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A COMPACT REACTOR/ORC POWER SOURCE

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ABSTRACT

A compact power source that combines an organic Rankine cycle (ORC) electric generator with a nuclear reactor heat source is being designed and fabricated. Incorporating existing ORC technology with proven reactor technology, the compact reactor/ORC power source offers high reliability while minimizing the need for component development. Thermal power at 125 kWt is removed from the coated particle fueled, graphite moderated reactor by heat pipes operating at 500°C. Outside the reactor vessel and connected to the heat pipes are vaporizers in which the toluene ORC working fluid is heated to 370°C. In the turbine-alternator-pump (TAP) combined-rotating unit, the thermal energy of the toluene is converted to 25 kWe of electric power. Lumped parameter systems analyses combined with a finite element thermal analysis have aided in the power source design. The analyses have provided assurance of reliable multiyear normal operation as well as full power operation with upset conditions, such as failed heat pipes and inoperative ORC vaporizers. Because of inherent high reliability, long life, and insensitivity to upset conditions, this power source is especially suited for use in remote, inaccessible locations where fuel delivery and maintenance costs are high.

COMPACT NUCLEAR POWER SOURCE (CNPS)

The CNPS is a combination of a nuclear reactor heat source and an ORC electric generating system. Overall dimension of the CNPS are 1.7 m diameter and 3.5 m high. In the reactor, 125 kWt of thermal power is generated and transferred to heat pipes embedded in the core. Flowing out of the heat pipes and into the vaporizers, the heat is absorbed in the toluene ORC working fluid. At a conversion efficiency of 20%, the turbine-alternator pump (TAP) of the ORC converts the heat in the toluene to 25 kWe of electric power. The condenser rejects the remaining 100 kWt of waste heat to the ambient air by forced convection.

Important design features of the CNPS are its transportability and modularity. With a total weight of under 10 Mg in its assembled state, transportation by helicopter, fixed-wing aircraft, barge, or tracked vehicle is possible. Remote, inaccessible locations such as communications or radar sites, characterized by high fuel delivery and maintenance costs, are prime applications for the CNPS. Because the CNPS is designed for 20-yrs of normal operation without refueling and for minimal maintenance, the potential for significant life cycle cost reduction over that of conventional diesel generators exists. High reliability is incorporated in the design through the use of proven component technology. A long mean-time-between-failure (MTBF) results from redundant components and a design with few moving parts. Figure 1 is a three-dimensional cutaway view of the CNPS showing the vessel, reactor core, reflectors, control rods, heat pipes, and vaporizers.

*Numbers in parenthesis designate References at the end of the paper.

The reactor combines a number of inherent safety features (1*). Safeguards considerations are minimized by the use 19.9% enriched ^{235}U fuel. The coated particle fuel retains virtually all the fission products generated throughout the 20-yr life of the reactor. Transient effects are mitigated by the large graphite mass of the core. A strong negative temperature coefficient of reactivity is the salient inherent safety feature, limiting peak reactor temperatures well below failure limits in any credible accident scenario. No active cooling system is required for decay-heat removal. With mechanical stops on the control rods, core temperatures are limited to a maximum of 750°C under an uncontrolled reactivity insertion accident.

Several types of converters were investigated for possible use in the CNPS. Among those investigated were thermoelectric converters, Brayton Stirling, and Rankine cycle engines. Because of the requirement for high reliability and the desire to achieve this by incorporating proven technology, the less well known technology embodied in the Stirling cycle concepts was not considered.

Brayton cycle converter efficiencies are in general lower than Rankine cycle converters for the same inlet and outlet temperatures. To achieve reasonable efficiencies of 20 to 25% from a Brayton cycle, the reactor design operating temperature would have to be increased appreciably, with attendant reliability and materials concerns.

