X. APPLICATIONS OF POWER SYSTEMS TO SPECIFIC MISSIONS

Bernard Lubarsky and Lloyd I. Shure

The new power systems, previously described, are discussed in terms of typical mission applications. A comparison of the use of these new powerplants is made with existing systems, such as photocells. The relative interest in different kinds of power systems varies greatly from mission to mission. In a survey of power-system applications to future missions, an important feature is breadth of coverage. If a broad range of presently unapproved missions is covered, the depth of coverage cannot, of necessity, be very great. Therefore, the numbers given for the various systems are only approximate and not definitive because details have not been sufficiently established for these advanced missions. Many of these comparisons are made with two significant figures, but these figures are only the product of the assumptions used in each case.

The missions discussed begin with near-Earth orbital and progress outward to the planetary missions. The first mission, the near-Earth, large, manned, orbiting laboratory, is one of considerable interest to NASA at this time.

A summary of the weights and area characteristics of solar power systems for manned orbiting stations is shown in table X-1. These solar power uses are divided into what are called day and night applications. Day-power weight is the weight of photocell panels required to provide a kilowatt of power while exposed to the Sun. Night-power weight is the sum of two weights, namely, the weight of photocell panels required in sunlight to charge batteries plus the weight of the batteries required to deliver power during the night, or shade, part of the orbit. For day power, the conventional photocell system is quite light, about 50 pounds per kilowatt. This number represents the probable lower limit of what can be achieved in large lightweight multikilowatt solar arrays based on technology work that has just begun and is of the order of half the weight of arrays currently in use. The 1.5-kilowatt array described in paper I and flown by the Air Force on the Agena vehicle weighed approximately 130 pounds per kilowatt; hence, the weight shown for conventional photocells is fairly optimistic. This is done for comparability, that is, in order to compare future photocell systems with other advanced power systems. Hence, for the photocell-and-battery system, which is fairly well developed today, optimistic weights are shown in order to reflect the inevitable improvement that will occur. In the case of other advanced systems, the weights shown are representative of the first flight system; that is, they are conservative in the sense that future developments beyond that time could undoubtedly produce still lighter systems.

The night-power computations are based on the Sun and shade times for a 260-nautical-mile ecliptic orbit. A typical value of 55-percent charge-discharge efficiency for the batteries was assumed. The discharge voltage obtained from the batteries is about 55 percent of the voltage required to charge them, and, of course, the ampere-hours are the same. Also included is a 95-percent efficiency for the battery charger. From these assumptions, the photocell power required for the night power is obtained. Battery weights were based on 2 watt-hours per pound, a value typical of nickel-cadmium cells from which an extremely large number (thousands) of charge-discharge cycles is obtained. Currently, nickel-cadmium batteries flying in low-altitude orbit normally produce about 1 watt-hour per pound so that, again, current systems weigh about twice what is shown in table X-1. When all these assumptions are added, a specific weight of 450 pounds per kilowatt is obtained. The collector area shown in the table is the photocell array for both day and night power.

In the case of thin-film photocells and batteries, a range of weights is presented. This range corresponds to two efficiencies: a 5-percent efficiency, which is an average of presently demonstrated technology, and a 7-percent efficiency, which is currently typical of occasional cells as produced, although they do not retain this 7-percent efficiency for a long time. Thus, this 7-percent efficiency represents the upper range of what can reasonably be anticipated for advanced development. The weight of structure assumed ranges from 0.1 to 0.2 pound per square foot for the thin-film array. In a conventional photocell array for which the cells are heavier and more brittle, the structural weight is about 1/3 pound per square foot. For the thin-film cells with their lighter weight and greater flexibility, a lower structural weight was chosen. In spite of this, there really is no significant difference in weight between conventional and thin-film photocells for this particular application. This result was anticipated since the predominant weight of the system has little to do with the weight of the photocell array, but is primarily involved in the energy-storage requirement for night power. This characteristic applies throughout nearly all the missions discussed herein. Therefore, wherever any kind of substantial energy-storage requirement is concerned, the weight of photocell systems, both conventional and thin film, will be approximately the same. The choice then between these two systems will be based on other factors, such as the ease of packaging, or lower cost of the thin-film system, or the lower collector area of the conventional photocell array. For the remainder of this discussion, since the weights of these two systems are nearly the same, only the conventional photocell system is considered.

The Brayton cycle, instead of using batteries for energy storage, stores energy in the form of heat of fusion, in this case, of lithium fluoride. This method results in lighter weights for low-altitude orbit than battery storage. The Brayton cycle system thus shows a significant weight advantage. Therefore, where energy-storage requirements are high, such as in this application, the Brayton cycle is expected to offer some advantage in weight. However, whenever energy-storage requirements are low, the Brayton cycle is less attractive on a weight basis. Of course, it does offer an advantage in reduced collector area because of its higher efficiency.

Figure X-1 shows a 30-kilowatt conventional photocell array on a three-spoke orbiting manned station of the kind that might be put into orbit by a Saturn V. The approximate dimensions are 100 feet from the middle of the hub to the tip of the spoke and approximately 80 feet in width across the photocell array. The weight capability of the Saturn V for this mission is approximately 250 000 pounds. Figure X-2 shows a typical 30-kilowatt solar Brayton system on the same space station to the same scale as shown in figure X-1. Here, three 10-kilowatt solar Brayton systems are shown, one at the end of each spoke. The mirror diameter for this system is 30 feet.

Table X-2 is a summary of nuclear power systems for this same application. In the solar power system, energy storage for night power was a predominant feature in system weight. In the nuclear power systems, a different feature becomes very important and prevails in many instances, namely, shielding. In this table, four different nuclear power systems are given with their weights and radiator areas. The weights have been broken down into unshielded weights and the weight of the shield itself. The unshielded isotope Brayton system weighs about 350 pounds per kilowatt, and because it uses plutonium 238 with its relatively low level of emitted radiation, the shield weight required is small, of the order of 0 to 50 pounds per kilowatt, where the shield weight depends on isotope location and shielded area.

