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ATOMIC ENERGY
OF CANADA LIMITED

L'ENERGIE ATOMIQUE
DU CANADA, LIMITEE

THE NUCLEAR BATTERY: A SOLID-STATE, PASSIVELY COOLED REACTOR FOR THE GENERATION OF ELECTRICITY AND/OR HIGH-GRADE STEAM HEAT

LA BATTERIE NUCLEAIRE: UN REACTEUR SOLIDE REFROIDI PASSIVEMENT, PRODUCTEUR D'ELECTRICITE ET/OU DE CHALEUR DE VAPEUR A HAUTE TEMPERATURE

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Etablissement de recherches nucléaires de Whiteshell

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RÉSUMÉ

Dans cette communication, on examine l'évolution et l'état actuel d'un programme de l'Énergie Atomique du Canada, Limitée pour mettre au point un petit système d'alimentation électrique à réacteur solide refroidi passivement appelé la Batterie Nucléaire. Les principaux éléments techniques du coeur du réacteur de la Batterie Nucléaire comprennent un circuit de caloportage primaire à caloducs, un modérateur de neutrons en graphite, un combustible à particules enrobées TRISO (TRIPLY ISOTROPIC) (triplement isotrope) et des poisons combustibles pour le règlage de la réactivité à long terme. Un circuit de caloportage secondaire externe extrait l'énergie thermique utile qu'on peut transformer en electricité dans une machine à vapeur à cycle de Rankine ou utiliser pour produire de la vapeur à haute pression. Le système de référence actuel peut produire environ 2400kW(t) (environ 600kW(e) nets) pendant 15 ans de service à pleine puissance. On y décrit les éléments techniques et de sûreté ainsi que les progrès récents réalisés dans les programmes de mise au point du matériel à sous-systèmes et les travaux d'évaluation du marché.

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ABSTRACT

This paper reviews the evolution and present status of an Atomic Energy of Canada Limited program to develop a small, solid-state, passively cooled reactor power supply known as the Nuclear Battery. Key technical features of the Nuclear Battery reactor core include a heat-pipe primary heat transport system, graphite neutron moderator, low-enriched uranium TRISO coated-particle fuel and the use of burnable poisons for long-term reactivity control. An external secondary heat transport system extracts useful heat energy, which may be converted into electricity in an organic Rankine cycle engine or used to produce high-pressure steam. The present reference design is capable of producing about 2400 kW(t) (about 600 kW(e) net) for 15 full-power years. Technical and safety features are described along with recent progress in component hardware development programs and market assessment work.

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AECL-9570

CONTENTS

1. BACKGROUND

The Nuclear Battery is a small nuclear power supply designed to generate electricity and/or high-grade steam heat. It is being pursued by Atomic Energy of Canada Limited (AECL) as a complementary, follow-up product to the Slowpoke Energy System district heat source, but is at a much earlier stage of development.

The Nuclear Battery program originated in 1984 as a joint project with the Los Alamos National Laboratory (LANL) to develop a small, 20-kW(e) nuclear power supply [1,2,3,4,5] for unattended short-range radar stations in the new North Warning System (NWS). However, the joint project was cancelled when it became apparent that the full-power demonstration of a prototype unit could not be completed in time to meet the demanding deployment schedule for the NWS application.

The inherent technical attractiveness of the Nuclear Battery concept enables it to address a diverse range of applications that are especially suited to Canadian energy needs. Thus, Canadian development of the concept continued in an independent program that focussed for a time on use as an air-independent auxiliary power source for Diesel submarines as part of the Canadian Submarine Acquisition Project (CASAP) [6]. Although the CASAP program ultimately opted for full-powered nuclear submarines of proven, conventional design, the design exercise was useful in that it forced the consideration of more powerful versions of the concept, better matched to the needs of the commercial marketplace.

AECL's long-term interest in the Nuclear Battery has always been its potential usefulness for broad-based commercial applications. Therefore, the Nuclear Battery program mandate has been redirected to address small-scale, base-load electricity generation in remote communities that are at present served by Diesel generators. Consequently, the remainder of this paper largely concerns our progress toward this end.

More recently, it has been recognized that the same Nuclear Battery reactor core that is being designed to produce electricity might also be used to generate high-pressure steam heat for industrial applications and thereby greatly expand the application market. Some preliminary thoughts regarding possible application to the specific case of the in situ recovery of bitumen from the Alberta Oil Sands are discussed.

