NUCLEAR VS SOLAR POWER FOR EARTH-ORBIT MISSIONS

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Abstract

The anticipated development of advanced nuclear-radioisotope power systems has led to a reevaluation of their possible utility in earth-orbit missions of various kinds. Because such missions almost always have the option of using solar-power, a decision for nuclear power will have to be based on clear economic grounds, in most cases. However, the economic evaluation must be based on overall system factors, not on power-system cost comparisons alone. On this basis, the advanced nuclear systems can be justified for many operational missions. Examples to be discussed include synchronous-orbit commercial communications satellites and inclined-orbit navigation satellites.

I. Introduction

The successful application of radioisotope thermoelectric generators (RTG's) in the Apollo and Pioneer programs has established the utility of these devices for lunar surface and interplanetary applications. With the exception of a few experimental missions, however, their use in earth orbit has been precluded by the ready availability of solar power and the high cost of the nuclear alternative.

The conjunction of two new developments, however, leads to a reevaluation of this conclusion for many earth-orbit missions: 1.) The next generation of RTG's, now in development, promise to reduce the cost of these systems substantially, while improving their performance. 2.) The use of satellites for operational missions places an economic value on increased performance.

The use of space as an operational, as opposed to an experimental, medium is now beginning on an important and rapidly growing scale. Satellites with substantial commercial application are being built and launched. The first of these are the synchronous-orbit communications satellites. Soon to follow will be navigation satellites, aircraft control and communications satellites, data-relay satellites, and others. These will, for the most part, sell commercial services. The penalty for reduced performance or satellite lifetime will be far more visible and quantifiable than in experimental missions. Stated positively, the return achievable due to increased performance can justify the added cost which may be incurred in achieving this improvement.

A clear economic superiority of nuclear power appears achievable for many operational missions, if the advanced nuclear systems are postulated. These systems, now scheduled for development within the next 3-to-5 years, promise to deliver significant improvements in both specific power and cost compared to present day RTG's.

In general, synchronous-orbit missions are quite favorable for solar power. However, the advanced nuclear systems can offer substantial economic benefit for such applications. This has been detailed in recent publications,^{1,2} and will be summarized here.

A mission which flies in lower and/or inclined orbits, is generally less favorable for solar power. For such missions, the performance improvement achievable by the advanced nuclear systems is even more apparent. In both cases, much of the improvement comes about by substantially relieving other spacecraft sub-system requirements, e.g., attitude control, battery charging, thermal control and others.

Most operational missions as now envisioned will fly in geosynchronous orbit. A prominent example of a lower-orbit mission in the "Navstar" Global Positioning System, the military navigation satellite system. The potential benefits of nuclear power for this system are discussed.

The analyses presented herein are postulated on the use of existing, weight-limited launch vehicles. The use of the Space Shuttle as the booster, with its different design constraints, operational profile, and economic valuations, would clearly have an impact on these analyses. In general, however, a firm weight limitation will continue to be observed, and this is bound to remain a limiting factor for many missions, particularly the high altitude operational missions considered herein.

II. Reference Power Systems

1. Candidate Nuclear Systems

State-of-the-art radioisotope generators all employ thermoelectric solid-state converters made of doped lead-telluride or silicon-germanium, and use plutonium-238 radioisotope fuel. Because the plutonium fuel, at 650 dollars per thermal watt, has been the most expensive part of these RTG's, converter efficiency has a strong influence on the unit cost of these devices. Therefore, a strong incentive has existed to increase conversion efficiency.

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Increased conversion efficiency is now believed to be achievable in either of two ways: 1.) new high-efficiency thermoelectric materials, 2.) turbine-generator conversion.³

The first approach has resulted in the development, under AEC sponsorship, of a new class of thermoelectric materials based on selenide alloys. Using selenide thermoelements, RTG's capable of at least 10-percent efficiency are now clearly within reach.⁴

The other approach now believed to be feasible in the several-hundred-watt range, uses miniature turbine-generator units. The turbines are driven by gas which has been heated by the nuclear fuel, and which is then returned to the heater in a closed cycle. Low- and fractional-horsepower turbines and non-contacting hydrodynamic gas-film bearing for the rotating unit, have been developed for aircraft APU and other applications. Successful long-term operation under multiple start-stop conditions has imparted confidence in the readiness of this approach.

Both Brayton-cycle and Organic-Rankine-cycle systems which make use of this new technology have been studied,^{5,6} and both are now capable of breadboard demonstrations in the 1/2-to-2 kW range. Both systems are predicted to achieve 20+ percent efficiencies in this power range. The Brayton system is projected to be capable of higher efficiencies, particularly toward the upper regions of the power range; the Organic Rankine system operates at lower peak cycle temperature and is lower in weight throughout the power range.

