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Megawatt Class Nuclear Space Power Systems (MCNSPS) Conceptual Design and Evaluation Report

Volume I—Objectives, Summary Results and Introduction

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NUCLEAR SPACE POWER SYSTEMS (MCNSPS)
CONCEPTUAL DESIGN AND EVALUATION REPORT.
VOLUME 1: OBJECTIVES, SUMMARY RESULTS AND
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1.0 ABSTRACT

This study was conducted in 1984 under the direction of the NASA Lewis Research Center, for the Triagency (DARPA, NASA, DOE) SP-100 program office. The objective was to determine which reactor, conversion and radiator technologies would best fulfill future Megawatt Class Nuclear Space Power System Requirements. Specifically, the requirement was 10 megawatts for 5 years of full power operation and 10 years system life on orbit. A variety of liquid metal and gas cooled reactors, static and dynamic conversion systems, and passive and dynamic radiators were considered. Four concepts were selected for more detailed study. Namely:

- 1) A gas cooled reactor with closed cycle Brayton turbine-alternator conversion with heat pipe and pumped tube-fin heat rejection.
- 2) A Lithium cooled reactor with a free piston Stirling engine-linear alternator and a pumped tube-fin radiator.
- 3) A Lithium cooled reactor with a Potassium Rankine turbine-alternator and heat pipe radiator.
- 4) A Lithium cooled incore thermionic static conversion reactor with a heat pipe radiator.

The systems recommended for further development to meet a 10 megawatt long life requirement are the Lithium cooled reactor with the K-Rankine conversion and heat pipe radiator, and the Lithium cooled incore thermionic reactor with heat pipe radiator.

1.1 Objectives

The objectives of the Megawatt Class Nuclear Space Power Systems (MCNSPS) study were to:

- o Identify the plausible combinations of nuclear reactor heat source types and power conversion equipment, including waste heat disposal and power conditioning options, which would comprise an integrated space power system capable of providing up to 10 MWe of continuous electric power for up to 5 years;
- o Determine which of these postulated system concepts are capable of fitting within the volume and liftoff mass constraints of the Shuttle Space Transportation System (STS), and determine the number of STS launches required for each system surviving the criteria of power level, duration, and STS volume and mass constraints;
- o Intercompare those systems which can be orbited to a low earth orbit (LEO) with 5 or less STS launches, in terms of size, mass, performance, technology development requirements, and relative difficulty of achieving development;
- o Refine the system conceptualization for the two concepts which indicate the lowest system mass, minimum number of STS launches required, and most probable success in resolving critical technology areas, in terms of configuration and layout, performance capability, system mass, identification of key technology areas and the means for their resolution;
- o Identify the key elements of a Program Plan for system development, and provide a preliminary estimate of the cost and schedule required to provide a technology readiness for the development of a system which meets MCNSPS requirements.
- o Identify the key adjunct elements which must be addressed by any program which proposes to use a MCNSPS.

1.2 Performance Requirements

- o Electric power level of up to 10 Megawatts (scalable 1-10 MWe)
- o 5-10 year life with a minimum of 5 years at full continuous power
- o Unmanned - compatible with strategic defense
- o High reliability
- o High survivability - natural and strategic defense environment
- o Launch entire power plant to LEO in one STS shuttle, or
- o Minimum number of shuttle launches to place 10 MWe in LEO, or
- o Determine how much power in one shuttle launch? and/or
- o Determine which launch vehicle is required to launch a 10 MWe, 5-year system?

1.3 Study Goals

- o Define technologies which will best meet the MCNSPS requirements
 - * Near term 1995-2005
 - * Long term 2005-2015
- o Recommend a technology readiness development plan which includes
 - * Technologies required
 - * Schedule
 - * Costs

1.4 Systems Considered for MCNSPS

The systems considered included variations of previously studied or partially developed concepts. Figure 1.1 identifies the important combinations. The following comments apply to these combinations.

Initial Survey

- o The liquid metal cooled reactor was initially considered for coupling with thermo-electric, out-of-core thermionics, Brayton gas turbine, Stirling, and potassium Rankine cycle power conversion systems.

PRELIMINARY MCNSPS CANDIDATE SYSTEMS TO BE EVALUATED

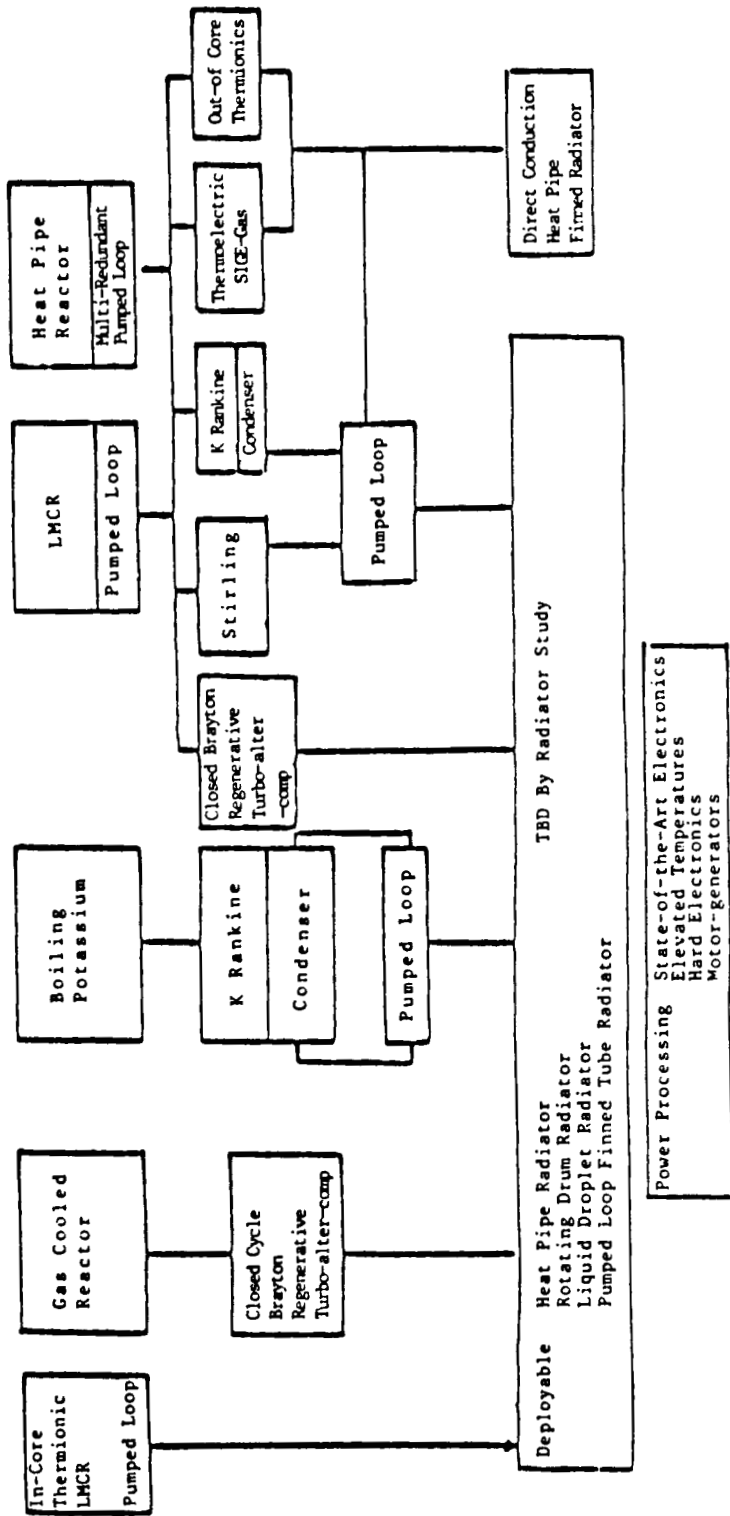


Fig. 1.1

- The following systems were considered appropriate for in depth study:
 - o The lithium cooled, uranium nitride fueled reactor (LUNR) was evaluated with free piston Stirling engines.
 - o The uranium nitride fueled reactor was also evaluated in conjunction with the boiling potassium Rankine cycle.
 - o The gas cooled reactor was coupled to the Brayton closed cycle gas turbine.
 - o The in-core thermionic reactor was evaluated with lithium coolant directly coupled to heat pipe radiators.

1.5 Study Results

Of the concepts which meet the MCNSPS requirements (1.2 above), the alkali metal Rankine system and the in-core thermionic system have the best potential for achieving 5 MWE in one shuttle, or 10 MWE in 2 shuttle loads with the lowest mass, smallest size and potentially highest reliability and longest life. For both concepts there is an inadequate data base on materials. Each concept has its own specific critical technology areas and concerns for component reliability and endurance potential, all of which require development and demonstration before one concept can be selected over the other, for either near term or long term application. Both concepts also have several critical technology areas in common, relating to: the stability of the reactor fuel under long endurance, high burnup conditions; reactor and system startup and control; high temperature power conditioning, and the waste heat radiator.

The conclusion favoring the Rankine and thermionic cycles is similar to that reached by consensus of the AEC and NASA by 1968 after 12 years of advanced nuclear space power system concept research and development. The same conclusion has apparently been reached in the Soviet Union [1], where both technologies are apparently being developed.