2. REACTOR DESCRIPTION

The name "Nuclear Battery" was coined early in the program to highlight the passive and solid-state features of the concept and distinguish it from conventional water-cooled power reactor designs. The term "battery" reflects the function of its graphite core block as a thermal energy storage cell, or well, from which useful energy is extracted in a passive manner. Nuclear fission of a small quantity of uranium atoms located in fuel rods embedded directly in the graphite provides sufficient energy to maintain the core at a high temperature for many years. The basic features of the Nuclear Battery reactor core module are shown schematically in Figure 1.

Unlike conventional power reactors, no fuel is added or removed from the Nuclear Battery for the life of the system. Thus, skilled reactor operators trained in the handling of highly radioactive materials are not required and the core containment boundary need not be breached for refuelling. These attributes make the concept practical for use in remote locations, where maintenance costs would be prohibitive.

The fuel for the Nuclear Battery is based on the TRISO (triply isotropic) coated-particle design developed for use in high-temperature gas-cooled reactors (HTGRs) and amply demonstrated in the Ft. St. Vrain reactor in the USA and the AVR and THTR reactors in West Germany. The fuel meat consists of tiny spheres, or kernels, of enriched UO_2, about 0.5 mm in diameter. The Nuclear Battery would use LEU (low enriched uranium, less than 20 at.% ^{235}U) fuel material. The fuel kernel is sealed in successive protective layers of low-density buffer graphite, high-density pyrolytic carbon, SiC ceramic, and a second layer of pyrolytic carbon to form finished particles about 0.9 mm in diameter.

The TRISO coated fuel particles are mixed with a graphite matrix binder and formed into solid cylindrical compacts, a few centimetres in diameter and several centimetres long. A "fuel rod" consists of a vertical stack of fuel compacts, about 1.5 m long, inserted into predrilled holes in the graphite core moderator blocks. Approximately five hundred fuel rods are arranged in the core on a regular triangular lattice pitch. The required fissile inventory to sustain operation at 2400 kW(t) at a nominal core graphite temperature of 550°C for 15 full-power years is less than 35 kg of ^{235}U and may be reduced further as the core design is refined.

Heat passes by conduction from the fuel rods, through the solid graphite moderator, to the heat pipes regularly dispersed throughout the fuel lattice. Each heat pipe is of identical construction and consists of a sealed metal tube, about 5 cm in diameter and 3 m long. The bottom end of the heat pipe terminates in the lower axial reflector while its top end protrudes above the reactor core. A schematic diagram of a Nuclear Battery heat pipe is shown in Figure 2.

The heat pipe has a thin wall thickness and is constructed from a niobium alloy to minimize parasitic neutron absorption losses yet maintain adequate resistance to creep-buckling collapse at high temperatures. A composite wick structure lines the inside wall of the heat pipe and serves to distribute the liquid working fluid uniformly around the inner surface of the pipe while providing a permeable protective barrier to interaction with the fast-moving vapour core.

Each heat pipe contains a few hundred grams of potassium working fluid, most of which fills the wick and lines the inside wall of the pipe as a liquid film or collects as a pool at the bottom of the pipe; less than a gram of potassium is in the vapour state in the central core. At the

