

NUCLEAR POWER SUPPLIES: THEIR POTENTIAL AND THE PRACTICAL
PROBLEMS TO THEIR ACHIEVEMENT FOR SPACE MISSIONS

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ABSTRACT

This paper discusses various issues associated with getting technology development of nuclear power systems moving at a pace which will support the anticipated need for such systems in later years. The projected power needs of such advanced space elements as growth space stations and lunar and planetary vehicles and bases are addressed briefly, and the relevance of nuclear power systems is discussed. A brief history and status of U.S. nuclear reactor development is provided, and some of the problems (real and/or perceived) are dealt with briefly. Key areas on which development attention should be focused in the near future are identified, and a suggested approach is recommended to help accelerate the process.

BACKGROUND FOR A MANNED MARS MISSION: THE RELATIONSHIP OF POWER REQUIREMENTS TO OTHER SPACE POWER ACTIVITIES

The next major US program for the development of space infrastructure will be a manned space station scheduled to be operational in the early 1990's.^{1,2} The space station program will provide for an expandable manned facility to conduct scientific and commercial activities. The facility will be serviced from the Earth by the shuttle.

Envisioned is an evolving facility, increasing in capacity, features, and capability to support research and development activities, materials processing, and other tasks which are, or may prove to be, cost beneficially performed in the unique environment of space microgravity and near vacuum. Too, the space station is anticipated to serve as a key element to the expansion of space exploration and utilization, including the possibilities of establishing a manned base on the Moon and missions to Mars. As this evolution of the space station use occurs, the power requirements of the station, including the accommodation of future scientific and commercial activities, can reasonably be expected to grow. The basic question is simply how best to meet these future requirements in a timely, cost effective fashion.

The initial space station power requirements are projected to amount to a connected load of about 200 kWe, with peak loads in the 100-200 kWe range, average loads in the 90-100 kWe range, and with station keeping requirements amounting to 25-35 kWe. These ranges provide for 6-8 person crews and include the best estimates for the experimental and/or commercial tasks.³ The power source will be photovoltaics, the only available system capable of supplying this magnitude of power in the time frame desired. The magnitude of these power loads strains the applicability of photovoltaic systems--the systems simply become very large, constitute a real design concern, and are a serious constraint to future space activity expansion possibilities.

The second generation space station, although ill-defined at this time, is projected to require power levels in the range of 200-300 kWe. If space activities expand as might reasonably be expected, this modest growth in power requirements may prove to be seriously underestimated, particularly if commercial processing of materials proves viable. It would be unfortunate indeed if the horizons of space station activities were to become constrained by the lack of a suitable power source.

Establishing a manned base on the Moon or visiting Mars makes the power supply question even more serious. Both the Moon and Mars have day/night cycles to contend with and the solar source strength decreases with distance from the Sun. For the long-duration Mars mission, the choice of feasible power sources is very restricted. The power requirements for either of these two missions are unknown because the planning is in such an early state, but life-support and in-transit experimentation can be expected to be comparable to that of the space station, i.e., up to a few hundred kilowatts. If, in addition, nuclear electric propulsion is used, we might reasonably expect levels up to a few thousands of kilowatts.

The anticipated growth of the space station power requirements noted above provides a good example of the problem the space nuclear power supply developers have to contend with: should a reactor power supply be developed that attempts to be all things to all missions, i.e., is highly flexible in its ability to meet a wide variety of missions, or should the development of a reactor system await a specific mission definition and be customized to this mission? This leads, of course, to a chicken-and-

egg situation which will be addressed subsequently. Suffice it to say that, for power requirements of several hundreds of kilowatts or more, no nuclear power source exists or is even far enough along in the definition stage (much less the development stage) for NASA to reasonably assume probable availability within the next 10 years.

STATUS OF SPACE NUCLEAR REACTOR DEVELOPMENT

The history and status of space nuclear reactor development can be summarized quickly. In 1965 the US launched the SNAP 10A reactor system, a nominal 0.5 kWe power plant consisting of a zirconium hydride moderated, fully enriched uranium core, a beryllium reflector which contained control drums for startup in orbit, and a thermoelectric power conversion system mounted on a waste heat rejection conical radiator. The reactor was liquid metal cooled with pumping of the liquid metal by a electromagnetic pump. The power system was successfully launched into Earth orbit, started up, and operated for over 40 days with a performance level as designed and in accordance with an identical and simultaneously operated ground based system. Operation ceased upon the failure (suspected) of a voltage regulator.

