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Speculations on Future Opportunities to Evolve Brayton Powerplants Aboard the Space Station

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SPECULATIONS ON FUTURE OPPORTUNITIES TO EVOLVE BRAYTON POWERPLANTS ABOARD THE SPACE STATION

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ABSTRACT

The Space Station provides a unique, low-risk environment in which to evolve new capabilities. In this way, the Station will grow in capacity, in its range of capabilities, and in its economy of operation as a laboratory, as a center for materials processing, and as a center for space operations. Although both Rankine and Brayton cycles, two concepts for solar-dynamic power generation, now compete to power the Station, this paper confines its attention to the Brayton cycle using a mixture of He and Xe as its working fluid. Such a Brayton powerplant to supply the Station's increasing demands for both electric power and heat has the potential to gradually evolve higher and higher performance by exploiting already-evolved materials (ASTAR-811C and molten-Li heat storage), its peak cycle temperature rising ultimately to 1500 K.

Adapting the Station to exploit long tethers (200 to 300 km long) could yield large increases in payloads to LEO, to GEO, and to distant destinations in the solar system. Such tethering of the Space Station would not only require additional power for electric propulsion but also would so increase nuclear safety that nuclear powerplants might provide this power. From an 8000-kWt SP-100 reactor, thermoelectric power generation could produce 300 kWe, or adapted solar-Brayton cycle, 2400 to 2800 kWe.

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INTRODUCTION

The Space Station itself will evolve in a variety of ways, chief among them being simply growth in capacity; that is, the Station will grow in size, in its capacities to carry out various tasks, in its range of capabilities and, not least, in its economy of operation. Essentially all these evolutions in capability will require increasing amounts of power. Let us contemplate how some of this evolution might come about.

The environment provided by the Station is different from what we have previously encountered in space flight. In general, the Station will be modular in its construction, and so will its powerplant. During successive flights from the Earth, modules will be added. Each flight will also be an opportunity to service or replace failed or degraded modules. Failure of a given power module, for example, would result in only partial loss in power, not a catastrophe, and module service or replacement could later restore the full power capability. The environment provided by the Station is thus of much lower risk than for all previous missions. From such evolution of both the Station and its components, the potential gains are large and the risks small. I will therefore stress that evolution in what follows.

Let us consider briefly how the Station might evolve as an operations center. The Shuttle (or other launch vehicle) will have a given capacity to boost payloads into low Earth orbit (LEO), but some payloads will occupy only part of this capacity. Several such spacecraft could be launched by a single Shuttle, could at the Station be separated one from the other, and could then be sent on their separate ways. Structure required by a spacecraft to withstand the launch loads could be stripped away, and only the essential, minimum mass would be launched toward its destination. Alternatively, some large payloads will require more than one Shuttle flight to LEO, the payload portions launched by several Shuttles then being assembled at the Station into

a single craft ready for dispatch. A fleet of ancillary spacecraft orbiting near the Station could also be serviced either at the Station or during short flights of an orbit-maneuvering vehicle between the Station and those craft.

Propellant required for flight beyond the Station might be launched aboard the Shuttle as water instead of hydrogen and oxygen, an approach improving the safety of Shuttle operations. And this water is very dense when compared with the mean density of payloads within the Shuttle's payload bay (only 0.1 g/cc). This water is also able to fit into any available volume so that adding the water could shift the Shuttle's center of mass in a favorable direction. Once in LEO, this water could be electrolyzed into hydrogen and oxygen and these gases liquefied for use as propellants; boiloff could be entirely eliminated. This approach might permit the Shuttle to boost its maximum payload on every flight and thereby to improve its economy of operation. Power is, of course, required for this electrolysis and liquefaction, roughly 10 kWe providing 1 ton of these propellants each month.

Life support can benefit from both power and heat from solar-dynamic powerplants. Otherwise-wasted heat can support sanitation, sterilization, and water recovery from human waste. Oxidation of human feces when combined with electrolysis of water can recover oxygen for reuse, the residual gases being useful as arcjet propellants.

The Station's utilities can also evolve to improve economy of operation. For example, early experiments aboard the Station that need liquid cryogen may be required to include their own supply of cryogen, but venting this cryogen would limit duration of the experiment, just as for the Infrared Astronomical Satellite (IRAS) in 1983 (Neugebauer et al. 1984 and Habing and Neugebauer 1984). That wasteful process might first be reduced by a nitrogen-liquefaction utility aboard the Station. Active cooling of IR sensors could prolong their lives and thereby expand their value. Eventually the Station's regenerable

utilities might even be extended to include liquid helium, the ultimate cryogen.

Early concepts requiring heat for materials processing might use joule (I-squared R) heating, but the search for more economical sources will reveal other ways to provide this heat. A solar-Brayton powerplant will discharge waste heat at temperatures up to 550 K, and this heat might find application in materials processing. The technology for heat collection by such a solar-Brayton powerplant can also provide heat at high temperatures for other purposes (English 1986, English 1978, and Heath and Hoffman 1967), perhaps up to 2000 to 2500 K. Focusing the collected heat onto an aperture in an oven (as in the solar heat receiver) would be the most direct way to heat materials, but evaporation or sublimation of the heated material might contaminate the mirror's surface. Conceivably, the mirror's surface might be rejuvenated in space by evaporation and deposition of a new aluminum coating, just as in the mirror's manufacture here on Earth. Ultimately, the solar heat might be transported from the solar receiver to separate processing ovens as sensible heat of, say, BeO briquets.

Opportunities thus abound to evolve the Space Station in both its range of capabilities and in its economy of operation. In general, these evolving capabilities will require increasing amounts of both power and heat. Evolution of the Station's powerplants is crucial in realizing these potential gains for the Station itself.

EVOLUTION OF BRAYTON POWERPLANTS

If selected as the principal source of electric power for the Station, solar-Brayton powerplants could evolve to higher power from each module, to higher efficiency of power generation and to higher operating temperatures in order to achieve these performance gains. Eventually, a nuclear reactor might

replace the solar-Brayton's mirror and heat receiver. Let us briefly consider how these advances might be realized.

Figure 1 schematically portrays the Brayton cycle with, successively, compression of the cold gas, usually a mixture of He and Xe, from 1 to 2, heating in the recuperator (from 2 to 3), heating by the heat source (from 3 to 4), expansion in the turbine (from 4 to 5), heat recovery by the recuperator (from 5 to 6), and cooling by the waste heat exchanger (from 6 to 1), this waste heat being conveyed to the waste-heat radiator.

The solar-Brayton powerplant is suited to evolve in the following ways: Mirror compaction will permit increasing amounts of power to be launched on successive flights. Size and mass of the solar heat receiver might decrease through substitution of molten lithium for the heat-storage medium. Refractory-metal alloys would permit higher operating temperatures. Eventually, the solar mirror and heat receiver might be replaced by a nuclear reactor. Below, the technologies that could produce these gains will be made specific.

Current Brayton Technology

Before contemplating these advances, let us review the state of technology for Brayton powerplants. An enormous background of gas-turbine technology exists in industry and government for both aircraft propulsion and for terrestrial power generation. Although evolved with air (mean molecular mass, 29) as the principal working fluid, this gas-turbine technology is broadly applicable to any gaseous working fluid. This breadth of applicability is illustrated by NASA Lewis design in the 1950's of the compressors in the then-AEC's gaseous-diffusion plants, in which uranium hexafluoride (mean molecular mass, 352) is compressed for isotopic separation of U-235 from natural uranium (Johnsen and Bullock 1965).