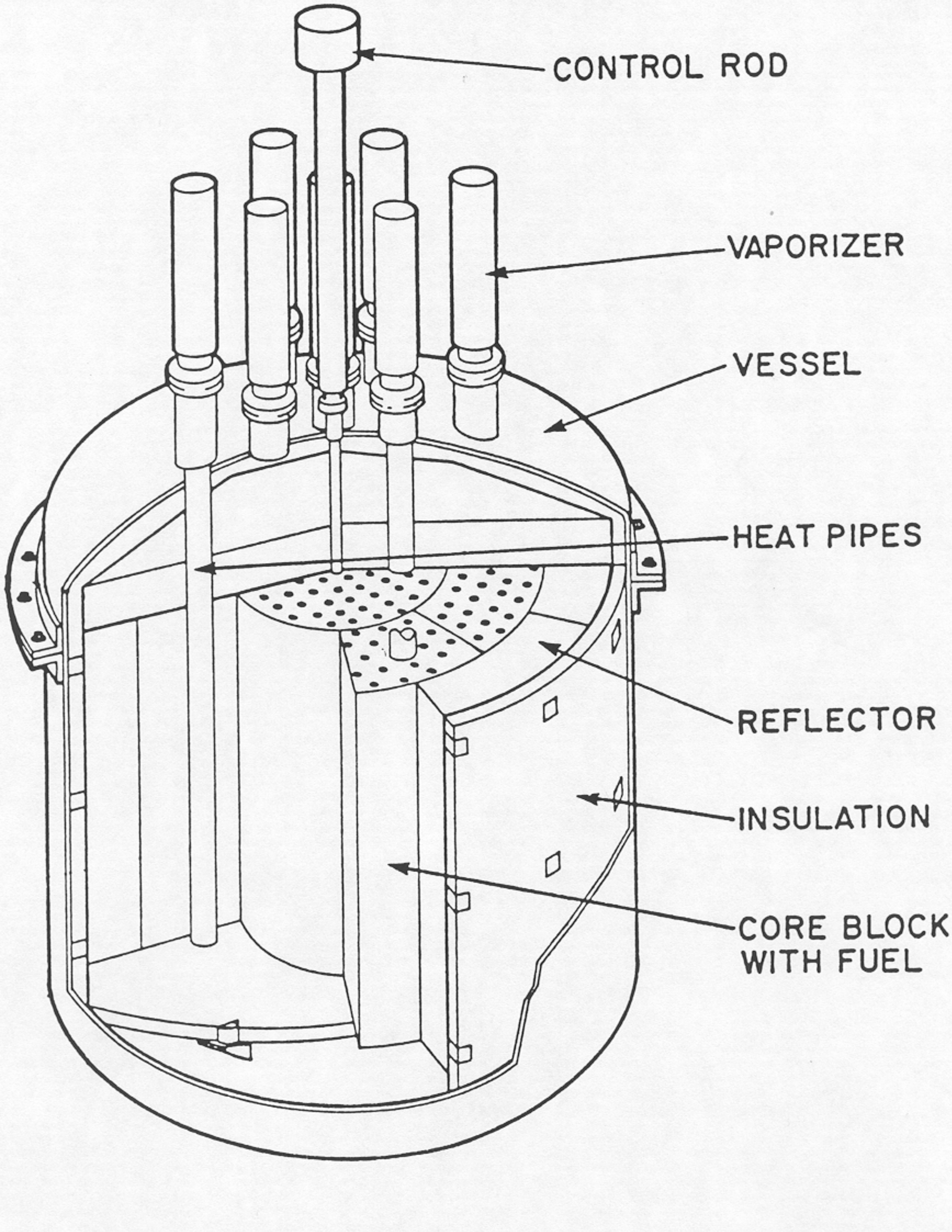

FIGURE 1: Nuclear Battery Reactor Core Module

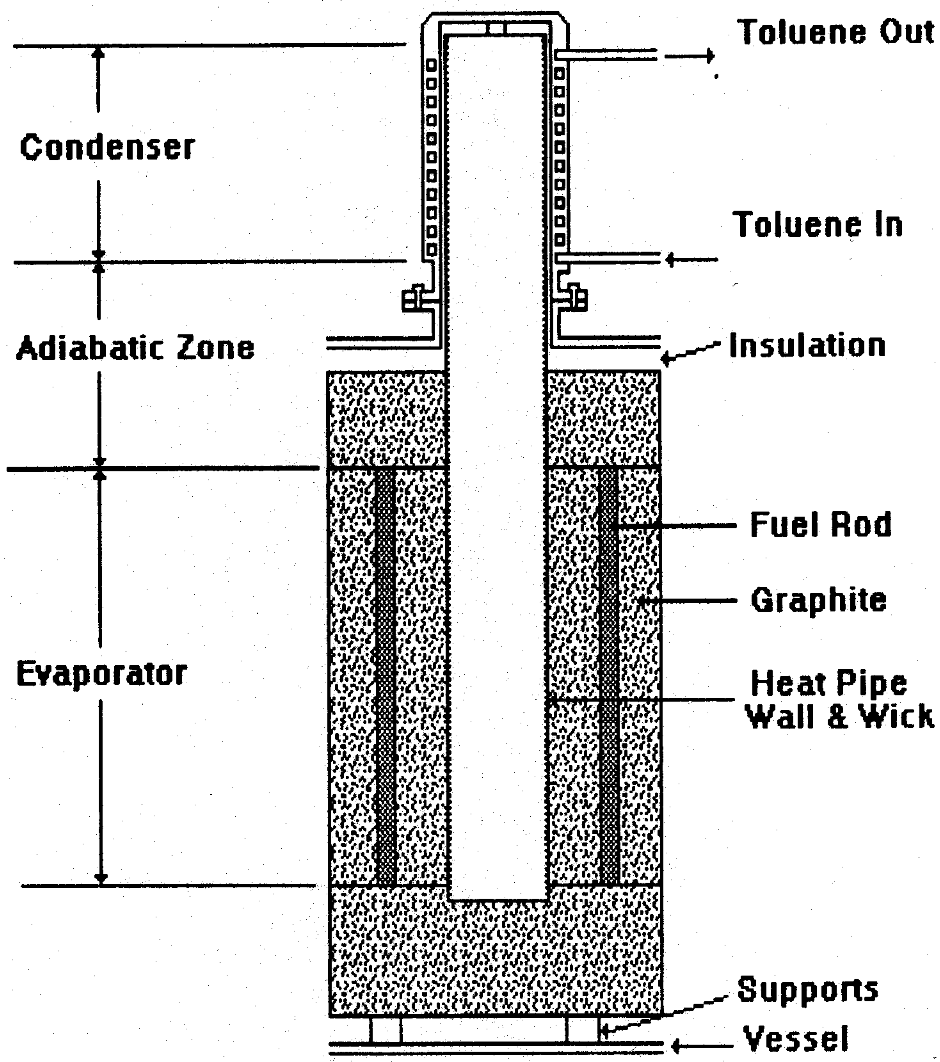

FIGURE 2: A Nuclear Battery Heat Pipe/Vaporizer Assembly

design operating temperature, the pressure of the potassium vapour within the pipe is sub-atmospheric.

Individual heat pipes act as independent, localized cells for passive primary heat transport by natural processes. Thermal energy is extracted as latent heat in the in-core or evaporator section of the pipe by the evaporation of potassium from the liquid film lining its interior surface. The hot vapour passes into the central core where natural pressure gradients propel it at high velocity to the top or condenser region of the pipe.

The potassium vapour gives up its heat through condensation on the slightly cooler interior surface at the top of the pipe. Liquid potassium returns by gravity to the evaporator section where the cycle is repeated. The evaporator and condenser sections of the heat pipe are separated by an adiabatic region where heat is neither added nor removed.

The heat pipe transports large quantities of thermal energy in a near-isothermal manner for a small quantity of working fluid since it involves the energetic phase changes between the liquid and vapour states. Moreover, the absence of active pumps promotes overall efficiency by eliminating primary system pumping power losses.

The size of the Nuclear Battery core is determined by both the neutronic properties of graphite and the heat pipes. The large mass ratio of carbon moderator nuclei to that of the neutron necessitates a large number of collisions to achieve adequate thermalization of fission neutrons. Consequently, the fuel rods are widely spaced, providing ample room for the heat pipes. Displacement of graphite by the heat pipes and neutron absorption losses in heat-pipe materials further increase the required core size. The present reference design has a cylindrical fuelled core region surrounded by radial and axial graphite neutron reflectors, so that the overall core dimensions are about 2.5 m in diameter by 2 m high.

