Space nuclear reactor concepts for avoidance of a single point failure

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Abstract

Nuclear reactor power systems could revolutionize space exploration and support human outpost on the moon and Mars. This paper reviews various energy conversion technologies for use in space reactor power systems and provides estimates of the system's net efficiency and specific power, and the specific area of the radiator. The suitable combinations of the energy conversion technologies and the nuclear reactors, classified based on the coolant type and cooling method, for best system performance and highest specific power, are also discussed. In addition, four space reactor power system concepts, developed at the University of New Mexico's Institute for Space and Nuclear Power Studies, with both static and dynamic energy conversion for nominal electrical powers up to 110 kWe, but no single point failures in reactor cooling, energy conversion and heat rejection, are presented. Two power systems employ liquid-metal heat pipes cooled reactors, thermoelectric (TE) and Alkali-Metal Thermal-to-Electric Conversion (AMTEC) units for converting the reactor power to electricity, and potassium heat pipes radiators. The third power system employs SiGe TE converters and a liquid metal cooled reactor, with a core divided into six identical sectors. Each sector has a separate energy conversion loop, a heat rejection loop, and a rubidium heat pipes radiator panel. The fourth power system has a gas cooled reactor, with a sectored core. Each of the three sectors in the core is coupled to a separate Closed Brayton Cycle (CBC) loop with He-Xe (40g/mole) working fluid and a Nak-78 secondary loop, and two separate water heat pipes radiator panels.

Keywords: Space nuclear reactor power systems; heat pipes, sing-point failure; liquid metal coolants; thermoelectric; alkali metal thermal-to-electric conversion (AMTEC); closed Brayton cycle; heat pipes radiator.

1. Introduction

The absence of the solar option and the vast traveling distances to the planets and satellites in the solar system strongly justify consideration of space reactor power systems to support future robotic and human exploration and outposts on the moon and Mars. Space reactor power systems would be started, for the first time, in an earth orbit, thus eliminating radiological concerns during launch from earth. In addition to the longevity and compactness, these systems could operate at multiple power levels and be designed for bi-modal operation of electricity generation and propulsion [1].

Desirable design and operation features of space reactor power systems are to avoid single point failures in reactor cooling, energy conversion, and heat rejection and the likelihood of a criticality of the bare nuclear reactors upon submersion in wet sand and being flooded with seawater, following a launch abort accident. The latter is typically accomplished using neutron poison materials, such as Gadolinium, Europium, etc., as additives to the nuclear fuel and as a thin coating on the outer surface of the nuclear reactor vessel [2].

The avoidance of a single point failure in reactor cooling could be accomplished by either: (a) dividing the nuclear reactor into a number of identical sectors that are thermally and neutronically coupled, but hydraulically decoupled; or (b) cooling the reactor with liquid metal heat pipes. Using separate energy conversion loops/modules, each with a separate radiator panel, not only enhances the power system reliability and redundancy, but also avoids single point failures in energy conversion and heat rejection [1-6]. These design measures for avoiding single point failures in space reactor power systems come at the expense of increased complexity and total mass of the system. They may not be necessary for short duration missions and when operating at low temperatures, thus using structure and fuel materials with well known properties and irradiation behavior.

This paper reviews various energy conversion technologies for use in space reactor power systems and provides estimates of the system's net efficiency and specific power, and the specific area of the radiator. The suitable combinations of the energy conversion technologies and the nuclear reactors, classified based on the coolant type and cooling method, for best system performance and highest specific power, are also discussed. This paper also presents four nuclear reactor power system concepts, with static and dynamic energy conversion and no single point failures, for nominal powers up to 110 kWe [3-6].

The first two space reactor power systems use liquid-metal heat pipes reactors, thermoelectric (TE) and Alkali-Metal Thermal-to-Electric Conversion (AMTEC) units, for converting the reactor thermal power to electricity, and potassium heat pipes radiators. The third power system employs SiGe TE converters and a liquid metal cooled reactor with a core divided into six identical sectors. Each sector has a separate energy conversion loop, a heat rejection loop, and a rubidium heat pipes radiator panel. The fourth power system has a gas cooled reactor, with a sectored core. Each of the three sectors in the core is coupled to a separate Closed Brayton Cycle (CBC) loop with He-Xe (40g/mole) working fluid and a Nak-78 secondary loop, and two separate water heat pipes radiator panels.

2. Energy conversion technologies

In addition to operation compatibility, the selection of an energy conversion technology is based on considerations of total system size and mass, safety, scalability, modularity, load following, system integration, radiation hardness, efficiency, reactor exit temperature and the average heat rejection temperature and size. The following subsections briefly review various static and dynamic conversion technologies considered for use in space nuclear reactor power systems.

2.1 Static energy conversion

In addition to the absence of moving parts, static conversion technologies are inherently modular and load following [3-5,7-13]. The SiGe thermoelectric converters operating between 1273 K and 790 K have an efficiency of ~ 6%, representing ~ 16% of Carnot. The segmented thermoelectric (STE) converters are more efficient than SiGe, because the materials of the segments in the n- and p-legs operate in the temperature range in which they possess the highest Figure-Of Merit (FOM), or Z value. A number of STE converters have been fabricated, using p-type $CeFe_4CoSb_{12}$ and Bi_2Te_3-based alloys and n-type $CoSb_3$ and Bi_2Te_3-based alloys, and tested at cold and hot shoe temperatures of 300 K and 973 K, respectively [7-9]. At a cold shoe temperature of 300 K, the efficiency of a space reactor power system that uses STE could be ~ 13%. Increasing the radiator temperature to 373 K and 573 K decreases the projected system efficiency with STE converters to 12.4% and 7.8%.