Figure 2 illustrates the general scale at which gas-turbine technology is investigated at NASA Lewis. This compressor 50 cm (20 in.) in diameter is driven by a 10-MW electric motor; its measured efficiency exceeds 0.90. The 6-m (20-ft) compressor in figure 3 is driven by 100-MW electric motors in order to supply compressed air to a supersonic wind tunnel; the mechanic nestled among the rotor blades at the right side of the photo illustrates visually the compressor's size; the efficiency of this compressor also exceeds 0.90. Gas turbines exploiting this technology and ranging in power output from 1 to 100 MW are manufactured and sold every day for service in industry here on Earth.

The smallest gas turbines for propelling aircraft have power outputs of about 1000 kW. When we at NASA Lewis first began to explore gas turbines for generating power in space, we asked ourselves how small they might be made while still performing well. To answer this question, we explored the performance of very small components, both radial-flow and axial-flow compressors and turbines being investigated; in figure 4, the mechanic's hands convey the scale of the components. Of the two types, the radial-flow components had the better efficiencies, our tests extending down to 81-mm (3.2-in.) diameter (fig. 5). The performances measured are shown by figure 6.

Given these components performances, we chose to explore performance of a powerplant (sans only its heat source) that incorporated these components to generate power output of the order of only 1/100 that of the smallest aircraft engines, namely, 10 kWe. Our stated goal was to achieve an overall powerplant efficiency of 0.25 at this 10-kWe level, the gas turbine's working fluid being a blend of He and Xe. The turbomachine (fig. 7) consisted of a radial-flow turbine, a synchronous alternator, and a radial-flow compressor, all on the same shaft; the gas bearings to support this shaft used the powerplant's gaseous working fluid as the bearing lubricant. While the powerplant is

running, the rotor and the stator are therefore always separated by a gas film, thus eliminating any possibility of wear from that source.

The powerplant (complete but for its heat source) was assembled and installed in the Space Power Facility (SPF), a very large vacuum chamber at NASA Lewis (fig. 8). While operating with a turbine-inlet temperature of 1140 K (1600 °F), the powerplant exceeded the efficiency goal of 0.25 and reached 0.29 at 10 kWe (fig. 9). (These efficiencies are based on the thermal input to the powerplant and on the net electric power delivered after deduction of all power consumed internally for pumping, controls, generator excitation, voltage regulation, etc.) Following 3000 hr of testing in vacuum, the powerplant was moved to a conventional test cell and operated in air for an additional 35 000 hr, turbine-inlet temperature being maintained at 1140 K. Performance was stable over this entire period. In this powerplant test, the approach was to design, build, and test the powerplant, not develop. The broad applicability of the precursor, air-based gas-turbine technology was forcefully demonstrated.

During this same period, the performances of the individual components of the powerplant were also explored. Modest performance deficiencies were uncovered and corrected by component modification and test; for example, efficiency of the compressor was raised 0.03 by resetting its stator vanes by 3°. Had these improved components been installed in the powerplant, we calculate that powerplant efficiency would have risen from 0.29 to 0.32 (Klann and Wintucky 1971). This efficiency is substantially greater than that demonstrated by any other thermal powerplant for use in space.

This performance is the state of the Brayton art at the 10-kWe level, representing a great extension of gas-turbine technology to powers only 1 percent of those in current use in the smallest aircraft engines. Any need for higher powers (toward, say, 100's or 1000's of kWe) would move the design

conditions toward the main body of gas-turbine technology and thereby improve component performance. For those reasons, design of a larger power-generating system would be easier than and performance superior to that just cited; the larger heat sources (solar or nuclear) and the necessary waste-heat radiator have yet to be demonstrated, however.

Materials for Brayton Powerplants

During the 1960's and early 1970's, a family of tantalum-base alloys was evolved (Buckman and Goodspeed 1968, Buckman and Begley 1969, Harrod and Buckman 1969) for high-temperature long-time creep resistance. ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C) is the most highly evolved and evaluated member of this family. In particular, this alloy was subjected to 98 individual creep tests spanning a total of 314 140 hr (Klopp et al. 1980), in excess of 35 yr of testing. Six tests exceeded 10 000 hr apiece, and one test continued for 23 694 hr. The tests spanned the temperature range of 1144 to 1972 K (1600 to 3090 °F).

By the Larson-Miller method, these data on ASTAR-811C were statistically correlated in addition to those for the molybdenum alloy TZM (English 1982). In each case, the allowed stress was reduced by two standard deviations of the test data from the correlating line. The stress criterion postulated was 1-percent creep, not rupture, over a period of 40 000 hr of operation. This approach shows that this alloy combination is strong enough for use in Brayton powerplants at peak cycle temperatures up to 1500 K (2240 °F).

On fundamental grounds, we would normally not expect problems of compatibility of the refractory-metal alloys with the inert gases. On the other hand, contamination of these gases by trace amounts of O, C, and N is a potential problem (DeVan et al. 1984). Charlot et al. (1967) also showed that in a refractory-alloy loop containing superalloys, the superalloys, if hot

enough to evaporate Cr and Fe, can transfer these constituents to the refractory. Potential solutions to these problems are the following:

(1) The refractory-alloy loop and its inert gas must be baked out at gradually increasing temperatures, the inert gas circulated, and the contaminants gettered.

(2) Sources of contamination must be excluded from the loop.

(3) If any superalloys are used in the loop, their operating temperatures must be so low that their constituents do not evaporate.

Scheuermann et al. (1987) found no problems in He-filled capsules of Nb-1Zr if Sm-Co permanent magnets (a powdered-metal material containing adsorbed gases) were excluded. However, additional investigation of the potential solutions is still required.

Technology of Mirrors ad Heat Receivers

The mirror in figure 10 is 6 m in diameter, and its surface accuracy was measured at 32 400 points (fig. 11), the standard deviation of the surface errors being 3 arc-min. Another mirror 1.52 m in diameter had standard error for its surface of only 1 arc-min (Heath and Hoffman 1967).

A solar heat receiver (Cameron et al. 1972) to receive and store the heat from such mirrors is shown in figure 12, the heat-storage medium being LiF. Three Nb alloys were tested for compatibility with the LiF (Harrison and Hendrixson 1970), Nb-1Zr being chosen after these tests. This receiver is probably the largest, most complicated assembly of refractory-metal alloy ever built. A test of three of its tubes continued for 2002 hr (1251 simulated sun-shade cyclic orbits about the Earth) and met the performance goals (Namkoong 1972).

Lithium for Storing Solar Heat

Molten Li is a candidate to replace this LiF for heat storage. Because of its low molecular mass, lithium has high specific heat, matching that of

water. Thus, it has the potential to store large amounts of sensible heat with only modest temperature changes. The combination of lithium heat storage with Brayton cycles is propitious because of the inherent, substantial temperature rise in the Brayton's gas when it passes through the heat source (1017 to 1500 K, fig. 1(b)). In a counterflow heat exchanger, a stream of molten lithium might be cooled by an equal amount, namely, by 483 K, the temperature difference producing heat transfer being kept constant through the heat exchanger. Under these conditions, the sensible-heat capacity of molten lithium exceeds the latent-heat capacity of any of the competitive salts (table I) and is 250 percent that of the salt ($LiF-CaF_2$ eutectic) for the solar-Brayton powerplant that is a candidate for use aboard the Space Station.

