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TITLE LOW POWER REACTOR FOR REMOTE APPLICATIONS

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ABSTRACT

A compact, low power reactor is being designed to provide electric power for remote, unattended applications. Because of the high fuel and maintenance costs for conventional power sources such as diesel generators, a reactor power supply appears especially attractive for remote and inaccessible locations. Operating at a thermal power level of 135 kWt, the power supply achieves a gross electrical output of 25 kWe from an organic Rankine cycle (ORC) engine. By intentional selection of design features stressing inherent safety, operation in an unattended mode is possible with minimal risk to the environment. Reliability is achieved through the use of components representing existing, proven technology. Low enrichment uranium particle fuel, in graphite core blocks, cooled by heat pipes coupled to an ORC converter insures long-term, virtually maintenance free, operation of this reactor for remote applications.

REACTOR POWER SUPPLY CONCEPT

Salient features of the reactor power supply are its 19.9% low enrichment uranium (LEU) fuel, graphite moderator and reflectors, thermal neutron spectrum, and heat pipe cooling. Of the 135 kWt total reactor power, 10 kWt is lost through the vessel and 125 kWt is transferred via heat pipes to the ORC working fluid, as shown schematically in Fig. 1. Waste heat is rejected to ambient air by the ORC condenser. The reactor power supply provides 25 kWe gross electrical power, of which a net of 20 kWe is delivered to the load. A "housekeeping" load of 5 kWe is required for controls, cooling fans, and power conditioning equipment. With sufficient fuel for 20 years of normal operation, the reactor does not require refueling.

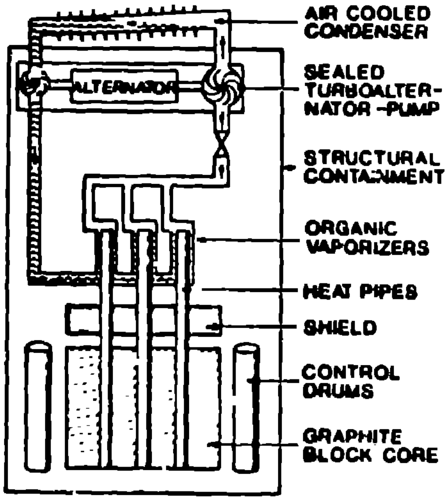

Fig. 1. Reactor and ORC system.

The reactor power supply has few moving parts and possesses high reliability. The fission product retention capability of the fuel at temperatures and burnups far in excess of design conditions, the large graphite mass and relatively low operating temperature, and the strong negative temperature coefficient of reactivity result in an inherently safe design. By combining existing, proven reactor and converter component technologies, the need for major development is eliminated. Redundant heat pipes and dual ORC converter systems allow for failures in either or both components with no reduction in electrical power output.

The present concept of the reactor power supply with an ORC converter is shown in Fig. 2. Placing the reactor below grade, where conditions permit, reduces the shielding requirements. Heat pipes extend above the reactor and into the ORC vaporizers. Overall dimensions of the power supply are 1.7 m diameter and 3.5 m high.

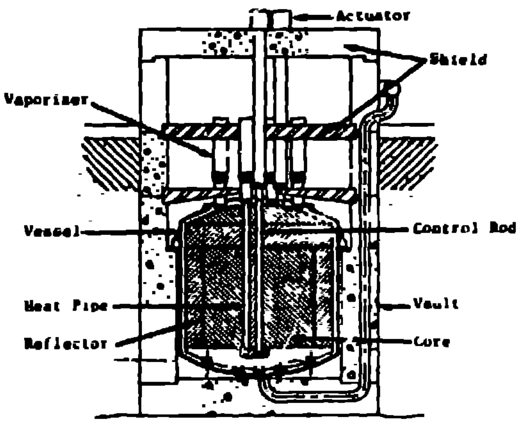

Fig. 2. Reactor for remote applications.