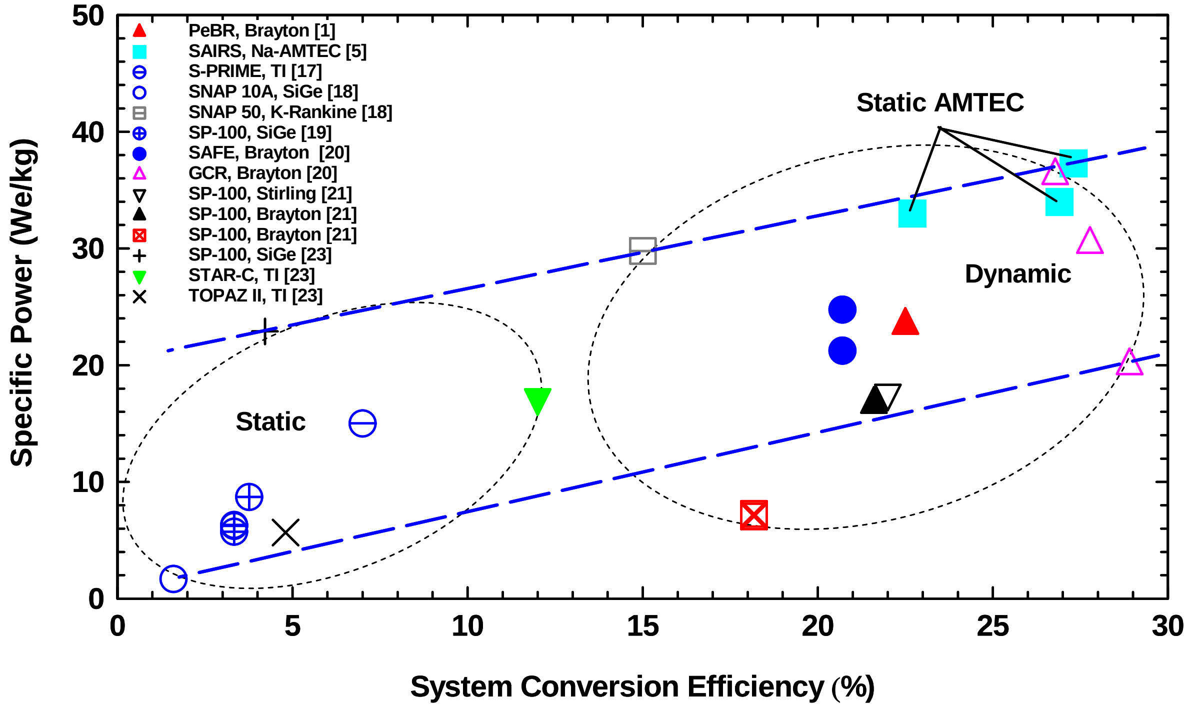


Fig. 1. Specific power estimates for space reactor power systems with different energy conversion technologies.

The relatively lower hot-side temperature for AMTECs decreases the reactor exit temperature to ~ 1180 K [5,10-13], making it possible to use relatively lighter super-steels, titanium alloys, or Mechanically-Alloyed Oxides Dispersed Steels (MA-ODS) as structure materials [14]. AMTEC units typically operate at moderate hot-side temperatures, T_h, of 1000 K to 1123 K and relatively high radiator temperatures, T_R, of 550 to 650 K, with potassium and sodium working fluid, at a net conversion efficiency of 22% to 27% [5, 10 -13].

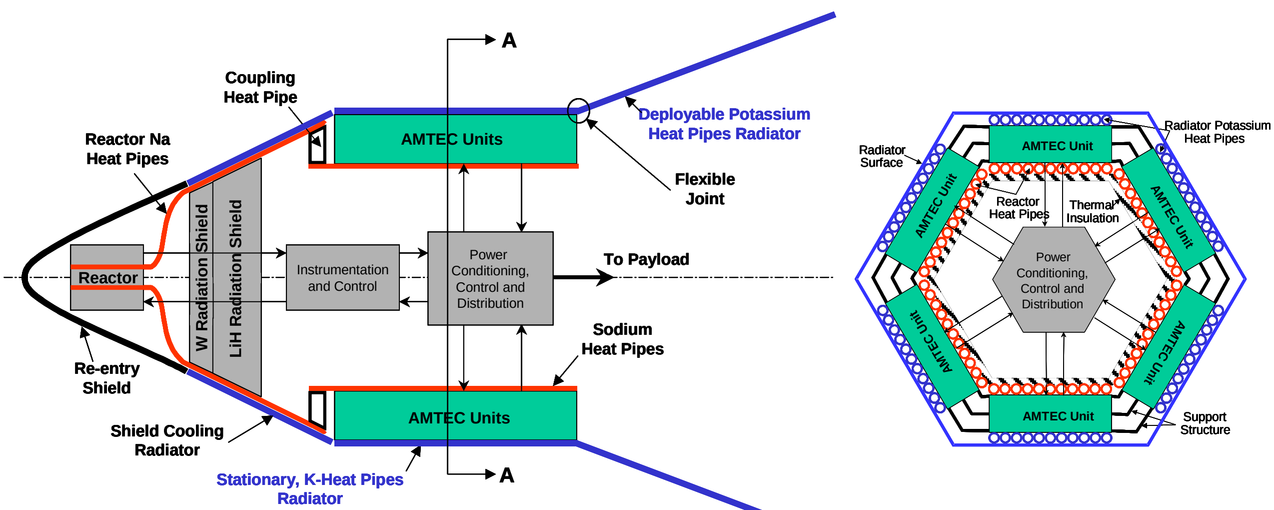
Depending on the type of alkali metal working fluid (K or Na), the AMTEC units employ thin ($\leq$ 0.5 mm) membrane of K-beta" alumina or Na-beta" alumina solid electrolyte (BASE) [10]. The BASE material has a "spinel" crystal structure of extended alumina (Al_2O_3) blocks separated by ion conductions planes of loosely packed alkali-metal ions and equal number of O^{--} ions [11]. The spinel blocks are low activation energy barriers for the alkali-metal ions, which jump from one site to the next in the conduction planes and in the direction of the applied pressure difference across the BASE [10]. The spinel crystal structure causes the electron conductivity of the BASE to be very low and the ionic conductivity to be very high.