Thermoelectrics (TE's) were studied extensively for this application and may have superior reliability because the conversion system is essentially a

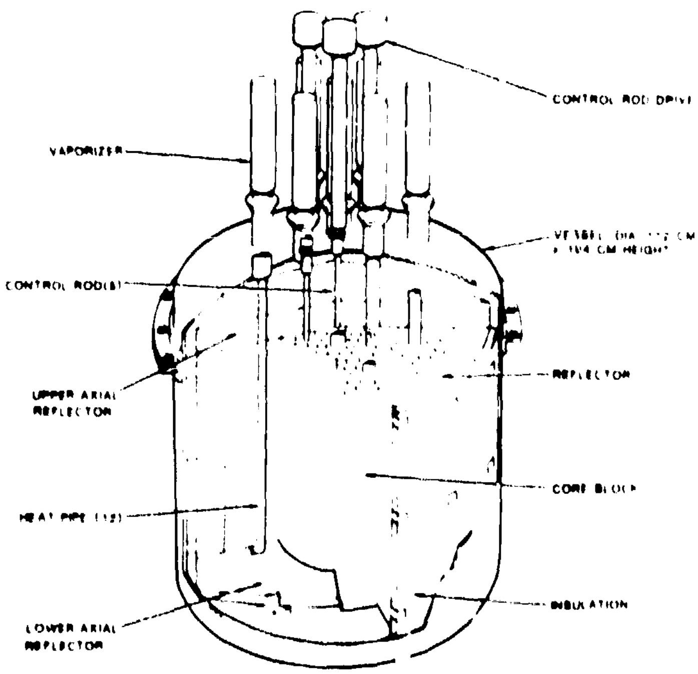

Fig. 1. CNPS reactor.

static system. However, several disadvantages accrue to thermoelectrics (TEs). Because of the lower efficiency of TEs and their decreased output with time, the cost of the overall system is higher. A TE converter system is also relatively larger and heavier, and costs extrapolate linearly with power.

The Rankine cycle converters evaluated were ORC, steam, and liquid metal. Liquid metal Rankine systems are not sufficiently developed and have not demonstrated long-term reliability. Steam Rankine systems present water quality and corrosion problems that require maintenance. In addition, an arctic environment could pose water freezing difficulties.

An ORC converter was selected for the CNPS because of its relative high efficiency, compactness, and demonstrated long-term reliability. High efficiency leads to reduced costs, size, and weight. Several ORC systems have been designed and tested in the past several years (2). Lower temperature, freon-working-fluid units deployed in the field have shown multiyear reliability in remote and arctic applications (3). Therefore, for this application, the ORC showed the most promise and cost effectiveness.

As schematically shown in Fig. 2, 125 kWt of reactor heat at 500°C is removed from the core by 12 heat pipes. Surrounding the upper condenser section of the heat pipes are the coiled tube vaporizers in which the toluene is heated to 370°C. The TAP generates 25 kWe of electrical power and efficiency is improved by incorporating a regenerator between the turbine exhaust and condenser to preheat the toluene as it is returned to the vaporizers by the pump.

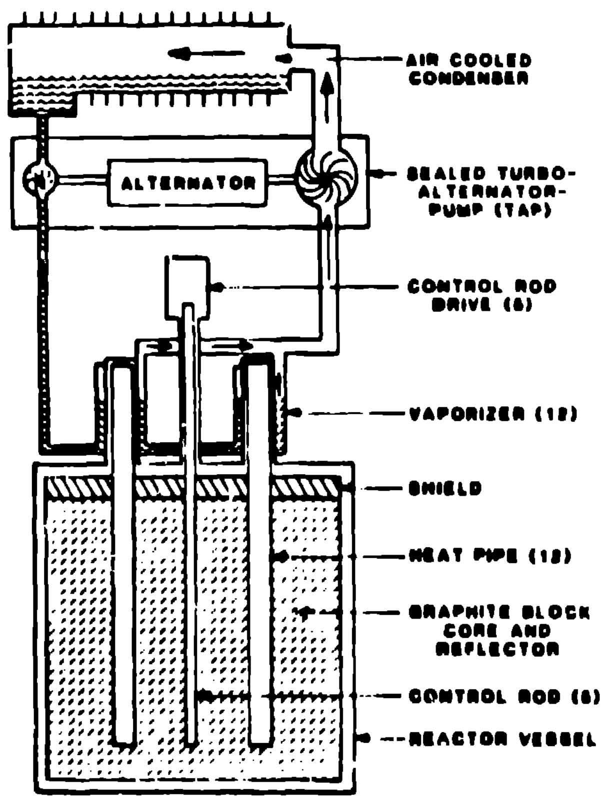

Fig. 2. Compact reactor/ORC power source.

REACTOR

The CNPS reactor core is 120 cm in diameter and 110 cm high. Surrounding the core is a graphite radial reflector 20 cm thick. The axial reflectors are graphite, and both the lower and upper reflectors are 25 cm thick. Above the upper reflector is a 20-cm-thick graphite top reflector/shield that serves primarily as a neutron attenuating shield. Both the lower and top reflectors are contoured to the shape of the vessel head.