The 35-kilowatt SNAP-8 system includes a completely redundant power-conversion system. These two complete systems are connected to one reactor. This redundancy was necessary in order to assure the high reliability usually associated with manned missions. Either of these power-conversion systems is capable of producing 35 kilowatts. The isotope Brayton system does not have redundant machinery since it is assumed that a 30-kilowatt system could utilize three 10-kilowatt modules; if some redundancy were required, a fourth standby system could be provided. In any event, the weights can be adjusted from the values given in table X-2. The SNAP-8 thermoelectric system has a lower efficiency than the SNAP-8 mercury Rankine system and is also heavier; hence, it produces less electric power from the same thermal power of the SNAP-8 reactor and accordingly weighs more unshielded. The large increase in shield weight for the SNAP-8 thermoelectric reactor system is a result entirely of the lower power; the shielding is the same as that required for SNAP-8, but because of the lower power output of the SNAP-8 thermoelectric system, the unit weight (lb/kW) is higher. The reactor systems are significantly heavier for this mission than the corresponding isotope systems because the large amount of penetrating radiation put out by the reactor requires reactor shields that are thicker and correspondingly heavier than isotope shields.

Currently, three advanced reactor power systems are being evaluated, namely, Rankine, Brayton, and thermionic systems. The numbers shown in table X-2 are representative of the potassium Rankine system. For the thermionic system, the weights would be quite similar, but the radiator area would be still smaller. For the Brayton system, the weights would probably be of the order of 50 percent larger, and the radiator area would be larger by a factor of perhaps 5. In comparison with the other reactor systems, there is a substantial reduction in shield weight per kilowatt due primarily to the higher power level of the advanced reactor system. This reactor, although producing nine times the power of the SNAP-8 reactor, would only be slightly larger with the result that total shield weight would increase only slightly, while the unit weight (lb/kW) would decrease markedly.

Figure X-3 is a conceptual view of SNAP-8 on a manned space station. The reactor is at the apex of the cone in the lower right of the figure. The distance from the reactor to the nearest occupied point in the space station is 125 feet. The base of the cone containing the SNAP-8 system is approximately 22 feet in diameter. This configuration is typical of a SNAP-8 configuration for space-station application.

As shown in figure X-3, the station could be assembled from two launches of a Saturn IB, which has an orbital capability of the order of 30 000 pounds. The space station would be taken up by one launch, and the SNAP-8 system with its shield would be taken up on the second launch for rendezvous with the space station. If a Saturn V were used for this type of mission, there would be a much larger orbital weight capability, and a much larger space station similar to the three-spoke version in figure X-2 would probably be used.

It is now possible to draw several conclusions related to advanced power systems for the manned orbiting space station. The Brayton cycle system, either solar or isotope powered, would have low weight. The photocell systems would be next, and the SNAP-8 system would be the heaviest. Although the advanced reactor system is the lightest, the technology of such a system (papers VII and VIII) is considerably behind that of the Brayton and SNAP-8 systems. Although the SNAP-8 and Brayton cycle systems will be available for missions in the 1970's, the earliest that the advanced Rankine system will be ready is the very late 1970's or the 1980's.

If an advanced reactor system were available, it would probably be the most attractive of those compared in table X-2. Among the other systems, it appears that, since the Brayton cycle is the lightest, it would be the system of choice. However, if a 30-kilowatt manned orbiting space station is the application, these unit weights can be multiplied by 30 to obtain the total power-system weight that would be required. The SNAP-8, even at 900 pounds per kilowatt, is of the order of 30 000 pounds. On a Saturn V class of space station with a 250 000-pound total weight, this 30 000 pounds represents a little over 10 percent of the total weight. Hence, there is ample weight and surface area to accommodate any of these power systems at the 30-kilowatt level. The weight constraint in this particular mission is not as significant as that which will be shown for others. Weight is certainly not unimportant and, all other things being equal, the lightest power system would be selected. In a mission for which there is ample weight capability and many power systems to choose from, other characteristics besides weight can prevail. For example, availability is an important factor in any mission planning. If during mission planning, one power system is not fully developed or its safety has not been fully demonstrated and if sufficient weight capacity is available, the system of choice will more than likely be the one that has been proved. Another feature that can be important is the spatial orientation associated with solar power systems. The mission manager may be happy to be relieved of the requirements to orient continuously any of these solar supplies. In such a case, a nuclear power system may be chosen.

Cost might also be an important factor. Plutonium 238 for the 10-kilowatt isotope Brayton system could cost $20 to 25 million; for a 10-kilowatt isotope thermoelectric system, between $60 and 75 million worth of plutonium 238 would be required. This cost difference is certainly significant. Of course, plutonium 238 has an 86-year half-life, and since only a small amount would actually be consumed, it can be argued that the isotope can be recovered for reuse and costs can thereby be reduced; however, just how the bookkeeping would be handled is not certain. The photocell array of 30 kilowatts would cost between $10 and 15 million. SNAP-8 or thin-film photocells would be much cheaper, as would the solar Brayton system.

An additional penalty associated with the solar power systems on this mission is atmospheric drag. In a 260-nautical-mile orbit, the drag of a 30-kilowatt conventional photocell array is sufficiently high that, if bipropellant rockets are used to counterbalance the drag, about 5000 pounds of fuel would be required each year.

Ample weight capability characterizes such a mission. Any of these power systems could be chosen. The choice will depend on the details of just how the mission will be performed and to some extent the preference of the project manager involved. The selection will more than likely not be dominated by weight considerations alone.