The vapor pressure on the anode side of the BASE (40-80 kPa) is much higher than on the cathode side (20-60 Pa). This pressure difference is balanced by the electrochemical potential resulting from the diffusion of the alkali metal ions to the cathode side of the BASE. The electrons from the anode side circulate through the external load to the cathode side where they recombine with the alkali metal ions emerging from the BASE, producing low-pressure sodium vapor (< 80 Pa). This vapor diffuses through the porous cathode electrode (~ 1 μm thick $WRh_{1.5}$) and traverses the low-pressure cavity to a remote condenser. The resulting liquid condensate is then circulated back through a porous artery by the capillary action generated in the surface pores (< 4 μm in radius) of the evaporator wick in the high-pressure cavity [13].

The electrochemical potential generated across the BASE is typically $\leq$ 0.5 V and the electrical current is proportional to the cathode electrode area and the circulation rate of the liquid metal working fluid in the AMTEC units. Typical operating current density for the cathode electrode is ~ 0.2 - 0.5 A/cm^2. Structure materials, which are most compatible with liquid metal working fluid, the BASE, and the electrode materials are molybdenum-rhenium (Mo-Re) alloys [14]. A Na-AMTEC unit (4 - 6 kWe each), operating between 1123 K and 650 K, could have an efficiency of ~ 26% [5,13], representing ~ 60% of Carnot.

2.2 Dynamic energy conversion

Despite the relatively high conversion efficiencies (23- 35%), the low radiator temperature (< 400 K) of CBC and Free Piston Stirling Engine (FPSE) significantly increases the radiator's size and mass and those of the power system. Figure 1 provides estimates of the specific power of space reactor power systems with static and dynamic energy conversion technologies. With TE and Thermionic (TI), the specific power of the power system ranges from 5 to 15 We/kg [3,7-19] and may exceed 30 We/kg with AMTEC [5,13]. With dynamic conversion technologies that include K-Rankine cycle, CBC, FPSE, the system's specific power could vary from as little as 10 to as much 30 We/kg (Fig. 1) [6, 20-23].



(a) Longitudinal Cross-Sectional View. (b) Cutaway View A – A.

Fig. 2. SAIRS, a 100-kWe space power system with heat pipes cooled reactor and AMTEC units [5].

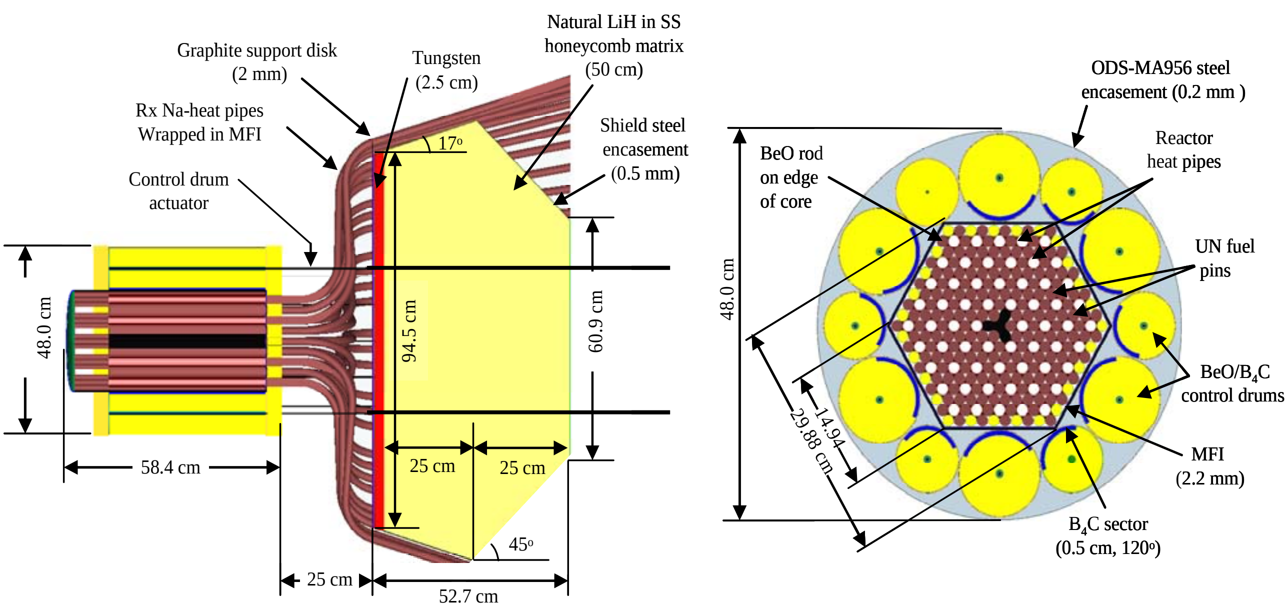
3. Space power system concepts

This section presents four space nuclear reactors and power systems for the avoidance of single-point failures in reactor cooling, energy conversion, and heat rejection. The reactors presented are cooled with either liquid metal heat pipes or circulating liquid metal and noble gas binary mixture of He-Xe (40 g/mole). For the latter two circulating working fluids, the presented reactor cores are divided into 6 or 3 sectors. These sectors are thermally and neutronically coupled, but hydraulically decoupled, and each has its own energy conversion primary loop, secondary loop, and heat rejection radiator panels.

3.1 SAIRS – Scalable AMTEC integrated reactor space Power system

Figure 2 presents the Scalable AMTEC Integrated Reactor Space (SAIRS) power system [5], developed with no single point failures, employs a fast neutron spectrum nuclear reactor, cooled with a multitude of sodium (Na) heat pipes, and 18, 5.6 kWe Na-AMTEC units, or 24, 4.2 kWe Na-AMTEC units [13]. The AMTEC units are divided into six blocks of 3 or 4 units and each block is cooled by a multitude of potassium (K) heat pipes in a separate radiator panel (Figs. 2a and 2b). The six AMTEC blocks are connected electrically in parallel, and the units in each block are connected in series, providing excellent redundancy, while supplying electrical power to the load at high (> 176 V) DC voltage. Thus, with a failure of more than one AMTEC unit, in more than one block, the power system will continue to operate, but at a reduced reactor thermal power [5].