With a C/^{235}U ratio of about 3000 to 1, the graphite purity and density have a large effect on reactivity. Purity is measured by boron equivalent (BE), which is derived by ratioing the neutron absorption cross section (σ_n) of a particular element or isotope to the cross section of natural boron (σ_B), multiplying by the concentration of the element in parts per million by weight, Xn (ppm), and summing over all elements.

$$BE = \sum_{i=1}^{n} \frac{\sigma_n}{\sigma_B} Xn \text{ (ppm)}$$

Because critical mass, hence size, and fuel loading, hence cost, are important, a very low BE is desired in the reactor. For the graphite core blocks and radial reflector, the BE is specified at a maximum of 2.0 ppm. A BE as high as 6.0 ppm can be tolerated in the axial reflectors.

Also, the graphite density must be relatively high so as to provide the necessary coefficient of reactivity, k_{eff}, without an undue increase in size. Both the core blocks and radial reflector have a specified density of 1.8 g/cm^3. Because the reactivity effect of the axial reflectors is less, the density of these blocks is 1.78 g/cm^3. The high graphite densities are achieved by pitch impregnation of the graphite prior to machining.

A total of 492 fuel rod holes are drilled into the core blocks as shown in Fig. 3. Twelve heat pipes made of Zr2.5Nb, with potassium as the working fluid, transfer the reactor heat out of the core at 500°C. Five control rods, made of B_4C absorber pellets contained in stainless steel cladding (or possibly Inconel), reside in the central core block.

Between the reflectors and the Inconel vessel is 5 cm of Min-K cellular insulation to reduce heat losses from the reactor. Protruding through the insulation are ceramic standoffs around the reactor circumference and at the top. Ceramic pedestals support the 6-Mg reactor internals from below. A 1-cm-thick hermetically sealed Inconel vessel contains the reactor. Helium cover gas fills the interstices between graphite blocks, heat pipes, and control rods. In addition to supplying helium to the CNPS, the helium cover gas system has the capability of removing off-gas products evolving from the insulation and graphite blocks.

FUEL

The CNPS reactor fuel is in the form of uranium oxycarbide (UCO) spherical kernels 500 μm in diameter. Sequential coating of the kernels with porous carbon, pyrolitic carbon, silicon carbide, and pyrolitic carbon results in spherical particles ≈1 mm in diameter. Acting like tiny pressure vessels, the so called "TRISO" particles are designed to retain virtually all fission products generated throughout the 20-yr life of the reactor, and at temperatures a factor of two higher than normal operating

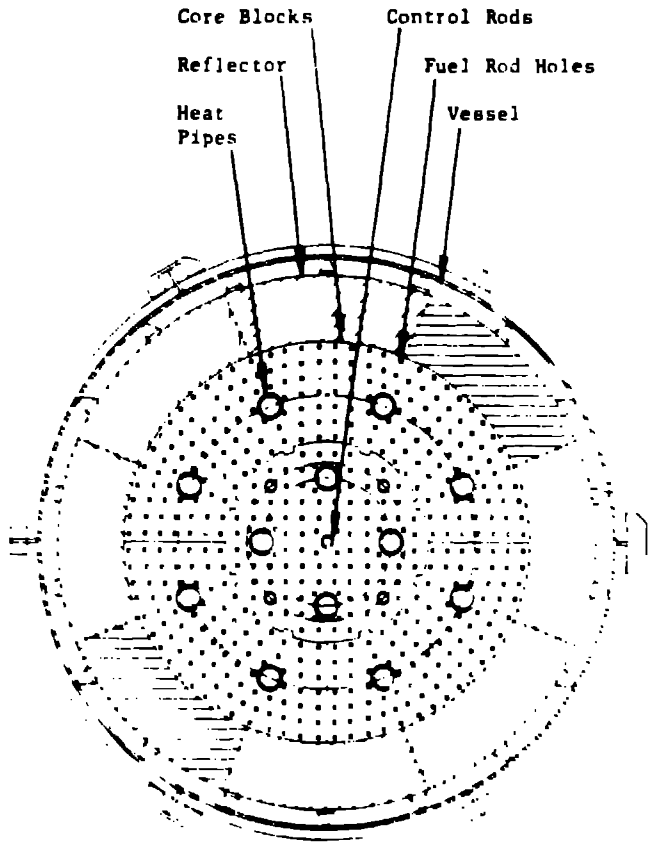

Fig. 3. Reactor cross section.