Up to this point, the discussion has centered around a manned orbiting space station with a nominal 30-kilowatt electric power requirement, and as noted earlier, the high-powered advanced reactor systems would not be available until the 1970's at the earliest. It is anticipated, however, that eventually powers of the order of 300 kilowatts, which could be supplied by the advanced reactor system, will be required for these missions. Figure X-4 illustrates the kinds of power systems that might be considered for this application in this time period. A conventional photocell-and-battery system is compared with an advanced reactor system. Both systems produce 300 kilowatts for a large manned orbiting station, the same three-spoke station described earlier. At the 300-kilowatt level, the performance of an advanced reactor system far exceeds the capability of any of its competitors. If an advanced reactor system is available in this time period, it can provide very large powers for weights with which no other system can compete. It is interesting, however, that if the need for a 300-kilowatt conventional photocell system were great enough, it could conceivably be built. However, the weight of this system is such that it would more than likely require the separate launch of a Saturn V class vehicle.

In low-altitude orbit, NASA programs specify a much larger number of unmanned than manned missions. The unmanned missions are characterized by power requirements from much less than 1 kilowatt up to a fraction of a megawatt. The two power systems currently in use are the solar photocell and isotope thermoelectric system. These systems will be difficult to displace by any of the advanced systems discussed herein. The Brayton and Rankine systems are both mechanical. At very low powers, a fraction of a kilowatt, the parasitic losses of machinery become dominant, and they become unattractive. The only potential contender for these low-power missions of the three new power-conversion techniques discussed here is the thermionic system; as yet, not enough is known concerning temperature levels attainable with isotope fuels for any real prediction to be made. There is, however, the possibility that the isotope thermionic system might someday be attractive for this application.

At higher altitudes, the next class of missions is a 24-hour, or synchronous, orbit. The remarks made previously relevant to the solar photocells and isotope thermoelectric systems apply without change to this class of missions. For those missions that require higher power levels, solar and nuclear power systems are again compared for the 24-hour orbit (table X-3). In this orbit, there are about 80 dark periods per year. The longest of these is 72 minutes and they diminish to zero. For this reason, the energy-storage requirements for the photocell-and-battery system are much reduced. Instead of the thousands of cycles required for the low-Earth-orbital missions, only a few hundred cycles are required for a very long-life space station. It should be noted from paper II that the energy (W-hr/lb) available from batteries increases rapidly as the number of cycles is decreased. For this application, it appears reasonable to assume an energy capacity of 10 watt-hours per pound instead of the 2 watt-hours per pound utilized for the low-altitude orbit, which are probably equally optimistic numbers. It is reasonable to assume that by the time this mission is flown, some increase beyond this 10 watt-hour per pound capability can be anticipated. The net result is a significant reduction in the weight required for the shade or night power. Also, the shade-to-sun ratio becomes much more favorable since there are approximately 23 hours of light and 1 hour of darkness in the worst circumstances; hence, the additional weight of extra photocells for charging batteries is also decreased. Thus, the importance of energy storage on overall system weight is diminished. In the case of the

Brayton cycle, its biggest advantage as noted previously in low-altitude orbit was its lighter energy storage. For the 24-hour orbit, the energy-storage requirements are about the same as in the low-altitude orbit. There is slightly less weight of collector required because the light-dark ratio is more favorable, but there is somewhat more weight of heat-storage material required because the longest time period is extended from 35 to 72 minutes. When both these effects are included, the weight remains nearly the same; hence, the weight advantage has shifted decidely in favor of the photocell system.

Table X-3(b) is a summary of nuclear power systems for this 24-hour-orbit television-broadcast satellite. For this mission, the shield weights are significantly lower than those discussed earlier for the low-altitude orbits. This marked reduction in shield weight derives from the unmanned character of the mission. Men and photofilm are probably the two most radiation sensitive "devices" that exist, and the payload in this case is considerably more radiation resistant; consequently, for this and other unmanned applications, relatively lightweight shields are possible. The characteristics of the basic power-conversion system without shielding are not affected by the change to a higher orbit and hence are the same as those shown earlier (table X-2) for the manned orbiting station. It is interesting to note that, with the exception of the advanced reactor system, the photocell-and-battery system is by far the lightest.

The importance of weight will be a significant factor for this 24-hour television-satellite mission. For example, if a Saturn V were selected as the booster for this mission, the cost could well equal the total capitalization of the COMSAT Corporation. As a result, there is a strong incentive to utilize smaller and cheaper boosters. The next largest vehicle to the Saturn V would be the Saturn IB. The Saturn IB with the Centaur upper stage has a weight capability of approximately 9000 pounds in the 24-hour orbit. Comparable to this would be the Titan 3C-Centaur, which would have about the same weight capability. The Titan 3 with its trans-stage is comparable to the Atlas-Centaur kick-stage combination, each having a weight capability of approximately 2200 pounds in a 24-hour orbit. Thus, in this case of vehicles, the total payload capability will range from 2000 to 9000 pounds.

To be attractive, however, the direct-broadcast satellite requires substantial power. If each home receiver is equipped with, for instance, a 6-foot-diameter parabolic antenna, several tens of kilowatts will be required to cover one-fourth the United States with television reception of the present quality. If a value of 50 kilowatts is selected to meet this requirement, table X-3(a) shows that the photocell system would approach 10 000 pounds, which, by itself, is beyond the weight capability of the launch vehicles noted previously. Hence, it is clear that there is going to be considerable pressure in this mission to pick the lowest weight system. Therefore, again excepting the advanced reactor systems, which would be very attractive when available, the photocell system appears the most likely candidate. When this mission is examined in greater detail, the orientation problems and penalities associated with the photocell system might be significant enough to warrant selection of either the isotope Brayton or SNAP-8 system in spite of the weight disadvantage. From the two basic missions examined so far, it is apparent that both selection criteria and system characteristics are very sensitive to the mission application.

Manned missions on the lunar surface is the application of power to be considered. Manned missions to the moon with currently existing vehicles will be limited to relatively modest efforts because of the low landed-weight capabilities. The following discussion is based on a cryogenic hydrogen-oxygen landing stage not currently developed. The present Saturn V plus this hypothetical upper stage could land approximately 26 000 pounds on the lunar surface. The following discussion considers power supplies of interest for manned operations based on this 26 000-pound payload capability.

