high-speed, fine-grain, cut films. Electro-Optical Instruments, Inc., Pasadena, Calif. (315)