The system masses and number of shuttle launches required to place a 10 MWe system into LEO are summarized in Fig. 1.2. The conclusions associated with this summary are:

- o Liquid metal cooled reactors with thermo-electric, out-of-core thermionic, free piston Stirling engine, and Brayton cycles show little or no potential for meeting MCNSPS requirements.
- o No "realistic" potential exists for placing a 10 MWe, long endurance (5 year full power), space nuclear power system into a single manned shuttle.
- o The potential for placing a 5 MWe, long endurance, space nuclear power system into a single shuttle for launch to LEO does exist.
- o The potential for placing 10 MWe, long endurance, space nuclear power plants into two shuttles for launch to LEO with minimal in-orbit assembly requirements exists.
- o The potential for placing 10 MWe, long endurance, space nuclear power plants plus up to 35,000 kg of payload and payload radiator into a single shuttle-derived, 90,000 kg cargo launch vehicle (SDCLV) (Fig. 1.3) , exists.
- o The 1700-1800 K boiling sodium cooled reactor, sodium Rankine turbine power system, using a telescoping moly-sodium heat pipe radiator, is the most compact system studied. A 10 MWe system might be packaged into one shuttle volume, but is overweight.
- o The unignited mode, 2100 K emitter, 1200 K lithium cooled in-core thermionic reactor, with telescoping moly-sodium heat pipe radiator, might also fit into one shuttle, but is overweight.
- o These most compact maneuverable and survivable systems are an extreme extension of technology for long life. They could be further explored for shorter life requirements.
- o The 1550 K lithium cooled uranium nitride fueled reactor (LUNR), utilizing a potassium Rankine vapor turbine power conversion system (KRS) and a deployable heat pipe radiator, potentially provides the lowest mass and size, long lived nuclear space power system concept. The system is compatible with future manned applications and missions, and with manned payload maintenance.

SUMMARY OF PRELIMINARY SYSTEMS ANALYSIS

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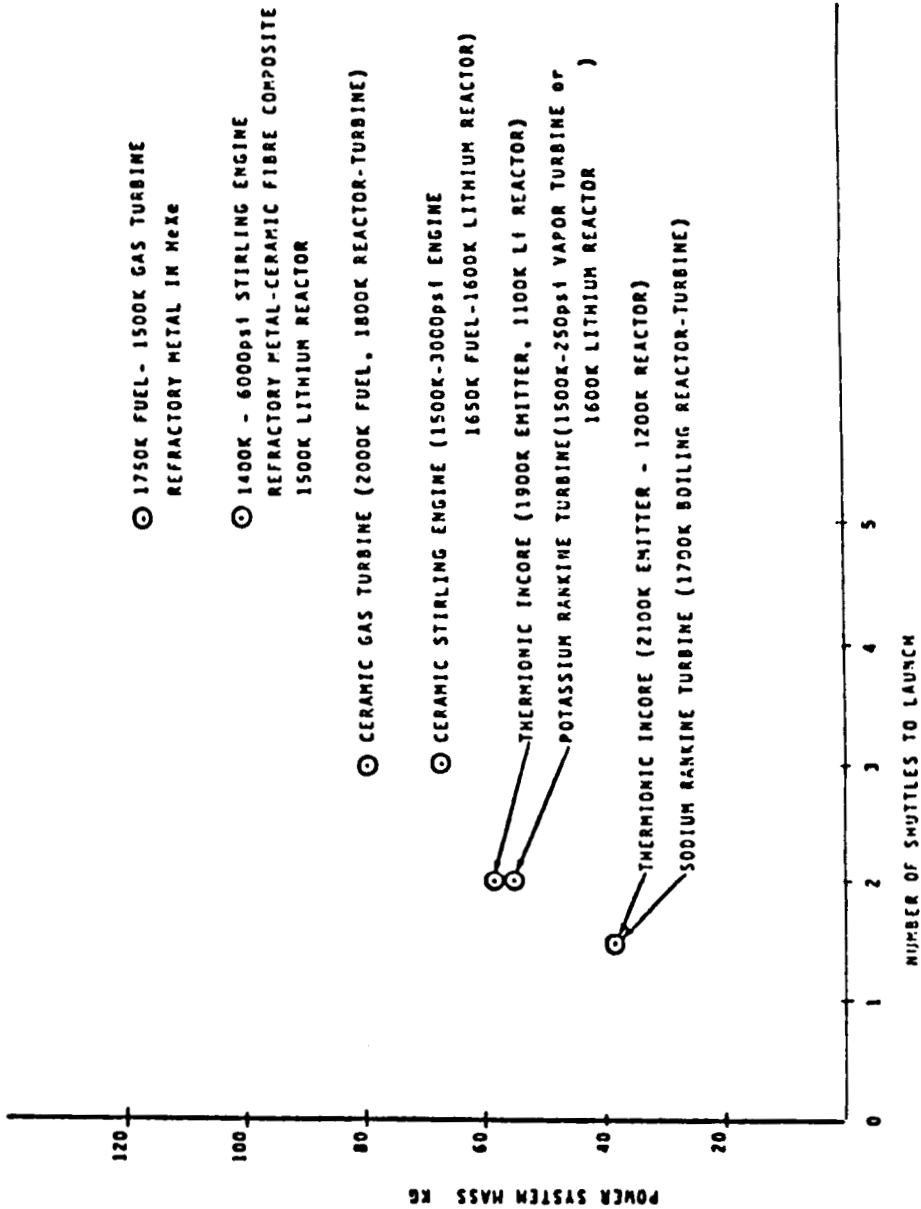


Fig. 1.2

Full Size SDCLV

- 4 SEGMENT SRBS
- STANDARD STS ET WITH MODIFIED LO₂ TANK
- 3 SSMS MOUNTED ON AFT END OF ET

	<u>WEIGHT (POUNDS)</u>
Gross Lift Off Weight	4,503,000
SRB GROSS	2,585,700
SRB PROP	2,214,300
CORE GROSS	1,718,800
CORE PROP	1,564,600
PAYLOAD	198,500

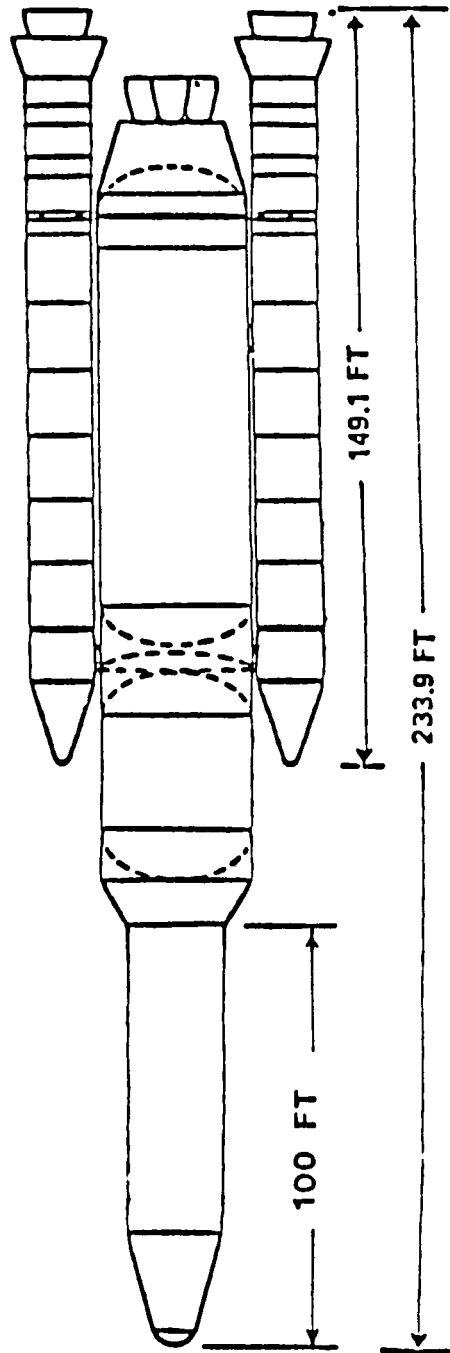


Fig. 1.3

- o The 1070 K lithium cooled in-core thermionic conversion reactor (ITR), utilizing a 1900 K to 1950 K emitter and a deployable heat pipe radiator, potentially might provide the most reliable and survivable long lived nuclear space power system at competitive mass and size. This system is also compatible with manned payload maintenance and with future manned missions.

2.0 CONCLUSIONS

2.1 Study Concept

This study screened a number of combinations of nuclear reactors and power conversion system concepts. As a result of this screening, two 10 MWe nuclear electric generating plants capable of being launched and operated in space for a period of 7 to 10 years, with a design full power lifetime of 5 years have been defined, evaluated, and inter-compared. The 50 to 60 tonne, 10 MWe plants, when coupled to their payloads, would both require a large shuttle derived cargo launch vehicle (SDCLV) to achieve earth orbit as a self-contained, self-deployed unit. The deployed configurations of these two systems, designated as the potassium Rankine and incore thermionic power systems, are shown in Figs. 2.1 and 2.2. These low vulnerability deployment concepts might best utilize nuclear electric propulsion for orbital transfer from low altitude (400 km) injection orbit to high altitude operational orbits [2].