Active reactivity control is provided by four axial control/ shutdown rods inserted from above the core and arranged in an outer ring of three plus a single central rod. Passive long-term reactivity control is provided by burnable neutron poisons mixed with graphite and inserted in holes in the graphite moderator between the fuel rods in the inner core region. Besides limiting the available excess reactivity, the burnable poisons are highly effective at flattening the core radial power profile and thereby limiting the peak-to-average fuel burnup ratio.

The graphite core is surrounded by a few centimetres of thermal insulation, to minimize thermal leakage losses, and rests on ceramic supports within a steel containment vessel. A helium cover gas system maintains an inert core environment while promoting heat transfer across clearance gaps. The vessel's internal pressure is held at just slightly above one atmosphere*, to minimize the potential for air ingress in the event that a leak occurs.

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* 1 atm = 101.325 kPa

The core containment vessel is suspended in a concrete shield vault that would typically be located below grade level. Passage of air through the gap between the vessel and the concrete cools both surfaces so that they are maintained within their design temperature ratings. At full power, the normal heat loss through the vessel would be in the range of about 30 kW(t) and is comparable to the decay heat load at one hour after reactor shutdown from full power.

Useful energy is extracted from the Nuclear Battery by the circulation of organic coolant in a coiled tube surrounding the condenser portion of the heat pipe. In a version of the Nuclear Battery to produce electricity, the organic working fluid is toluene and the coiled tube structure is referred to as a vaporizer. Each heat pipe has its own vaporizer, which is connected in parallel between inlet and outlet headers.

The vaporizer housing forms an extension to the core containment vessel and is bolted to it at a flanged joint, which has a metal ring seal. A narrow, helium-filled gap between the heat pipe wall and the vaporizer housing serves to drop the peak outlet temperature experienced by the organic fluid to about 370°C.

The minimum spacing of the vaporizers above the core limits the number of heat pipes that can be inserted into a core of a given diameter. Thus, the maximum useful power output from the Nuclear Battery is constrained by the axial heat transport performance of its heat pipes.