These studies have shown that, for the subject missions on the existing weight-limited booster vehicles, weight is a highly-leveraged economic factor. For these missions, therefore, the Organic Rankine system was selected as the representative power system.

2. Cost & Weight Comparisons with Solar Power Systems

Comparisons of the weights of these nuclear and solar power systems alone (excluding the effects on other subsystems) have been made, as shown in Figure 1. The present day nuclear systems at 1-to-2 watts per pound are shown along with the advanced systems spanning the range of 3-to-5 watts per pound. The low weight selenide RTG, described in another paper of this conference⁷, appears to be capable of achieving the highest specific power of any nuclear system in this power range, capable of 6 watts per pound in a fully optimized design. However, the integration aspects of these RTG's makes them less suitable than the Organic Rankine system for the two missions discussed herein.

Figure 1: Power Systems Weight Comparisons

Although, from Figure 1, the Organic Rankine system appears to be capable of lower weight than conventional oriented solar array/battery systems, even including violet cells, the advent of the nickel-hydrogen battery (assuming 18.3 W-hr/lb with 85% depth-of-discharge) would restore the solar-system weight advantage rather clearly. As will be seen, however, on an overall spacecraft basis the nuclear-powered design can continue to demonstrate a weight (and consequent economic) advantage, even against the advanced technology batteries, assuming these can be made to sustain long-term space operation without failure. This advantage can be decisive, particularly if the nickel-hydrogen cells fail to meet the stated objectives of either performance or lifetime.

The projected costs of the solar and nuclear systems are shown in Figure 2. The cost spread shown for the Organic Rankine system reflects the range of possible plutonium fuel costs, from the current 650 dollars per thermal watt, to a possible 350 dollars per thermal watt. This latter figure is now believed to be achievable at increased production rates for ²³⁸Pu.

Figure 2: Power Systems Recurring Cost Comparisons

There is some justification for including non-recurring costs for the solar systems only, in view of the multiple-mission usefulness of the same nuclear systems, e.g., interplanetary as well as various earth orbits, while solar systems must generally be redesigned for each mission. Even so, on the basis of these direct subsystem cost comparisons, the nuclear systems are predicted to remain more costly. However, as will be seen in Section IV, this may no longer be true on a system level, where differing methods of cost accounting may be applied to the two systems.

In general, however, with the new high-efficiency nuclear systems the cost differences will be considerably narrowed, such that these could readily be counterbalanced by the increased performance of the nuclear-powered spacecraft, which can be converted to a net economic benefit to the overall system.

III. Synchronous-Orbit Communications Satellite

1. Satellite Design Approaches

In reference 2, a comparison between solar- and nuclear-powered versions of a synchronous-orbit commercial communications satellite is described. The baseline solar satellite, shown in Figure 3, contains 24 C-band transponders and is designed for launch on the uprated Delta 3914.

Figure 3: Solar-Powered Domestic Communications Satellite

A preferred nuclear version has almost the identical external configuration, minus the extended solar arrays, and without the mirrored equipment radiators seen in Figure 3. Internally, however, the two designs are substantially different. Figure 4 shows the Rankine system equipment contained within the spacecraft envelope. The power-conversion system radiator operating at a nominal temperature of 104 F is used as the external skin of the spacecraft. The radiator is constructed of an aluminum honeycomb sand-

wich within which the condenser flow tubes are embedded. The external beryllium face sheets of the sandwich are coated uniformly with silver-on-tylon thermal-control material. All equipment is mounted to the internal walls of the radiator honeycomb panels.

Figure 4: Integrated Nuclear Design; Organic-Rankine Powered

Figure 5 shows the equipment mounting locations and basic structural truss-work. All of the electronic housekeeping modules are mounted on the walls opposite the heat source and turbo-alternator-pump assembly, effectively balancing the spacecraft for the spin-injection maneuver.

Figure 5: Equipment Mounting and Structure; Integrated Nuclear Design

A major advantage of this integrated power system/equipment radiator approach is the largely automatic control of equipment temperature which is achieved thereby. This is illustrated in Figure 6, where the maximum variation of radiator temperature is seen to be between 80 and 104 F, for the greatest thermal input and RF output variations expected to be encountered. This may be compared to the temperature variation of the solar-powered design shown on the figure; 20 to 110 F. In this case, the minimum temperature figure can only be maintained by heater-thermostat sets at critical locations, mainly on the east-west faces containing most of the housekeeping equipment, but also on the hydrazine propellant tanks and lines. It should also be noted that the life-limiting batteries of the solar-powered design, which require a separate thermal control region and heaters, are eliminated in the nuclear-powered version.

