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Space Colonies and Energy Supply to the Earth

Manufacturing facilities in high orbit could be used to build satellite solar power stations from lunar materials.

Gerard K. O'Neill

Within this century it may be feasible to establish manufacturing facilities in space, possibly in the vicinity of one of the Lagrange libration points of the earth-moon system (*1*, *2*). Near two of these points, called L4 and L5, there are orbits which are stable under the combined gravitational effects of the earth, the moon, and the sun. A space manufacturing facility (SMF; the terms space community and space colony have also been used to describe such a facility) would be a self-sustaining habitat for a large number of people (of the order of 10^4 to 10^5). Its energy needs would be met by solar power, used directly as sunlight for agriculture, as process heat for industry when concentrated by mirrors, or indirectly as electricity.

The SMF may be economically more effective than alternative industries on the earth for the construction of products whose end use would be in geosynchronous or higher orbits. Such products, if made on the earth, would have to be lifted by rockets out of the earth's gravitational potential well, which is about 6500 km deep. In contrast, the SMF would obtain the raw materials for its products from the surface of the moon, whose gravitational well is only 1/20 as deep. As a consequence of the moon's vacuum environment, and of that factor of 20 in energy, a launching device located on the moon could transport material to the SMF at low cost relative to shipment from the earth. In this article I suggest that solar power stations may be constructed at a space colony, and relocated in geosynchronous orbit to supply energy to the earth, at a lower cost than if such stations were to be built on and lifted from the earth.

Energy Needs

The increasing demand for electricity, the shortage of fuels on the earth, and concern about widespread use of nuclear energy have led to consideration of satellite solar power stations (SSPS's). Glaser (*3*) has studied the SSPS concept, which is the location in geosynchronous orbit of stations converting solar into electrical energy, to be sent down as microwave power for conversion to direct current or to a power line frequency at the earth's surface.

In 1975 the Energy Forecast Working Group of the Institute of Electrical and Electronics Engineers (IEEE) summarized forecasts, by 12 organizations, of the electric generating capacity which will be required by the United States during the years 1975 to 2000 (*4*). The IEEE summary estimated an increase from about 500 Gw in 1975 (*5*) to a required capacity of 781 to 1070 Gw in 1985, and to a capacity of 1880 to 2250 Gw in 2000. The IEEE estimates therefore correspond to an average construction rate of new generator capacity of about 65,000 Mw/year in 1990 and 115,000 Mw/year in 2000. A study by Associated Universities, Inc. (AUI), predicted a demand for 85,000 Mw/year of new capacity at the turn of the century (*6*). The discussion that follows is not sensitive to such differences in the estimates.

At current prices [typically \$450 per kilowatt installed for a coal-fired plant (*7*)] the forecasts therefore correspond to a market of \$30 billion per year in the United States alone in the year 1990, and \$40 billion to \$50 billion per year a decade later. [The dollar figure may be conservative; the AUI study (*6*) was based on the assumption that most of the increased capacity during 1985 to 2020 would be powered by nuclear reactors, with higher installed costs (*7*) of \$600 to \$1800 per kilowatt in 1972 dollars.] Economic self-interest would tend to enlarge the market to the wider range beyond national borders; assistance to developing nations in the form of electrical energy would also increase the total production requirement for new power plants.

Environmental Effects

Each method so far considered for power generation has characteristics which are potentially damaging. Nuclear power produces radioactive wastes and materials convertible for use in nuclear weapons. Coal-fired plants require extensive strip-mining to keep them supplied. In the year 2000, electric generation for the United States alone will require the mining of more than 2×10^9 tons of coal per year, unless alternative sources provide most of the energy needed at that time.

Transmission to the earth of the energy generated by an SSPS would require a microwave beam to a central antenna. That may be less desirable environmentally than the high-voltage lines used conventionally at the surface of the earth for the interconnection of large generator plants. Microwave transmission may, though, be more acceptable than the alternatives of nuclear power or strip-mining, and that is an important issue which should be studied carefully. Glaser (*3*, *8*) has stated that the microwave beam intensity outside the antenna site would be low enough to satisfy stringent environmental requirements. Because the conversion of microwave energy

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to direct current could be about 90 percent efficient, an SSPS antenna array would release into the biosphere only one-tenth as much energy as it would deliver for use. In contrast, a fossil-fuel or nuclear plant discards as waste heat about 1.5 times the energy which it delivers to the power lines. The land-use requirements for an SSPS ground antenna array would be only about 1/10 to 1/100 as great as for direct photovoltaic energy conversion of sunlight, because direct conversion is limited by low efficiency, the day-night cycle, seasonal variation of the day length, atmospheric absorption, and cloud cover.

