NUCLEAR APPLICATIONS IN MANNED SPACE STATION

W. A. Brooksbank, Jr.
Manager, Space Station Program, MSFC

G. J. Sieren
Systems Engineer, Space Station Task Team, MSFC

ABSTRACT

Current and future NASA Space Station studies will place a great deal of emphasis on economical systems which can start small and grow as the station itself grows. Space Station Electrical Power Systems based on nuclear sources will have to be increasingly adaptable to the lower power ranges to be competitive with other systems, while at the same time exploiting their inherent growth capability. Power growth capabilities as high as three of four-to-one will be required to meet the needs of a space station which is initially manned with a small crew and grows incrementally to a large station capable of accommodating a very complex experiment program.

The zirconium hydride reactor, coupled to a thermo-electric or Brayton conversion system, and the Pu 238 isotope/Brayton system, are considered to be the viable nuclear candidates for the Modular Space Station Electrical Power System.

This paper reviews the basic integration aspects of these nuclear electrical power systems, including unique requirements imposed by the buildup and incremental utilization considerations of the modular station. Also treated are the various programmatic aspects of nuclear power system design and selection.

INTRODUCTION

Nuclear devices of various types have played an important role in numerous NASA space missions over the last decade. These applications have ranged from use of nuclear materials to measure heat shield ablation during early nose cone reentry tests, to the relatively large and complex SNAP 27 generator used on the Apollo moon missions.

In the late sixties a new and prime candidate for the use of nuclear power appeared on the horizon. This application has been studied under the various names of Manned Orbiting Laboratory (MOL), Manned Orbital Research Laboratory (MORL), Earth Orbiting Space Station (EOSS) and, lately, simply the Space Station. In January 1971 NASA formally completed the Phase B (Preliminary Design) study of the 33-foot diameter Space Station. This station, with a 10-year lifetime, 1975-78 initial operating capability (IOC), 12-man crew, and 25-30 Kwe power requirement, was a prime candidate for the application of nuclear electric power, and the two parallel Phase B studies emphasized definition of the large isotope and reactor power systems in addition to solar array system.

Several factors influenced NASA to discontinue effort on the 33-foot diameter station and turn instead to the concept of an evolutionary modular space station consisting of several modules delivered to orbit by the space shuttle and assembled on-orbit to form an integrated space station. Among these factors were the suspension of Saturn V production, increased shuttle utilization and the overriding consideration of minimizing funding for the space station in the early years of the program.

In addition to meeting the requirement for low initial funding, the modular concept also lends itself well to early use of the station through incremental manning. Although the modular station concepts now under study have the capability of growing to the equivalent capability of the 33-foot diameter space station, they are intended for manning and limited experimental work at the intermediate levels of three and six man crews. Thus, the six-man modular station has come to be known as the Initial Space Station (ISS); the twelve-man version is known as the Growth Space Station (GSS); and the three-man version if known as the Initial Space Station with incremental manning. Representative modular stations are shown in Figures 1, 2 and 3.

The two primary areas of interest for nuclear applications are the electrical power generating system and the process heat generating subsystem of the environmental control and life support (EC/LS) system. The electrical power system (EPS) will be treated in more detail below. Before discussing these applications, however, it is useful to review the mission requirements of the modular space station as they affect the selection of subsystems for which nuclear applications are candidates.

INITIAL SPACE STATION (ISS) WITH INCREMENTAL MANNING

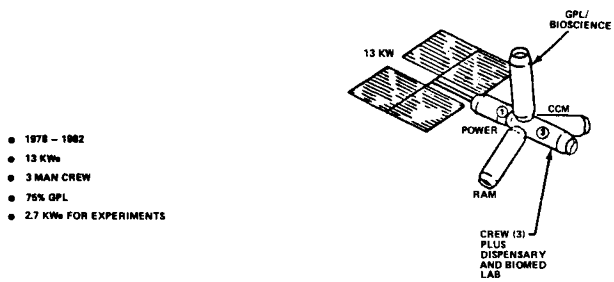

FIGURE 1

GROWTH SPACE STATION (GSS)