REACTOR DESCRIPTION

At the heart of the power supply is the reactor core, which contains 19.9% LEU fuel in the UCO-kernel particle form. This type of fuel is presently used in high temperature gas reactors (HTGRs) in the US and West Germany. Numerous tests have shown that the particle fuel will contain virtually all the reactor fission products up to temperatures of 1400°C and burnups of 100 MWd/kg. In this reactor very large safety margins exist because the average core temperature is 570°C and the burnup during 20 years of normal operation is a relatively low 15 MWd/kg.

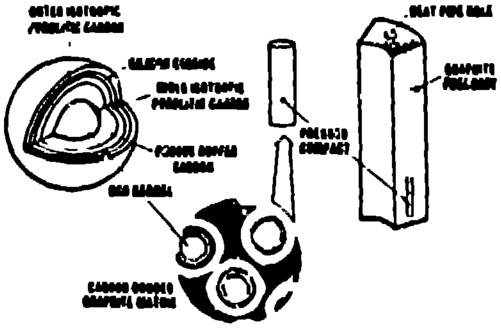

Fig. 3. Fuel element components.

REACTOR FUEL

In the low power reactor the fuel is in the form of spherical particles, with 500 μm UCO fuel kernels. The kernels are alternately coated with porous carbon, pyrolitic carbon, silicon carbide, and pyrolitic carbon to form spherical pressure vessels about 1 mm in diameter, which are called "TRISO" particles. When compressed together with a binder the particles form fuel rod compacts 1.3 cm in diameter and 4 cm long, as shown in Fig. 3. The TRISO particles and fuel rod compacts are quite similar to those currently manufactured for HTGRs in the US.

Shown in Fig. 4 is a top, cross sectional view of the reactor. It consists of a 120 cm diameter, 110 cm high core composed of 12 graphite blocks. At the center of each block is a heat pipe that removes thermal energy from the core. Holes are bored in the blocks for 500 stacks of fuel rod compacts, 5 control rods, and 12 heat pipes. With a graphite to fuel compact volume ratio of 16 to 1, the neutron spectrum is nearly thermal. The radial reflector is graphite 20 cm thick and the axial reflectors are 25 cm thick. A total ^{235}U inventory at beginning-of-life (BOL) of 13.4 kg constitutes the fissile fuel inventory in this criticality limited reactor.

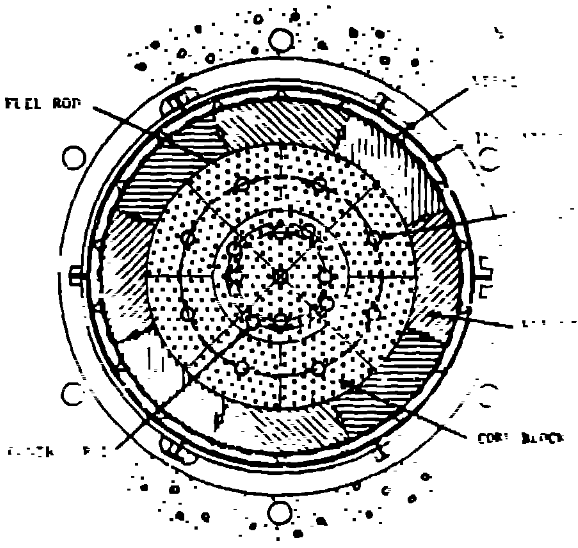

Fig. 4. ORC optimized reactor core.

REACTOR PHYSICS ANALYSIS

Extensive neutronics calculations have been performed on the reactor using both multigroup transport theory (TWODANT) and Monte Carlo (MCNP) methods.