Some potential problems with lithium are corrosive attack on its container and rupture of the container by its vapor pressure, especially at high temperatures. Fortunately, our experience shows that neither of these potential problems (compatibility nor strength) need be a real one, as shown below.

At Oak Ridge National Laboratory, a natural-convection loop of lithium in T-222 (Ta-9.5W-2Hf) was tested for 3000 hr at 1620 K (DeVan et al. 1984). The alloys T-111 (Ta-8W-2Hf), ASTAR-811C, and ASTAR-1211C (Ta-12W-1Re-0.7Hf-0.025C) were also tested in natural-convection loops for 5000 hr apiece at 1640 K (ibid., and DeVan and Long 1975). In addition, T-111 was tested in a pumped loop for 10 000 hr with hotside temperature of 1505 K and coldside temperature of 1410 K (Hoffman 1984 and Harrison et al. 1975). In all these tests, lithium was compatible with its Hf-gettered tantalum-alloy containers. From these tests, DeVan et al. (1984) conclude, "Sufficient corrosion data exist for T-111 and lithium to provide a reliable design data base up to 1370 °C," or 1640 K. The same judgment is very likely appropriate to ASTAR-811C inasmuch as its

composition is so close to that of T-111 and inasmuch as coupons of ASTAR-811C were in the same loop.

Weatherford et al. (1961) give the vapor pressure of lithium, plotted in figure 13 as logarithms (to the base 10) of both pressure and temperature. Long-time creep data for ASTAR-811C (Sheffler and Ebert 1973; also see Klopp et al. 1980) were Larson-Miller correlated (English 1982); for 1-percent creep in 10 yr, the high-temperature, low-stress range is plotted in figure 13, stress being taken as 10 and 100 times the vapor pressure. These curves intersect at 1568 and 1715 K. Thus, the conditions in table I can readily be met and the gain in heat capacity realized.

An additional factor is that Li produces such high heat-transfer coefficients that high solar fluxes are tolerated by Li-cooled surfaces. This will permit markedly decreasing the surface area, size, and mass of the solar heat receiver.

Evolution of Solar Brayton Powerplants

The combination of Brayton cycle and sensible-heat storage permits an unusual capacity for evolution of the powerplants. Neither a Brayton powerplant nor its sensible-heat store is tied to a given phase-change temperature. Such a powerplant, if built largely of ASTAR-811C, has the potential to operate at 1500 K, as outlined in Materials for Brayton Powerplants. But it might initially be operated at, say, 1200 K, the 300-K increment being strictly margin provided for quick, sure development of the powerplant. Following successful operation at this reduced temperature, a powerplant under test could have its operating temperature raised in successive increments toward its design limit. This gradual evolution in the rated operating conditions is a low-cost, low-risk path to realization of the ultimate in performance for the powerplant. The resulting gain in efficiency of power generation (efficiency of heat supply being ignored) is shown by

figure 14; each point plotted is a possible design point, the envelope of an entire set of points being the region of interest. Two points on the envelopes are marked boldly, one for 1100 K and the other for 1500 K. At 1100 K, efficiency of 0.30 is achievable with radiator area of 1.3 m^2/kWe. At 1500 K, efficiency at the designated point is 0.46, specific radiator area being reduced to 0.85 m^2/kWe. If we consider fixed areas for both solar collector and radiator, power output could rise by 50 percent, a very beneficial evolution in powerplant performance. A modest modification of the Brayton cycle could also provide cryogenic cooling (Klann 1973), a topic for further evolution.

Such a solar-Brayton powerplant also has the potential to evolve very readily into a nuclear powerplant. The Brayton cycle's heat source would already be a molten-Li heat receiver. A Li-cooled reactor could then be readily substituted for the solar mirror and heat receiver, providing evolution to nuclear power with lowest cost and lowest risk.

Recapitulation

By extension of existing gas-turbine technology to the power level of only 10 kWe, efficiency of 0.29 was demonstrated for a complete powerplant; the potential for powerplant efficiency of 0.32 was also demonstrated at the component level. Growth to higher powers (up to 100 MWe) would draw on the large industrial base of gas-turbine technology, competition among several industrial sources being assured for any governmental procurement.

The existing, extensive data base on refractory-metal alloys shows that design for 1500 K is practical. A solar-Brayton powerplant for the Space Station could evolve in performance through progressive upgrading to 1500 K by exploiting molten Li as a sensible-heat store. Transition to nuclear power would then be simple, of low cost, and of low risk.

A TETHERED SPACE STATION

Consider now division of the Space Station into two equal masses joined by a long tether (fig. 15); let us keep constant at 500 km the altitude of the Station's lower half. As considered herein, the tether would be radial, swinging of the tethered Station being deliberately avoided for both simplicity and conservatism. The lower half of the Station would orbit the Earth at a suborbital velocity, the upper half being superorbital. A Shuttle coming up to rendezvous with such a Station would then not need to burn so much propellant at its apogee; in turn, that propellant increment could be replaced by payload, the potential gains in Shuttle payload being shown by figure 16. Although a tether 10 or even 20 km long would add very little to the Shuttle's payload capability, the gains at 200 and 300 km are 36 and 53 percent, respectively. An additional benefit is that for tether length beyond about 75 km, propellant saving would be so large that the External Tank and its residual propellant would also be delivered to the Station on every flight.

Consider now that a chemically-propelled orbit-transfer vehicle (OTV) would transfer payloads between the Station's upper half and geosynchronous Earth orbit (GEO). Propellant could be saved inasmuch as the Station's upper half is at a higher-than-normal altitude and is traveling at superorbital velocity, factors that add to the OTV's payload, the gains being shown in figure 17 for both one-way and round trips. For tether lengths of 200 and 300 km, payload delivered by the roundtrip OTV would be increased 61 and 95 percent, respectively; comparable gains in payload could be achieved for missions to distant destinations in the solar system. Although these are long tethers, the potential gains in payloads are very large for these very important missions. Not only do these potential gains in payload justify further exploration of long tethers for the Station, but they may also help to

justify the Station itself through lowering transportation costs of all missions exploiting the Station.

These payload gains are not without some cost. Transfer of the large payloads from the Shuttle to the Station's lower half would lower the Station's center of mass and require propulsion both to maintain the Station's orbit and to stabilize its radial attitude. Elevation of payloads along the tether to the Station's upper half would also require propulsion to compensate for the Coriolis force, as would payload departures to GEO. In each instance, electric propulsion of the Station is especially suitable, both because of its low demand for propellant and because of its potential to effectively exploit otherwise-wasted material as propellant.

Tethering would produce aboard the Station's lower half the sensation of modest acceleration, a factor easing both human habitation and utilization of that module but also forcing that materials processing requiring very low acceleration to be shifted to roughly the tether's midpoint. The heavy Shuttle payloads resulting from such tethers might also increase the Shuttle's landing mass above tolerable limits during emergency conditions, a problem requiring further study.