3. REACTOR SAFETY FEATURES

Although no nuclear reactor design can claim absolute inherent safety, reactors can be designed with safety attributes that will prevent the catastrophic release of radioactive fission products in severe accidents, so that no evacuation of surrounding areas would be required. Passive safety features that obviate the need for immediate human action and that cannot be overridden by misguided intervention have been of paramount importance throughout the Nuclear Battery program.

Containment of radioactive fission products begins at their source — the type of nuclear fuel selected. The TRISO coated-particle fuel chosen for the Nuclear Battery embodies perhaps the ultimate in containment principles because the fuel inventory is finely subdivided into 3×10^8 independently protected entities. The small particle size enables its coating layers to withstand internal pressures and stresses that would destroy most macroscopic engineered structures. Indeed, even violent dismemberment and dispersion of the core for whatever reason would not negate the containment properties of the individual TRISO particles.

The most outstanding safety feature of TRISO fuel is its demonstrated ability to withstand extreme temperatures. No failures of the particle coatings would be induced by exposure to a temperature of 1600°C for up to 100 h. In contrast, the peak fuel temperature in the Nuclear Battery during normal equilibrium full-power operation is about 600°C and it is not possible to increase this value by more than about 100°C, even with all four control rods fully withdrawn.

Many of the safety arguments for the Nuclear Battery are strikingly similar to those of its TRISO-fuelled, graphite-moderated cousins, the prismatic-block and the pebble-bed HTGR designs. Amplification of these safety arguments is possible for the Nuclear Battery because it operates at a much lower temperature and power density, and because its maximum total fission product inventory (equivalent to that of about 77 irradiated CANDU fuel bundles) is quite small.

A brief qualitative review of the response of the Nuclear Battery to various hypothetical "worst-case" accident scenarios will help to highlight some of its most important safety features. First, consider a complete loss of coolant accident (LOCA) in which all heat pipes or vaporizers abruptly cease to function. Second, suppose that the protective system fails to detect this event so that shutdown is not initiated.

Because the Nuclear Battery possesses a strong negative core temperature reactivity coefficient of about -0.08 mk/°C, self-regulation would occur and the core power level would drop to match the available passive means of heat removal. Recriticality would occur after some hours at a stable power of about 30 kW(t), while the decline in the equilibrium xenon poison load (about 4.4 mk) would enable the core temperature to increase by about 55°C. No release of fission products would occur.

Third, assume further that instead of merely failing to shut down the reactor, the control rods are fully withdrawn at their maximum permitted speed (loss of regulation accident coincident with LOCA). With burnable poisons to provide passive long-term reactivity control, only a maximum of about 7 mk of additional reactivity would be available, corresponding to a further temperature increase of about 88°C. Again, no release of fission products would occur.

Fourth, assume that, coincident with the other events, breach of the secondary containment vessel occurs, exposing the core graphite to ambient air. At this point, the maximum graphite temperature would have increased to about 693°C while the temperature at the reflector surface would be less; a temperature drop of roughly 125°C from the core centre to its surface would be necessary to transport 30 kW(t), assuming uniform heat generation and spherical geometry.

Burning, or self-sustained oxidation, of graphite in air is quite difficult to achieve. According to reference 7, a graphite temperature of 650°C is the minimum necessary, but not sufficient, requirement to initiate burning. Additional requirements include an adequate supply of air, removal of the gaseous reaction products, and a favourable geometry that inhibits cooling by conduction, convection and radiation heat loss mechanisms.

It seems unlikely, therefore, that exposure of the Nuclear Battery reactor core to air, even during a LOCA with all control rods withdrawn, could generate sufficiently rapid oxidation of the graphite to raise the core temperature to values that would induce fuel particle coating failures. Instead, erosion of the graphite through oxidation would reduce the available reactivity and thereby gradually reduce the core temperature that is sustainable neutronically.

A second class of severe accident of importance to reactor safety is a large and rapid reactivity insertion, such as might be induced by rapid withdrawal of a control rod. For the Nuclear Battery, this type of accident is pertinent only during startup because, once the reactor has achieved its full temperature and power operating condition, a maximum excess reactivity of only about 7 mk is available.

Pulsed power tests performed many years ago in the KIWI-TNT experiments [8] at LANL using a variety of coated fuel particles (likely inferior to modern-day TRISO design) demonstrated that an energy deposition of at least 10^{13} fissions/gU (equivalent to about 80 cal/gU) was necessary to induce coating failures in particles with 0.5-mm-diameter UO_2 kernels. This criteria was applied to the Nuclear Battery core in preliminary transient analyses and it was found that a corresponding instantaneous reactivity insertion in the range of roughly 20 mk would be required to induce coating failures.