conditions. Safeguards problems are eliminated because the kernels contain low-enrichment uranium (LEU), which is 19.9% ^{235}U. The CNPS reactor contains 64 kg of heavy metal, of which 13 kg is ^{235}U. Despite the relatively long operating time of 20-yrs without refueling, fuel burnup is a relatively low 15 MWd/kg (1.6% FIMA), compared to particle design burnup of 100 MWd/kg. The fuel particles are mixed with a pitch binder and formed into cylindrical fuel rod compacts 1.3 cm in diameter and 4 cm long. Similar compacts are currently manufactured for high-temperature gas reactors (HTGRs) now operating in the United States.

NEUTRONICS AND SAFETY

Analytical neutronics calculations were used to determine the reactor physical size and fuel loading (4). Design calculations were performed with the multigroup transport theory computer code TWODANT (4), and supporting benchmark calculations were made with the Monte Carlo code MCNP (4). Reactor design trade-off studies were performed to reach a configuration that was inherently safe, and could operate for 20-yrs without refueling, but was also of minimum cost, size, and weight. The graph of Fig. 4, shows that a low mass, but high fuel cost, low-cost reactor can be built with a low 10 to 1 $C/^{235}U$ ratio. However, the graph of Fig. 5 shows that at a low $C/^{235}U$ ratio the temperature coefficient of reactivity is also very small. A large negative temperature coefficient of reactivity is one of the most important safety characteristics of the CNPS

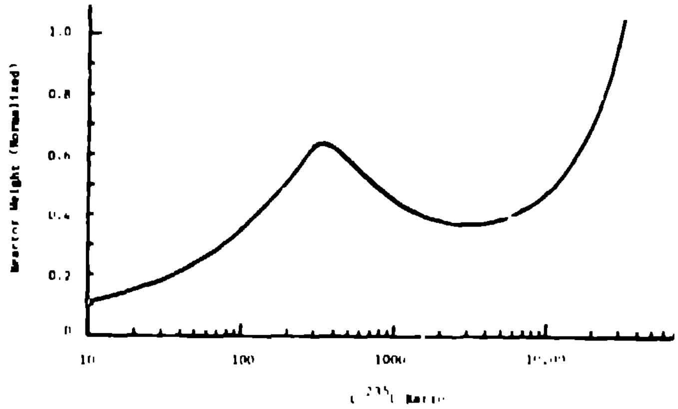

Fig. 4. Reactor weight vs. $C/^{235}U$ ratio.

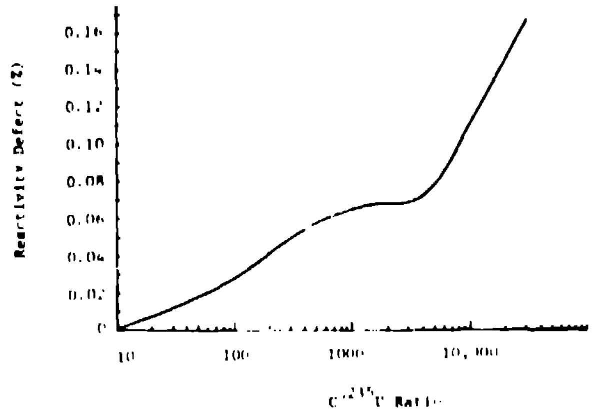

Fig. 5. Reactivity defect vs. $C/^{235}U$ ratio.

reactor. At the CNPS reactor design $C/^{235}U$ ratio of 3000 to 1, a secondary weight and size minimum exists and a large negative temperature coefficient is present. Also, the fissile inventory is significantly reduced resulting in a major cost savings. With mechanical stops on the control rods, the temperature coefficient limits the maximum reactor temperature to a safe level of 750°C. This temperature limitation occurs during the maximum credible accident scenario in which all rods are driven out to the stops and all heat-pipe cooling ceases.

This and other accident scenarios have been investigated and have found the CNPS reactor to be safe under all credible accident conditions (5). With the reactor shutdown, decay-heat removal is maintained by passive conduction to the environment. The safety characteristics of this reactor are such that it is not possible for the fuel to reach temperatures in excess of 950°C, which is far below the temperatures at which particle fuel failure begins (1400°C).