Tethering the Station would also provide an unusual opportunity to use nuclear power in a safe way, the Station's nominal altitude being below a nuclear-safe orbit (DOE 1982). Given the tethered Station (fig. 15), consider adding a nuclear powerplant to the Station's upper half by means of a second tether perhaps 1 or 2 km long (Bents 1985). Two benefits result:

(1) The reactor's altitude is raised by the length of the main tether.

(2) The reactor would be traveling at a superorbital velocity.

If jettisoned, the reactor would thus automatically be in an elliptical orbit, the resulting perigee and apogee altitudes being given by figure 18. For example, a tether length of 300 km and lower-half altitude of 500 km would

produce perigee and apogee altitudes of 800 and 1800 km, respectively, the reactor's orbital period and orbit energy corresponding to a 1300-km circular orbit.

A synergism thus prevails between nuclear power and tethers for the Space Station. Tethering the Station not only requires propulsion that electric propulsion can effectively provide but also increases the safety with which a nuclear powerplant can provide the power for this propulsion.

THE NEED FOR NUCLEAR POWER ABOARD THE STATION

The management of the Space Station has expressed no need for nuclear power. Instead, the current plan for the Station is to provide all the electric power from solar energy.

In contrast with this point of view, long-range plans (National Commission on Space 1986) consider flights of personnel to the Martian surface and establishment of permanent bases on the Moon, missions for which nuclear power is surely a candidate. In particular, the lunar night of about 350 hr makes nuclear power not only low in cost and mass-superior but almost an absolute necessity. Occasionally consideration of the lunar landings is restricted to the poles as an approach by which solar power might be relied upon; this restriction would so diminish the potential benefits from the lunar bases that, in my view, the bases would not be worth their cost. Early results from such lunar laboratories will almost surely raise questions requiring laboratories at other, complementary sites; isn't that the usual nature of scientific inquiry? Instead, we should strive to establish a capability to set up scientific laboratories anywhere on the lunar surface. For these reasons, I view nuclear power as a necessary, enabling technology for permanent lunar bases at a variety of sites of the scientists' own choosing.

But where will the nuclear powerplants be evolved and demonstrated before the lunar flights? In my view, we should not entrust the lives of the lunar

scientists (selenonauts?) to a nuclear power station before its durability and reliability have been demonstrated by actual service in space. Where should these qualities of nuclear power be demonstrated but aboard the Space Station? THIS is the justification for installing nuclear power on the Station.

The Station, by its nature, supplies the low-risk environment (See INTRODUCTION) in which nuclear power can readily evolve and in which the power generated can be readily used. The Station is the site at which a host of capabilities can be evolved to enable future, bold, inhabited missions in space. By exploiting the Station's inherent capacities for evolution and demonstration, we can substantially reduce the risks to the crew on these future missions as well as decrease the mission costs.

NUCLEAR POWER ABOARD THE STATION

Among the powerplant characteristics addressed by the SP-100 program, one potential powerplant has the following characteristics: An 8000-kWt nuclear reactor would heat a stream of molten lithium to 1350 K. With an overall efficiency of 0.0375, thermoelectric conversion would generate 300 kWe of electric power from the 8000 kWt. Circa 2000, one or two such SP-100's could be added to the 300 kWe of solar power already installed aboard the Station at that time, raising total power of the Station to 600 to 900 kWe. Such a powerplant could also power a coorbiting platform or an independent materials processing laboratory.

As an alternate to that approach, the evolved solar-Brayton powerplant discussed earlier might be used with that same reactor. Recall that molten lithium appears to be an effective heat store for such a solar powerplant. And that available data on refractory alloys, when used in a conservative way, show that peak temperature for the Brayton cycle can reach 1500 K, the molten lithium reaching 1600 K. Substitution of a 1350-K nuclear reactor and its

lithium coolant for the solar mirror and heat receiver would thus be a small step of low risk. Powerplant efficiency of 0.30 to 0.35 would already have been demonstrated by the Brayton powerplant itself. From an 8000-kWt SP-100 reactor, 2400 to 2800 kWe could thus be readily generated by the Brayton powerplants. Use of two such reactors to supplement the Station's 300 kWe of solar power would thus provide 5100 to 5900 kWe of total installed capacity.

In its recent reorientation, the SP-100 program now emphasizes 2500 kWt from its nuclear reactor and 100 kWe from its thermoelectric generator. From this same reactor, Brayton powerplants have the potential to produce 750 to 875 kWe. In addition, the project management of SP-100 predicts scaling both the current reactor and its thermoelectric generator from 100 kWe to an output of 1000 kWe; from such a reactor, a Brayton powerplant could generate about 8000 kWe.

CONCLUDING REMARKS

Evolution is thus the crucial factor for progressive advance in performance of both the Space Station and its powerplants, the Brayton cycle, if selected, offering unusual potential for such evolution to progressively higher efficiency of solar-power generation and, ultimately, to generation of nuclear power. Adapting the Station to exploit long tethers (200 to 300 km) might not only increase payloads deliverable by the Shuttle as well as to various destinations in the solar system but might also increase nuclear safety so that nuclear power might be readily accepted for use on the Station. From an SP-100 reactor of 8000-kWt output, thermoelectric power generation could produce 300 kWe, and adapted solar-Brayton could generate 2400 to 2800 kWe.

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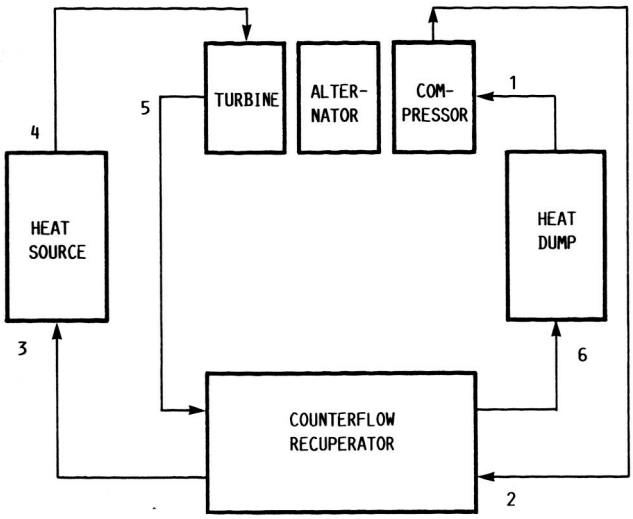
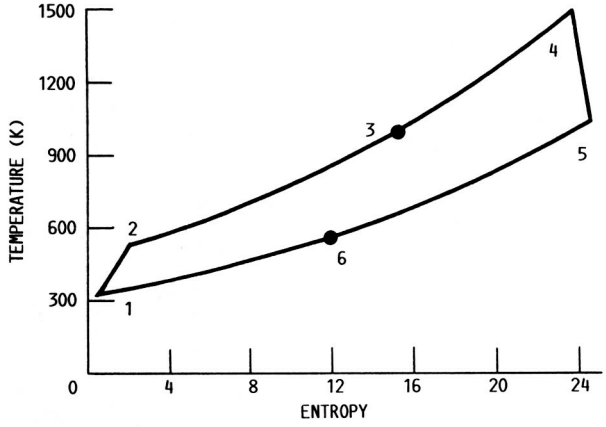
TABLE I. - SOLAR HEAT-STORAGE MATERIALS

Storage medium	Heat capacity, J/g	Use temperature, K
LiOH	930	743
$LiF-CaF_2$	791	1042
LiF	1044	1121
Lithium (ΔT = 483 K)	1980	500-2000



(A) SCHEMATIC DIAGRAM.