The calculated temperature response of the Nuclear Battery to a rapid reactivity insertion transient is quite similar to that reported in simulations of the pebble-bed HTR-Module reactor [9]. In general, the wide dispersion of the fuel throughout the core of the Nuclear Battery and its strong negative core temperature reactivity coefficient would cause a sharp power pulse response, somewhat analogous to that which is obtained in the homogeneous TREAT pulsed graphite reactor [10,11].

The reactivity requirements of the control/shutdown rods for the Nuclear Battery are about 43 mk from cold to hot, 4.4 mk for equilibrium poisons and 7 mk for long-term fuel depletion, for a total of about 54 mk. Thus, limiting the individual rod worths to about 20 mk would be sufficient to ensure the integrity of the fuel during startup since only one rod would be withdrawn at a time. Also, this scheme would permit cold shutdown to be achievable with one rod stuck in its uppermost position.

The neutronics features of the Nuclear Battery and its transient response during a control rod withdrawal accident are discussed in a companion paper [12].

4. ELECTRICITY GENERATION

The Nuclear Battery is an effective energy source for small-scale electricity generation because its high temperature offers good Carnot efficiencies of about 54%. To produce electricity in a reliable manner for extended periods, the Battery is coupled at the present time to a toluene organic Rankine cycle engine, as shown schematically in Figure 3.