Each of the two 10 MWe system concepts can be engineered into two separate loads for transport to LEO by the manned shuttle. This approach would require low earth orbit mating of the large radiator module to the reactor power conversion module and to separately boosted propulsion and payload modules. The mating could be astronaut supervised for accomplishment in less than one day of EVA. No welding should be required. The astronauts would guide the two large cargos together, activate mating clamps and deployment actuators and conduct inspections. This orbit assembly approach might not be suitable for systems in inclined or polar orbits, due to higher Van Allen radiation levels or possible laser threats.

The two concepts also have each been considered for a complete 30 tonne self-deploying, 5 MWe power system and radiator in a single manned STS shuttle. Shuttle launched systems must rendezvous and dock with their payload module and OTV in low earth orbit (LEO).

10MWE

FULL SIZE BOEING SDCLV - 90,000 Kg

K-RANKINE SYSTEM

50,000 Kg

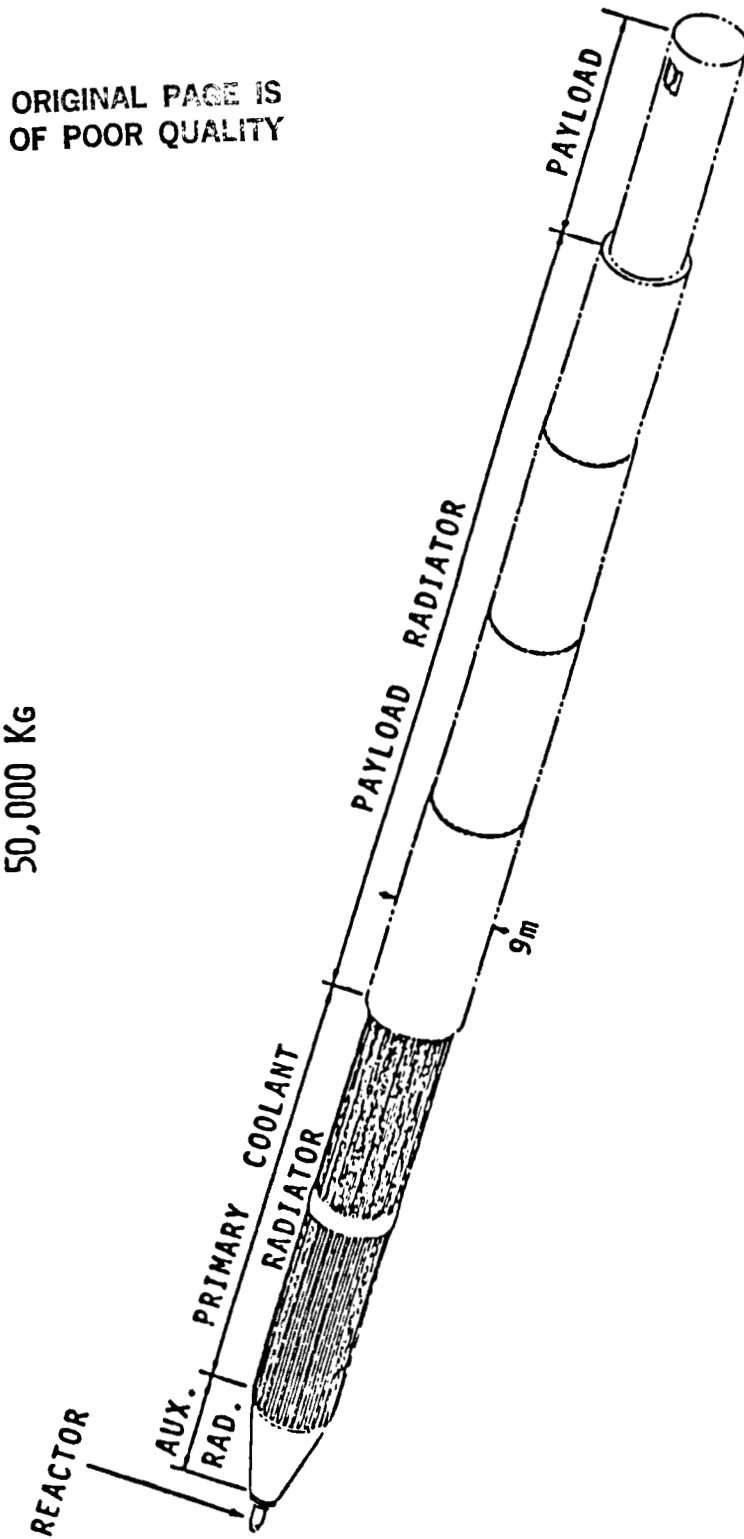


Fig. 2.1

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RELATIVE SYSTEM SIZES:

10MWE IN BOEING F.S. SDCLV 90,000 Kg

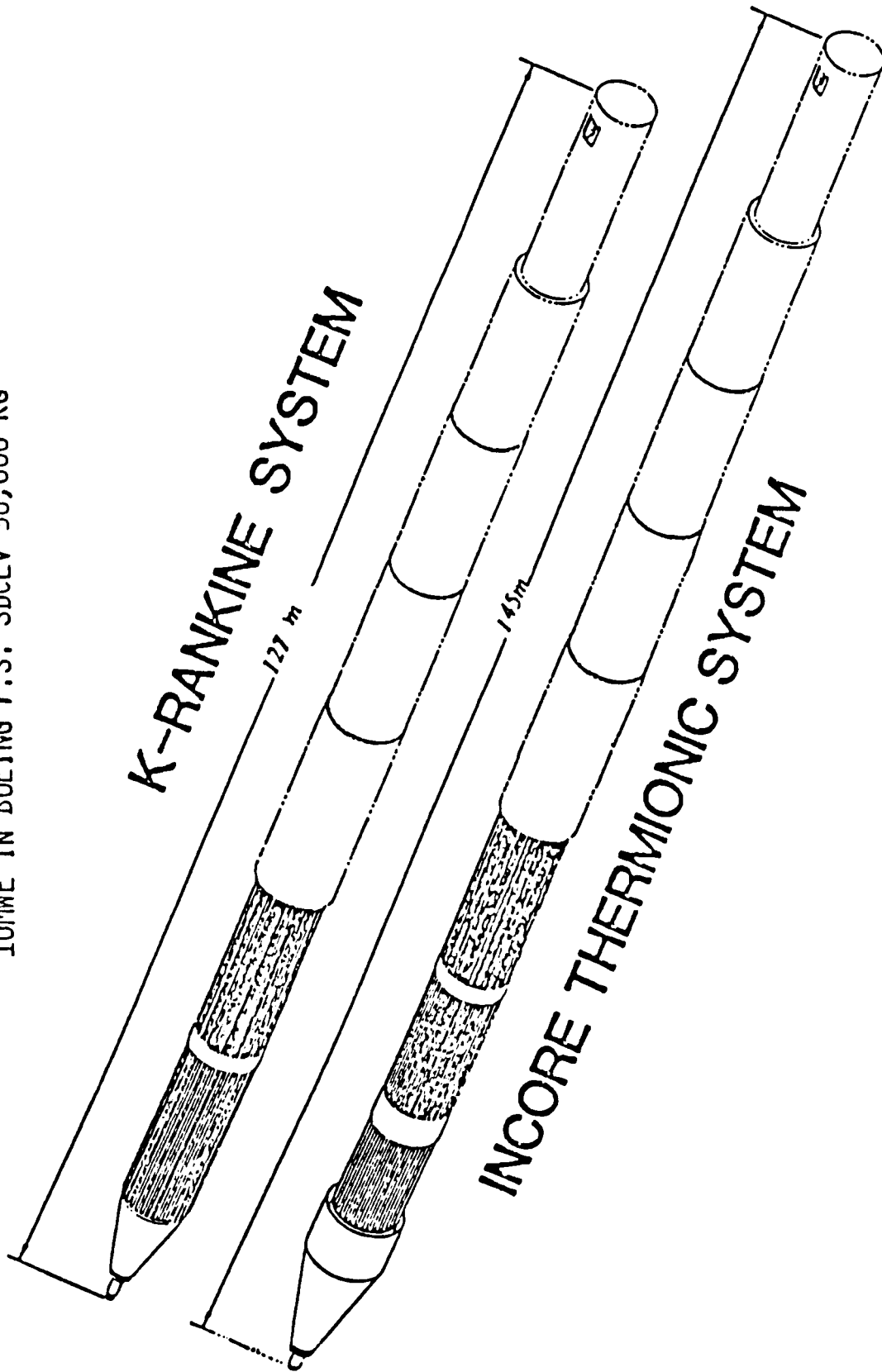


Fig. 2.2

2.2 Application

A 10 MWe generating plant could propel large manned spacecraft to Mars and return. Such space power plants could also enable large, economically significant, space manufacturing industries in earth orbit.

Multimegawatt space nuclear power generation capability could enable man to establish a permanent lunar base for research, lunar exploration, mining, materials processing, manufacturing, and communications. A lunar based spaceport may be a necessary element in man's future interplanetary explorations.