Start-up and control of the reactor is provided by five in-core control rods of B_4C (natural boron). Table I summarizes the operational modes of the reactor and the corresponding reactivities. At BOL the reactor is brought from a very subcritical state (a k_{eff} less than 0.9) to a cold critical configuration by slowly withdrawing the control rods (one at a time) from the core, starting with the outer four rods. At cold critical, the central rod will be fully in and the outer rods will still be partially in. Withdrawal of the remaining outer rods and partial withdrawal of the central rod will bring the reactor thermal power up to 135 kW. The increase in the temperature of the core (from ambient to 570°C) will absorb about 6% reactivity. The reactivity worth of the remaining partially withdrawn central rod will be about 3.5%, which will be used to compensate for the effects of fuel depletion (1.4% in k_{eff}) and fission product build-up (2.1% in k_{eff}) over the scheduled 20 year life. At any time, the insertion of any two of the control rods would be sufficient to reduce the reactor to a cold subcritical state.

Since the reactor is reactivity limited, rather than power density limited, there is little incentive for power flattening, which would increase the fuel inventory and hence the capital cost of the system. The presence of the central control rod in the core during operation depresses the power densities in the region around the rod (see Fig. 5), but this is localized and no difficulties are encountered in maintaining a constant 135 kW output as the rod is moved out during the 20 year life.

Table I

Reactor Operational Modes

Reactor Condition	Core Temp.	k_{eff}	Reactivity Reserve in Rods (ΔK)
BOL, shutdown	300C	0.850	0.250
BOL, cold critical	300C	1.000	0.100
BOL, 135 kW	570C	1.000	0.040
EOL, 135 kW	570C	1.000	0.005
EOL, shutdown	300C	0.82	0.250

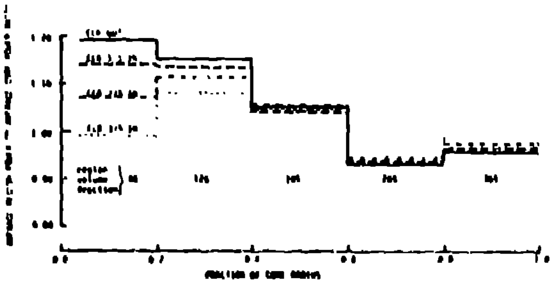

Fig. 5. Effect of central control rod insertion on radial power distribution.

The C/^{235}U atom ratio of about 3000 to 1 produces a neutron spectrum with a large thermal neutron fraction (about 75%). Associated with such a soft spectrum is a very large negative temperature coefficient of reactivity made up of several components, as shown in Fig. 6. Of the 6% reduction in k_{eff} between ambient and operating temperature, about 4% is caused by the effect of the increase in graphite temperature on neutron thermalization, another 1.75% is produced by the Doppler broadening of the ^{238}U resonances and the remainder is caused by an increase in the neutron leakage from thermal expansion of the core. This large negative coefficient makes it impossible for the fuel to reach the particle failure temperature of 1400°C even during a control malfunction or other accident.

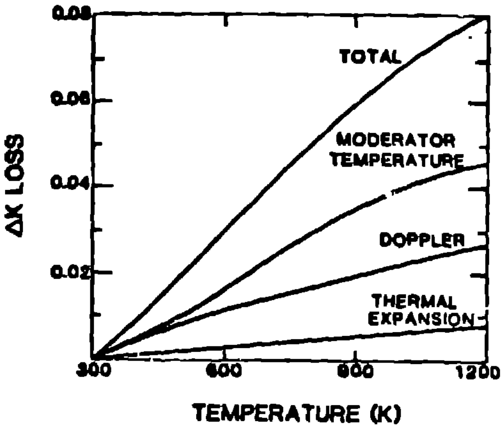

Fig. 6. Effect of temperature on k_{eff}.

SAFETY

This reactor was designed so that a number of inherent physical characteristics limit the k_{eff}, the power, and the temperatures in the reactor during any conceivable accident scenario. This results in an "inherently safe" system that requires no operator intervention to preclude significant risk to the public or the environment.

Reactor safety studies were performed on accident scenarios that have the greatest risk potential: loss of coolant (LOC) and transient overpower (TOP) without scram. Each of the core heat pipes is independent of the others and thus provides a degree of redundancy in the cooling system not found in other reactors. Furthermore, the large thermal inertia of the reactor core provides ample time for system failures to be detected, analyzed, and for corrective measures to be taken. However, in the extremely unlikely event that all of the heat pipes fail and the scram system fails to operate, the core power self-regulates to balance the available heat removal through the vessel wall. This equilibrium power level is about 15 kW and the core temperature equilibrates at about 600 to 650°C. Thus, a reactor damaging LOC accident is not a serious event in this design.