Figure 6: Maximum Temperature Variations; Integrated Nuclear & Solar Satellites

2. Power, Weight, and Economic Comparisons

The comparison of the two designs is based on detailed consideration of subsystem differences, which are believed to be more significant than the absolute values of subsystems weight and power. Nevertheless, the absolute values are based on a highly detailed preliminary design for the solar-powered spacecraft, from which the nuclear-powered design was derived.

This comparison is illustrated in Figure 7. On the left the power-consumption budgets are shown. Major differences in power consumption are seen to occur in two areas: in the thermal control systems (TCS) and in the electric power control and distribution (EP&D) systems. Reductions in the former are due mainly to the elimination of most of the thermal-control heaters, as discussed above. Most of the power consumed by the EP&D system in the solar-powered design is dissipated in power regulation equipment for the heaters and for battery charging. A large portion is consumed by the power cable extending to the solar arrays and to and from the battery bus.

Most of this is eliminated in the nuclear design, where the output of the Rankine system alternator is regulated at the source. The power consumed by the communications payload is the same in both designs.

Figure 7: Commercial Communications Satellites: Power & Weight Comparisons

The net result is to require some 15-percent less power in the nuclear version as a result of a greater than 50-percent reduction in the housekeeping load. This in turn leads to the weight distribution shown on the right side of Figure 7.

Structurally, the two designs are virtually identical. However, the external panels, normally assigned to structure, now include the radiator of the Rankine system. This combination of structural functions results in a small but significant weight saving. Other weight savings result from reduction of power harness length, EP&D equipment, and the solar-array drive assembly (assigned to ACS). (Although removal of thermal control heaters results in substantial reductions in power consumption, the weight reduction is minimal, and compensated by added requirements for thermal control surface material.)

The net result, however, is that the nuclear-powered spacecraft has some 75 pounds of additional weight margin. Each system will make use of such an added weight capability in the way which enhances the quantities most sought, e.g., reliability, lifetime, output power, or others. In the case of a commercial satellite, this quantity is profitability. In a separate study⁸, it was determined that, for the satellite in question, this quantity is most enhanced by adding propellant for stationkeeping, thus extending the useful lifetime of this satellite.

Used in this manner, the 75-pound weight advantage can result in three additional years of useful satellite lifetime, which can have a substantial impact on the revenue produced by this satellite. This is illustrated in Figure 8, where the right-hand scale

shows the present value of expected revenue assuming an average revenue of 1-million dollars per year per transponder. The scale is based on a 10% per annum discount rate and assumes that individual transponder failures occur at statistically-predicted intervals.

Figure 8: Lifetime/Revenue Comparisons

Thus, compared to a conventional- or violet-solar cell-powered spacecraft, the revenue advantage of the nuclear spacecraft can be of the order of tens-of-millions of dollars. Compared to the most advanced solar system, assuming nickel-hydrogen cells as described previously, this advantage can still be several million dollars, or well in excess of the projected cost differences between these two systems.

This serves to illustrate how, in the framework of an operational system, the performance advantages of an advanced nuclear system can result in a substantial economic benefit to the deployment of such a system.

IV. Navigation Satellite System

1. System Background Summary

The "Navstar" Global Positioning System (GPS) is a useful example of an operational system in sub-synchronous, non-equatorial orbit. This is a joint AF/USN-sponsored system, designed to provide navigation information (position and velocity) to any suitably-equipped receiver anywhere in the world. The active portions of the system consist of satellites and ground stations. The satellites will fly in 12-hour orbits at 63-degree inclinations in three orbital planes, separated by 120-degrees. It is planned that 8 satellites will occupy each plane. There will be a master ground station and a number of other ground stations to monitor the satellites and update their ephemeris and clock data. Users will be equipped with receivers and interpreters of varying cost and complexity, depending on accuracy and type of information needed.

GPS is designed to upgrade existing military (and civilian) navigation capability in three significant ways:

1. Continuous global coverage
2. Greater accuracy and more information
3. Availability to small mobile users, e.g. aircraft, tanks, and ground forces.

Item 3 requires that enough power be radiated by each satellite to be usable by receivers with small non-directional antennas.