Economic Factors

Delay in the realization of the SSPS concept appears to be due mainly to lift costs and power plant mass. The installed cost of an SSPS would depend primarily on four factors: the capital cost per kilowatt of the power plant for converting solar energy to electricity (\$/kw); the specific mass of the power plant in kilograms per kilowatt of output (kg/kw); the cost per kilogram of lifting the power plant from the earth to geosynchronous orbit (\$/kgsy); and the overall efficiency of converting electricity into microwave energy, transmitting it to the earth, and reconverting it into direct current or to a power line frequency (ϵ). The installed capital cost of the installation, per kilowatt of power output from the antenna busbar on the earth, would be approximately

$$\frac{1}{\epsilon}\ [\$/\text{kw} + (\text{kg/kw})\,(\$/\text{kgsy})]$$

plus interest charges, development costs, and smaller additive terms for the ground antenna and the land it would occupy.

Earth-Launched Power Satellites

Solution of the microwave transmission problem (*9, 10*) for the SSPS appears to be progressing well: tests have already demonstrated a transmission efficiency ϵ (direct current to direct current by a microwave link) of 55 percent. The goal is an efficiency of about 63 percent. For an earth-launched SSPS, the economic problem lies in the remaining factors: capital cost, power plant mass per unit power, and lift cost.

Two alternatives for the conversion of solar energy to electric energy in an SSPS have been considered: photovoltaic cells (solar panel arrays) and turbogenerators powered by mirror-concentrated sunlight.

Glaser (*3*) has estimated that for an earth-launched SSPS the specific mass for solar panel arrays will have to be reduced to about 0.88 kg/kw. For comparison, the value for photovoltaic solar cell arrays in operational satellites of the last decade has ranged from 78 to 107 kg/kw; one experimental satellite designed as a short-life test vehicle achieved 29 kg/kw (*11*). For the Solar Electric Propulsion System space probe scheduled to fly in 1984, the specific mass is intended to be 13 kg/kw (*12*).

Present costs of solar panel arrays for space applications are based on manual assembly techniques and are therefore much too high for application to an SSPS; they are typically \$175,000 per kilowatt (*3*). A more reasonable starting point is the 1971 figure of \$5,000 per kilowatt for single-crystal wafers 5 cm in diameter. The necessary target figure (*3*) for a competitive SSPS launched from the earth is about \$220 per kilowatt, about half the present cost of a large, coal-fired central power station.

As an alternative to a photovoltaic array for SSPS power, Woodcock and Gregory (*13*) have considered the use of closed-cycle helium turbines (*14*) driving conventional electric generators. In that alternative the specific mass must be reduced from presently attainable values (10 kg/kw) to about 5 kg/kw. To achieve that reduction, Woodcock and Gregory have assumed a development program in which the turbine inlet temperature could be increased to a value considerably higher than that used in current practice.

For an earth-launched SSPS the cost of lifting components to geosynchronous orbit from the earth would be critically important. For a photovoltaic SSPS of 0.88 kg/kw, the necessary lift cost figure would be \$220/kgsy (*3*). For a turbogenerator SSPS of 5 kg/kw and efficiency ϵ of 70 percent, the performance demands on the lift vehicle would be even more severe: \$75/kgsy (*13*).

Launch Vehicles

An advanced, chemically propelled "space tug" could bring from low earth orbit to geosynchronous orbit, as payload, about one-third of the total payload delivered to low earth orbit from the earth's surface. When the cost of space-tug operations is included, the cost of transport (\$/kgsy) from the earth to geosynchronous orbit can then be taken as roughly four times the cost of transport to low earth orbit. For simplicity, lift cost figures in the following discussion will refer to the overall transport from the surface of the earth to geosynchronous orbit (\$/kgsy) and will be taken as four times the cost to low orbit. An additional uncertainty of about $\pm$ 30 percent is a consequence of this simplification.

The target figure for the space shuttle, planned for operation in the early 1980's, is \$1400/kgsy, not including development costs of several billion dollars (*15*). A heavy-lift launch vehicle (70-ton payload) using the same kind of engines that are already being developed for the shuttle, and therefore obtainable without large additional expense for development, is estimated to be capable of achieving \$600/kgsy to \$1000/kgsy (*16*).