Multimegawatt power capability in geosynchronous orbit (GEO) could provide sufficient power for high frequency (eg. 60 GH) penetration of a moist atmosphere over large areas. Such capability could lead to establishing an industry simultaneously handling thousands of individual point to point international communications with miniature mobile receiving antennae. Such power plants could power large, high-altitude radars capable of observing large areas of the earth and detecting (and tracking) many small objects simultaneously. Large bi-static geosynchronous space radar transmitters powered at such levels and encoded would permit aircraft and ships to utilize compact, mobile passive radar.

Such power plants could provide the prime power for space station and satellite constellation defense against attack from hostile satellites or missiles. Multimegawatt power plants, coupled to nuclear electric propulsion, could also provide the propulsive power to transfer large defensive systems that are assembled in low earth orbit (LEO) to their effective operating orbits. Multimegawatt NEP space tugs could economically transfer commercial and strategic payloads from low earth shuttle delivery, assembly and manned station orbits to GEO and other high operating orbits.

The multimegawatt long-lived space nuclear power generating unit may be man's single most crucial new development for establishing major space scientific, commercial, and defensive operations in high earth orbits, lunar and translunar space. The society that develops and intelligently utilizes

a multimegawatt long-lived power generating system in space will economically and strategically prevail far into the 21st century.

2.3 Technology Status

Power Plant. Any reactor type, power conversion system, and waste heat radiator concept that could achieve the MCNSPS goals will represent a major extension of current materials technology. At least 5 to 10 years of intensive academic, technologic, component, facility, engineering, manufacturing and testing development will be required before serious mission oriented systems engineering should be undertaken. More than a decade of technical momentum has been lost since the U.S. space nuclear power program cancellation of the late 1960's. Some 3 to 5 years will be required to fund, attract, train, and inspire a new generation of high-temperature refractory materials investors, businessmen, scientists, engineers, technicians, and skilled advanced metal working mechanics. These people, and the result of their work output, will determine many ultimate decisions regarding concepts selection, technology emphasis, design goals and even potential missions objectives.

Payload. Large multimegawatt space nuclear power plants will be only one important element of much larger systems. Utilization of megawatts of power in space would require payload radiators that are 3 to 12 times larger than the power plant radiator, if current state of the art electronics, electrical and hydraulic practices are used and if human survival and comfort are considered. Consequently, in order to reduce payload radiator size to the same order as the power plant radiator, technology developments that must parallel large space nuclear power technology are:

- o Reduced dependence upon on-board human presence.
- o Payload equipment for remote diagnosis, and maintenance by on-board or visiting teleoperator equipment.
- o Teleoperator maintenance equipment capable of reliable operation in space and radiation environments.

- o Secure and reliable communication between payload and teleoperator with manned presence at mission control, whether earth, orbiting station or lunar based.
- o High temperature 400 K to 700 K electronics and high power, high frequency switching devices.
- o High temperature 600 K to 800 K insulators, conductors, capacitors, transformers, switches, relays, breakers, motors, alternators, solenoids, etc. that are engineered for base plate or conduction cooling to active thermal transport systems.
- o Rearrangement, compaction, and physical-thermal isolation of cooler solid state electronics from hotter, more temperature tolerant electrical equipment.
- o High efficiency, reliable, high temperature, high ΔT heat pumps and refrigeration.
- o Long (high L/D), high power density, alkali metal heat pipe development at temperatures of 1200 K to as low as possible temperatures.
- o Long distance 2-phase pumped flow for lowest temperature thermal transport systems.
- o Low mass, high efficiency electromagnetic pumps, for payload heat transport.
- o Electric propulsion systems.
- o Large, high frequency, high temperature communications and radar equipment.
- o Large boosters.

2.4 Candidate Technologies

This study concentrated its resources upon examining four basic reactor-power conversion system technologies, which were regarded as having the highest potential for achieving the program goals. The Megawatt Class Nuclear Space Power System (MCNSPS) goal is to select a concept and provide a conceptual design capable of 10 MWe output in a 7-year life, 50,000 kWe-yr system. If possible the system should be capable of being launched in one

booster vehicle near the turn of the century. The four concepts studied in detail were:

1. Gas cooled reactors (GCR) with Brayton gas turbines (BGT).
2. In-core thermionic conversion reactors (ITR).
3. Lithium metal cooled, uranium nitride fueled reactors (LUNR), coupled to free piston Stirling engine (FPSE), linear alternator systems.
4. LUNR or boiling potassium reactor or boiling sodium reactor coupled to alkali metal vapor Rankine turbines.

2.5 Study Results

The above four applicable concepts have been technically advanced further than any other concepts by the U.S., European, and Soviet technical communities. Other concepts have been proposed and were considered, but only these four were sufficiently credible to study in detail at this time. None of these four advanced 10 MWe and 50,000 kWe-yr capacity systems could be fitted into the single manned shuttle payload volume and mass limitation with credible advances in materials or component technology.

The reactor-shield-power conversion subsystems (without radiator) of three of the concepts could potentially be configured into one shuttle. The 10 MWe LUNR, Free Piston Stirling Engine (FPSE) system (SANS Radiator) does not now appear to offer the potential for packaging into one shuttle load. However, advanced unrecognized FPSE ideas do exist, and with further study, research and development, this concept might achieve the single shuttle load goal without radiator. Of the remaining three candidate concepts that might fit into the shuttle without radiator, the GCR-Brayton Gas Turbine system would require 2 to 3 extra shuttle loads for the radiator and would require large mass maneuvering, docking, assembly, and extensive leak-tight pipe welding in space. The other two concepts, described next, offer the potential for single shuttle packaging without radiator and would not require pipe joining or welding to unite with radiator.

The LUNR-potassium Rankine turbine system (KRS) and the in-core thermionic reactor (ITR) each have very high heat rejection temperatures. These high heat rejection temperatures permit use of alkali metal vapor heat pipe thermal transmission lines. Parallel heat pipe lines arranged into self-radiating cylindrical arrays can be telescoped within one another during launch, Fig. 2.3. Upon reaching orbit, the telescoped arrays are deployed into a longer self-radiating cylindrical array, Fig. 2.4. Thermal transfer from one array section to the next is made through pressure contacts and vacuum self-welded surfaces. Properly engineered, the radiator develops into a very strong and rigid structure capable of sustaining considerable acceleration forces arising from maneuverability requirements.

The lower heat rejection temperature inherent in the gas cooled reactor-Brayton gas turbine concept prohibits the use of the "compactable" telescoping heat pipe thermal transmission bus. As a consequence, pumped loop thermal transmission lines are required to transport reject heat to heat pipe radiator elements, Fig. 2.5. This radiator concept is limited by the shuttle volume capacity rather than the mass lift capability, Fig. 2.6.

The liquid metal droplet radiator might also have been well suited to the GCR-BGT concept. However, the droplets were found to miss their collector by many meters during 0.1g or greater evasive maneuvers. It will not be possible to shut the system down during hostile activity when its operation is vital. The long endurance gas cooled system cannot be easily shut down for dormancy or vehicle maintenance in zero gravity because the gas coolant must be circulated to eliminate shutdown fission product decay heat.

In summary, the two systems that appear to have the greatest potential for providing compactness, survivability and in orbit maintenance are the high temperature heat rejection cycles: 1) the alkali metal vapor Rankine turbine concept, and 2) the in-core thermionic conversion reactor concept.