The Phase-I satellite, currently in development, is a body-stabilized solar-cell powered system launched by the Atlas-F booster and a new orbit-transfer stage. Although the experimentally-oriented phase-I mission objectives can be satisfied with a marginally-powered system it is expected that more RF power will be desired for later phases of the program. A radiated power increase of several dB may permit significant expansion of the user population, thus providing the potential economic incentive to increased performance.

2. Baseline Solar-Powered Design

Because this study was performed prior to the availability of reference solar-powered design, it was necessary first to generate such a design in order to have a comparative basis. This was done to a highly preliminary order, with emphasis on defining the attitude- and reaction-control systems and the SEPS, since these were the subsystems expected to undergo major revision in the transition to a nuclear-powered satellite.

In addition to the orbital requirements, three major constraints influence the design selection:

1. requirement for earth-center directed antennas,
2. desire to maximize RF output power,
3. Atlas-F weight limit.

This inevitably results in the selection of a body-stabilized spacecraft with independent orientation of either solar array or antennas.

Due to natural regression of the orbit planes and motion of the earth around the ecliptic path, the angle between the sun line and the orbit-plane-normal changes continuously over the year. Any attitude control system, therefore, will require 4 separate control channels distributed in some fashion between the solar array steering and the antenna bore-sight steering. At least one moving mechanical assembly is required to decouple the antenna from the solar array axis. Figure 9 shows a design approach using a rotating RF joint which allows the use of a single (fully redundant) bias-momentum wheel rather than a heavier 3- (or 4-) wheel system. In this approach, the momentum wheel is used to stabilize the solar-array plane by directing its axis at the sun.

The antenna is pointed toward the earth by rotating it around an axis orthogonal to this wheel axis while varying wheel speed and hence spacecraft attitude around the sun-line axis. The spacecraft rotates about the wheel axis once per orbital revolution. The momentum wheel is precessed to follow the sun with seasonal variations (~ 1 deg/day).

Figure 9: Solar Baseline Conceptual Design, Bias Momentum Approach

Clearly, other design approaches are possible, and may be preferred following a more detailed consideration of other system factors. However, these should not be expected to result in significantly simpler or lighter attitude and reaction control subsystems. These are estimated to weigh 86 and 40 pounds respectively (dry weight) including redundant sun and earth sensors and also including the RF despin motor and drive. Propellant requirement was estimated at 44 pounds, with 30 pounds used for an initial orbit velocity correction of 200 ft/sec.

A major advantage of this design approach is the simplification of thermal control. The four spacecraft faces which are orthogonal to the solar array plane are continuously kept parallel to the sun line. This should permit the use of a passive thermal control subsystem, i.e., without louvers and with a minimum of heaters.

The solar-array/battery subsystem weight and power estimates were based on aluminum honeycomb panel construction using either standard n-on-p solar cells or the newer violet cells with 30% increased output. Panel weight is 0.7 pounds/square foot, with 5-year array output of 5.5 and 7.1 W/ft² for the two types of cells. Battery weight was calculated based on standard Ni-Cd cells with 60% depth of discharge (DOD). The weight of nickel-hydrogen cells was also estimated, using 85% DOD.

The weights and power requirements of other subsystems were, in general, not independently determined, but were based largely on information supplied by the GPS program office at USAF/SAMSO.

3. Nuclear-Powered Design Alternatives

Elimination of the need for solar-array pointing opens up the possibility of various system design approaches which are foreclosed to the solar-powered spacecraft. Figure 10 shows four attitude control options, and the weights and power requirements estimated for each, based on a nuclear system. While the two on the right side of the figure can be used with both solar and nuclear designs, the two options on the left can only apply to nuclear-powered systems within the given orbit/weight limitations.

Figure 10: Attitude Control Options For GPS Satellites

The gravity-gradient approach was determined to require the double-V boom configuration illustrated in order to achieve an attitude predictability of ± 1 -degree relative to the antenna boresight, with oscillations of ± 1 -degree. This leads to the somewhat higher weight estimate for this system than may be otherwise anticipated. However, the cost and reliability advantages of a gravity-gradient system make it worthy of further consideration, including a more exhaustive exploration of simpler boom configurations.

The possibility of a nuclear spinner has not been previously explored, to the knowledge of the authors. However, it offers the possibility of various simplifications of sensor and thruster technology well-known from the previous spinner designs, leading to the very favorable weight and power estimates shown, including the weight penalty assigned to the RF despin joint. Its cost is also likely to be substantially lower than either of the three-body control systems. When used with the Organic Rankine system, it offers the added advantage of an artificial g-field to assist in boiling and condensing heat transfer.