A significant TOP accident requires the inadvertant addition of reactivity to a degree which overcomes any inherent negative reactivity feedback available at a time when protective engineering devices are inoperative. During the operation of this reactor the only significant reactivity available for insertion is the 3.5% Δk_{eff} held in reserve in the central control rod. A control malfunction that completely removes the control rods at the maximum allowable rod drive speed would, in the event of no automatic or manual intervention, result in an equilibrium temperature of about 1000°C. This is 400°C below the onset of failure for the TRISO particles. Because of the large thermal mass of the core, this temperature would be approached very slowly following the control malfunction. Since the heterogeneous arrangement of fuel and moderator in the core was designed to be the maximum reactivity configuration, any redistribution of core materials would also result in a decrease in k_{eff}. In addition to the inherent safety characteristics of the reactor, redundancy was built into the safety and control rod system. Each of the rods has a reactivity worth of several percent, and all but one of these, the central rod, will be out of the core during operation at power. The central rod will be partially withdrawn at BOL. Insertion of two rods would reduce the reactor to a cold subcritical state.

In most thermal reactors there is a special excess reactivity requirement known as xenon override. The amount of ^{135}Xe build-up is dependent on the operating power density of the system. In this reactor the power density is several orders of magnitude lower than in conventional thermal reactor systems and the build-up is negligible. No override is required and the reactor can be started up at any time.

SHIELDING

Personnel and sensitive system components must be protected from the neutron and gamma radiation produced by the reactor during operation, and gamma radiation after shutdown. Above the reactor core 20 cm of borated graphite and 20 cm of steel will reduce the amount of radiation incident on the organic working fluid and the control mechanisms during normal operation as well as to maintenance personnel during reactor shutdown. Around the sides of the reactor about 180 cm of ilmenite concrete will reduce radiation fluxes to acceptable levels (2.5 mrem/h). If local materials are suitable, a combination of the concrete reactor vault and rock/earth could be a viable shield design.

CORE THERMAL AND STRUCTURAL ANALYSIS

The ABAQUS(1) finite element code analysis was used to perform a thermal/structural analysis on the reactor. Normal operation with 500°C heat pipes produces an average graphite temperature of 570°C, with a maximum of 590°C. With a gap of 0.1 mm between the heat pipes and graphite blocks the gap ΔT is 15°C when filled with helium gas at 1 atmosphere pressure. The current design incorporates core and reflector blocks made of purified reactor grade graphite. At BOL the thermal conductivity of this extruded graphite is 170 W/mK with the grain and 110 W/mK against the grain.(2)

Shown in Table II is a compendium of core ΔTs for various operating scenarios, including that of failed heat pipes, at EOL when thermal conductivity is at a minimum. Sufficient margin exists in both the reactor and heat pipes to allow for failures of one or two heat pipes without reduction in electrical output from the system. Sufficient design margin is built into the heat pipes to allow those remaining to increase their heat load so as to maintain a constant 125 kWt to the ORC system.

The reactor vessel is filled with helium to a pressure slightly above 1 atmosphere. Core ΔTs and maximum temperatures are thereby reduced. Atmospheric oxygen ingress to the vessel is also precluded. Although not detrimental on a short time scale, oxygen would react with the graphite over the 20 year life of the system.

Structural analysis of the core has shown that the maximum tensile stress in the graphite blocks during normal operation is approximately 25% of the ultimate tensile strength (UTS) of the graphite. This stress exists at the heat pipe hole where the temperature gradient is a maximum. When a heat pipe fails, the stress increases in the graphite surrounding the neighboring heat pipes. However, the maximum stress is still only about 30% of the UTS. Compressive stresses are quite low throughout the core.