To summarize, for an economically viable earth-launched photovoltaic SSPS the specific mass (kg/kw) must be reduced by about a factor of 30 to 60 below the corresponding figure for satellites of the 1970's; the lift cost to geosynchronous orbit must be reduced by about a factor of 4 below figures estimated to be attainable in the 1980's without large additional development costs; the capital cost (\$/kw) must be reduced by a factor of about 30.

For an earth-launched turbogenerator SSPS the capital cost must be held equal to that of a present-day coal-fired plant; the specific mass must be reduced to about half the value currently attainable; ϵ must be raised to 0.70; and the lift cost must be reduced by about a factor of 10 below the figure now considered to be attainable in the 1980's without substantial postshuttle development.

Table 1 summarizes the values of these factors which have been assumed in several studies and, where the information is available, the resulting estimate of power cost. Extrapolations to vehicles more advanced than shuttle-derived rockets are necessarily subject to large uncertainties; new developments in engines, heat shields, reusable fuel tanks, and other components would all be needed before their construction. For a very large vehicle, capable of lifting 180 tons to low orbit, estimates of attainable recurring cost range from \$80/kgsy to \$900/kgsy, and estimates of development cost range from \$5 billion to more than \$25 billion (*17*).

Power Plant Economics

In power generation, the busbar cost is crucial to the achievement of market penetration. Power plants are characterized as base load (operating nearly all the time), intermediate load (operating part of each day), and peak load (operating only during coincidences of maximum industrial and residential demands). Peak-load plants are normally simple and inexpensive to build and, when called into use, generate electricity at a cost up to 60 mills (that is, \$0.06 per kilowatt-hour). Intermediate-load plants are capitalized more heavily and generate electricity at 20 to 25 mills.

Table 1. Critical factors in satellite power station economics. The numbers assumed in several studies for the factors specific power plant mass, component lift cost from the earth, transmission loss factor (ϵ^{-1}), and interest rate are summarized; in each case a higher number corresponds to a more conservative assumption. Earth-launched SSPS values are from (*13*) for those with turbogenerators and from (*3*) for those with photovoltaic cells. Data in the last column are from this article. The lift cost from the earth to geosynchronous orbit is approximately equal to the cost for lift to Lagrange point L5. For base-load service, busbar power costs are now typically 15 to 17 mill/kwh.

SSPS	Specific mass (kg/kw)	Lift cost ($/kgsy)	ϵ^{-1}	Interest rate (%)	Initial busbar power cost (mill/kwh)
Earth-launched					
Turbogenerator	5	75	1.43	8	25
Photovoltaic	0.8	220	1.54		
Built in space from lunar material	10	950	1.6	10	15

Eventually photovoltaic solar cells located in the American Southwest may be competitive with one type of intermediate-load service: the supply of energy for air conditioning. Base-load plants (mainly coal-fired and nuclear) supply power at 15 to 17 mills. Nuclear plants in particular are best suited to base-load service; they must run nearly all the time to amortize the heavy capital investment required for their construction. Once started, a nuclear plant is kept running for another reason also: each time it is turned off there is a risk of component failure due to temperature changes.

If electricity could be obtained from an inexhaustible source at 4 to 8 mills, lower even than base-load rates, it could have a profound impact on economic security and independence: residential and industrial heating could then be shifted to electricity, relieving demands on natural gas and oil supplies, and the production of synthetic fuel alternatives to gasoline could become practical.

Like a nuclear plant, an SSPS would have to operate nearly all the time to amortize its construction cost. Economic viability of an SSPS would require, therefore, that it operate in base-load service, at rates not over 15 to 17 mills. If SSPS power is to have major impact on the problems of energy resources and dependence, a way must be found to build and locate large numbers of SSPS plants (up to 20 to 40 per year of 5-Gw size) and the electricity rates at which they operate must be low enough so that they will achieve market penetration, being chosen for new construction in preference to alternative (coal or nuclear) plants. If those two conditions are not met, SSPS power can be no more than an exotic rarity, classed with hydroelectric and geothermal power among fringe sources (1 to 5 percent) of energy.

My purpose in stating these necessary economic conditions is not to discourage the development of a prototype SSPS. Clearly, though, it will be difficult to meet these conditions with SSPS plants built on, and launched from, the earth. In support of the viewpoint that SSPS development is justified nevertheless, I will outline what may be a way to meet the conditions of SSPS mass production and low electrical rates.