CYLINDRICAL HEAT PIPE ARRAYS

STOWED CONFIGURATION

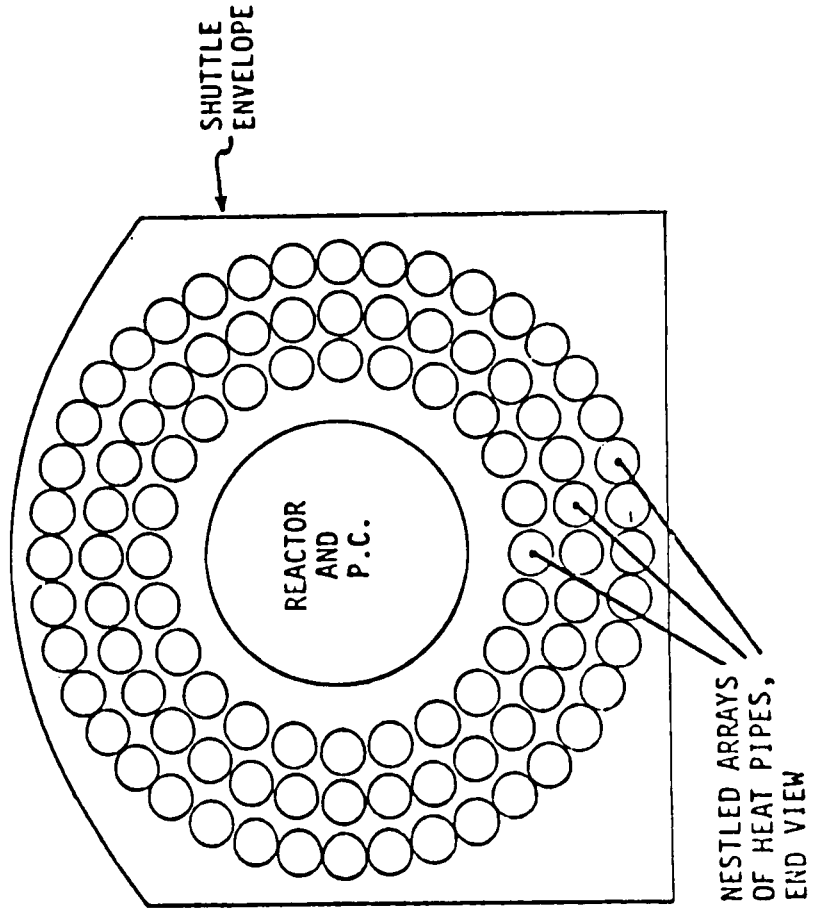


Fig. 2.3

CYLINDRICAL HEAT PIPE ARRAYS

EXTENDED CONFIGURATION

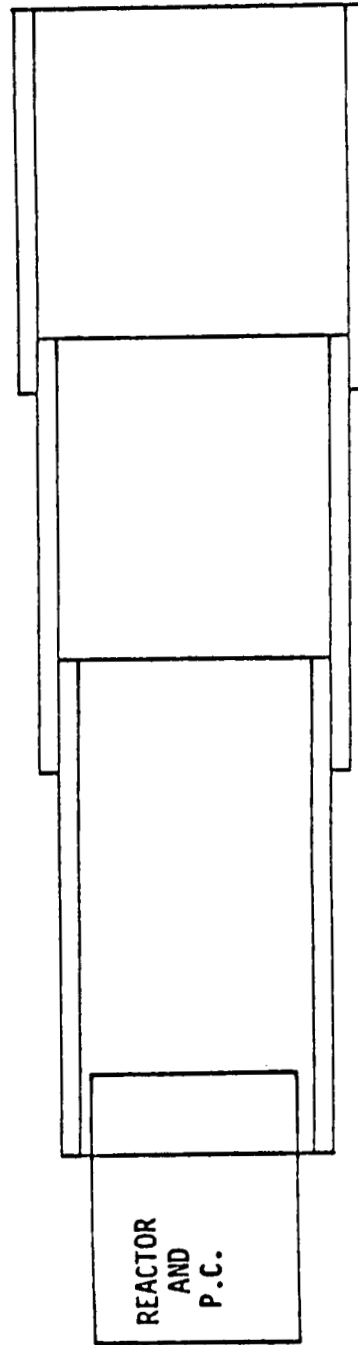
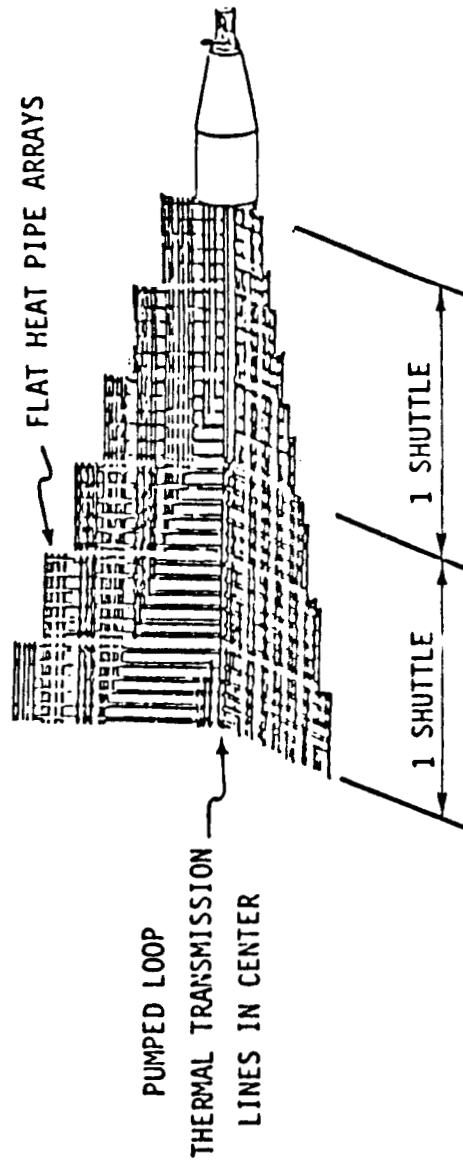


Fig. 2.4

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TRIFORM RADIATOR CONCEPT



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Fig. 2.5

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TRIFORM RADIATOR LAUNCH CONFIGURATION

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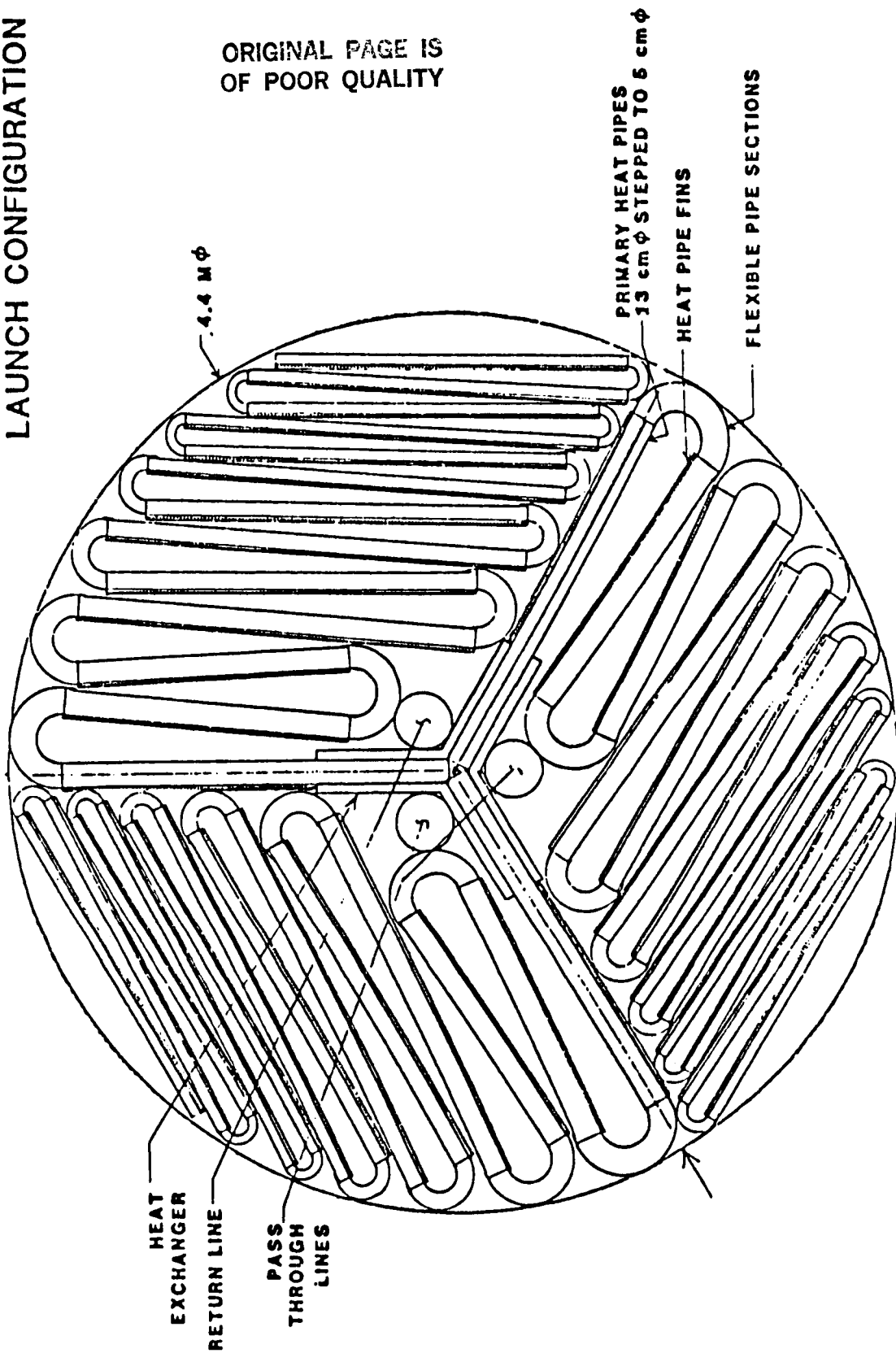


Fig. 2.6

2.6 Critical Technology Development Requirements

The LUNR alkali metal vapor turbine system has a number of serious technical obstacles to be overcome.

- o High temperature (1600 K) lithium containment.
- o Uranium nitride ceramic fuel capable of high uranium metal burnup (6% to 10%) at 1600 K to 1700 K surface temperatures without excessive swelling.
- o The development of a no-leak, high temperature and pressure boiler-superheater using advanced tungsten alloys.
- o Very high temperature (1500 K) electromagnetic lithium pumps, or a canned rotor motor driven pump, or a K-vapor driven turbo pump for lithium.
- o A reliable alkali metal vapor resistant non-conducting alternator bore seal.
- o High temperature liquid metal hydrostatic and hydrodynamic shaft bearings and seals.
- o Reliable high temperature remote operated check valves, blocking valves and flow control valves.
- o Tungsten "ultra" low creep alloy (at 1550 K) turbine blade development.
- o Vapor turbine operation with low erosion in moist vapor, and/or turbine development incorporating vapor reheat or interstage moisture separation.