(B) TEMPERATURE-ENTROPY DIAGRAM.

FIGURE 1. - THE BRAYTON CYCLE.

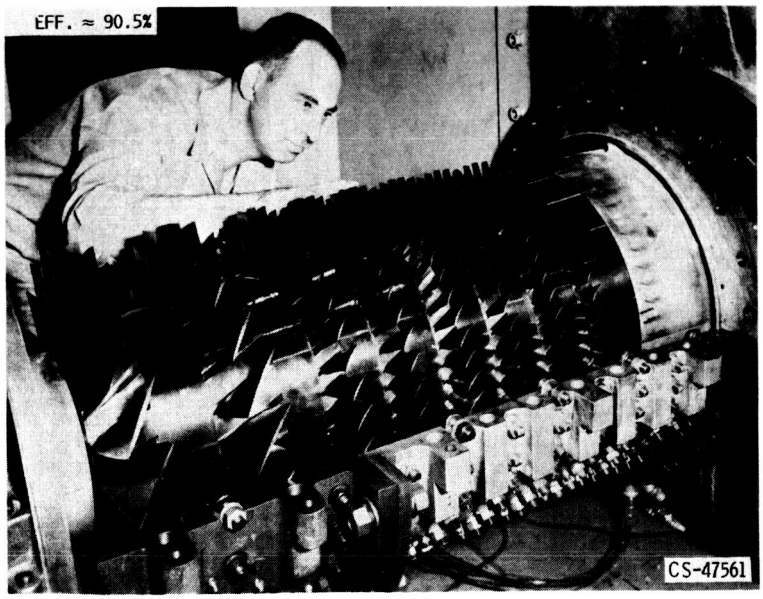


FIGURE 2. - A REPRESENTATIVE EXPERIMENTAL COMPRESSOR. DIAMETER, 50 CM; POWER CONSUMPTION, 10 MW.

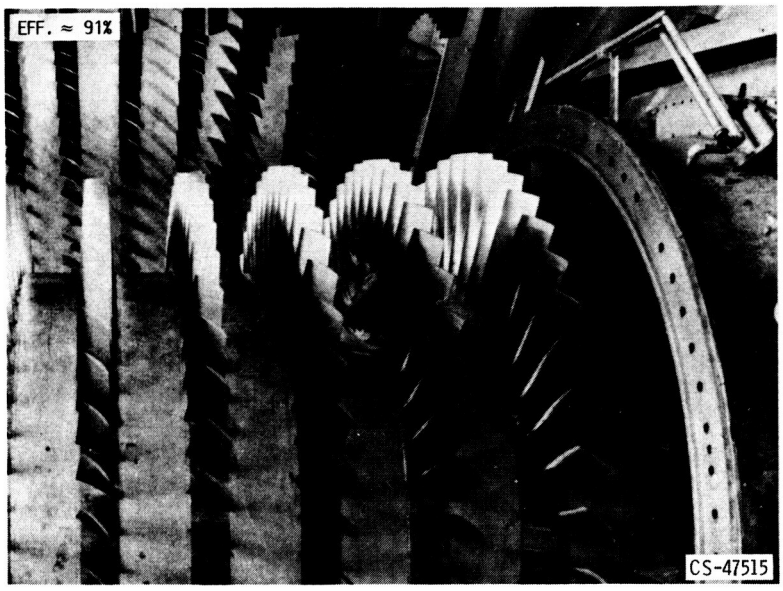


FIGURE 3. - A COMPRESSOR FOR DRIVING A WIND TUNNEL. DIAMETER, 6M; POWER, 100 MW.

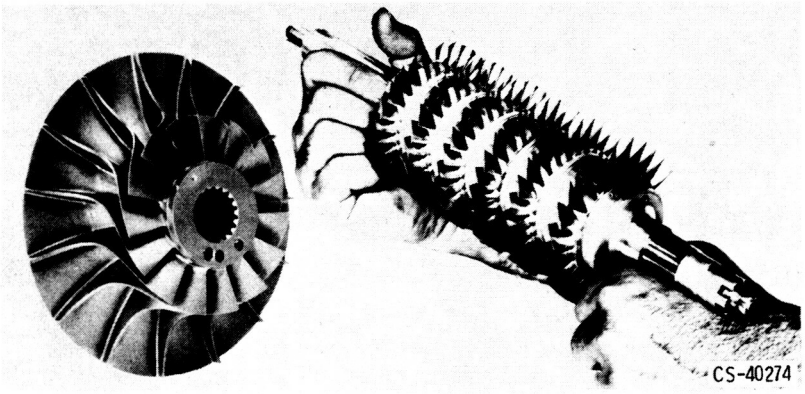
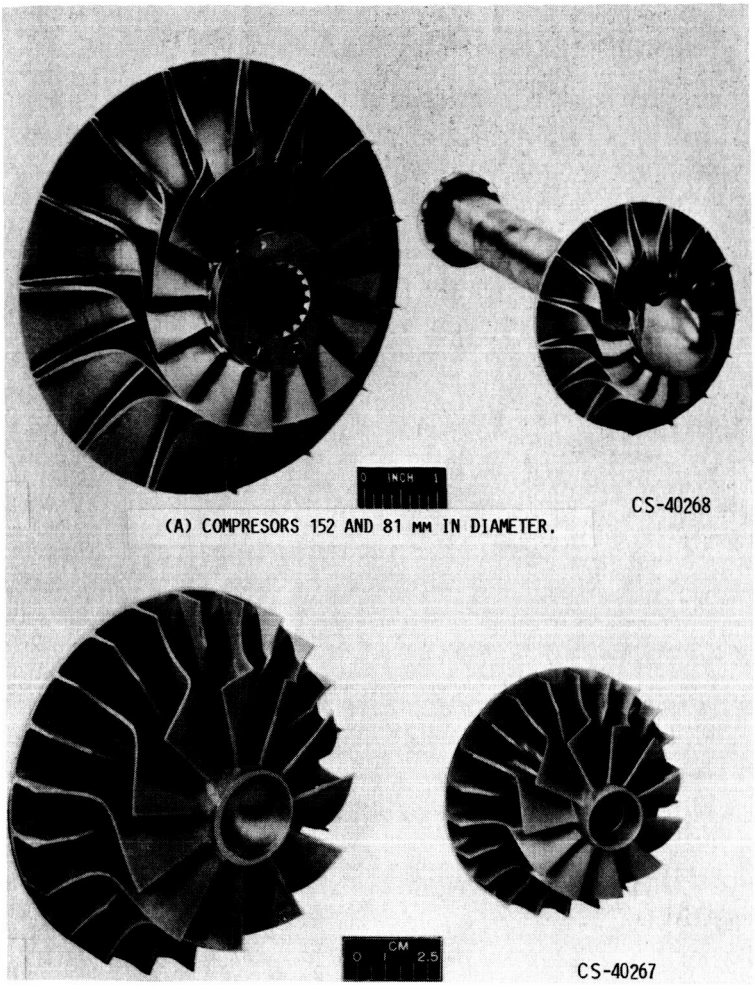


FIGURE 4. - EXAMPLES OF SMALL EXPERIMENTAL COMPRESSORS 152 AND 89 MM IN DIAMETER.