The Space Manufacturing Alternative

The effectiveness of an SMF program for the achievement of economical solar power on the earth would depend on two key elements: the use of lunar materials and the "bootstrap process"—the construction by the first SMF not only of SSPS units but of additional SMF's. The use of lunar materials would circumvent the problem of lift cost ($/kgsy) and therefore of power plant mass (kg/kw). The bootstrap process would replace linear growth in the number of SSPS units by exponential growth.

The establishment of the first SMF would require the transport of 3,000 to 10,000 tons to the lunar surface, and 10,000 to 40,000 tons to L5 (*2*). The structural mass of the SMF has been estimated as 150,000 tons (*18*), and the total mass including cosmic-ray shielding could be 25 to 65 times larger. The SMF would be built almost entirely of lunar surface materials. The lunar soil (regolith) as found, unselected, contains 20 to 30 percent metals, 20 percent silicon, and 40 percent oxygen by weight (*19*). Depending on whether the first SMF were provided at the outset with a massive cosmic-ray shield, or acquired such a shield over a period of years by the accretion of industrial wastes (slag) from the manufacturing operations at L5, the transport machine (mass-driver) for lunar surface materials would be required to lift 80,000 to 700,000 tons per year from the moon to L5. With full-time operation at a cycling rate of 30 kg/sec, the mass-driver previously described (*2*) would transport 940,000 tons per year.

After completion of the SMF, the lunar mass-driver would continue to export raw materials to the SMF site. There, the processing plant already used for SMF construction would continue to produce metals, glass, ceramics, and other materials. In zero or low-gravity construction bays adjacent to the SMF habitat, those materials would be formed into SSPS components.

An SSPS built at a space colony would be considerably simpler than one launched from the earth, because the colony-built SSPS could be designed without launch vehicle constraints. Turbogenerators could be fewer and of the most efficient size rather than kept within vehicle limits. Solar reflectors and waste-heat radiators could be built in large sizes and would never have to withstand launch accelerations. That is a significant advantage because an SSPS would be mechanically fragile: the specific mass figures of Table 1 imply an overall average thickness for the SSPS, including solar energy converters, radiators, conductors, mirrors, supports, and transmitting equipment, of only 0.08 to 0.6 mm of aluminum.

The linear dimension of the SSPS would be several kilometers, about ten times larger than those of the SMF. On completion, the SSPS would be tested in space close to the construction site. It would then be moved to geosynchronous orbit through the small velocity interval (2.1 km/sec) which separates that orbit from L5. A second mass-driver, similar to the one which by then would have been in operation on the moon for several years, could be used for this task. It would be assembled outside the SMF and attached to the completed power station, to serve as a reaction engine. It would use as reaction mass industrial wastes, possibly liquid oxygen, left over from the processing of materials for the SSPS. As a reaction engine, the mass-driver would have an exhaust velocity of 2.4 to 3.7 km/sec and a thrust controllable from zero up to a maximum of several tons. It would be powered by the SSPS during the orbital transfer time of 1 to 4 months.

The economics of SSPS construction at L5 requires a fresh viewpoint: in that construction almost no materials or energy from the earth would be required. The colony itself, once established, would be self-sustaining, and its residents would be paid mainly in goods and services produced by the colony.

The economic input to the combined colony–SSPS program (Fig. 1) is the sum of development and construction costs for the first colony, the cost of lifting the materials needed from the earth for subsequent colonies and for noncolony-built SSPS components, a payment on the earth of $10,000 annually to every colonist, repre-

Table 2. Cost estimates for establishing a first manufacturing facility in space. Cost figures not in parentheses are based on transport rates of \$1900/kg from the earth to the lunar surface and \$950/kg to Lagrange point L5. Those in parentheses are based on the assumption (*13*) of transport rates reduced by a factor of 12, with an additional \$10 billion added for vehicle development and no change in administrative costs. In this simplified table, personnel rotation, if required, and material resupply are within the tonnage figures.

Type of estimate	Lift to lunar surface		Lift to L5		Development and construction (\$ billion)	Administrative and salaries (20%) (\$ billion)	Total cost, rounded (\$ billion)
	Tons	\$ billion	Tons	\$ billion			
Minimal	3,000	5.7	10,000	9.5	11.0	5.2	31.4 (27.4)
Intermediate	10,500	20.0	42,000	40.0	20.0	16.0	96.0 (50.8)
High	20,000	38.0	80,000	76.0	40.0	30.8	185 (89.8)

senting that portion of salaries convertible to goods and services on the earth (for subsequent use on visits or, if desired, on retirement), and a carrying charge of 10 percent interest on the outstanding balance in every year of the program (*20*). That is approximately equivalent to discounted economics with a 10 percent discount rate.