Figure 11 shows a preliminary sketch of an integrated-radiator nuclear spinner design, clearly derivative from the synchronous-orbit communications satellite. Its length has been increased to accommodate the added power capability of this design, as seen below.

Figure 11: Nuclear Dual-Spin Conceptual Approach With 800 W(E) Organic Rankine System

4. Weight and Power Comparisons

Figure 12 shows weight and power distributions for the baseline solar satellite and the nuclear spinner design. A total weight of 800-pounds, excluding the AKM, has been used as the design limit. As seen from the left side of Figure 12, the major weight savings for the nuclear approach results from the attitude/velocity control system. Other reductions in structure and electric power and distribution subsystems have been estimated based on the commercial commsat design experience. An increase in the navigation payload weight was estimated from the weight of additional amplifier stages required for the added output power.

Figure 12: Nuclear vs. Solar Powered GPS Satellite

From the weight estimates, approximately twice as much weight is available for the nuclear system, as compared to the solar system. This leads to approximately twice the prime DC output power as seen on the right side of Figure 12. Considering reductions in housekeeping power requirements, mainly in AVCS, EP&D and battery charge loads, the power available for the navigation equipment is almost 3.5 times greater in the nuclear-powered version.

The potential improvements offered by violet cells and nickel-hydrogen batteries are also shown on Figure 12, as is the reduced power capability of the nuclear version if an all-aluminum radiator structure is substituted for the aluminum-beryllium design described previously.

It has been assumed in this analysis that all of the additional weight margin of the nuclear design is invested in added electrical power. This may in fact not be the most economically effective use of this resource. It is probably the highest cost use, and if user requirements can be satisfied at a lower level of output power, this weight advantage may be used to increase system reliability and mean-mission-duration, for example. Obviously, the proper apportionment of this weight resource should be the subject of an overall system economic-benefits analysis.

5. Cost Studies

Development and recurring costs of both solar and nuclear designs were calculated from the SAMSO Cost Model, 1973 Update, for all subsystems except the nuclear power system. The latter cost was based on contractor cost estimates and on the current and projected fuel costs, as previously discussed. While the development costs of these systems are frequently underestimated, the recurring costs are believed to be fairly accurate, particularly as these are usually dominated by the fixed fuel costs.

The results, shown in Figure 13, illustrate how the cost of the nuclear spacecraft can vary from almost one-million dollars less than the solar baseline design to as much as 3-million dollars more, depending on desired RF output power, and on designated fuel costs.

Figure 13: GPS Spacecraft Recurring Cost vs. Power

The surprising conclusion that the nuclear spacecraft can cost less than the solar design with corresponding performance, or can produce from 1-to-3 dB more RF power at equal unit recurring cost, comes about from several factors:

1. The direct-charge recurring costs of the dual-spin ACS/RCS is estimated to be approximately \$700,000 less than the solar three-axis system. When program-level costs and burden factors are included, this results in a net difference of over 2-million dollars from this factor alone. (This conclusion, based on the SAMSO cost model, was largely verified by reference to more recent cost estimates of specific 3-axis spacecraft designs not included in the cost model.)

2. The nuclear system was treated as a sub-contract procurement, with only approximately half the program-level and burden factors applied, as specified in the cost model. This is justified by virtue of the fact that the nuclear system cost estimates already include full program-level and burden factors as required of a sub-contract procurement item.

3. The nuclear fuel costs were treated as a totally unburdened direct charge.

Figure 13 illustrates that the minimum-cost nuclear design should be based on aluminum structure up to its maximum weight-limited capability, with beryllium used if more power is desired. It should be noted, however, that this trade only involves power system (and structural) cost variations. A complete economic-benefits analysis could well result in a conclusion calling for beryllium structure throughout, with the added weight margin invested in other subsystems.

V. Conclusions

- It has been demonstrated that nuclear-powered spacecraft based on the Organic Rankine power-conversion system can offer increased performance in earth-orbit applications compared to solar-powered spacecraft with the most advanced solar-array and battery technology now foreseen. For operational systems, this increased performance can be translated into direct economic benefit by improving the system characteristic most highly leveraged; e.g., mean-mission-duration or radiated output power.
- Comparisons of solar- and nuclear-powered spacecraft must be based on overall systems evaluations rather than on power subsystems alone. Changes in other subsystems, or in the basic design approach, which is made possible by the nuclear power system, can result in net savings in power and weight of the overall spacecraft system.
- Although radioisotope power system costs are expected to remain higher than solar power system costs for the foreseeable future, in certain cases overall system costs can be comparable or even lower for the total nuclear-powered spacecraft, leading to a trade-off between system cost and system performance.

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