As noted earlier, a key factor in solar systems is energy storage. In the case of the moon with its 14-Earth-day night cycle, energy storage will be a major factor. Table X-4 summarizes the energy-storage requirements for these systems. It is apparent that the batteries and the heat storage are both prohibitively heavy. Heat storage still shows an advantage over batteries, as was the case in the Earth-orbital missions considered earlier. However, neither is competitive with fuel cells. These fuel cells would operate as follows: During the lunar day, power from the photocell system would be utilized to electrolize water. The hydrogen and oxygen obtained would be stored for subsequent use during the lunar night. A fuel-cell system of this type is described in paper II. Current fuel cells degrade with use; although some few fuel cells have operated several thousand hours, many others have failed at earlier times. Neither a really long-life fuel-cell system nor the required long-life electrolyzer is currently available. Hence, it is not known whether the weight of the fuel-cell system described herein can really be achieved. It has been assumed that the performance currently obtained from fuel cells and electrolyzers for short periods can be achieved for these very long times.

Another concept for heat storage is a large bed of lunar soil to cover a tube-and-fin heat exchanger (fig. X-5). Above the bed of soil are a series of plastic windows and a reflector-insulator. This reflector-insulator is pulled over the bed at nightfall to preserve as much heat in the bed as possible. In the daytime, the reflector-insulator is rolled aside, and the plastic windows act as a greenhouse to trap heat in the lunar soil bed. Heat removed from the bed by the tube-and-fin heat exchanger might provide an energy supply to a thermal power system. Preliminary analysis of this idea indicates that its value is heavily dependent on the thermal conductivity that can actually be achieved for the lunar soil bed. For this preliminary analysis, the thermal conductivity of lunar soil was assumed to be that of sand in a vacuum and indicated that not much heat could be gotten into or out of the bed. Investigations are continuing on schemes for enhancing this conductivity in some practical way.

Nuclear power supplies for this mission on the lunar surface will have essentially the same unshielded weight as shown earlier. For this manned mission, shield weight will again be a significant factor. However, lunar material may play an important role. The extent to which this lunar material can be counted on for shielding, if at all, will then determine the shield weight required to be launched with the powerplant.

Two basic approaches were used to evaluate power systems for manned lunar operations. First is the lunar shelter concept that utilizes the photocell system (fig. X-6(a)). The 26 000-pound capability of the cryogenic lander is utilized to land a single complete shelter that includes the power supply, life support, living space, and experiments that would be required for a small lunar station. In the case of the isotope Brayton system (fig. X-6(b)), approximately 1000 to 1500 pounds of the total system weight would consist of shielding. These relatively high weights would be required because of the proximity of the power supply to the men for long periods. If lunar material could be utilized for shielding, or if the power supply could be removed from the vehicle and placed at some distance from the men, the weight of this system could be reduced to approximately 2000 pounds. The isotope power supply is considerably lighter than the photocell system for this application, and weight will be quite important since 26 000 pounds is the weight limitation on a Saturn V launch vehicle. The Saturn V itself is estimated to cost approximately $100 million. On this basis, weight is quite significant, and the nuclear power systems are the more attractive.

The second approach to evaluating power systems for manned lunar operations is shown in figures X-7 and X-8. In this case, it was assumed that the entire payload of a cryogenic lander could be devoted to the power system for an advanced and relatively elaborate lunar base. With this weight capability, a 20-kilowatt photocell - fuel-cell power system could be landed. In the case of the SNAP-8 power system, the unshielded weight with one set of redundant power-conversion equipment is shown. For SNAP-8, it was assumed that advantage would be taken of local topographical features such as the crater rim shown in figure X-8 and that lunar material could provide a substantial portion of the shielding requirements. On this basis, the 35-kilowatt SNAP-8 would only use half the weight capability of the cryogenic lander if no shielding were required. Thus, once again, because of the severe energy-storage requirements for solar power systems in the lunar environment, it appears that the nuclear system is the more attractive.

One additional manned lunar mission was considered, that of the three-man roving vehicle; figure X-9 illustrates this concept. The deployed panels on the top of the vehicle are radiators for the hydrogen-oxygen fuel-cell system for motive power. The phantom outline represents the radiators for an isotope Brayton system to provide this same power requirement. Figure X-10 shows the weight requirements as a function of propulsion time. The weight of the fuel-cell power system is nonlinear because, as the weight of reactants increases with propulsion time, the horsepower required to drive the vehicle increases. The weight of the isotope system is, of course, constant with time because of the long half-life of the isotope. For relatively short propulsion times (of the order of 100 hr), the fuel-cell system offers a weight advantage. However, for longer propulsion times, the nuclear system becomes more attractive.

The interplanetary missions comprise the next group of applications considered. For the unmanned exploration of the inner solar system (anywhere from Mercury to Mars), it appears that either solar photocells or an isotope thermoelectric system can provide the power. This application will not be considered further; however, table X-5 compares power systems for a manned Mars mission. The day-power weight shown for photocells is more than twice that shown earlier for this system because the design power here is that generated at Mars, and the diminished solar flux at Mars results in increased photocell weight. No night power is required for this planetary mission because the trajectory can be selected to be in the Sun continuously. Normally, some batteries would be required to furnish peak power with the photocells providing a constant average power; however, the greatest requirement for batteries on this mission is likely to occur at planetary entry. This mission would probably use atmospheric drag in the planetary entry either at Mars or at Earth return, or perhaps at both. For this phase of the mission, the solar panels would have to be folded. It is assumed that this period of time would be approximately 1 hour. This portion of the mission has not been analyzed in sufficient detail for this time period to be accurately estimated; however, the penalty in table X-5 of 70 pounds per kilowatt for batteries is indicative of this requirement. The weight penalty would be linear with the time required for aerodynamic breaking; hence, if it were 5 hours, a 350-pound-per-kilowatt penalty would be incurred. Thus, as far as weight is concerned, it is again an important feature on this manned planetary mission, photocells and batteries will be the most attractive system provided that the energy-storage requirement is not severe. If the planetary entry period is protracted, interest might very well shift to the isotope Brayton, which would require no orientation or deployment.