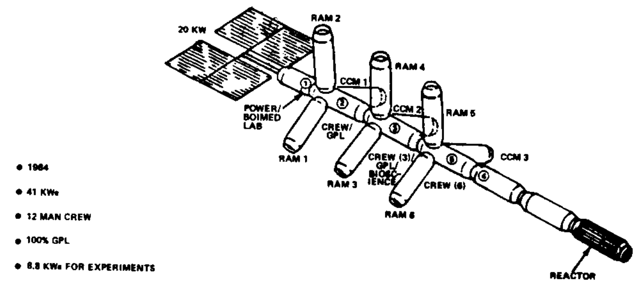

FIGURE 3

INITIAL SPACE STATION (ISS)

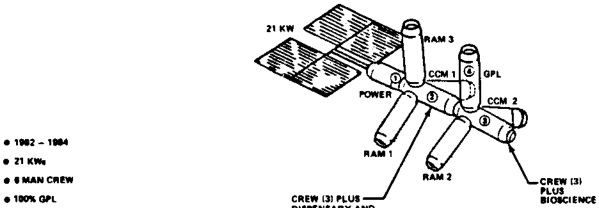

FIGURE 2

MODULAR SPACE STATION REQUIREMENTS

A minimum cost ISS which in addition minimizes early development costs yet meets the mission requirements and is designed to allow efficient expansion to at least the equivalent capabilities of the 12-man, 33-foot diameter station is a primary consideration. Although the IOC date for the ISS is later than for the original 33-foot station, thus allowing more time for development of technology, the cost constraints imply less optimistic technology advancements over this period, thereby reducing the development risk that can be tolerated. The 10-year mission lifetime constraints imposed on the 33-foot space station have now been broken into time periods at various manning levels. One timeline under study retains the 3-man level for four years, 6 men for two years, and finally reaches 12 men in 1984. With a maintenance philosophy permitting the addition or replacement of entire modules, subsystem lifetimes are less related to mission lifetimes. It is conceivable that mission lifetime will exceed ten years, depending only on how much of the NASA Blue Book experiment program NASA is able to accomplish and funding available. Even with an indefinite mission lifetime and the capability for module return/refurbishment, long life subsystems will still be required, but this constraint is somewhat softer than it was for the 33-foot station.

Mission flexibility, in terms of one design accommodating a variety of missions such as polar, synchronous, lunar and low earth orbits, has been reduced for the modular space station program. This implies that development costs for the station will be written off against a smaller number of missions and tends to favor those subsystem approaches which have a lower non-recurring to recurring ($\frac{NR}{R}$) cost ratio.

The space shuttle has a significant impact on the modular space station program. Besides module weight and volume constraints, the shuttle has a direct impact on such things as resupply, maintenance philosophy, and even subsystem selection. The degree of EC/LS loop closure is a strong function of the cost per pound for delivering expendables and other supplies to orbit. High resupply costs tend to favor subsystems with low resupply requirements. Current values being used for maintenance launch cost vary from $140 to $250 per pound delivered to orbit.

The requirement for artificial-g, which was a particularly strong configuration and subsystems selection driver on the 33-foot station, has not been retained in the modular space station program.

In the 33-foot diameter space station study, commonality meant commonality of the space station structures, subsystems, etc., to those of the fifty-man space base and the Mars interplanetary mission. As it is being developed in the modular station study, commonality has a dual meaning: commonality of structures and subsystems of the modular space station with those of the research and applications (RAM) experiment modules and the crew/cargo module; and, secondly, structural and assembly level commonality between the various modules of the modular space station itself.

The requirement for flexibility in crew manning level imposed on the modular space station results in a variable electrical power requirement. Figure 4 shows an early estimate of power required at various times in the mission. As compared to the 33-foot station, the electrical power requirements have increased due to the dispersed configurations of the modular space station, revised Blue Book experiment electrical power requirements, and changes in subsystems requirements such as limiting the cabin CO_2 partial pressure to 3 MM of mercury as opposed to 4 MM. The 1984 12-man growth version of the modular space station, although equivalent to the 12-man, 33-foot diameter station in its ability to conduct experiments, will likely have an electrical power requirement in excess of 40 Kwe.