Further launchings were postponed because of the lack of missions requiring the particular capabilities of SNAP 10A and because of the successful development of solar electric systems. The fact of the matter is that for the NASA or DoD applications of that era, SNAP 10A was unable to compete in a cost effective manner.

The development of the SNAP 10A and the associated engineering phases conducted for the 3 kWe SNAP 2, the 30 kWe SNAP 8, and the 50-100 kWe thermionic reactor systems resulted in a considerable amount of space-specific reactor system technology. These activities took place during the period from the late 50s to 1972, and the technologies included dynamic (turbine) power conversion systems, thermionic and thermoelectric conversion, shadow shielding, development of system and sub-system analysis techniques, compact reactor design and analysis, related launch and orbital safety aspects. In addition, an active program to develop a nuclear rocket for space propulsion proceeded through a relatively extensive experimental phase. These programs were all terminated at year's end in 1972.

The US renewed its' interest in space reactor power in 1981 with a modest study activity that has become known as the SP-100 program. The first objective of this program has been to reevaluate the competing technologies which might be capable of providing 100 kWe for periods up to 7 years in duration. To date the old technologies have all been revisited, evaluated in light of advances during the intervening years, and reduced to four candidate power conversion systems: in-core thermionics, Brayton cycle (expansion of a hot gas through a turbine), Stirling cycle (a reciprocating piston engine), and thermoelectrics. Selection of one of these systems took place in July 1985 and a Request for Proposal for the selected system development is to be issued.

A second space reactor program has only recently been initiated to develop reactor power systems for the Strategic Defense Initiatives program. This so-called multimegawatt program encompasses systems beyond the capability of the SP-100 project and includes nuclear propulsion as well. The program is classified and consequently its status cannot be presented here.

RESEARCH AND DEVELOPMENT REQUIREMENTS

The achievement of a successful space reactor program will not occur overnight. Considerable applied research and engineering development is required to advance beyond the achievements of the 1960's. This R&D encompasses many technology areas, will require the services of our "best and brightest," and will be expensive and time-consuming. The key areas and potential solutions are already identified, so the problem is not that of fundamental technical feasibility, but rather of conducting the systematic studies, experiments, breadboard testing, component prototype development and demonstration, and finally of building flight-qualified hardware.

Here, only a few key R&D areas are touched on, with a few examples to provide an indication of the types of issues being addressed (or projected to be within the immediate future).

It should be emphasized from the outset that the overriding consideration for the development of a space reactor power source is that the system must be safe. Safe means safe in every aspect: from construction and checkout testing, through delivery to the launch site, during launch and startup, throughout its useful life, and after shut-

down. This applies to the crew, support personnel, and the general public. Every aspect of the R&D is guided by this consideration. A safety record at least comparable to that of commercial power reactor program, which by any measure is unparalleled in the technologies of power generation, can and must be achieved.

For the reactor power source, the key areas requiring attention are fuels which: (1) can accommodate requirements in the event of a launch failure under worst-possible scenarios (e.g., immersion), and (2) will provide long life through the accommodation of fission products and the use of burnable poisons; mechanical/neutronic control systems which provide acceptable margins of safety and redundancy under all situations and which will operate reliably and accurately for long periods; cooling systems which will not introduce additional safety complexity, constitute a single point of failure, vulnerability, or require excessive power for achieving their function of maintaining system temperatures at design levels; neutronic shields which are light-weight and stable with regard to radiation damage; and overall reactor systems that are reliable in their operation and flexible with regard to their operational power level and longevity or which can accommodate changes in these parameters with a minimum of difficulty.

The general objectives for power conversion systems (PCS) follow the same line of thought: they must not constitute a compromise to safety at any phase of the mission, they must operate reliably for long periods under essentially maintenance-free conditions, they must be adaptable to a wide variety of mission-specific conditions and requirements, and they must be capable of power level growth with a minimum of system modification or flight requalification. These will be the governing principles, whether the PCS is a static (thermoelectric, thermionic), or dynamic (Brayton, Rankine or Stirling cycle) system.

As adjuncts to the PCS, electrical transmission to the payloads, power conditioning, and system control also require considerable attention. These areas are equally crucial to achieving attractive reactor-based power systems but are not considered to constitute limitations to feasibility. Power transmission includes laser, tether, or microwave options (allowing separation between the reactor power source and radiation-sensitive areas), all of which have appealing features on paper

but which also have significant problems to their practical realization. Highly efficient power conditioning, capable of accommodating a wide variety of operational conditions and high (for space) combinations of currents and voltages, will be required for the power levels of interest. System controls will likely be required to incorporate artificial intelligence in the form of a real-time "expert system", combining the desirable features of sophisticated process control with systems which will automatically detect, analyze, and correct disturbances using on-line fault-free analysis, faster-than-real-time predictions, and automated decision making.