Figure X-11 compares power systems for unmanned outer-planetary missions. At Jupiter, for example, the solar flux is only 4 percent of that occurring at Earth. While use of solar photocells is theoretically possible, it appears that the solar photocell system will be unattractive for this mission. The radioisotope thermoelectric generator would, however, be a logical choice. As the distance from Earth increases, however, the communication bit rate diminishes rapidly. For example, with the 210-foot dish (the largest ground antenna under construction today) and an 8-foot vehicle antenna, a power supply of approximately 500 watts could furnish about 4 bits per second from the orbit of Jupiter. From Neptune, this bit rate would diminish to perhaps 1/2 bit per second. Typical Surveyor pictures of the moon contain about 10^6 bits of information. Thus, if pictures are desired, it is theoretically possible to obtain them, but the continuous times required (days or weeks) do not appear practical. In order for the bit rate to be increased, and hence, for the information to be obtained more quickly, a method for augmenting power at planetary encounter was considered and is shown in figure X-11. The 500-watt radioisotope thermoelectric generator would provide power on the way out when not much power is required; a 10-kilowatt hydrogen-oxygen fuel-cell system is also provided in order to increase the information rate when required, as at planet encounter, for example. This hybrid system is then compared with a 10-kilowatt isotope Brayton system that would have the 10-kilowatt power available over the entire mission. If all the information desired can be returned in a few days or less, a chemical supplement, such as the hydrogen-oxygen fuel cell, to a 500-watt thermoelectric generator would seem an acceptable power system. However, if longer periods are desired, once again, the isotope Brayton appears to be the system of choice.

There is one other mission that has not been considered in this discussion and that is electric propulsion. For the electric propulsion missions of interest, both very high power and very light weight will be required. The chances are good that the advanced reactor system is the only power supply really suitable for electric propulsion. Because of their light weight, if energy storage is not a requirement, photocells have been considered, and it is conceivable that solar cells might be of some interest for electric propulsion.

This concludes the mission survey. Throughout this discussion, it is apparent that the interesting powerplants depend heavily on the mission itself. Energy-storage requirements, the amount of sunlight available, shielding requirements, and the extent to which lunar material can be utilized all have their effect on the attractiveness of these powerplants. The general conclusion that can be drawn from this discussion is that there is clearly a place for both solar and nuclear power systems for the missions discussed here and probably a place also for the advanced systems described in this conference.

TABLE X-1. - SOLAR POWER SYSTEMS

FOR MANNED ORBITING STATION

System	Weight, lb/kW			Total collector area, ft^2/kW
	Day power	Night power	Total	
Conventional photocells and batteries	50	400	450	230
Thin-film photocells and batteries	30 to 70	380 to 420	410 to 490	400 to 600
Brayton cycle	240	60	300	70

TABLE X-2. - NUCLEAR POWER SYSTEMS

FOR MANNED ORBITING STATION

System	Power, kW	Weight, lb/kW			Radiator area, ft^2/kW
		Unshielded	Shield	Total	
Isotope Brayton	10	350	0 to 50	350 to 400	80
SNAP-8	35	350	250 to 550	600 to 900	35
SNAP-8 thermoelectric	20	550	450 to 950	1000 to 1500	100
Advanced reactor	300	30	30 to 70	60 to 100	4

TABLE X-3. - TELEVISION-BROADCAST SATELLITE

IN 24-HOUR ORBIT

(a) Solar power systems

System	Weight, lb/kW			Total collector area, ft^2/kW
	Day power	Night power	Total	
Photocells and batteries	50	140	190	120
Brayton cycle	240	60	300	50

(b) Nuclear power systems

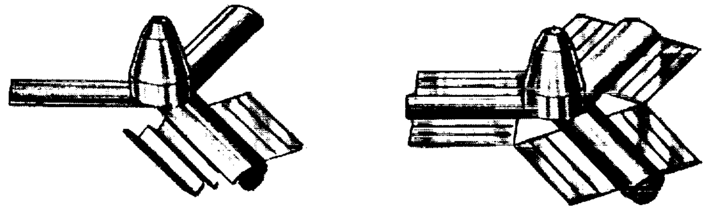
System	Power, kW	Weight, lb/kW			Radiator area, ft^2/kW
		Unshielded	Shield	Total	
Isotope Brayton	10	350	0	350	80
SNAP-8	35	350	50	400	35
Advanced reactor	300	30	5	35	4

TABLE X-4. - ENERGY STORAGE FOR SOLAR POWER SYSTEMS ON MOON

System	Weight, lb/kW
Batteries	34 000
Fuel cells	1 000
Heat storage (Brayton)	15 000

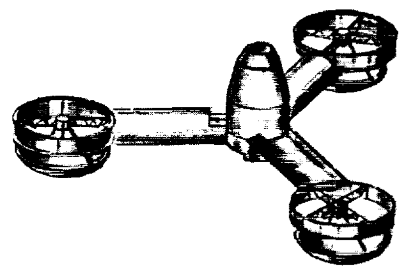
TABLE X-5. - POWER FOR MANNED MARS MISSION

Day power, lb/kW	Planet entry power, lb/kW	Total, lb/kW
Photocells and batteries		
120	70	190
Isotope Brayton		
Unshielded, lb/kW	Shield, lb/kW	Total, lb/kW
350	0 to 150	350 to 500