The 33-foot station was somewhat limited in radiator area available, and was only marginally capable of satisfying both the EC/LS and primary electrical power system requirements without utilizing more extreme measures such as deployable radiators. The large amount of surface area available on the modular stations relieves this problem.

POWER REQUIREMENTS

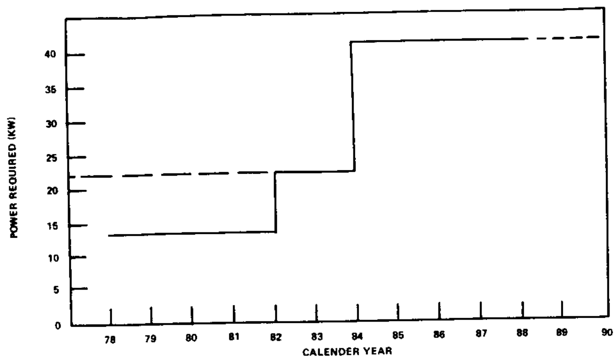

FIGURE 4

Aerospace nuclear safety, while still an important consideration, has been shown in the recently completed 33-foot space station Preliminary Safety Analysis Report (PSAR) to have a less significant impact than previously anticipated. Although the systems sized were one-to-two orders of magnitude larger than present systems, it has been shown that the mission risk attributable to these large systems can be reduced to the level of that for systems previously flown.

These are the mission requirements for the modular space station, summarized in Figure 5. They exert a strong influence on subsystems selection and design.

MODULAR SPACE STATION
REQUIREMENTS SUMMARY

- COST
  - DEVELOPMENT
  - TOTAL PROGRAM
- DEVELOPMENT RISK
- MISSION FLEXIBILITY
- SPACE SHUTTLE COMPATIBILITY
- ZERO-G
- MISSION LIFETIME
  - ISS (INCREMENTAL MANNING)
  - ISS
  - GSS
- COMMONALITY
- POWER LEVEL

FIGURE 5

CANDIDATE POWER SYSTEMS/GROWTH OPTIONS

The applicability of nuclear power candidates to the modular space station will now be examined. Due to the intimate relationship between the issue of which of the candidate systems to consider and the growth options that exist for each candidate, these subjects will be discussed together. Furthermore, past studies have indicated that from the standpoint of vehicle integration, the real issue in nuclear electrical power system definition and comparison is the energy source itself, and that the choice of a power conversion system is somewhat of a second order consideration. Nevertheless, certain energy source/conversion system combinations have classically been linked together, as shown in Figure 6. The growth options for these electrical power systems are shown in Figure 7. Based on considerations of lowest initial development cost, development risk, initial and maintenance launch weight, and general suitability in satisfying the mission requirements, only Options 1 to 3 have been retained for further consideration in the modular space station study.

MODULAR SPACE STATION
POWER SYSTEM CANDIDATES

- SOLAR ARRAY
- ISOTOPE – BRAYTON
- REACTOR – THERMOELECTRIC
- REACTOR – BRAYTON

FIGURE 6

Option 1 typically uses a minimally sized array for the ISS in the 1978-82 period, but with booms, structures, gimbal drives, etc., sized to accommodate a slightly larger array with which it could be replaced for the 1982-84 period. Two of these arrays, one at each end of the station, provide the required power for the 12-man GSS in Option 1. Option 3 would typically start (1978-84) as in Option 1. In the period 1982-84, however, a 20-40 Kwe reactor system would replace one of the arrays and the other array would be retained as the backup system. In this option the solar array backup system pays its way, so to speak, by providing primary power for a period of time and its development cost as a backup to the nuclear reactor need not bias the nuclear system cost comparison.

POWER SYSTEM
GROWTH OPTIONS

OPTION	INCREMENTAL MANNING (3)	ISS (6)	GSS (12)
1	SA ⟶	⟶	⟶
2	SA ⟶	⟶	IB
3	SA ⟶	⟶	Rx/TE OR Br SA BACKUP
4	IB ⟶	⟶	⟶
5	Rx/TE OR Br SA BACKUP ⟶	⟶	⟶

FIGURE 7

Option 2 is considered to be a somewhat unlikely candidate whose position could only be improved upon by significant changes in mission requirements such as reinstatement of artificial-g requirements or the requirement for commonality with some other mission for which it is desired, such as the Mars interplanetary mission.