The estimates of the system's specific power are 29.7 - 34.8 We/kg and of the radiator area are 21.1 - 26.9 m^2. The heat rejection radiator panel for each AMTEC block is made of two sections, a stationary forward section attached to the AMTEC units, and a rear conical deployable section, which is folded onto the stationary section in the stowed launch configuration (Fig. 2a). The K-heat pipes in the two sections of the radiator panels are connected using flexible joints and the surface of the radiator is armored to protect against impact by meteoroids [5]. The specific mass of the potassium heat pipes radiator of 7.67 kg/m^2 is the same as that for the SP-100 system [19].



(a) Axial Cross-section in SAIRS Reactor and Shield. (b) Radial Cross-section in SAIRS Reactor.

Fig. 3. Cross-sectional views of SAIRS reactor and radiation shadow shield.

The SAIRS hexagonal, fast-spectrum nuclear reactor is cooled by 60, 1.5 cm OD, Mo-14%Re sodium heat pipes. Each heat pipe serves a module comprised of three UN, Re clad, fuel pins arranged in a triangular lattice and brazed to a centrally positioned heat pipe, with a Mo-14%Re wall of the same OD (1.5 cm). Six, Re tri-cusps braze the heat pipes wall (0.4 mm thick) to the Re cladding of the fuel pins along their active length [5]. The UN fuel modules placed in the reactor core are delineated in Figs. 3a and 3b. Figure 3a shows the routing of the sodium heat pipes after exiting the reactor. The shadow radiation shield (Fig. 3a) consists of a 2.5-cm thick tungsten layer for attenuating the high energy gammas rays, followed by a 50 cm thick LiH, for attenuating fast neutrons from the nuclear reactor.

To minimize the physical penetrations through the shield, the heat pipes exiting the reactor vessel and the axial BeO reflector are bent around the shadow shield before entering the radiator cavity (Figs. 2a and 3a). These heat pipes are structurally supported using a 2 mm-thick graphite disk placed in front of, but thermally insulated from, the radiation shadow shield (Fig. 3a). The heat deposited in the shield (< 6 kW) by the attenuation of the fast neutrons and the primary gammas from the reactor is dissipated by thermal radiation into space from the conical side surface of the shield, keeping the LiH temperature within a desirable range of 600–680 K [24].

The reactor heat pipes are kept 3.0 cm away from the side surface of the shield, thus allowing the emitted thermal radiation to stream into space, and do not obstruct the drive shafts (or actuators) of the 12 BeO/B_4C control drums in the radial reflector (Figs. 3a and 3b). The length of the evaporator section of the reactor sodium heat pipes is the same as the active height of the UN fuel in the core (42 cm), and the length of the condenser section is the same as that of the AMTEC units block (1.23 -1.64 m). For a 100 kWe space power system, the reactor thermal power is quite low, 452 - 542 kW [5]. In order to minimize the diameter and the mass of the radiation shadow shield (628 kg) as well as the minor diameter of the radiator, the shield is placed as close to the reactor as possible (25 cm) (Fig. 3a).

3.2 Heat pipe cooled reactor with segmented thermoelectric module converters (HP-STMCs)

The HP-STMCs space reactor power system is nominally designed to generate 110 kWe (Figure 4) [3,9]. The hexagonal heat pipe reactor core in HP-STMCs power system is comprised of 126 heat pipe-fuel modules [3]. Each module consists of three UN, Re clad fuel pins arranged in a triangular lattice and brazed to the central lithium heat pipe with a Mo-14%Re wall of the same OD (1.5 cm) as the fuel pins. The evaporator length of the lithium heat pipes is 45 cm and the lithium heat pipes reactor, including the radial and the axial BeO reflectors, has a 56 cm OD and is 66.1 cm tall [3]. The active core is 45 cm long and 35.4 cm wide flat-to-flat. The control of the reactor is accomplished using a total of 12 BeO/B_4C rotating drums in the radial reflector. The B_4C segments (5 mm-thick 120^o sectors) in the drums face the reactor core during launch and at startup and face away from the reactor core at the end of life.

The nominal thermal power of the reactor is 1.6 MW and the average design power throughput per lithium heat pipe is 12.7 kW. This power throughput represents an operation design margin of at least 28% relative to the prevailing wicking limit [25]. An auxiliary radiator with a surface area of 1.0-m^2 cools the instrumentation and control equipment placed behind the shield (Fig. 4). The number of the K-heat pipes (162) in the front and the rear sections of pf the power system radiator are the same, but their diameter in the rear section is slightly larger to ensure their nominal operation at 43.6% of the sonic limit [3,25]. During nominal operation, the hot-side temperature of the STMCs is constant at 1300 K, for a SiGe hot junction temperature $\geq$ 1270 K, and the evaporator temperature of the K- heat pipes in the radiator is 776 K. At these temperatures, the efficiency of the power system is 6.7%, the net electrical power is 110 kW_e (Fig. 4), and the system's specific power is ~ 26.8 We/kg.