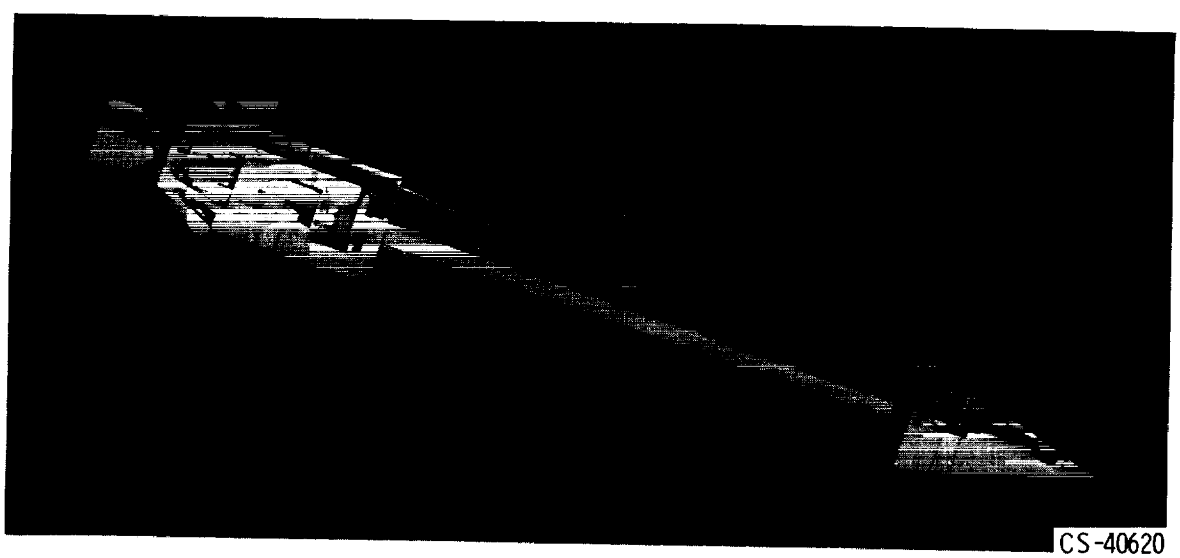
CS-40370

Figure X-1. - 30-Kilowatt conventional photocell system for manned orbiting station.



CS-40372

Figure X-2. - 30-Kilowatt solar Brayton system for manned orbiting station.



CS-40620

Figure X-3. - SNAP-8 power system for manned orbiting station.

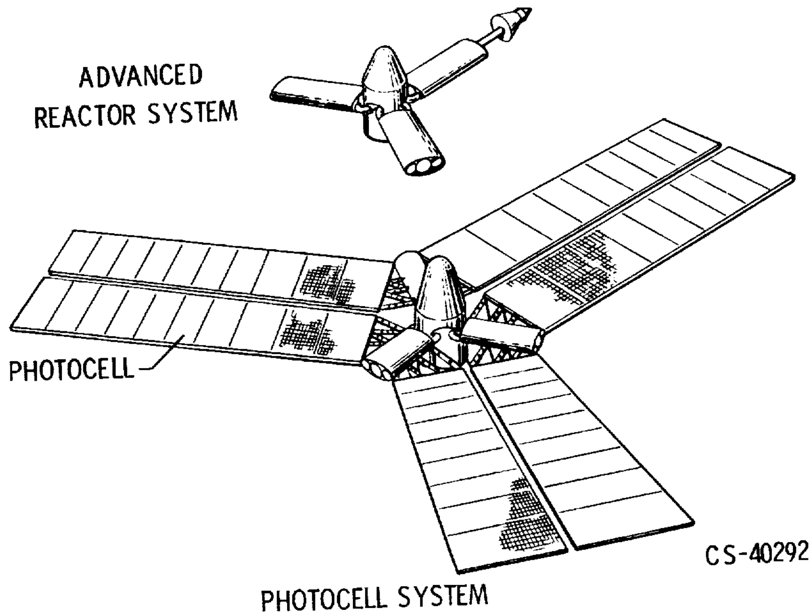


Figure X-4. - 300-Kilowatt power systems for manned orbiting station. Photocell-and-battery system: weight, 138 000 pounds; area 69 000 square feet. Advanced reactor system: weight, 24 000 pounds; area, 1200 square feet.