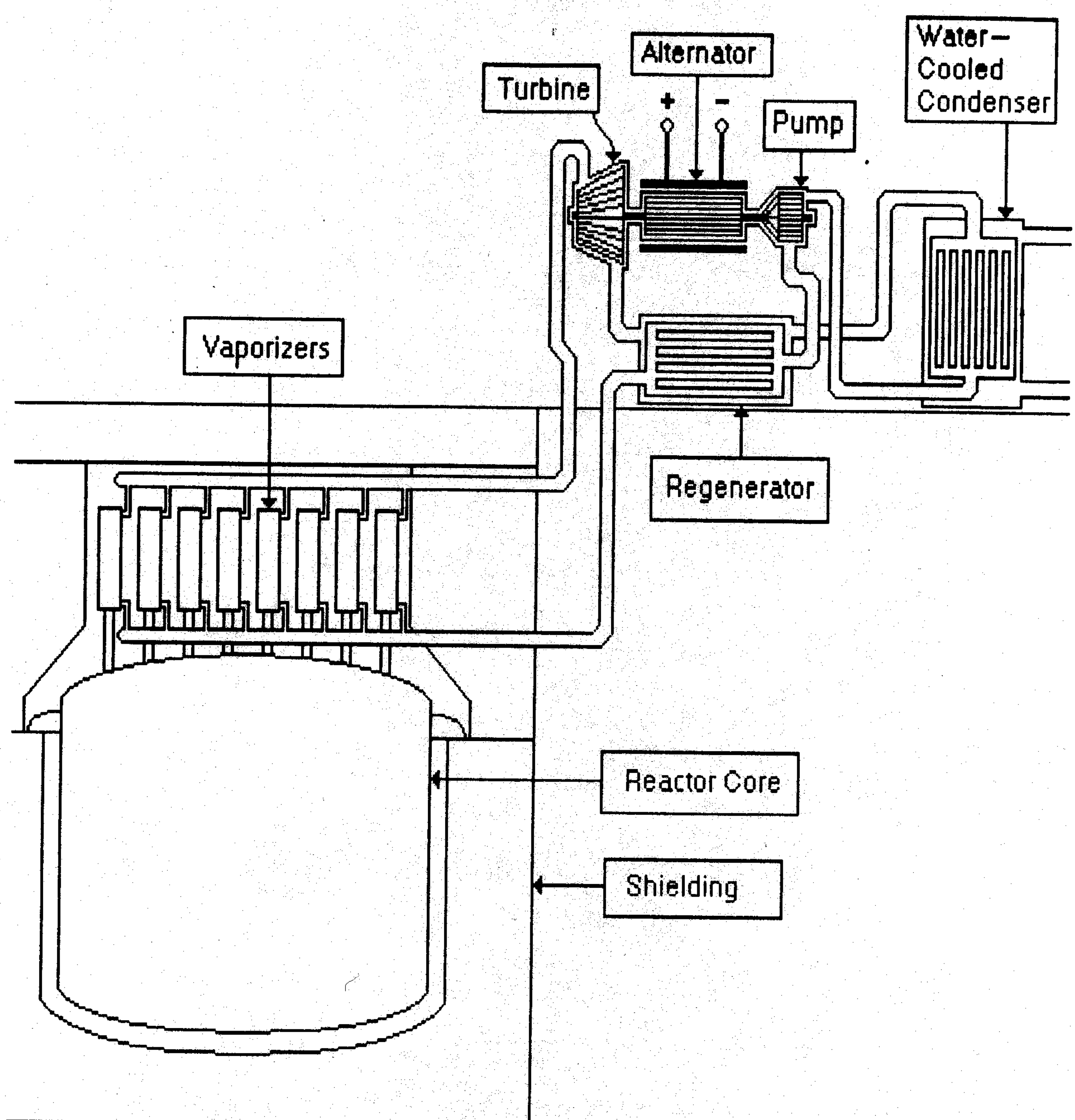

FIGURE 3: Schematic of a 600-kW(e) Nuclear Battery for Village Electricity

Toluene is heated to about 370°C in helical-coil vaporizers surrounding the condenser end of the heat pipes. Supercritical toluene vapour is collected from the parallel vaporizer streams and fed to the turbine inlet. Expansion of the vapour through the single-stage high-speed turbine converts a portion of the thermal energy into rotary mechanical motion to turn an ac generator and a Pitot feed pump. The three rotating elements are usually combined on a single rotating shaft, the only moving component in the engine. The compact rotating unit is supported on twin hydrodynamic bearings lubricated by the toluene working fluid.

Exhaust vapour from the turbine is passed through a waste heat regenerator to improve the cycle conversion efficiency. The toluene vapour is then condensed in a water-cooled condenser. The Pitot feed pump draws toluene from the condenser and forces it through the regenerator, where it is preheated to about 190°C. The output from the regenerator is then distributed to the individual vaporizers to complete the cycle. The net conversion efficiency is estimated to be about 25% for a 2400 kW(t) Nuclear Battery with a water-cooled condenser.

Some of the key technical advantages of the toluene organic Rankine cycle engine for this particular application include

1. high reliability as a result of the lubricating qualities of toluene in the hydrodynamic bearings and very few moving parts;
2. low maintenance as a result of the non-corrosive behaviour of toluene and its good resistance to thermal decomposition;
3. extremely low activation of toluene in neutron radiation fields above the core;
4. good net conversion efficiency at modest peak temperatures for the supercritical, regenerative cycle;
5. relatively compact and lightweight engine components;
6. low working-fluid cost and its high availability; and
7. adequate demonstration of the underlying technology.

5. CANADIAN DIESEL-GENERATED ELECTRICITY MARKET

The economic goal of the Nuclear Battery is to substitute for fossil-fuel energy sources wherever and whenever the delivered cost of such fuel becomes an excessive burden for the consumer. This need is likely to be felt first and strongest in the dozens of small, remote Canadian communities that are totally dependent on Diesel generators for their electricity. The total annual production of electricity from Diesel generators in Canada is about 1000 GWh, most of which is produced by units of less than 1 MW(e) capacity.

The cost of electricity in remote Canadian villages varies widely since it depends strongly on both the distance and means of fuel transport. A recent internal study by AECL has established the average cost of delivered Diesel fuel to be in the range of 0.15 to 0.20 $/kWh and this has been adopted as the cost target for the Nuclear Battery.

The estimated lifetime unit energy cost for electricity from a 600 kW(e) Nuclear Battery operated in a base-load mode (95% capacity factor) is shown as a function of core lifetime in Figure 4. It is assumed here that only the initial uranium fuel inventory is increased to maintain criticality for the required lifetime. Also shown in Figure 4 is the partial unit energy cost component associated with the uranium fuel inventory. The fuel partial unit energy cost is seen to be generally fairly flat and increases slightly at high core lifetimes as a result of both the present-value financial methodology employed and the gradual perturbation of the fuel-to-moderator atom ratio. Evident from Figure 4 is the need to achieve product lifetimes of 15 to 20 full-power years and the fact that the Nuclear Battery might already be competitive today with Diesel generators in selected locations. The capital cost of the Nuclear Battery used for the analysis is preliminary. We expect further reductions as our program matures. In addition, further economics-of-scale will be achieved through the mass production of identical units.

Because remote communities vary in size and undergo significant seasonal variations in load requirements, only a portion of the Canadian Diesel-electricity market is addressable in a practical manner by base-loaded Nuclear Batteries. It is estimated that the mature Canadian market potential is for up to one hundred and fifty 600-kW(e) units.

In the most logical circumstances, it is envisioned that multiple Nuclear Batteries would be sited in a phased sequence at a common location. A new unit would be commissioned every five years or so, in perpetuity, as older units complete their output cycle. Diesel generators would be retained for peaking and backup power roles by virtue of their low capital cost.