At beginning of life (BOL), the maximum reactivity at room temperature is $k_{eff} = 1.105$ with all rods out. The temperature rise from ambient to the average graphite operating temperature of 560°C results in a reactivity change of $\Delta k_{eff} = -0.06$.

During the 20-yrs after BOL, depletion of ^{235}U and buildup of fission products results in an additional Δk_{eff} = -0.04. Gradual withdrawal of the B_4C control rods compensates for the negative reactivity resulting from increasing temperature and fuel depletion throughout the 20-yr life. Total reactor power is 135 kWt, of which 125 kWt is transferred to the toluene and 10 kWt is lost by conduction through the insulation, support structure, etc.

HEAT PIPES

Heat pipes transfer 125 kWt of reactor heat from the core through the vessel head to the toluene vaporizers. In the CNPS, there are 12 heat pipes, each transferring 10.4 kWt. The heat-pipe tubes are made of a zirconium/niobium alloy, Zr2.5Nb, and are 6.1 cm o.d. by 5.7 cm i.d. and 2.5 m long. Reactor heat flows from the core blocks, across a helium-filled gap, to the heat pipes, where the potassium working fluid evaporates and flows upward to the condensing region of the pipe. As the potassium condenses, it releases its latent heat to the toluene flowing through coiled Inconel tubes in the individual vaporizers which encircle each heat pipe. The heat pipes constitute a closed system and have no moving parts. The potassium flows back to the evaporator region in the core by gravity and is evenly distributed by a knurled-wall wicking structure.

Although extensive testing has been performed on many types of heat pipes (6,7), testing has not been performed on this type of alloy tube with a knurled-wall wick, potassium working fluid, and in close contact with graphite. A 2 m long Zr2.5Nb test heat pipe was fabricated and testing in a graphite cylinder with a helium cover gas is now being conducted, and has passed 5000 h of successful operation at 500°C. Because the test primarily investigates materials compatibility rather than heat-pipe performance limits, the power level is 2 kWt and the axial power density (0.2 w/cm^2) is approximately half of what will exist in the CNPS heat pipes.

ORGANIC RANKINE CYCLE CONVERTER

Because of previous design and fabrication experience and demonstrated long term reliability at high efficiency (8), an ORC concept was chosen to convert 125 kWt of CNPS reactor heat into 25 kWe of electrical energy. High efficiency reduces the overall CNPS cost, size, and weight. Life cycle cost competitiveness with fossil fueled systems is important. Minimization of size and weight is also important for ease of installation in remote and inaccessible locations.

As shown in Fig. 6, the main components of the ORC are the TAP, vaporizers, regenerator, and condenser. A simplified temperature entropy diagram is provided in Fig. 7. Toluene was chosen as the working fluid because of previous experience with and successful operation of ORC units with this fluid. A supercritical operating cycle provides high thermal efficiencies in the 20-24% range, and with a freezing point of -95°C, arctic conditions present no complications.

In Figs. 6 and 7, the cycle can be traced starting at point 1 and proceeding to point 2, where the pump raises the toluene ORC fluid pressure to 5 MPa (700 psi). Regenerative heat addition, from points 2 to 3, raises the vaporizer inlet temperature to 225°C. Vaporizer heat addition raises the toluene to supercritical conditions at 370°C and 5 MPa. Nearly isotropic expansion takes place in the

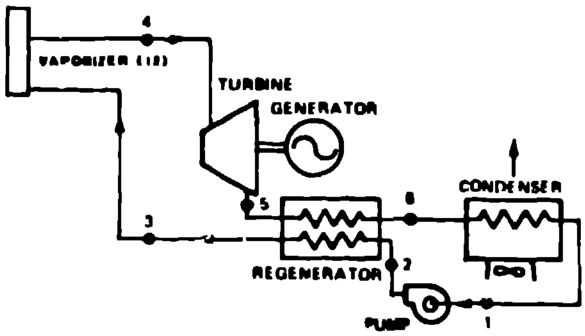

Fig. 6. ORC system schematic.