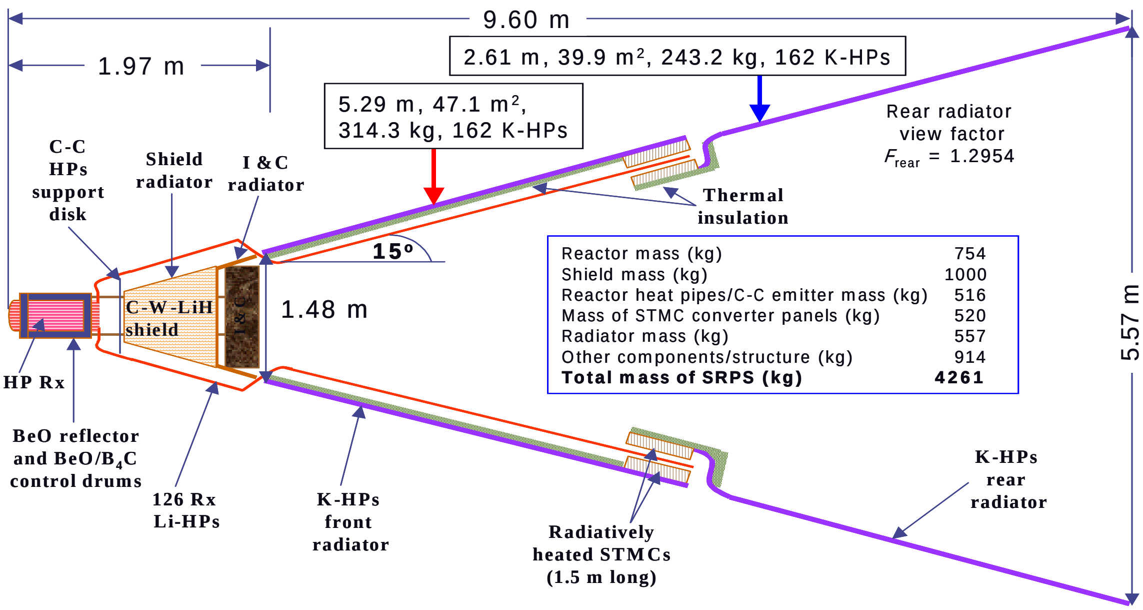
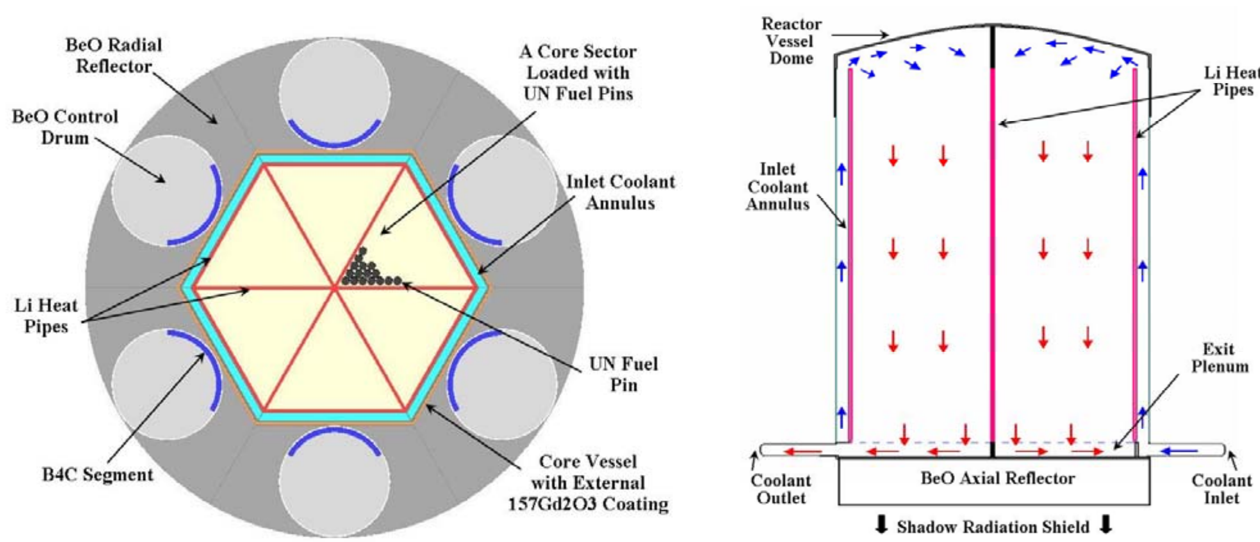


Fig. 4. A Layout of the reference 110 kWe, HP-STMCs space reactor power system [3].

3.3 Sectored, compact reactor (SCoRe) space power system

The Sectored, Compact Reactor (SCoRe) in Figure 5 is convectively cooled with a circulating liquid metal of NaK (78% Na), sodium, or lithium, in order of increasing reactor temperatures of 850 K, 1100 K, and > 1100 K. The hexagonal reactor core is divided into six, thermally and neutronically coupled, but hydraulically decoupled sectors. The reactor hexagonal core is surrounded by a 16 cm-thick radial BeO reflector and has 4.0 cm thick axial BeO reflectors. The reactor control is accomplished using 6, BeO rotating control drums in the radial reflector, with 0.5 mm thick, 120^o, B_4C segments (Fig. 5a). The liquid metal coolant enters the reactor and flows upward in an annulus on the inside of the reactor vessel wall, reverses direction at the opposite end to flow through the core sectors, then flows to the lower plenums from which it exits the reactor core (Fig. 5b) [26].

The coolant inlet annuli, the exit plenums, and the dome of the six sectors of the reactor core are physically separated. In the event of a break in the inlet or the exit pipe of a sector, resulting in a loss of coolant (LOC), the reactor continues to operate, but at a lower power. The common dividers between the sectors in the reactor core and the inner wall of the coolant inlet annulus are made of flat-plate, liquid metal heat pipes. These heat pipes facilitate the passive cooling of the reactor sector experiencing a LOC, by transporting the fission generated heat in it to the circulating coolant in the two adjacent sectors and coolant flowing through the inlet annulus (Figs. 5a and 5b).



(a) Radial cross-section of SCoRe core in shutdown mode.

(b) Axial cross-section of coolant circulation In SCoRe Core.

Fig. 5. Cross-sectional views of SCoRe for space power systems [26].

The SCoRe core is loaded with UN fuel pins, 0.74 cm OD. These pins are arranged in a triangular lattice with a pitch of 0.8 cm. The UN fuel pellets in the pins have as-fabricated porosity of 10%, and the Mo-14%Re cladding has a wire wrap (0.6 mm OD) brazed in a helical pitch onto its surface. The Mo-14%Re wires, which run the length of the fuel pins, maintain uniform spacing between the pins, provide structural support, and create a spiraling coolant flow path for enhanced convective cooling.