In space, waste heat rejection can be accommodated by thermal radiation or very specific applications possibly by a mass loss means. Development of light-weight materials for radiators, geometrical configurations which change according to the amount of heat being rejected, and mass ejection devices are all under consideration, but the practical realization of any of the options at higher power levels is far from being clearly defined. Complicating the development is the strong interdependence between the amount of heat to be rejected and the design features of the rest of the system, including the payload requirements.

To repeat, these development requirements cannot be resolved overnight and will not be resolved within a time frame useful for a lunar base or Mars mission unless a broad and concerted technology development effort is soon undertaken. If the US is serious about establishing a meaningful space infrastructure beyond the space station and in making significant technological advances which unquestionably will have consequences far beyond just the space mission applications, then this commitment to development must be pursued. NASA must take initiative for this to happen.

THE REAL PROBLEMS OF DEVELOPING SPACE NUCLEAR REACTOR SYSTEMS

As NASA well knows and has experienced, the real problems of developing and delivering technologically advanced systems do not tend to be only technical in nature, but rather political and budgetary. The Manhattan and Apollo projects are good examples of the importance of these factors. Nuclear programs, in addition to these "normal" factors, must also contend with a further complexity: the perceived "safety" of anything having to do with nuclear-derived energy. As the civilian power

program in this and other countries have amply demonstrated, public participation in matters nuclear have become an accepted way of life. The nuclear community is well aware of this fact of life, and hence the previously stressed emphasis on ensuring safety through all phases of a nuclear system's lifetime.

Fortunately, the use of nuclear power plants in space for NASA missions will likely involve little general public concern, provided the launch safety can be shown not to entail a radiation risk (avoided by system startup only after a safe orbit has been achieved) and the systems are not used in low Earth orbit, where a repetition of the Cosmos 954 reentry could be perceived. Technically, these safety issues can be or are resolved. More likely, the misconceptions and safety concerns will come from the higher echelons of NASA who are in politically sensitive or vulnerable positions and who will be on the firing line with the public, with Congress, and the the Executive Branch. It will be important for these persons to be knowledgeable about the nuclear aspects and the detailed attention accorded to the safety issue. Those within the nuclear community are confident that, properly handled, the safety issue can be a non-issue, but it will require careful communication between DOE and NASA to ensure that this happens, and that public sensitivity receives proper attention.

The real problem of space nuclear power is what was previously referred to as the "chicken-and-egg" syndrome: DOE will not develop a space reactor system for NASA without a firm mission, and NASA will not specify a firm mission requiring a space reactor because such a system doesn't exist and development is perceived not to be feasible within the time frame of the mission. The problem is how to break this cycle.

The SP-100 program has taken an important first step to breaking this cycle, but this program is too design-specific to achieve a broad technology base necessary to provide latitude in achievable power level.

In contrast to the SP-100 approach, a wider perspective is needed to facilitate the development of the technologies required to provide the latitude in power levels, the desired power levels can be broken into ranges, say, from 100 kWe to 1000 kWe, and from 1000 kWe to 10,000 kWe or greater. The various technologies will require careful evaluation through meaningful developmental tests, in and during which evolutionary

improvements are incorporated in order to determine their true potential with regard to operational longevity. It is vitally important that this recommended approach be recognized for what it is: a broad technology program, not a mission-specific one! The technology development goals cannot be dictated by a mission schedule, but must instead be based on desired levels of performance.

There are several recognized difficulties with this approach, of course. It doesn't have any public appeal or the pizzazz of an Apollo or Mars mission. It will probably not be perceived as a bold, imaginative program (even though, in reality, it will be if pursued appropriately), so that strong Congressional support may be difficult to obtain. A lot of blind alleys will inevitably be pursued. It will be a politically vulnerable program since it may not be identified with a specific large-scale programmatic goal (the same argument advanced in the congressional evaluation of the space station mission versus consideration of a large number of smaller activities).¹

If NASA foresees the eventual desirability of being unconstrained by power availability in their planning of future missions, they are going to have to take the initiative to break this cycle. Needless to say, the entire energy-related community would welcome such an initiative, since these developments would inevitably benefit terrestrial power generation as well.

REFERENCES

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3. Preliminary Power Profiles for 6- and 8-man Space Station IOC Configuration (NASA JSC-20120, September 1984).