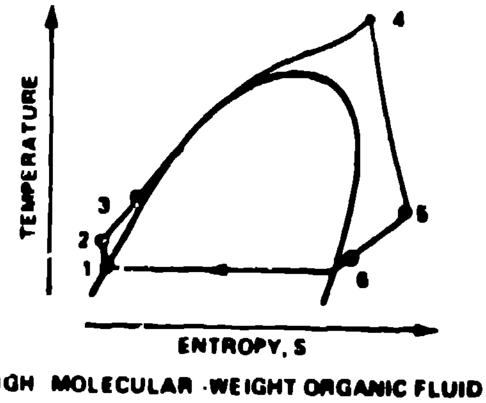

Fig. 7. Toluene temperature vs. entropy curve.

single-stage turbine at a flow rate of 14 kg/min (points 5 to 6). After regenerative cooling, the condenser returns the toluene (points 1 to 6) to pump entrance, at 300 kPa and 65°C. Not evident from Fig. 6 is the fact that the turbine, alternator, and pump are all on a common rotating shaft, and that system is hermetically sealed. Although the exact configuration of the ORC and system components has not been finalized, few moving parts are required. During normal operation only the TAP is rotating in the toluene loop. A cooling fan provides forced air convection for the condenser.

Of the 25 kWe of high frequency AC power generated by the TAP, 20 kWe is available to the load. Of the 5 kWe of housekeeping power, 2 kWe is required by the condenser fan, 1 1/2 kWe is consumed by the triple-redundant computer control system, and 1 1/2 kWe is dissipated in power conditioning equipment.

Two completely independent ORC systems are used in the CNPS. Either ORC can receive heat from the reactor when appropriate valve positions are selected. A fossil fuel heat source is available to provide 125 kWt of heat to either one of the ORC units in the unlikely event that the reactor needs maintenance. Dual ORC units allow continuous operation with one ORC while the second ORC unit receives annual maintenance. A few hours of preventive maintenance (PM) are all that is required to change filters and bleed the condenser of noncondensible gases.

The toluene thermal decomposition rate is well known, but the radiation-induced decomposition rate is not. Radiation-induced toluene decomposition experiments are being prepared and will be performed in a test loop fitted with a prototype heat pipe and vaporizer. Current estimates indicate that replacement of the toluene working fluid will be required at intervals of several years as PM.

SYSTEMS ANALYSIS

The CNPS was designed for reliable, long-term operation with minimal maintenance. To increase reliability, the core, heat pipes, and vaporizers were designed to withstand one or two heat-pipe (or vaporizer) failures and continue to operate at full rated power output.

A lumped-parameter systems analysis computer code, LASAN (9), is being used as a design tool to establish and confirm design parameters. One lumped-parameter analysis performed looks at the core temperatures at the radial midplane (Fig. 3). Included in the analysis are the core, radial reflector, insulation, vessel, cooling air, heat pipes, and vaporizers. Although as yet only partially complete, the analytical results show: 1) the effect on the system of one or two heat-pipe failures in the outer row where consequences are most severe; 2) the need for toluene flow redistribution away from failed vaporizers; 3) core conductance effects; and 4) vessel heat losses. The design basis values of core helium gap conductances were determined by calculations made with the ABAQUS (10) finite-element computer code and were used to benchmark the lumped-parameter analysis.

Results of the analysis are shown in Table I for steady state normal operation, operation with one outer-row heat pipe failed, and operation with two nonadjacent outer-row heat pipes failed. Because the toluene decomposition rate increases rapidly at temperatures above 400°C, it is desirable to keep the maximum toluene temperature below this level. As the data of Table I show, normal operation heat-pipe temperatures are 500°C and the maximum toluene temperature is 370°C. When a heat pipe fails, the reactor heat from that region of the core flows to neighboring heat pipes. The increased heat flow raises the temperature of the neighboring heat pipes, vaporizer, and toluene. Without flow redistribution, 1/12 of the toluene flows unheated through a nonoperating vaporizer. A maximum toluene temperature of 433°C results in neighboring vaporizers. By redistribution (that is, valving off the flow to failed vaporizers), toluene temperatures can be returned to an acceptable level: 390°C with two failed heat pipes. A thermostatically actuated, or motor-operated valve on each vaporizer exit would accomplish the necessary flow redistribution.

A second lumped-parameter systems analysis in the axial RZ plane is also being performed on the CNPS. The model is shown in Fig. 8. In addition to the reactor vessel and internals, the model includes axial vessel cooling air flow and the concrete vault. Insulation thickness can be varied, and cooling air baffles can be added.