The SCoRe-S_{11} is loaded with a total of 1026 UN fuel pines, 171 pins in each of the six sectors of the reactor core. When these fuel pins operate at an average thermal power of 2.5 kW, SCoRe-S_{11} generates 2.86 MW of thermal power and could operate consciously for up to 4 years. Reducing the reactor power increases its operation life commensurately. Each sector in the SCoRe-S_{11} core is thermal-hydraulically coupled to a separate pair of primary and secondary liquid metal loops and a rubidium heat pipes radiator panel for waste heat rejection.

Figure 6 shows an isometric view of the fully integrated space reactor power system with SCoRe-S_{11} fission heat source. This power system employs SiGe Power Conversion Assemblies (PCAs), which are placed between the primary and the secondary liquid metal loops. The liquid metal coolants in these loops are circulated using separate electro-magnetic pumps powered by separate SiGe Thermoelectric Conversion Assemblies (TCAs). These TCAs are also placed between the primary and secondary loops (Fig. 7).

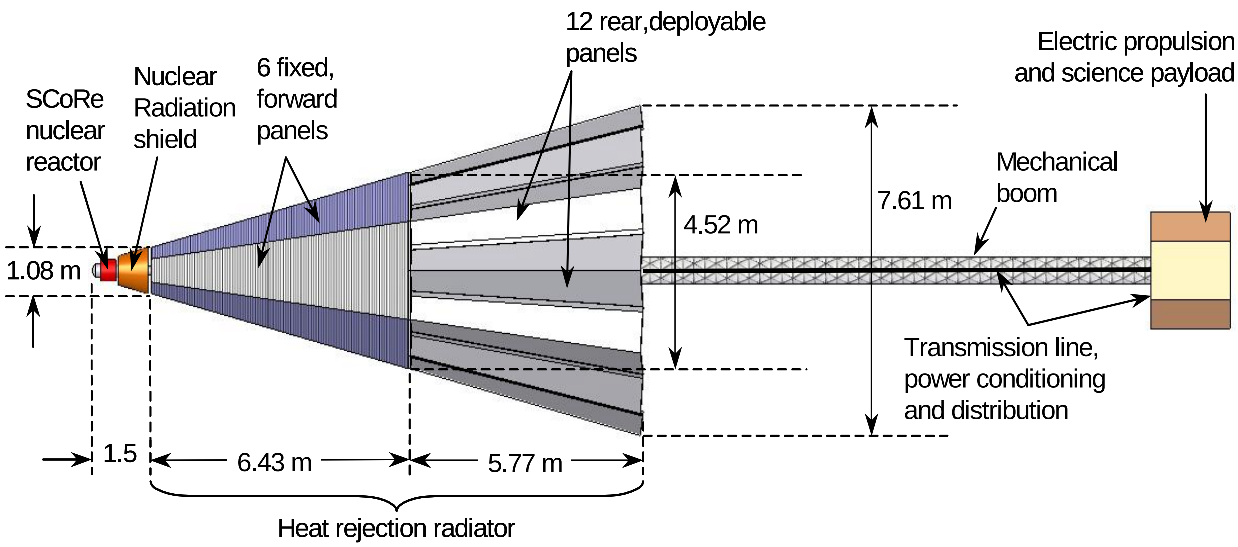


Fig. 6. SCoRe-S_{11} space reactor power system with SiGe TE converters for 111.5 kWe [4].

The nominal working fluids in the secondary and primary loops of the power system in Figure 6 could be any combinations of Li/Li, Li/NaK, Na/Na, or Na/NaK, depending on the selected operation temperatures of the power system [4]. Each primary and secondary loop has its own liquid-metal accumulator [27], designed to maintain appropriate coolant pressures and accommodates the volume expansion of the liquid metal coolants from strat up to nominal operation temperatures (Fig. 7). The performance results presented in Fig. 7 for this space reactor power system are for lithium coolants in the primary and secondary loops, SCoRe-S_{11} fission heat source, and SiGe converters.