With this initial selection of power systems and growth options as a function of modular station buildup, the evaluation process can continue by the application of tradeoff criteria such as those derived for electrical power system evaluation in the 33-foot space station study, to each specific option. However, it is beyond the scope of this dissertation to evaluate these criteria for each power system. Rather, we would prefer to make selected comments about how the various options fit into the modular space station program.

MODULAR STATION ELECTRICAL POWER SYSTEMS

Solar Array/Battery System: It is pertinent to the present discussion to evaluate the technical and programmatic implications of the use of a solar array system on the initial modular space station and to evaluate the by-product benefits to a later, add-on nuclear system. The solar array/battery system is significant since, if used as a primary power system on the initial station, it may serve as the backup electrical power system when a nuclear reactor is added, provided that the end-of-life output of the array is sufficient. The characteristics of this system are shown in Figure 8. Such a system might cost from $40 to $100 million dollars, with the low end of the range corresponding to a rigid Skylab-type array and the upper estimate resulting from advanced,

INITIAL SPACE STATION (ISS)
SOLAR ARRAY- BATTERY CHARACTERISTICS

ARRAY

- 6.0 WATTS/FT^2 (ORBIT AVG.)
- 2 AXES ORIENTED (± 10° ACCURACY)
- 0.3 LBS/FT^2
- 11% EFFICIENCY CELLS
- 5% DEGRADATION/YEAR
- 3–5 YR. LIFE

BATTERIES

- 100 AMP. HR. CAPACITY
- NICKEL-CADMIUM
- 30% DEPTH OF DISCHARGE
- 12–20 WATT-HOUR/LB
- 1 YEAR LIFE

SYSTEM (15 kWe)

- \$100 M (\$40 M, NO NEW TECHNOLOGY)
- 4500 SQ. FT. (3.33 WATTS/FT^2)
- 11,000 LB. (1.36 WATTS/LB)
- LOW DEVELOPMENT RISK

FIGURE 8

flexible roll-up arrays and increased capacity battery technology and development. An advantage of this system is its cost flexibility, enabling it to conform to varying budgetary constraints. Cost sensitivity analyses conducted in past studies have indicated that solar arrays are more sensitive to high power levels than the nuclear systems. This is due to two factors. First, the recurring costs for solar arrays are a near-linear function of array size. Secondly, the non-recurring costs increase rapidly for very large arrays due to the introduction of new technology. These factors are strong drivers toward use of a nuclear system for the GSS.

Past studies have also shown the solar array system to be the lightest by a comfortable margin. For the modular space station, however, the requirement for launching the arrays on a power module in a single shuttle payload will diminish that margin. If the batteries are kept centrally, in the power module, the supporting active cooling system with its radiators and other structures may also be charged to the system weight.

The relatively large maintenance launch weight required for the solar array system wipes out any initial weight advantage. This is largely due to frequent replacement of the batteries used for peaking and darkside operation, and an estimated three to five year replacement cycle for the array itself. Here again, the desirability of replacing the array with a nuclear reactor three to five years into the mission is clearly indicated. Just as the initial solar array became the backup to the reactor when it was added and in so doing eliminated that cost penalty, so can an advantage be realized in use of the solar array for primary power in the first three to five years of the mission, thereby eliminating the cost of replacing the reactor.

Isotope/Brayton System: It is difficult to evaluate the role of the isotope/Brayton system in the modular space station program. Those particular constraints which made the system attractive from the mission/systems integration viewpoint on the 33-foot station are lacking in the modular station program. Artificial-g requirements have been removed. Commonality with the Mars interplanetary mission module with implied writeoff of development cost has been deemphasized. In turn, significant unfavorable programmatic impacts associated with use of an isotope heat source are becoming apparent. Early commitment to a large fuel development and procurement program, involving extensive new processing facilities, is required to meet 1978 launch dates. The long lead time projected for fuel production implies a slow response to increased or decreased requirements late in the program; a significant disadvantage on the modular space station with its requirement for high flexibility in buildup and growth. A higher safety-risk-to-capability ($\frac{SR}{C}$) factor is indicated for the large isotope source as compared to the nuclear reactor.