Initial calculational results indicate that during normal operation the average vessel temperature is 165°C with an air flow of 750 kg/h (320 cfm) and an inlet temperature of 20°C. Without flow baffles, the center of the lower vessel head is relatively cold, and the edges of the upper vessel head are relatively hot. A 230°C temperature difference arises and unwanted thermal stresses result. Adding air flow baffles at the bottom center of the vessel

Table 1. Systems Analysis Results

PARAMETER	NORMAL OPERATION	NO TOLUENE FLOW REDISTRIBUTION: SINGLE HEAT PIPE FAILURE	NO TOLUENE FLOW REDISTRIBUTION: DOUBLE HEAT PIPE FAILURE	TOLUENE FLOW REDISTRIBUTION: SINGLE HEAT PIPE FAILURE	TOLUENE FLOW REDISTRIBUTION: DOUBLE HEAT PIPE FAILURE
MAX. CORE TEMP (°C)	589	700	744	692	726
MAX. VESSEL TEMP (°C)	126	142	150	140	147
MAX. ACTIVE HEAT PIPE TEMP (°C)	501	539	586	531	566
MAX. TOLUENE EXIT TEMP (°C)	371	399	433	380	390
AIR INLET TEMP (°C)	20	20	20	20	20
MAX. HEAT PIPE POWER (NOMINAL)	1.002	1.144	1.309	1.146	1.319

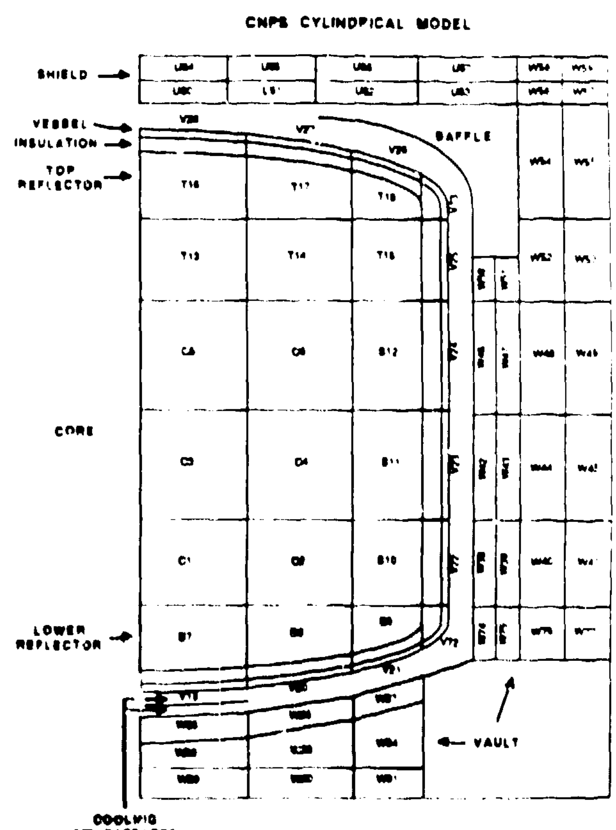

Fig. 8. Axial vessel cooling model.

and at the upper edges produces an average vessel temperature of 128°C, with only a 20°C top-to-bottom temperature variation.

A hypothetical loss-of-cooling-air accident scenario has been investigated with the axial systems analysis model. With all control rods out to the limit of the mechanical stops and no heat-pipe cooling, the reactor core temperature was assumed to rise to its equilibrium value of 750°C. Concrete vault temperatures will rise above 150°C in a few days without cooling air flow. Hence, some cooling air flow must be maintained, so that concrete temperatures will remain well below the desired 100°C structural limit.

STATUS

Zero-power criticality (ZP) tests are being prepared and will be performed on a core mockup of the CNPS reactor. The ZP tests will be performed on a configuration similar to that of the actual reactor, except that the core blocks and lower reflectors are placed on a movable hydraulic ram. The radial and upper reflectors are placed up above on a higher-level "balcony." A portion of the fuel is loaded into the core blocks and the ram is raised into the reflector assembly from below. A Californium (Cf)-isotope source provides neutrons to begin the chain reaction in what are called "approach-to-critical tests." When roughly one-third of the fuel is loaded into the core, cold criticality is reached. The ram drops out of the reflector assembly and the chain reaction is stopped before the components become activated. Other ZP tests will also be conducted to determine control rod worth, temperature coefficients, and power profiles.

Several components of the CNPS are currently being fabricated. The initial particle fuel load is in production. Graphite blocks for the core mockup are being fabricated. The fuel and the graphite blocks will be initially used to conduct the ZP critical tests, and then "recycled" for loading in the actual CNPS reactor vessel.

ACKNOWLEDGEMENTS

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