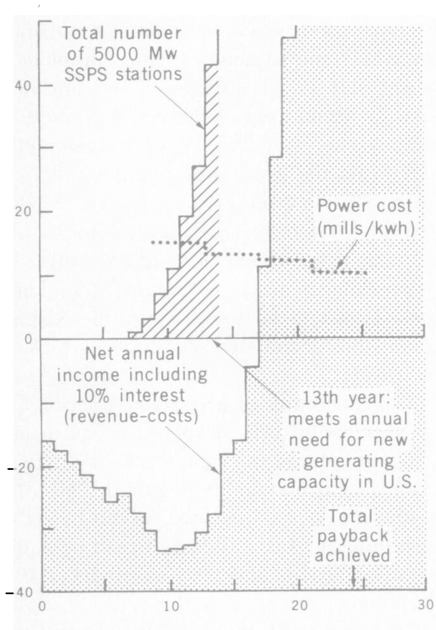
Cost estimates for the first SMF (Table 2) are based on making an early start, with the shuttle and a shuttle-derived freight vehicle. The lift costs assumed for Table 2 are therefore relatively high, equivalent to \$950/kgsy. The time line of Fig. 1 uses the intermediate cost estimate of Table 2.

Because of the high interest rate assumed, the cost-benefit analysis is sensitive to the speed of construction of the SMF, and therefore to productivity. The first colony, with a structural mass of about 150,000 tons, is assumed to be constructed in 6 years by a work force of 2,000 people. The corresponding productivity, 13 tons per person per year, is consistent with analyses by D. Morgan of current experience on the earth in materials processing and fabrication (*18*). I assume that subsequent colonies could be constructed in 2 years. This tripling of production rate would require devoting 4,000 people of a 10,000-person colony to new-community construction (compared to 2,000 people available at the construction site during the building of the first SMF) and an increase of efficiency by a modest factor of 1.5. I assume that most of the residents of the early space communities will be employed in production, support services being assisted as far as possible by automation. Later decreases in the employed fraction of the work force are assumed to be compensated by productivity increases.

The productivity required at L5 for the SSPS would depend on the ratio of kilograms to kilowatts of output at the time of construction. In my assumption, an SSPS supplying 5,000 Mw of electricity at the busbar would have a mass of 80,000 tons; in the study by Woodcock and Gregory (*13*), 35,000 tons; in the study by Glaser (*3*), only 11,000 tons. Assuming that the remainder of an SMF work force, 6,000 persons, were committed to SSPS construction, and that two SSPS units were produced per SMF per year, the corresponding requirements for productivity would be 27, 12, and 4 tons per person per year. Most of the production operations of SSPS construction would take place within the weather-free, zero-gravity, enclosed environment of a space community's assembly volume, which should favor high productivity. For 12 to 27 tons per person annually, and a peak production rate of 160 Gw/year of new generator capacity, a total work force of 100,000 to 200,000 people in space would be required. In Fig. 1, new colony construction is therefore taken to be halted after the 16th colony, because of market saturation. For the time line of Fig. 1 the benefit/cost ratio would be more than 3. Other time lines, with a variety of input capitalizations, productivities, and interest rates, have also been traced; only extreme cases yield benefit/cost ratios less than unity. The relative insensitivity of the peak funding requirement to the lift costs assumed can be seen by comparing Figs. 1 and 2. With the assumptions of Table 2, a reduction of lift costs by a factor of 12 would reduce peak funding by one-half.

Because of the exponential growth of the number of SMF's, satellite power could have a strong impact relatively soon. By year 11 from the start of SMF construction, the usable electric energy supplied to the earth by the program could exceed the peak capacity of the Alaska pipeline (2×10^6 barrels a day) (*21*). Two years later the production rate of SSPS plants could exceed the U.S. annual need for new generating capacity. By year 17, the total energy so far provided from the satellites could exceed the estimated capacity of the Alaskan North Slope (10^{10} barrels) (*21*).