On the other hand, with the exception of the radiator interface, the physical integration of the Isotope/Brayton system results in less impact on other station subsystems than either solar arrays or reactor systems. The external station configuration impact is minimal. The system is more amenable to IVA or shirtsleeve maintenance. The major areas of interface impact are in the ground handling, launch and recovery phases of the mission, as there must be a constant heat dump after the source is assembled. This requires extensive ground support equipment (GSE) for cooling and monitoring status in the launch, prelaunch, and recovery phases of the mission. Studies to date have indicated that credible backup heat dump modes are a problem to design. For the 33-foot station, the solution to this problem involved a meltdown of the multiple layer insulation between the heat source and shield, followed by a meltdown of the shield itself, enabling the heat source to radiate its heat directly into the subsystems compartment. The redundant heat dump problem is particularly critical for the recovery phase of the mission in which the heat source must be transported in the shuttle.

System characteristics for a nominal 15 Kwe unit are as shown in Figure 9. For higher power levels multiple units would be required, as this is about the largest system one could conceivably use.

Isotope/Brayton system costs are very sensitive to high power levels as compared to reactors, although not as sensitive as solar arrays. The system has a fairly large non-recurring to recurring cost ratio and the recurring cost is a linear function of power output. These recurring costs can be reduced by about one-third if the

MODULAR SPACE STATION
ISOTOPE/BRAYTON SYSTEM CHARACTERISTICS

HEAT SOURCE

- 52 KW_t/14.9 KWE SYSTEM
- PU-238
- 1900° F OPERATING TEMP.
- 10 YR. LIFE ASSUMED

SHIELD

- 5,500 LBS. LiH + TUNGSTEN

BRAYTON CONVERSION

- 1600° F TURBINE INPUT
- 63 FT^2/KWE RADIATOR AREA
- 32% EFFICIENCY
- GAS-BEARING BRAYTON "B" ENGINE
- 2 1/2 YR. LIFE ASSUMED

SYSTEM (14.9 kWe)

- 16,970 LB. (0.88 W/LB.
- 938 FT^2 RADIATOR
- 28.6% SYSTEM EFFICIENCY

FIGURE 9

fuel can be rented and/or costs prorated over the isotope's 86-year half-life. However, as system size increases this practice becomes less credible.

Although relatively light in weight and requiring minimum maintenance launch weight, the isotope/Brayton system weight is quite sensitive to higher power levels. Again, the relationship is near-linear. The initial system weight is also sensitive to separation distance and fuel purity.

The development risks of the isotope/Brayton system are hard to assess. Although the turbine inlet temperatures run to 1600°F and the air-bearings are definitely new technology, initial performance of the conversion subsystem has been better than projected. The high (32%) cycle efficiencies demonstrated in relatively short term (2,000 hours) tests are remarkable for space-applicable systems. The endurance test results are awaited for projection of degradation rates. The disturbing factor with dynamic conversion subsystems is the number of series elements with single point failure possibilities in an individual conversion subsystem coupled with the expense involved in demonstrating the reliability and production uniformity of a statistically significant number of flight-type units. Present implementation schemes usually have two or three redundant conversion subsystems on hand as installed or stored spares. This is at best an optimistic approach for the first use of such a system in a five or ten year mission. If the system may be maintained in space, even by complete conversion system replacement, relatively significant problems, apparent late in the program, may be tolerated by earlier-than-planned replacement. However, maintenance weight-to-orbit, on-orbit replacement manhours and launch costs must be considered soft constraints.

The heat source is vulnerable to questions concerning development risk. The long term, slow response processing chain for the fuel is significant in considering fuel availability for the development program. Of greater concern is the capability to track changes in station power requirements as the program evolves. Unless large quantities could be stockpiled without prohibitive costs, the real possibility exists in having to launch a power-limited space station. If net conversion system efficiencies change, due to larger heat leaks, parasitic loads of redundant supporting subsystems, or larger-than-expected degradation in heat transfer elements or machine efficiencies, the required power would not be available from a relatively fixed fuel quantity, sized several years previously. If power requirements increase and system net efficiencies do not, a hard power level constraint exists. A backup development option should be retained to decrease the program impact in case this should happen.