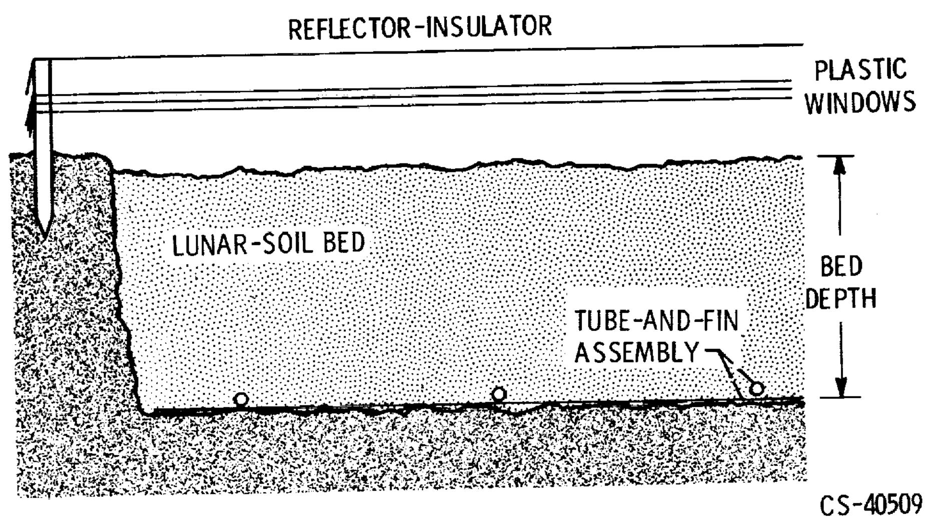
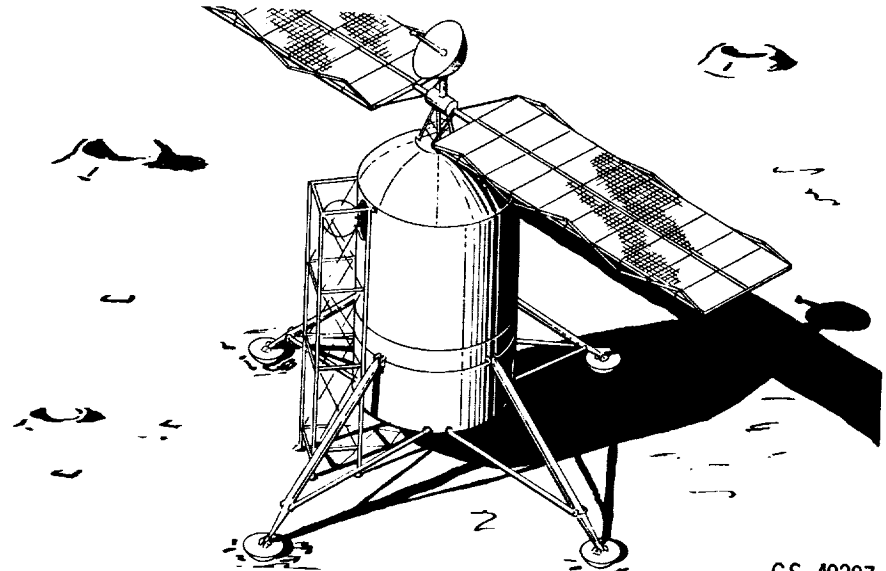
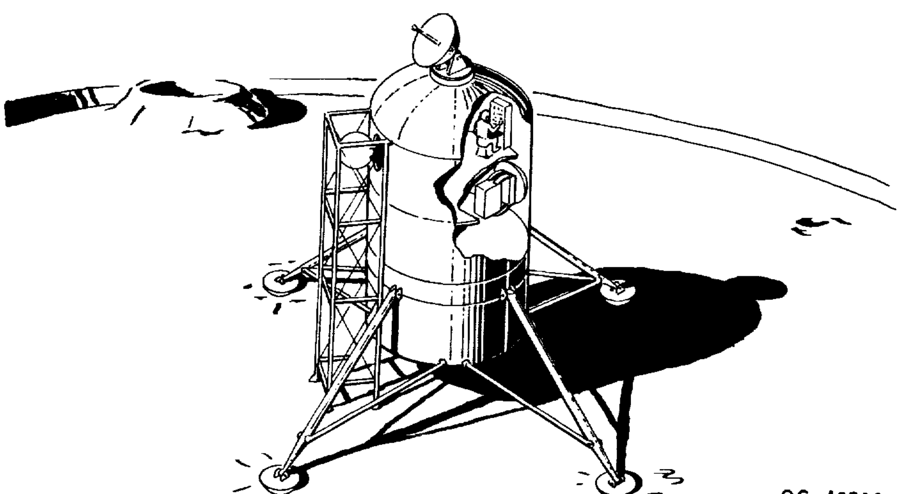


Figure X-5. - Conceptual lunar-soil heat-storage device.

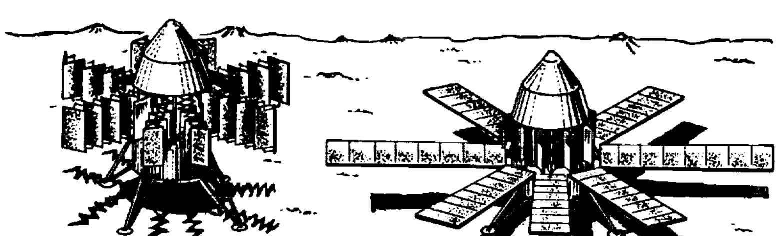


(a) 5-Kilowatt 6000-pound photocell system. CS-40297



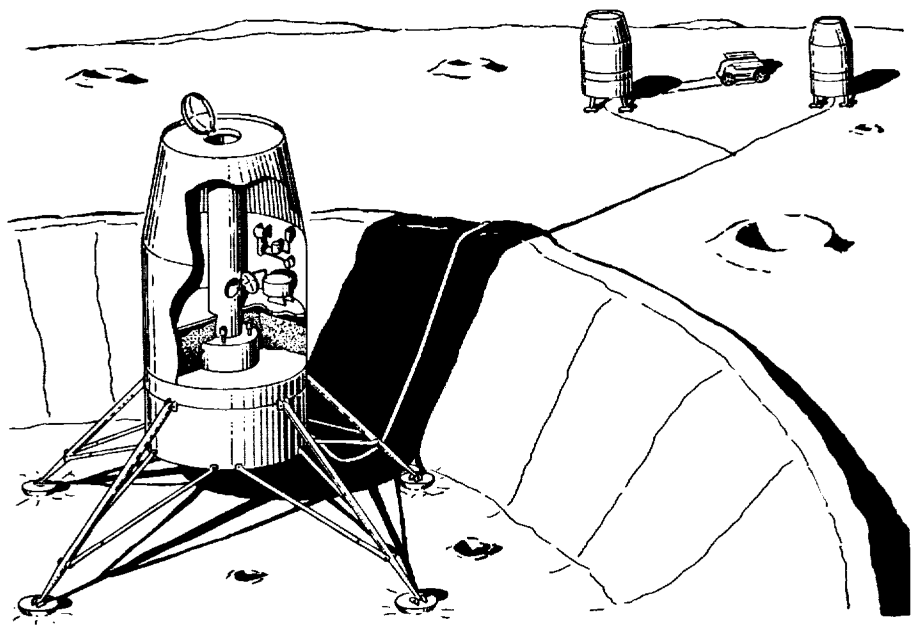
(b) 5-Kilowatt 3000-pound isotope Brayton system. CS-40293

Figure X-6. - Lunar shelter.