(A) COMPRESORS 152 AND 81 MM IN DIAMETER.

(B) TURBINES 152 AND 81 MM IN DIAMETER.

FIGURE 5. - EXAMPLES OF SMALL EXPERIMENTAL TURBOMACHINERY.

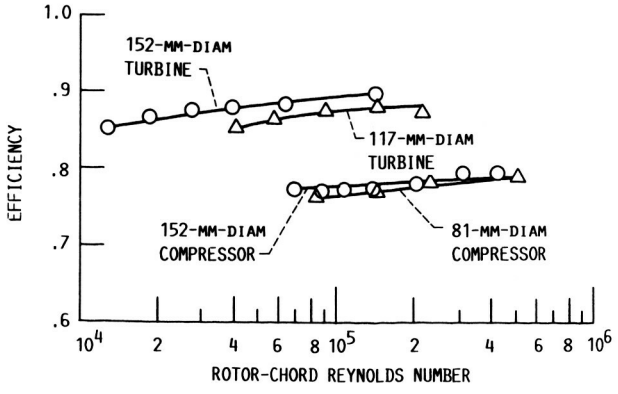


FIGURE 6. - MEASURED EFFICIENCIES OF SMALL TURBOMACHINERY. TURBINE FLUID, ARGON, COMPRESSOR FLUID, AIR.

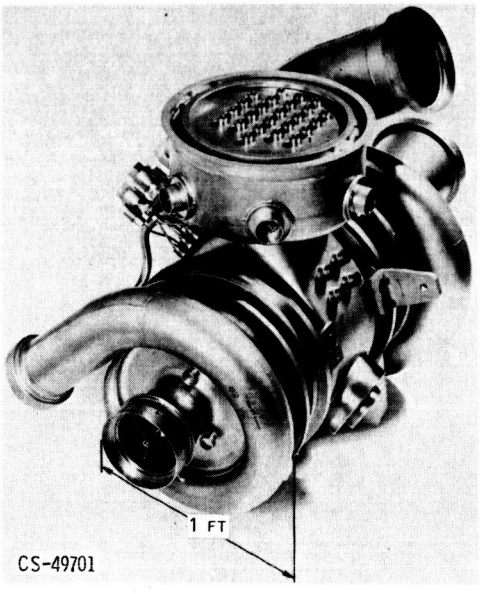


FIGURE 7. - THE 10-kWe BRAYTON ROTATING UNIT THAT WAS TESTED FOR 38 057 HR.

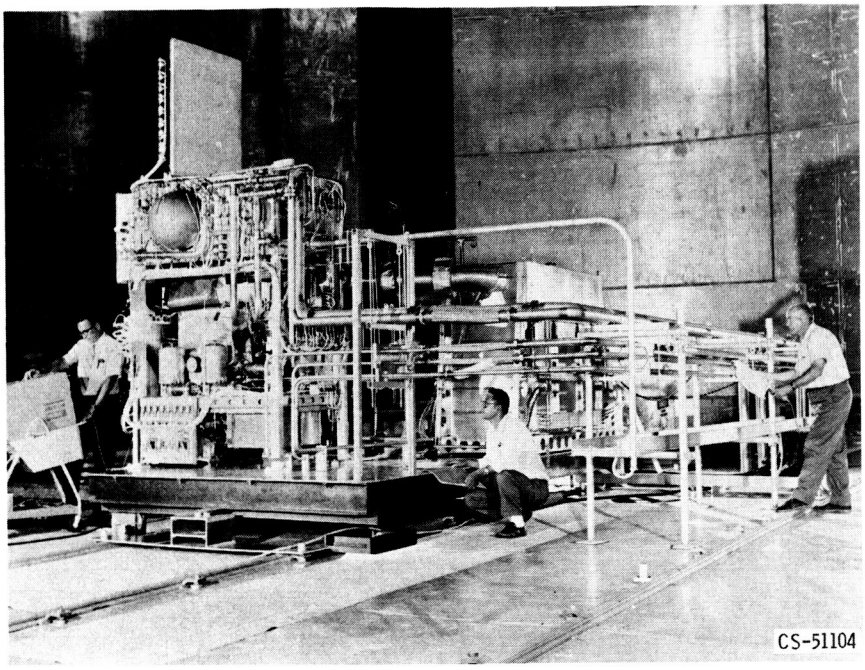


FIGURE 8. - THE BRAYTON POWER-GENERATING SYSTEM PRIOR TO TEST IN THE SPACE POWER FACILITY.

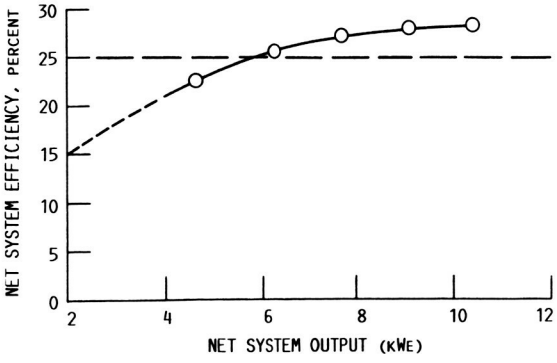


FIGURE 9. - MEASURED PERFORMANCE OF THE 10-kWe BRAYTON POWER-GENERATING SYSTEM. TURBINE INLET TEMPERATURE, 1140 K (1600 ^{o}F); COMPRESSOR INLET TEMPERATURE, 300 K (80 ^{o}F).

FIGURE 10. - AN EXPERIMENTAL PARABOLOIDAL SOLAR MIRROR 6 m IN DIAMETER.

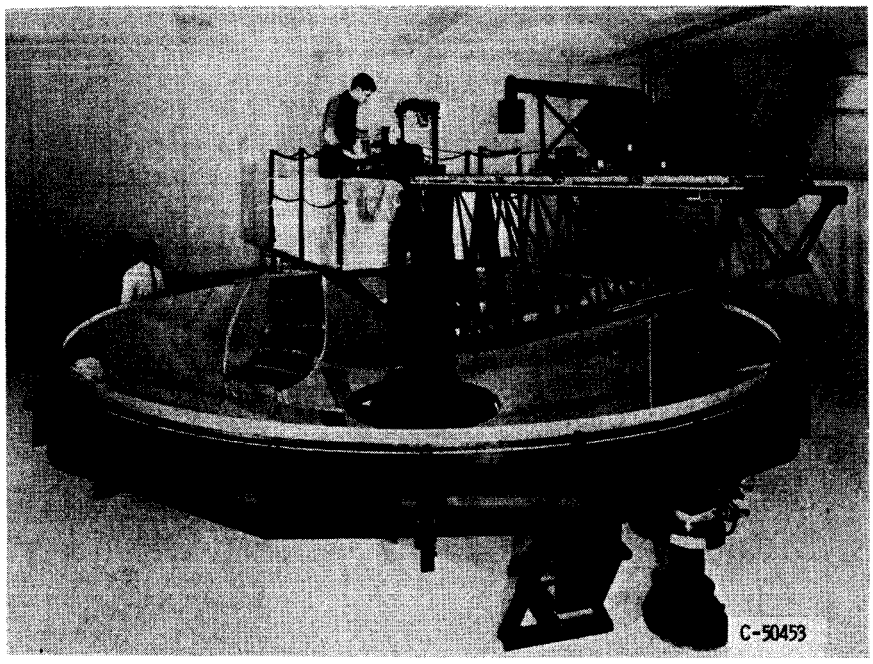


FIGURE 11. - THE OPTICAL DEVICE FOR INSPECTING THE 6-M PARABOLOIDAL MIRROR.