The isotope heat source design, although static in nature, operates at 1600°F to 2000°F. The probability of materials problems is high. The reduced selection of materials with which to evade problems is considered a hard constraint softened only by unpredictable development times. This risk can be assessed by implementation of a representative source and endurance testing.

The isotope/Brayton system, although not as well suited to the mission requirements of the present modular space station as it was to those of the 33-foot station, is still a viable candidate for this type of long-life mission. With a reinstatement of artificial-g requirements and reemphasis of commonality with 50 years of NASA missions, its relative position could be significantly improved.

Nuclear Reactor Systems: The modular space station concept might well have been proposed to exploit the nuclear reactor's best points, namely an insensitivity costwise and weightwise to high power levels. This system, as shown in Figure 7, forms the basis for meeting the electrical power requirements of the growth version of the modular space station under Option 3.

One of the primary disadvantages of the reactor system, as shown in the previous Phase B study, was the necessity of providing a backup power system. Under Option 3, the solar array which provides primary power to the initial space station is retained and fulfills this requirement.

Figure 10 shows system characteristics for the nuclear reactor and two candidate conversion sys systems. The two systems are very similar from the integration standpoint. Weight, cost and impact on other subsystems are very near the same. The separation distance required, heavy shields, non-redundant source and safety implications require special integration consideration. The main differences are in the required operating temperature and power level of the reactor. This leads to different system lifetimes, power growth capabilities, shielding weights, and separation distance requirements.

The potential for power growth within the space station's lifetime and the potential growth within reactor technology are the main advantages reactor systems offer. The initial investment in development and support equipment is large but the delta costs for growth thereafter are small compared to the other candidates.

Weightwise, the nuclear reactor is at a disadvantage, being the heaviest of the three candidates. However, this is partially offset by a low weight sensitivity at the higher power levels. The requirement for keeping shuttle launchable modules to 20,000 lbs requires launching the nuclear reactor in at least two modules, thus incurring a double launch penalty. At $250/lb each launch costs $5 million. Because of its initial weight the total weight-to-orbit is higher for the reactor also, for systems under 40 Kwe. The use of the solar array for primary power on the ISS could eliminate the need for replacement of the reactor if the mission lifetime was kept at ten years; however, it is likely that if the GSS is made operational in 1984, it will function beyond the 1988 point in time and reactor replacement would have to be considered.

MODULAR SPACE STATION
NUCLEAR REACTOR SYSTEM CHARACTERISTICS

	THERMOELECTRIC SYSTEM			BRAYTON SYSTEM			
	MINIMUM*		GROWTH**	MINIMUM		GROWTH	
ELECTRICAL CAPABILITY, KWE	29	29	41.5	29	29	43.5	53.5 43.5
REACTOR OUTLET TEMP., °F	1,200	[illegible]	1,200	1,200	1,200	1,200	1,300
REACTOR LIFETIME, YEARS	6.5	8.2	4.2	10	10	8.5	5.5
REACTOR POWER KWT	[illegible]	[illegible]	845	130	127	312	387
RADIATOR AREA, FT²	1,890	3,800	3,800	2,000	2,000	2,000	2,000
REPLACEABLE SYSTEM WEIGHT, LB.	26,750	27,770	27,770	24,016	26,016	26,016	26,016
SUPPLEMENTAL RADIATOR AREA, LB.	---	2,900	2,900	---	---	---	---
WEIGHT PENALTY FOR GROWTH, LB.	---	3,920		---		2,000	