Several unique problems with this cycle that can be solved with well informed engineering practice and development testing are:

- o Boiling and condensing moisture separation in zero gravity.
- o Zero gravity condensation and liquid collection for pumping liquid alkali metal.
- o Zero gravity startup, shutdown and restart.

The alkali metal vapor turbine concept that utilizes a boiling liquid metal (potassium, sodium, or NaK) reactor could virtually eliminate the first four issues above, but in their place the following developments would be substituted:

- o Uranium oxide ceramic fuel capability to high (6% to 10%) uranium metal burnup at approximately the same high surface temperatures of 1600-1700 K. Far more data and understanding exists for UO_2 than UN.
- o The no-leak boiler superheater requirement problem is traded for a large no-leak/no-creep reactor high pressure vessel that must be placed external to the control drums. Thus, the control drums must operate immersed in liquid metal or be radiation cooled to hot thimble walls.
- o The hot (1500 K) electromagnetic pump may be replaced with a hot jet pump for reactor coolant recirculation. These problems could be eliminated by use of the pressure tube reactor and modified Rankine cycle proposed herein.
- o Radioactive sodium and/or potassium will pass through the entire power conversion system. This will impact the shielding for manned applications, or man visited applications (shutdown maintenance) utilizing the multimegawatt systems.
- o Utilization of ^{39}K isotope for the coolant working fluid reduces the coolant activation problem, but increases the reactor startup-dormancy and restart problems relative to the use of a liquid cooled reactor.
- o Vapor-liquid separation and vapor drying are more difficult without possibility of superheating. Turbine interstage reheat or moisture separation are more critical.

Clearly the choice between the lithium cooled uranium nitride reactor (LUNR) over the boiling UO_2 reactor should be made several years after more basic data are available.

Several development problems common to both prime candidate concepts that are amenable to solution through informed engineering and laboratory development and demonstration are:

- o Frozen lithium system startup and shutdown heat removal.
- o Large, long, high power density alkali metal heat pipe development and demonstration.
- o Laboratory research, understanding and demonstration of high temperature, high vacuum thermal bonding.
- o Continuing radiator heat rejection design study to guide research and development.
- o Laboratory research, understanding and demonstration of the prevention of high temperature, high vacuum mechanical bonding of reactor control and shutdown mechanism bearings, gears and contact points.

The In-core Thermionic Reactor (ITR) concept alleviates some of the problems associated with the LUNR, boiling potassium or sodium vapor Rankine turbines concepts as follows:

- o Lithium coolant is reduced from 1600 K heat source temperatures to 1100 K heat sink temperatures. This reduction substantially reduces the lithium pump and containment problem to near state-of-art. It also allows near state-of-art reactor reflector, controls, shields, etc.
- o The inherent double containment of the fuel permits safe use of relatively well developed UO_2 in a lithium cooled reactor.
- o No pressures are developed, and valves, turbines, bearings, alternators, seals, and several external heat exchangers, are eliminated.
- o No zero gravity effects except in the design of the coolant volume expansion compensators.
- o Startup, shutdown, dormancy and restart are substantially more reliable with in-core thermionic static conversion.

However, the in-core thermionic concept has substantial technology problems and limitations which will require research, development, demonstration and life testing before its technology readiness for system design can be established.

The most serious problems are:

- o Fuel element emitter dimensional stability at high temperature (1900 K) and high burnup (5-6%).
- o In-core electric insulator stability at high neutron irradiation fluence, high temperatures, and increased voltage.
- o At credible fuel emitter temperatures and for long-lived operation, the ITR system efficiencies are lower than the potassium or sodium Rankine cycles. As a consequence, the heat rejection radiators are larger.
- o Development of thermionic fuel element (TFE) manufacturing cost control, quality assurance, and automated fabrication of a large number of precision parts and subassemblies.
- o Management of very high current (100,000 to 500,000 amps), low voltage (20-100 volts dc), electrical output through the development of a compact and reliable power conditioning subsystem that can switch low voltage dc output to ac for voltage transformation into high voltage.
- o Present compact power conditioners using silicon MOSFETS or HEXFETS are designed to operate at 400 K. Consequently, a large, low temperature auxiliary radiator is required. Development of a 500 K power conditioner reduces the auxiliary radiator by a factor of 2.5 and a 600 K conditioner by another factor of 2, in which case the radiator is relatively insignificant.

Recommendations:

- 1) Announce the desire to develop a multimegawatt long-lived space nuclear power, electric propulsion, and teleoperator remote maintenance technology for application in the 21st century.
- 2) Set aside a committed annual long-term budget for research and technology development.

- 3) Conduct continuing low level applications studies for multimegawatt space nuclear power and propulsion in order to identify opportunities and research and development requirements.
- 4) Report technology progress and application opportunities to the political base, as well as the technical community.
- 5) Conduct a nationwide long term, well published materials and physics research program within the universities, national laboratories, and specialist companies.
- 6) Develop, demonstrate and life test critical components and subsystems in specialist companies in the commercial sector to insure that technology spin-offs will benefit the populace and to insure the equal availability of the technology to all large systems contractors.
- 7) Use technology development in the NASA-DOE-DARPA SP-100 programs as a step toward development of multi-megawatt capability. In view of the limited resources to be available, and the technological infrastructure lost during the past 13 year technological pause, this policy would represent an efficient and responsible approach to redeveloping a national capability.

The primary technical development activities applicable to all four candidate power systems are:

- 1) High temperature, low creep, high strength, chemically stable materials capable of high fast neutron irradiations and some temperature cycling.
- 2) High surface temperature, high burnup, nuclear fuel and claddings.
- 3) High temperature, radiation resistant, electrical insulation and magnetic materials for alternators, transformers, electromagnetic pumps, solenoid valves and actuators, control motors, and thermionic application.
- 4) High temperature, radiation resistant electronics.
- 5) Enhancement and prevention of high temperature, high vacuum, low contact pressure, thermal and structural bonding.
- 6) Long heat pipe and pumped 2-phase thermal transmission.
- 7) Low mass, high efficiency, electromagnetic pumping. Both leading system concepts and 3 of the 4 systems concepts considered require research and development for:

- 8) Containment and pumping of liquid lithium.
- 9) Startup from the frozen coolant condition.
- 10) Advanced high temperature, ceramic fiber-reinforced, tungsten alloy, thermionic emitters to 1950 K and alkali metal vapor turbines from 1450 to 1800 K.

Specific advanced power conversion research and technology areas which must be supported are:

- 11) Alkali metal boiling at 1450 to 1750 K.
- 12) High frequency alternator bore seals compatible with alkali metal vapor.
- 13) High temperature (1850 K - 2050 K) thermionic-fueled emitters and 1100 K to 1250 K radiation resistant insulators.
- 14) High efficiency, high temperature, compact (shieldable) low voltage DC to high voltage AC-DC power conditioning and power transmission.

Key advanced research that will lead to opening up "backup" technologies are:

- 15) Advanced alternating current thermionic converters.
- 16) Ceramic (1800 to 1900 K) gas turbine blades in first few turbine stages.
- 17) High pressure, large ceramic cylinders compatible with lithium at 1600 K for possible Stirling engine development.

3.0 INTRODUCTION and BACKGROUND

This limited study deals with a complex technical issue: , namely, the conceptual design of a 10 MWe space nuclear power system capable of being launched into "safe operations orbits", and operating for 7 to 10 years, while delivering 50,000 kWe-years of energy output.

This requirement compares (20,000 times larger) to the actual SNAP-10A flight development experience of producing, launching and operating a 0.5 kWe space nuclear reactor power system designed for one to five years operation, and delivery of 0.5 to 2.5 kWe-years of energy output.

Beyond the single 1965 SNAP-10A flight, the United States and the free world have no further reactor flight experience.

For some 15 years the Soviets have continued to launch and to utilize nuclear reactor power systems in low earth orbit. Some 20 systems have been flown, serving to establish and maintain an experienced Soviet nuclear space flight scientific, production, and operations infrastructure. Advanced development and operation of thermionic direct conversion space reactors was continuing in the USSR in 1977-1978 when all communication with the West on this subject was terminated.

During the 1960's, prior to and following the U.S. SNAP-10A flight test, the U.S. developed and maintained a scientific and engineering capability oriented toward higher power output and advanced capabilities. The major projects were the 3-5 kWe mercury-Rankine SNAP-2 system, the 30-50 kWe mercury-Rankine SNAP-8 system, the nominally 300 kWe potassium-Rankine and the competitive in-core thermionic system. See Fig. 3.1.