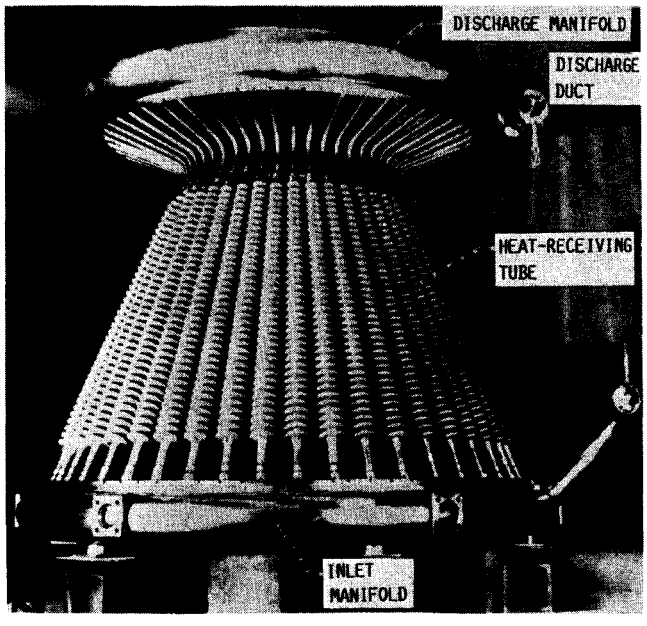


FIGURE 12. - AN EXPERIMENTAL SOLAR HEAT RECEIVER MADE OF NB-1ZR.

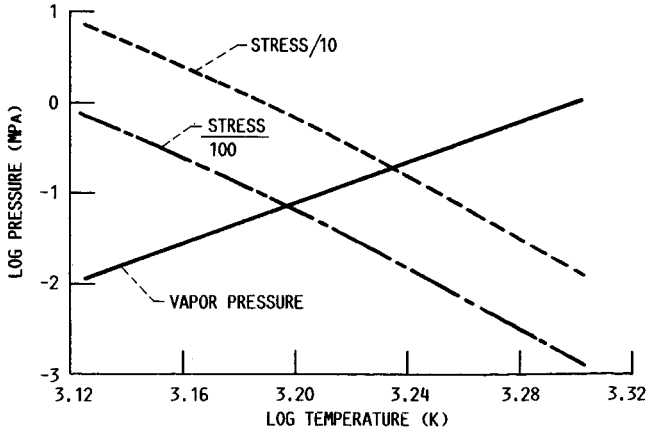


FIGURE 13. - CONTAINMENT OF LITHIUM IN ASTAR-811C WITH ONLY 1% CREEP IN 10 YEARS.

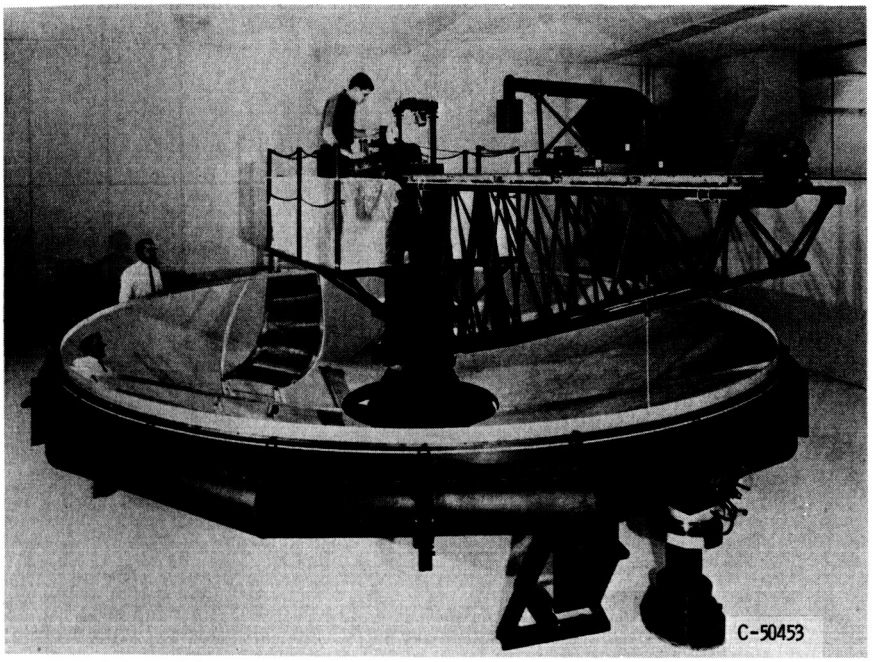
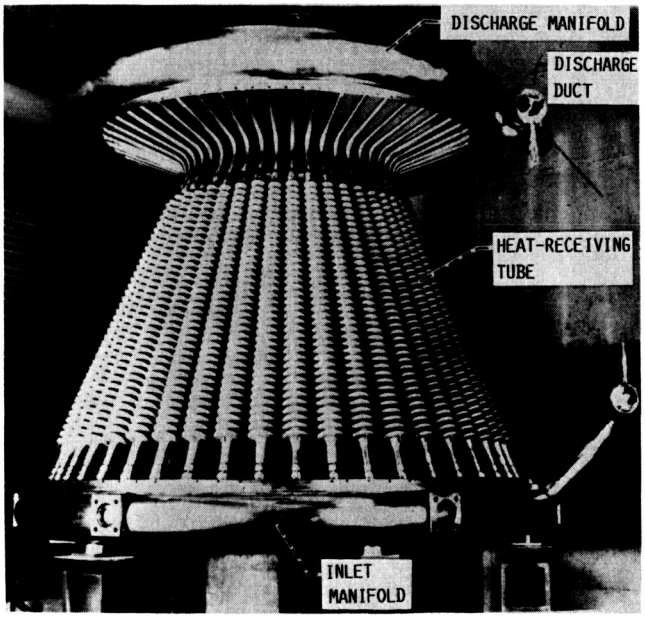


FIGURE 11. - THE OPTICAL DEVICE FOR INSPECTING THE 6-M PARABOLOIDAL MIRROR.