Table II

Reactor Temperatures and ΔTs °C

Normal Operation	
o Graphite average	570
o Graphite maximum	590
o Heat pipes	500
o Heat pipe gap	15
One Failed Heat Pipe	
o Graphite average	580
o Graphite maximum	660

With an average core neutron fluence of 5×10^{20} neutron/cm^2 ($E > 0.1$ Mev) at EOL, no significant graphite swelling exists.(3) The average core temperature is above the Wigner energy storage level. The only appreciable property change that occurs in the reactor materials is the two-fold reduction in graphite thermal conductivity.(4) Because the average core power is an extremely low 0.1 W/cm^3, the reduction in thermal conductivity is not detrimental to reactor operation.

Decay heat removal is not a problem in this reactor. After shutdown the decay heat rapidly decreases to less than 2 kWt and the reactor temperature drops to about 150°C. Essentially all of this heat is transferred through the vessel walls to the vessel cooling air because the heat pipes cease to function at this low temperature. One of the safety features of the design is that in the event of a reactor shutdown, no active decay heat removal system is required to maintain the reactor in a safe shutdown condition; natural convection of vessel cooling air is sufficient.

HEAT PIPES

Reactor heat is removed from the core by 12 heat pipes 6.1 mm o.d. x 5.7 mm i.d. x 2.5 m long, which transfer the heat to the ORC converter working fluid. Heat pipes are passive, isothermal devices that contain no moving parts. Compared to circulating, pumped liquid or gaseous reactor cooling systems the heat pipes are highly reliable. The reactor heat is removed from the core by evaporating the potassium working fluid from the interior walls of the evaporator section of the heat pipe. With its latent heat, the vapor flows to the condenser region of the heat pipe where the vapor condenses and the heat flows to the ORC vaporizers that encircle each heat pipe. The liquid potassium flows back to the evaporator region in the core over a knurled wall wicking structure, with an assist from gravity.

Because of its low neutron absorption cross section, zirconium was chosen as the heat pipe wall material. The extent of alloying of the zirconium is still under investigation, but molybdenum, iron, tin, or niobium may be present in small amounts in the heat pipe wall material.

Extensive heat pipe fabrication and testing has been performed successfully in the temperature range of interest. Although no specific data on zirconium/potassium heat pipes has been found, extensive data exists for similar metal wall materials and alkali metal working fluids. Nickel/potassium heat pipes have been successfully tested without failure for over 40,000 h(5) and Nb-1Zr/potassium heat pipes for 16,000 h. Successful operation of stainless steel heat pipes with both potassium and sodium working fluids in reactor environments has been achieved.(6) Corrosion tests have shown that zirconium/potassium heat pipes should be capable of reliable long-term operation in this reactor.(7) As shown in Fig. 2, the core blocks are sized and the heat pipes are situated so as to provide equal heat flow to each heat pipe, about 10.4 kWt. The maximum power that can be transferred at 500°C is 18.4 kWt as displayed in Fig. 7. Entrainment of the liquid by the vapor is the limiting physical phenomenon in this type of heat pipe. A large margin between the theoretical entrainment limit and the operating point is provided to accomodate a 33% power over-load caused by a failed heat pipe. Margin also exists to account for differences between the theoretical entrainment limit and the actual operating power limit. The radial heat flux in the evaporator is 5.3 W/cm^2, which is far below experimental limits.

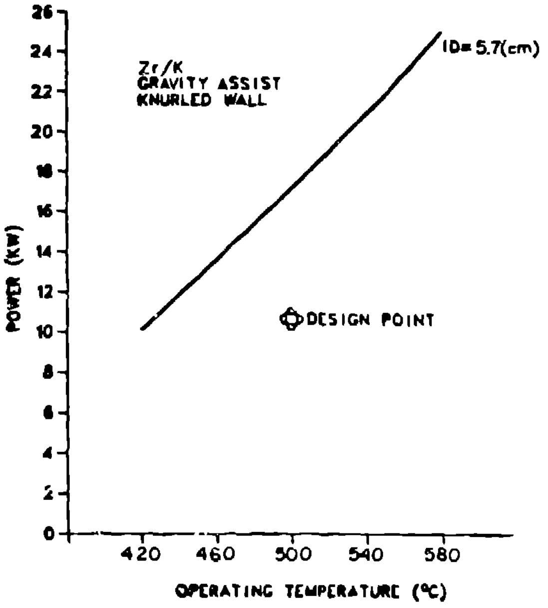

Fig. 7. Heat pipe entrainment limit power vs temperature.