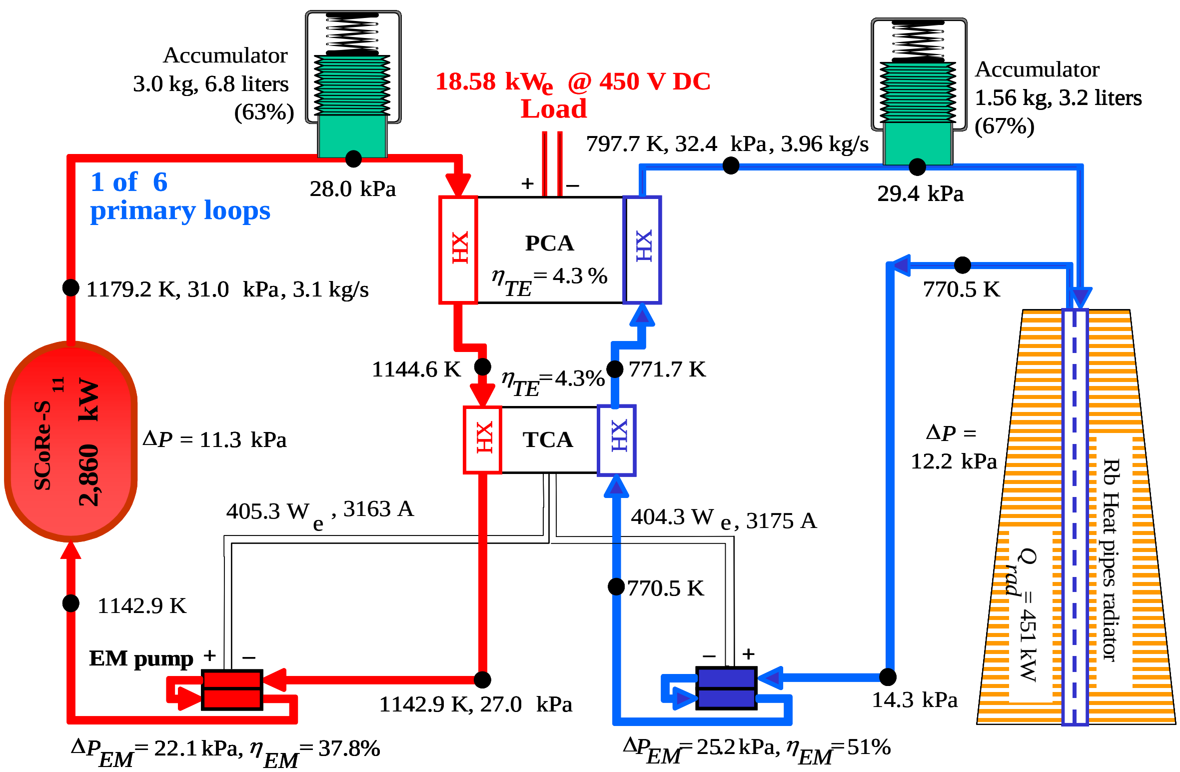


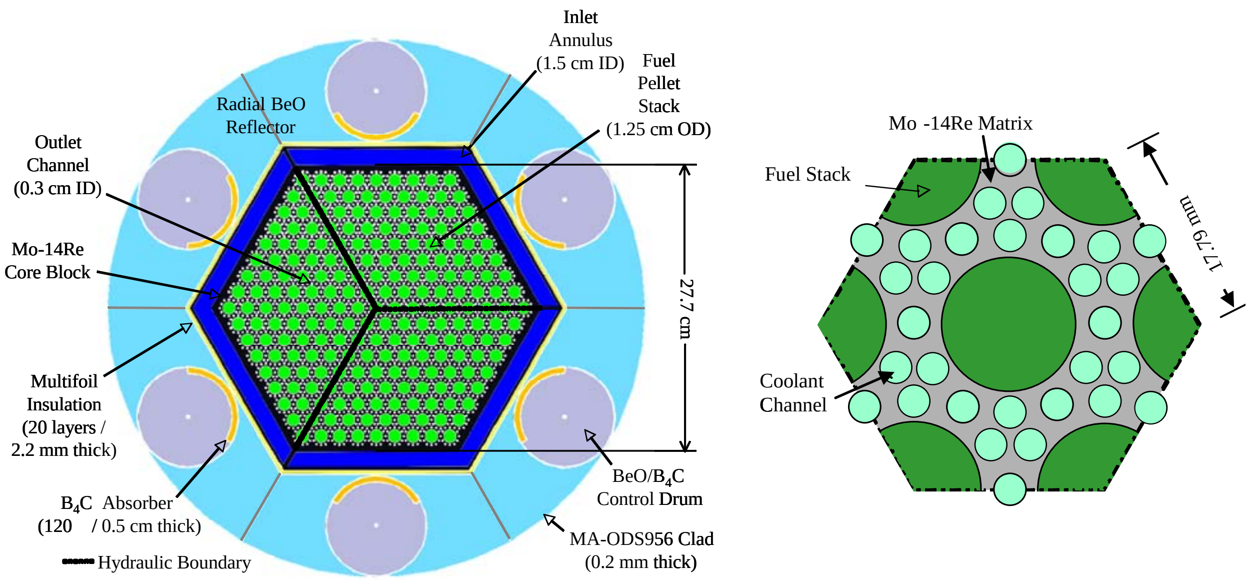
Fig. 7. A pair of primary and secondary coolant loops for one sector of SCoRe-S_{11} space power system [4].

3.4 Submersion-subcritial, safe space (S^4) reactor power system

The Submersion-Subcritical Safe Space (S^4) reactor, cooled with a He-Xe binary mixture (40 g/mole), nominally operates at 471 kW_{th} (Figs 8a and 8b). The S^4 reactor has a hexagonal, Mo-14Re (molybdenum with 14 wt% rhenium) solid core with cylindrical cavities loaded with uranium nitride fuel pellet and surrounded by coolant channels (Fig. 8b). The UN fuel stacks in the reactor core are 1.25 in diameter and arranged in a triangular lattice with a pitch of 1.779 cm. The coolant channels are 3 mm in diameter (Fig. 8b) [28].

The S^4 reactor core is divided into three sectors, that are thermally and neutronically coupled, but hydraulically decoupled. Each reactor sector has its own CBC loop, a Nak-78 secondary loop, and two water heat pipes radiator panels (Fig. 9) [6]. The two radiator panels, dedicated to each of the three CBC loop in the power system, are hydraulically connected in parallel to reduce pressure losses and the NaK-78 inventory in the secondary loop and hence, the volume and mass of the liquid metal accumulator (Fig. 9) [6].

The high thermal conductivity of the solid core block (> 68 W/m-K) facilitates the transfer of the heat generated by fission from a sector experiencing a LOC to the adjacent sectors by conduction. At nominal steady-state operation, the S^4 space power system generates a net electrical power to the load of 93.6 kWe, at a net efficiency of 21.4% (Fig. 9). The nominal pressure at the exit of the compressor units in the CBC loops is 2.0 MPa and the single-shaft, centrifugal flow turbo-machines rotate at 36,000 rpm [29] (Fig. 9). The power system continues to operate with only 2 CBC engines, but at a lower reactor power, following a failure of one of the turbo-machines, a loss-of-cooling, or a break in one of the CBC loops. The fission power generated in the reactor sector connected to the failed CBC loop is transported by conduction and/or radiation to the dividers with the two adjacent sectors, where it is then removed by forced convection of the circulating gas in these sectors.



(a) Radial Cross-Section of S^4 Reactor.

(b) Fuel Elements - Coolant Channels Unit Cell.

Fig. 8. A Radial Cross-Section of and the Arrangement of UN Fuel and Coolant Channels in S^4 Reactor [28].