The AEC-Air Force SNAP-2/10A program demonstrated some 27,000 hours of reactor operations and some 30,000 hours of Hg-Rankine turbine-alternator operation with hermetically sealed Hg bearings. The SNAP-8 AEC-NASA program demonstrated some 14,000 hours of reactor operation and several thousand hours of Hg turbine-alternator operation with separate loop oil-cooled

U.S. SPACE REACTOR PROGRAMS

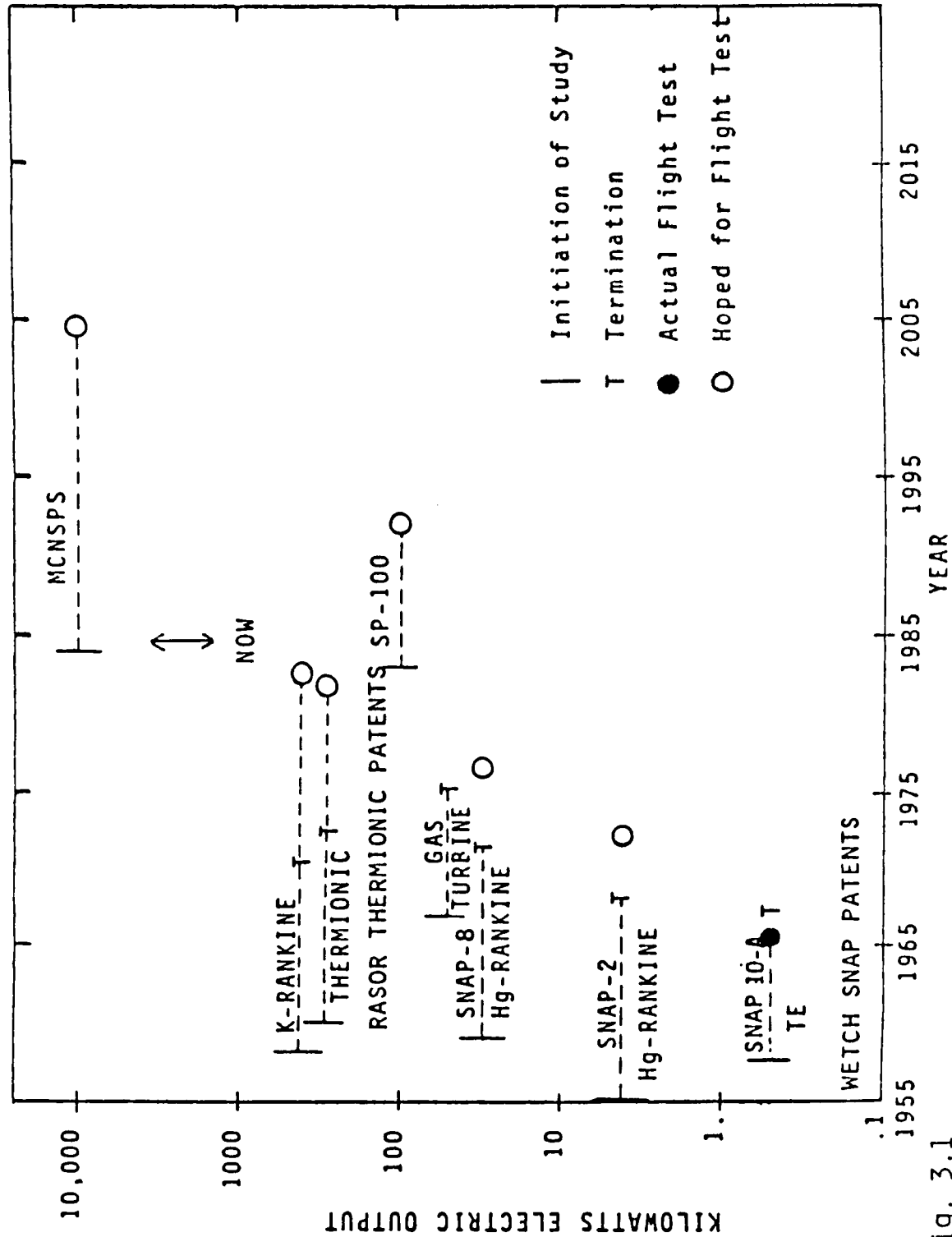


Fig. 3.1

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bearings. At the time of program termination, the SNAP-8 reactor was in prototypical flight configuration and the mercury turbine tests were in advanced breadboard configuration. The SNAP-8 objective was at least 1 year of operation in orbit. After the NASA SNAP-8 mercury turbine development program was terminated, a closed cycle Brayton gas turbine activity was sponsored at NASA-LERC for several years. Some impressive gas turbine and gas bearing life tests were demonstrated at low heat sink temperatures. The concept had potential for low power application.

The SNAP hydride reactor was ideal for low powers of a few kilowatts and was suited for power levels up to some tens of kWe at relatively short line and large size. The low nuclear fuel requirement (3 to 10 kg) provided good economics and safety potential for low powered systems.

However, it was recognized in the late 1950's that larger power levels, of hundreds and even thousands of kilowatts, would require prohibitively large thermal radiators for any known power conversion system that must utilize SNAP hydride reactor heat source temperatures (i.e., 900°F to 1300°F (750 to 977 K)).

In the late 1950's Wetch's SNAP team advanced the boiling rubidium, cesium fast reactor coupled to a Rankine turbine-alternator. These studies were superseded by Aerojets boiling potassium 3a concepts. This was later picked up by ORNL as the MPRE program. In the early 60's, ORNL and NASA LERC considered the lithium cooled fast reactor as a heat source to vaporize a working fluid in an external boiler for passage through a Rankine turbine.

In 1959, Rasor and Hirsch [1], working within the SNAP team's supporting research program, conceived of the in-core thermionic reactor concept utilizing a "flashlight" fuel element converter operating in the "ignited" mode. In the early 1960's the potassium vapor Rankine turbine concept and the Rasor in-core flashlight thermionic fuel element (TFE) concept received laboratory development funds. These two concepts were supported as advanced development programs through about 1970. Budget limitations and lack of clear requirements in the late 1960's led to AEC termination of the SNAP

hydride reactor program and the potassium Rankine advanced system development. The in-core thermionic program was making rapid progress with in-pile performance and endurance gains at GA. It was supported through 1972 when finally all AEC space reactor development support was terminated due to lack of user support and funding.

The significant aspect of these advanced higher powered programs was the higher heat source temperatures required to achieve higher heat sink radiator temperatures. In an idealized space power system, the Carnot efficiency which results in a maximum of the power output per unit of radiator area is 25%, corresponding to a hot-to-cold temperature ratio of 1.3. For this optimized Carnot cycle efficiency, and with overall system efficiencies expressed as the fraction of the optimized Carnot efficiency achieved, the maximum power output per unit of radiator area varies with the peak temperature as shown in Fig. 3.2. Note, in Fig. 3.2, the rapid increase in potential system power output per square meter of radiator area versus peak cycle temperature for system efficiencies approaching 50% of Carnot.

Fig. 3.3 shows the U.S. nuclear reactor endurance experience versus coolant outlet temperature. Noted on Fig. 3.3 are the coolant outlet temperature goals of the advanced reactors that are considered in this study. It is clear from Fig. 3.3 that the reactor temperature-endurance goals of this program are a significant departure from existing experience. It is also clear from Fig. 3.3 that the power level goals of this program that impact size, mass, complexity, temperatures, power densities, materials of construction, safety, survivability and launch systems are a significant extrapolation from prior research, development, and studies.

Following the program terminations, in the early 1970's, the U.S. space nuclear power development teams disbanded, became involved in other activities, retired, etc. A great deal of data was recorded, a great deal