ORGANIC RANKINE CYCLE CONVERTER

The low power reactor produces a 25 kWe of electrical power by converting 125 kWt of reactor heat into electricity in an ORC. The ORC system is quite simple, and consists of five main parts: the vaporizer, turbine, condenser, pump, and alternator. A regenerator can be added to increase system efficiency to greater than 20%.

Many ORC systems have been designed, fabricated, and successfully operated over a wide range of powers and temperatures.(8) Reliability of the ORC is of paramount importance. Also important, however, is the reduction of power supply size, weight, and cost that can be provided by an ORC of high efficiency. A supercritical toluene working fluid ORC appears to best meet these important objectives. The reactor heat is transferred through heat pipes to the 12 vaporizers, where the toluene is heated to ~370°C. A single-stage turbine extracts energy from the toluene to rotate the alternator and pump that are mounted on a common shaft with the turbine. The toluene flows through the regenerator to the condenser where it is cooled to 50-70°C. The pump pressurizes the toluene to about 5 MPa (700 psi) and returns it through the regenerator to the vaporizers. Control of the turbine-alternator-pump unit can be maintained with a flow or pressure control valve.

Because of the high working fluid temperature, an ORC efficiency in the range of 20-23% can be achieved. Gross electrical output is 25 kWe and net to the load is 20 kWe. Similar toluene ORC engines have been built and tested by Barber Nichols Engineering and Sundstrand.(9)

Waste heat is rejected to the atmosphere by the condenser. Dual fans provide system redundancy to transfer 100 kWt to atmospheric air. Although the fans could be eliminated in favor of a natural convection condenser, an increase in system size and weight would be incurred.

REACTOR MECHANICAL DESIGN

The reactor is hermetically sealed in a 1 cm thick stainless steel vessel that serves to prevent air ingress, He egress, and inadvertent damage to the reactor during shipment. The reactor is pressurized with He slightly above atmospheric pressure. Between the vessel and reflector is a 5 cm thick layer of cellular insulation that reduces reactor heat loss to about 10 kw. The heat pipe vaporizer and control rod portion of the power supply is structurally supported in a relatively thin cylindrical shell that provides support, and protection during transportation. Table III contains germane sizes and weights.

Although the heat pipes have proved extremely reliable in numerous multiyear tests, provision was made for their replacement through the use of flanges on the heat pipes and mating reseal devices on the vessel head. Replacement of actuators, fans, or He supply, although not anticipated, is quickly and easily performed. The redundancy of the aforementioned components allows for failures without the need for immediate or complicated maintenance.

Table III

Size and Weights

	Size (cm)	Weights (kg)
Reactor		
Core	120 o.d.	2200
Reflector	160 o.d.	3400
Vessel	172 o.d.	1400
Shield (Internal)		700
Heat Pipes		
Diameter	6.1	100
Length	250	
ORC		
Vaporizer		600
ORC system		500
Structure Rod Drives and Auxiliaries		700
Total Power Supply	172 o.d. 350 high	9700

CONCLUSION

Through innovative design choices and the use of proven technology, a reliable, inherently safe reactor power supply has been designed. Incorporation of an efficient ORC converter has reduced size, weight, and cost from previous, similar, reactor power supply designs,(10) while retaining desired safety and reliability characteristics. In remote areas where fuel and maintenance costs are high, such a reactor power supply can achieve life cycle cost reductions from those of diesel generators.

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