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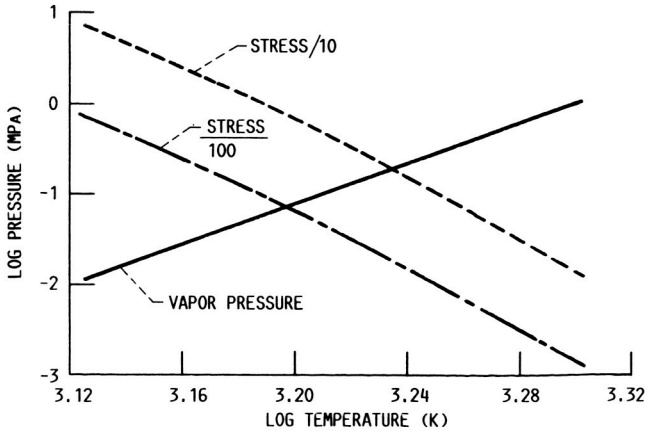

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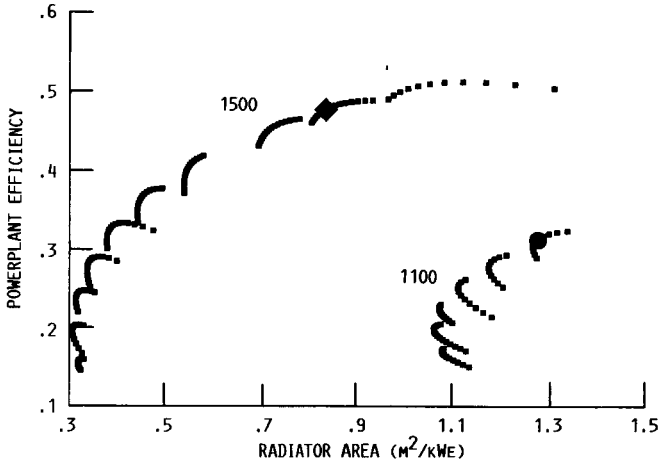

FIGURE 14. - PREDICTED PERFORMANCE OF BRAYTON CYCLES HAVING PEAK TEMPERATURES OF 1100 AND 1500 K.

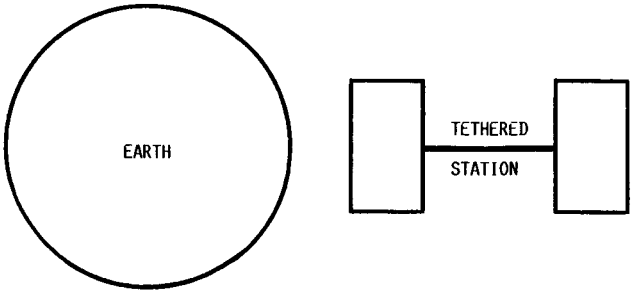

FIGURE 15. - A CONCEPT FOR A TETHERED STATION.

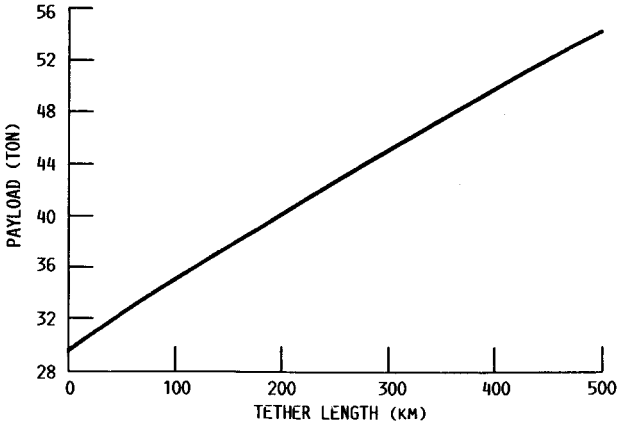

FIGURE 16. - LONG TETHERS WOULD PRODUCE LARGE INCREASES IN SHUTTLE PAYLOADS. LEO ALTITUDE, 500 KM.

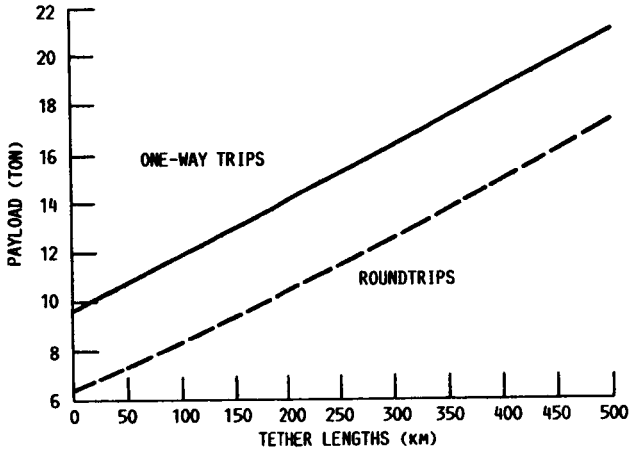

FIGURE 17. - LONG TETHERS WOULD ALSO GREATLY INCREASE OTV PAYLOADS. STATION'S LOWER HALF AT 500-KM ALTITUDE.

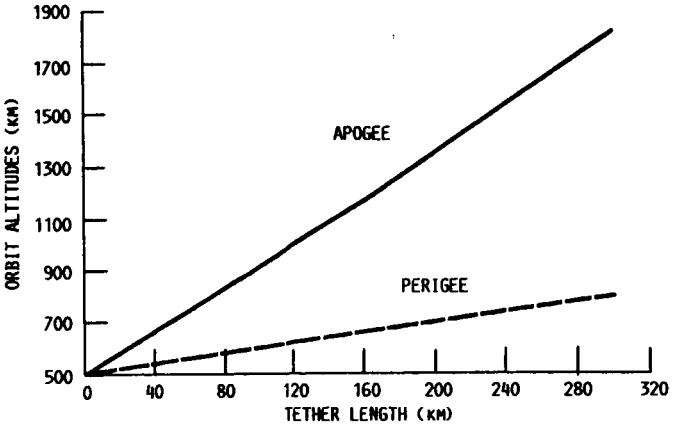

FIGURE 18. - THE REACTOR ORBITS AFTER BEING JETTISONED FROM A TETHERED SPACE STATION. STATION'S LOWER HALF AT 500-KM ALTITUDE.

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15. Supplementary Notes

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16. Abstract

The Space Station provides a unique, low-risk environment in which to evolve new capabilities. In this way, the Station will grow in capacity, in its range of capabilities, and in its economy of operation as a laboratory, as a center for materials processing, and as a center for space operations. Although both Rankine and Brayton cycles, two concepts for solar-dynamic power generation, now compete to power the Station, this paper confines its attention to the Brayton cycle using a mixture of He and Xe as its working fluid. Such a Brayton powerplant to supply the Station's increasing demands for both electric power and heat has the potential to gradually evolve higher and higher performance by exploiting already-evolved materials (ASTAR-811C and molten-Li heat storage), its peak cycle temperature rising ultimately to 1500 K. Adapting the Station to exploit long tethers (200 to 300 km long) could yield large increases in payloads to LEO, to GEO, and to distant destinations in the solar system. Such tethering of the Space Station would not only require additional power for electric propulsion but also would so increase nuclear safety that nuclear powerplants might provide this power. From an 8000-kWt SP-100 reactor, thermoelectric power generation could produce 300 kWe, or adapted solar-Brayton cycle, 2400 to 2800 kWe.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space Station; Space power; Solar power; Nuclear power; Brayton cycle	Unclassified - unlimited STAR Category 15

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