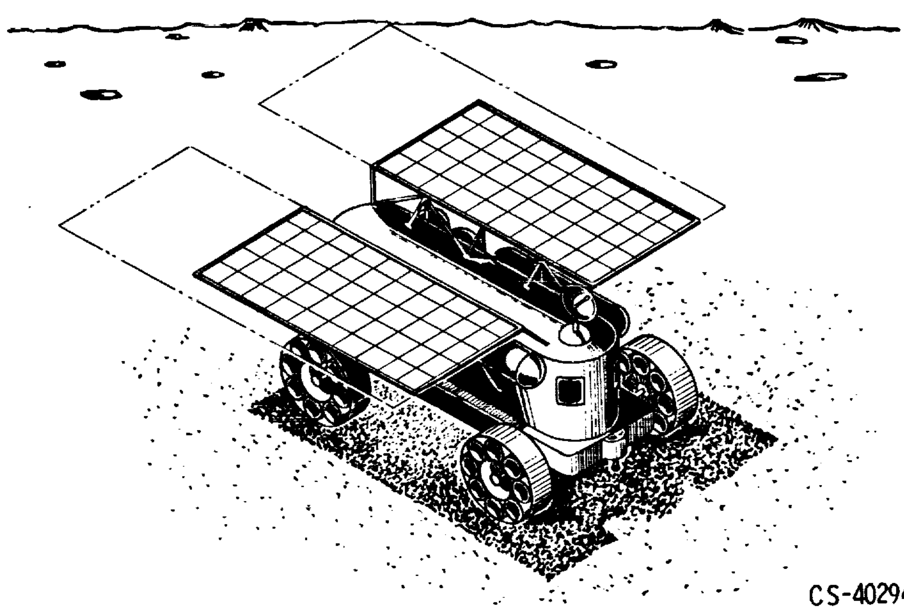
CS-40298

Figure X-7. - Lunar base 20-kilowatt, 26 000 pound photocell - fuel-cell power system.



CS-40536

Figure X-8. - Lunar base 35-kilowatt, 12 000-pound (plus shielding) SNAP-8 power system.



CS-40294

Figure X-9. - Three-man lunar roving vehicle.

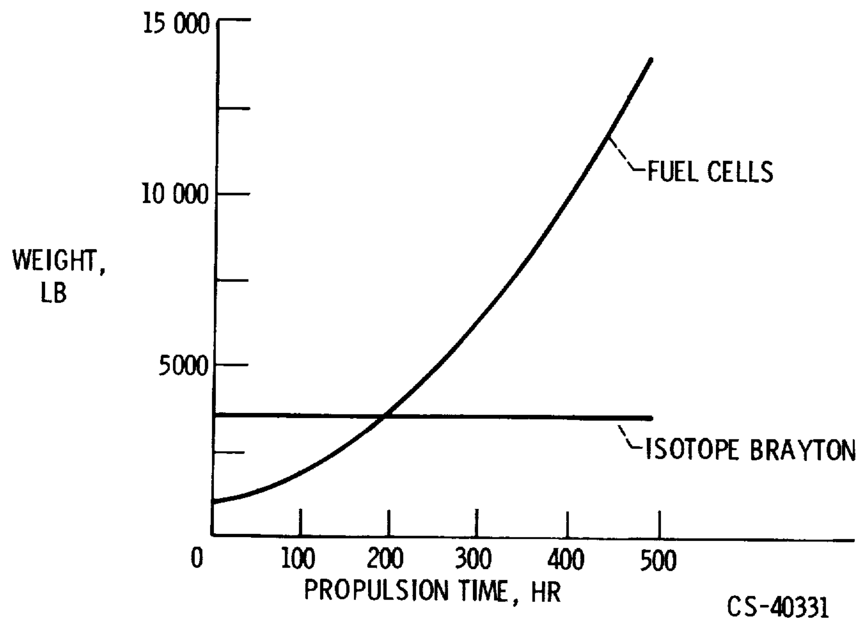


Figure X-10. - Three-man lunar roving vehicle power supply weights. Speed on level terrain, approximately 5 miles per hour.

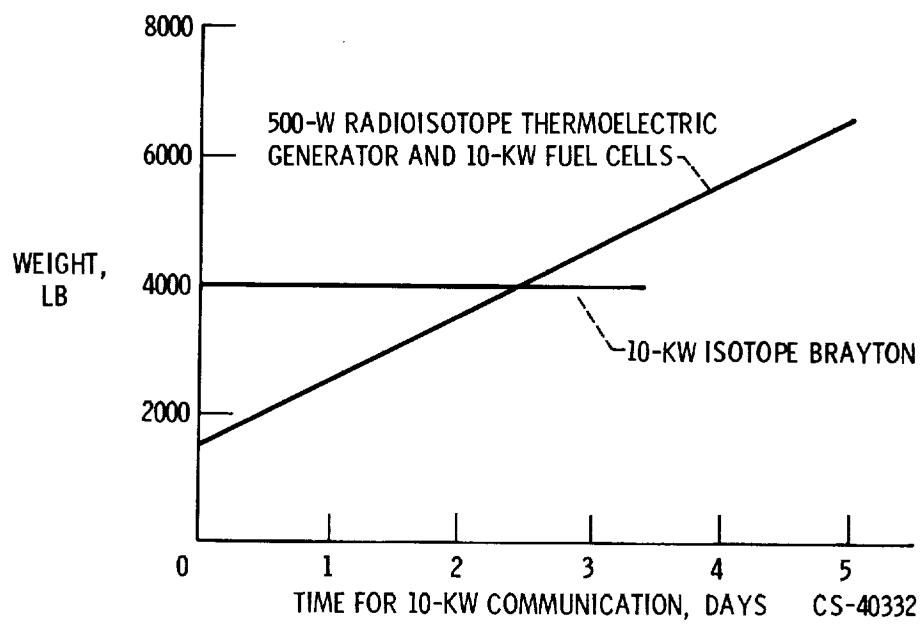


Figure X-11. - Power for unmanned outer-planetary missions.