This discussion has been confined to technical questions. Clearly, though, if an SMF program is initiated, it will have wider impact than the science-oriented space programs that have preceded it. As an enterprise with the potential to return a



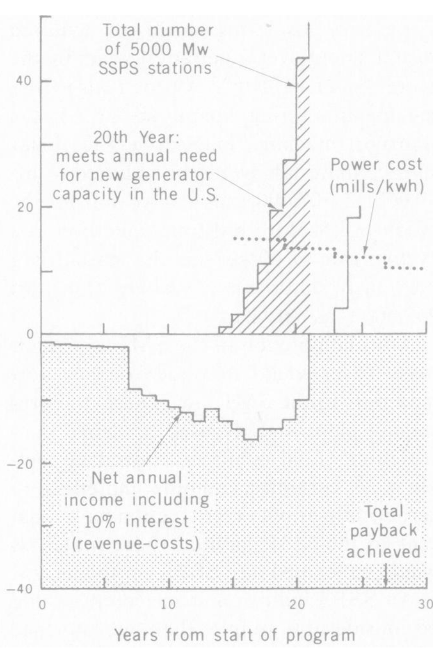


Fig. 1 (left). Estimated costs and benefits of a program for construction of space manufacturing facilities. With assumptions described in the text, the total input capitalization is \$178 billion over 14 years, in addition to the costs incurred on the earth for each power satellite produced. Interest of 10 percent is paid on the outstanding balance in each year. Power costs, initially 15 mill/kwh, are reduced in steps to achieve market penetration. Fig. 2 (right). Effect of a 7-year delay in the program to wait for advanced lift vehicles. Although lift costs are assumed to be cut by a factor of 12, the peak funding is reduced by only a factor of 2. Benefits, including energy independence, are delayed by 7 years.

profit and to tap an inexhaustible source of energy, it could be carried out as a joint venture of several or many nations. The worldwide food shortages that have been forecast for the next decades could be alleviated substantially by the provision to developing nations of low-cost energy for the manufacture of agricultural chemicals (*22*). In the SMF approach, subsidies of that kind to the Third World could be given out of new, nonterrestrial wealth, not requiring sacrifice by donor nations.

The data in this article should be considered not as definitive, but as requiring substantiation or correction by additional research. So far, during a year of exposure of the SMF concept to technical review, no major changes in the basic concept have been necessary, but it is almost certain that further work will uncover both unsuspected problems and new technical possibilities. A modest amount of research on the key questions of productivity, life support needs, SMF and SSPS construction methods, and lunar materials transport could substantially improve our knowledge of the cost and time required for the achievement of the first beachhead in space, and of the speed with which the initial investment could be returned.

Summary

The feasibility of establishing manufacturing facilities in a high orbit is under discussion. They could be used for the construction of satellite solar power stations from lunar materials. Estimates indicate that this may be considerably more economical than constructing power stations on the earth and lifting them into orbit.

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Diversity and Adaptation in Rodent Copulatory Behavior

Species differences provide ideal material for a broadened comparative psychology.

Donald A. Dewsbury

A 9-year research program in my laboratory has revealed a remarkable diversity in the copulatory patterns of different species of rodents. My colleagues and I have studied more than 30 species in an attempt to determine the range of variability and the adaptive significance of such patterns. This research is part of a new look in comparative psychology which, like many new looks, really represents a return to an older approach—the broad-based study of naturally occurring behavioral patterns with a concern for the adaptedness of behavior (*1*).

Psychologists have placed primary emphasis on finding answers to questions that relate to the immediate causation and development of behavior. However, as Tinbergen (*2*) pointed out, answers to four classes of questions—immediate causation, development, evolutionary history, and adaptive significance—are essential to a comprehensive understanding of animal behavior. With the new look in comparative psychology, increased attention is being devoted to questions of evolutionary history and adaptive significance and to the relation between animal behavior as observed in the laboratory and adaptations that are relevant to the natural environment. This emphasis can be seen in the work of Bolles, Lott, Owings and Lockard, Seligman, Shettleworth, and Warren (*3*). Ties with other areas of whole-animal biology (*4*) are being rebuilt. My project is one attempt to tackle problems of evolution and adaptive significance head-on through a comparative approach to the study of naturally occurring behavioral patterns.

Selection of Species and Behavior

Comparative behavioral studies are most useful when conducted on a group of closely related, but diverse, species (*5*). It is here that species differences can be most precisely attributed to particular factors. The rodent superfamily Muroidea represents an ideal group for such study (*6*). Rodents in this group are small, easy to obtain, and readily adaptable to the laboratory. Equally important, they are diverse. More than 200 genera are distributed throughout the world and are adapted to virtually every possible habitat. Many genera are large and diverse, too—the genus

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