The NaK-78 (78wt% Na and 22wt% K) in the secondary loops is circulated using an Alternative Linear Induction Pumps (ALIP). The secondary loops transport the thermal power extracted from the He-Xe, of the CBC loop working fluid, in the gas cooler, to the water heat pipe radiator panels where it is rejected into space. The NaK-78 coolant in the secondary loops enters the radiator panels at 530 K and exits at 395 K. Each radiator panel nominally rejects 54 kW_{th}, for a total 324 kW_{th} for the space reactor power system. The total thermal power generated in the three sectors of the S^4 reactor is 437 kW_{th}, which is slightly lower that the nominal design value of 471 kW_{th} [6]. The turbo-machines in each of the three CBC loops of the space power system (Fig. 9) deliver a net electric power to the load of 31.2 kWe per loop and 93.6 kWe total for the system. At this electrical power, the net efficiency of the system is 21.4%, after accounting for 10% transmission and inversion losses and the electrical power supplied to the ALIP.

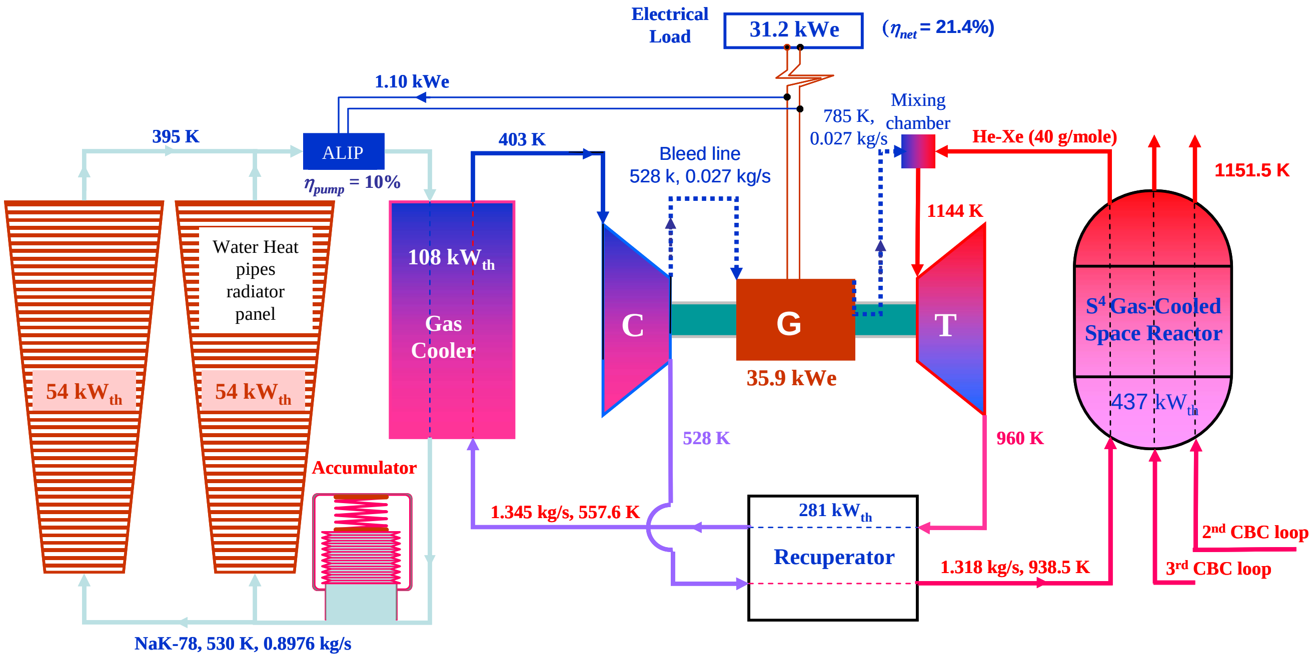


Fig. 9. Operation parameters of one of the three CBCs in S^4 reactor power system for 93.6 kWe nominal power [6].

4. Summary and conclusions

Future space exploration and human outposts would require high power sources that operate 24/7 for more than 10 years, independent of the sun. Such power sources are likely to use fast neutron spectrum, nuclear fission, reactors and either static or dynamic energy conversion. Owing to the need for high reliability, these power systems would be based on reactor and energy conversion technologies and nuclear fuel and structure materials with demonstrated performance and well known properties. Other desirable attributes for such power systems are the absence of a single point failure and, preferably, load-following characteristics. Presented is a summary of the projected specific power and conversion efficiency for a number of space nuclear reactor power systems reported in the literature, with static and dynamic energy conversion technologies and fast neutron spectrum reactors. These power systems employed SiGe TE, STE, AMTEC, CBC, FPSEs, R-Rankine Cycle, or TI for partially converting the reactor thermal power to electricity. Some of these systems used one loop or multiple loops for energy conversion, but all used single inlet and exit for the coolant in the nuclear reactor, thus have a single point failure in reactor cooling and energy conversion.

In addition, this paper presented four space reactor power system concepts, developed at the University of New Mexico's Institute for Space and Nuclear Power Studies, with both static and dynamic energy conversion, but no single point failures in reactor cooling, energy conversion, and heat rejection. The first two space power systems employ nuclear reactors cooled with lithium and sodium heat pipes, use SiGe thermoelectric (TE) and Alkali-Metal Thermal-To-Electric Conversion (AMTEC) static energy conversion units, and potassium heat pipes radiators. The reactors heat pipes operate at a fraction of their prevailing capillary or sonic limit. Thus, in case of a multiple heat pipes failure, those in the adjacent modules in the reactor core would remove the additional heat load, maintaining the reactor cooled and the power system operating, but at a reduced power.

The third space power system employs a liquid metal cooled reactor with a core divided into six identical sectors that are neutronically and thermally coupled, but hydraulically decoupled. Each sector in the reactor core has a separate energy conversion loop, a heat rejection loop, and a rubidium heat pipes radiator panel. When a core sector experiences a loss-of-coolant, the fission power of the reactor is reduced, and that generated in the sector in question is removed by the circulating coolant in the adjacent sectors. The fourth space power system employs a gas cooled reactor with a core divided into three identical sectors. Each sector is coupled to a separate Closed Brayton Cycle (CBC) loop with He-Xe binary mixture (40 g/mole) working fluid, a secondary heat rejection loop with a circulating NaK-78, and two water heat pipes radiator panels.

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