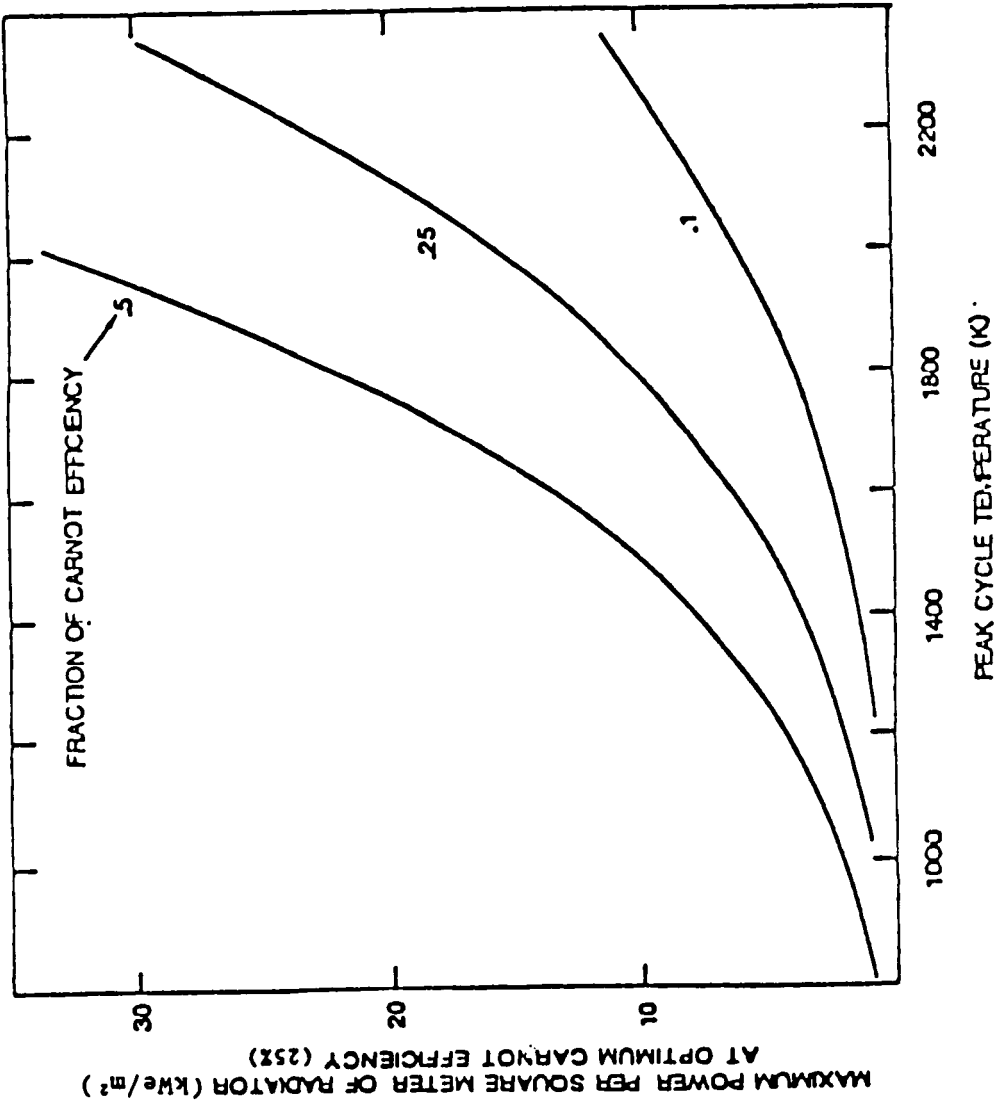


FIG. 3.2

Maximum electric power output per unit radiator area vs. peak power conversion cycle temperature - as function of fraction of optimum Carnot efficiency capability of P.C.S.

REACTOR COOLANT SYSTEM TEMPERATURES VS. OPERATING LIFETIME

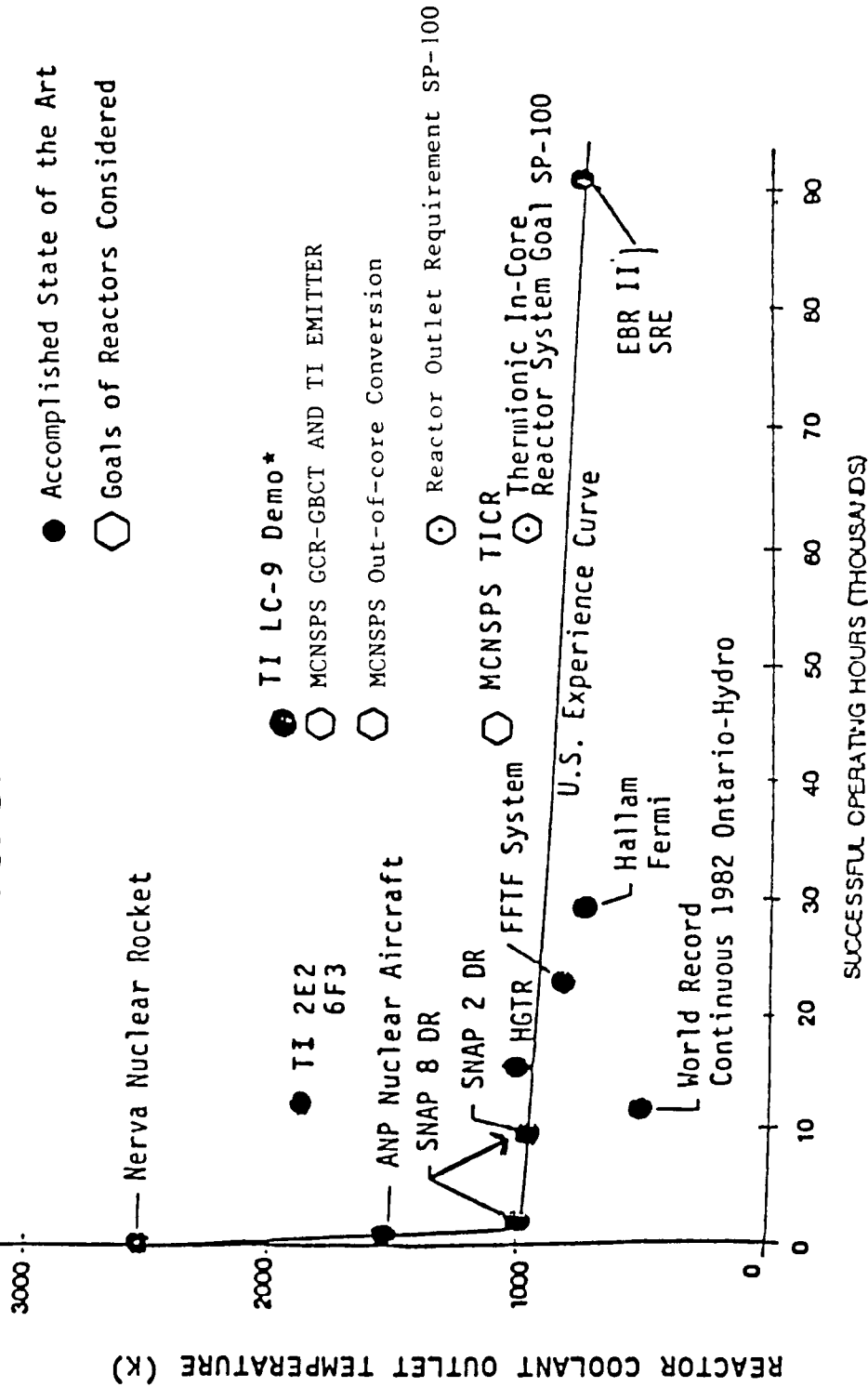


FIG. 3.3

OUT-OF-PILE THERMIONIC CONVERTER DEMO.

was not. Applicable laboratories' equipment and facilities were dismantled and diverted to other uses. Since the 1970's the only applicable technology maintenance or gains were:

- o UO₂ and UN fuel technology at state-of-the-art temperatures and in stainless steel for fast breeder reactors.
- o The development of fast reactor physics and control computer codes.
- o Materials improvement and gas bearings development for gas turbines.
- o High amperage MOSFET-HEXFET power switch development.
- o Thermionic conversion research.
- o Free piston Stirling engine research.
- o Alkali metal heat pipe research.

In the early 1980's the reawakening of space nuclear power interests led Los Alamos personnel to attempt to capitalize upon the UO₂ fast reactor and heat pipe technology advances of the 1970's with thermo-electrics from the SNAP-10A and RTG thermo-electric programs of the 1970's. However, the small program was directed toward low power output and has not sustained itself. The dearth of technical progress toward space power development in the past decade requires that some considerable attention be given to the technologies that were emerging and dominating in the closing years of the 1960's technical expansion era.

In 1983 a joint DOE-NASA-DARPA technology program for support of advanced space power was initiated and entitled SP-100. The SP-100 program has concentrated upon identifying technology that would provide a high assurance of providing a space nuclear power system with a nominal 100 kWe output for 10 years, and which would be capable of delivering 700 kWe-years of energy output.

The participants in the SP-100 program examined a variety of technical alternatives including thermo-electrics, potassium Rankine, Brayton gas turbines, Stirling engines, sodium heat engines (AMTEC) and in-core thermionics. After a year's study by four major contractors at a significant funding level, two static systems were selected for further technology

development. These were the in-core thermionic reactor and the high temperature lithium-cooled UO_2 or UN fueled fast reactor coupled to thermoelectrics. Following the competitive selection a third technology, the free-piston Stirling engine, operating with a moderate temperature reactor derived from the fast breeder technology, was selected for further exploratory development.

The ground rules for undertaking this study were not limited to systems that have been studied before. In the time and within the level of effort available the majority of study energy concentrated on discerning the most promising of four promising concepts, developing potentially feasible concept designs, and determining the priority technology that should be pursued in the next decade.

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16. Abstract This study was conducted in 1984 under the direction of the NASA Lewis Research Center, for the Triagency (DARPA, NASA, DOE) SP-100 program office. The objective was to determine which reactor, conversion and radiator technologies would best fulfill future Megawatt Class Nuclear Space Power System Requirements. Specifically, the requirement was 10 megawatts for 5 years of full power operation and 10 years system life on orbit. A variety of liquid metal and gas cooled reactors, static and dynamic conversion systems, and passive and dynamic radiators were considered. Four concepts were selected for more detailed study. Namely: 1) A gas cooled reactor with closed cycle Brayton turbine-alternator conversion with heat pipe and pumped tube-fin heat rejection. 2) A Lithium cooled reactor with a free piston Stirling engine-linear alternator and a pumped tube-fin radiator. 3) A Lithium cooled reactor with a Potassium Rankine turbine-alternator and heat pipe radiator. 4) A Lithium cooled incore thermionic static conversion reactor with a heat pipe radiator. The systems recommended for further development to meet a 10 megawatt long life requirement are the Lithium cooled reactor with the K-Rankine conversion and heat pipe radiator, and the Lithium cooled incore thermionic reactor with heat pipe radiator.					
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