*188 TE MODULES

**192 TE MODULES

FIGURE 10

MODULAR SPACE STATION
POWER SYSTEM COST COMPARISON

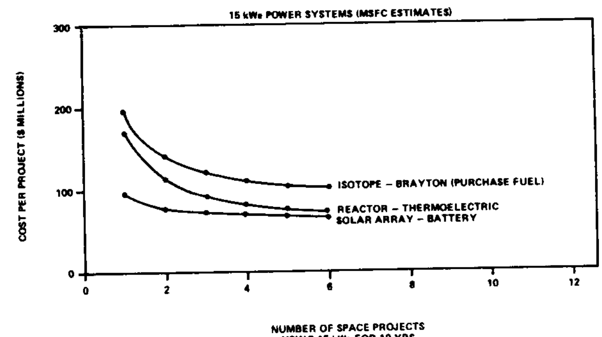

FIGURE 11

A major programmatic difference between the nuclear reactor system and the other two candidates is $(\frac{NR}{R})$ cost ratio. This ratio is much higher for the reactor, and has significant results. First, it means that for multiple applications, the total cost of using a reactor decreases in relation to the other candidates. As shown in Figure 11, at 15 Kwe no system is cheaper than the solar array, irrespective of the number of missions flown. However, as shown in Figure 12, for more than three 25 Kwe, 10-year missions, the reactor system costs less. Above 40 Kwe, the crossover occurs earlier and the reactor is cheaper from the very first mission. Secondly, a high $(\frac{NR}{R})$ ratio is desirable from the standpoint that whereas recurring costs involve large capital expenditures for materials, non-recurring costs provide jobs for people and expand technology—a preferable situation.

MODULAR SPACE STATION
POWER SYSTEM COST COMPARISON

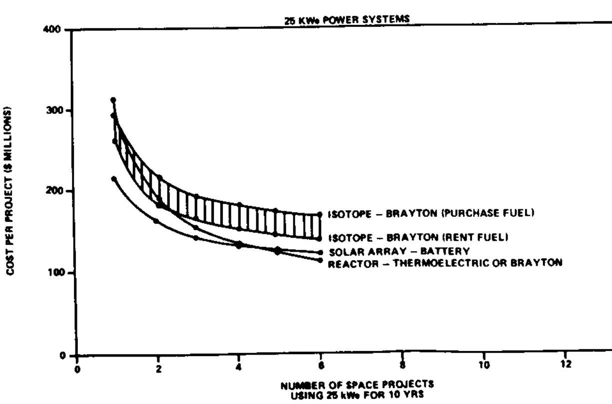

FIGURE 12

The development risks of the reactor systems vary according to the conversion system considered. Experimental and development models of the reactor have greatly contributed to mapping remaining development problems. Since remaining problems have "graceful" failure modes, the reactor would appear to be a small development risk for one to two years of operation. Due to development time available, the two year plus turn-around time in the problem-solution cycle is not as critical as when earlier station use was considered. The thermoelectric conversion subsystem appears also to have "graceful" failure or degradation modes. The temperature vs. performance vs. degradation characteristics appear to be amenable to statistical mapping so that once these trades are made, predictable performance can be expected. Although any higher efficiencies (5%) attained will be a function of success in the technology program, the flexibility of the reactor source, larger radiator area, and variations in system weight can be considered soft constraints for this subsystem.

The Brayton conversion system for the reactor source is in an anticipated development stage. If scaleup from the 2-15 Kwe machine to a 25-40 Kwe size is successful and if projected performance at reduced turbine inlet temperature is demonstrated, then comments before for the Brayton in the isotope/Brayton case are applicable here. Due to increased reactor problems at greater than 1100° - 1200°F, and due to Brayton efficiency or radiator problems below 1100° - 1200°F, the reactor and Brayton successful operation range do not overlap significantly. Higher maintenance weight-to-orbit, radiator area and cost are considered soft constraints in case a problem develops in this area.

CONCLUSIONS

The modular space station program is ideally suited to the application of nuclear power. While the impetus for this application is not present in the ISS to the degree that it was in the 33-foot station, certainly the growth flexibility and higher ultimate power levels required for the GSS support this conclusion. Many technical and programmatic advantages accrue which tend to make the overall consideration of nuclear power more attractive when growth options such as outlined here are considered.

The nuclear systems lack the experience under a variety of space flight conditions that would berequired to justify as low a development risk as for the solar array-battery system. However, contrary to the usual case, time can be considered somewhat of a soft constraint in solving the development problems of either system because of the evolving nature of the modular station itself.

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