6. STEAM GENERATION

Because the Nuclear Battery is a high-temperature heat source, the same reactor core module can be coupled through a secondary heat transport system to a steam generator, as shown in Figure 5. Since the choice of fluid is no longer constrained by the thermodynamic requirements of a Rankine cycle engine, other working fluids, such as the Monsanto product, OS-84, used in the WR-1 research reactor [13] for 19 years at the Whiteshell Nuclear Research Establishment (WNRE), might be considered in addition to toluene. Also, a Nuclear Battery to produce steam would be less costly to construct since a steam generator is less expensive than an organic Rankine cycle engine conversion system.

A very large Canadian market for high-grade industrial steam heat exists in the Alberta oil sands for the in situ recovery of bitumen using

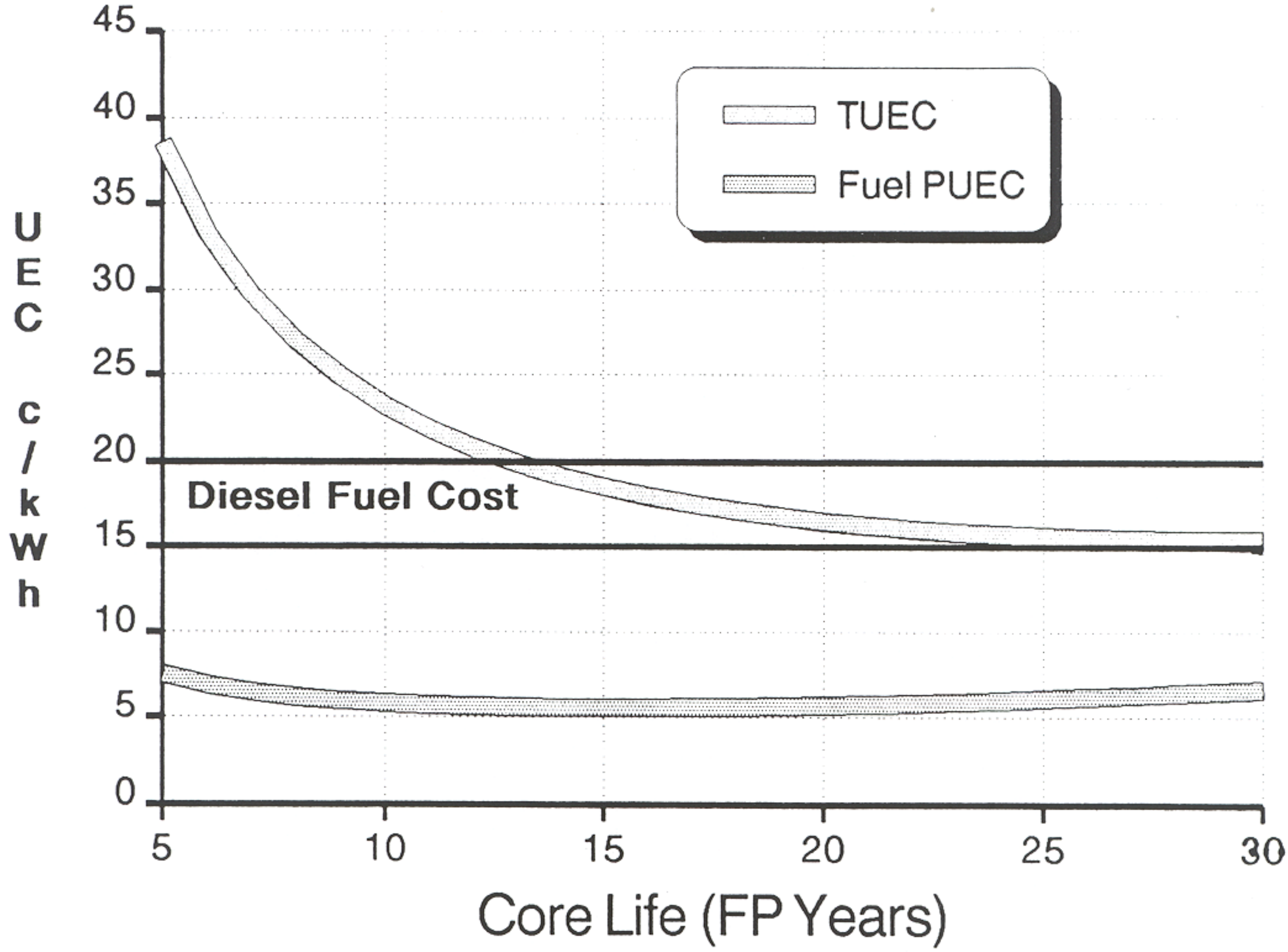

FIGURE 4: Nuclear Battery Lifetime Unit Energy Costs for Electricity

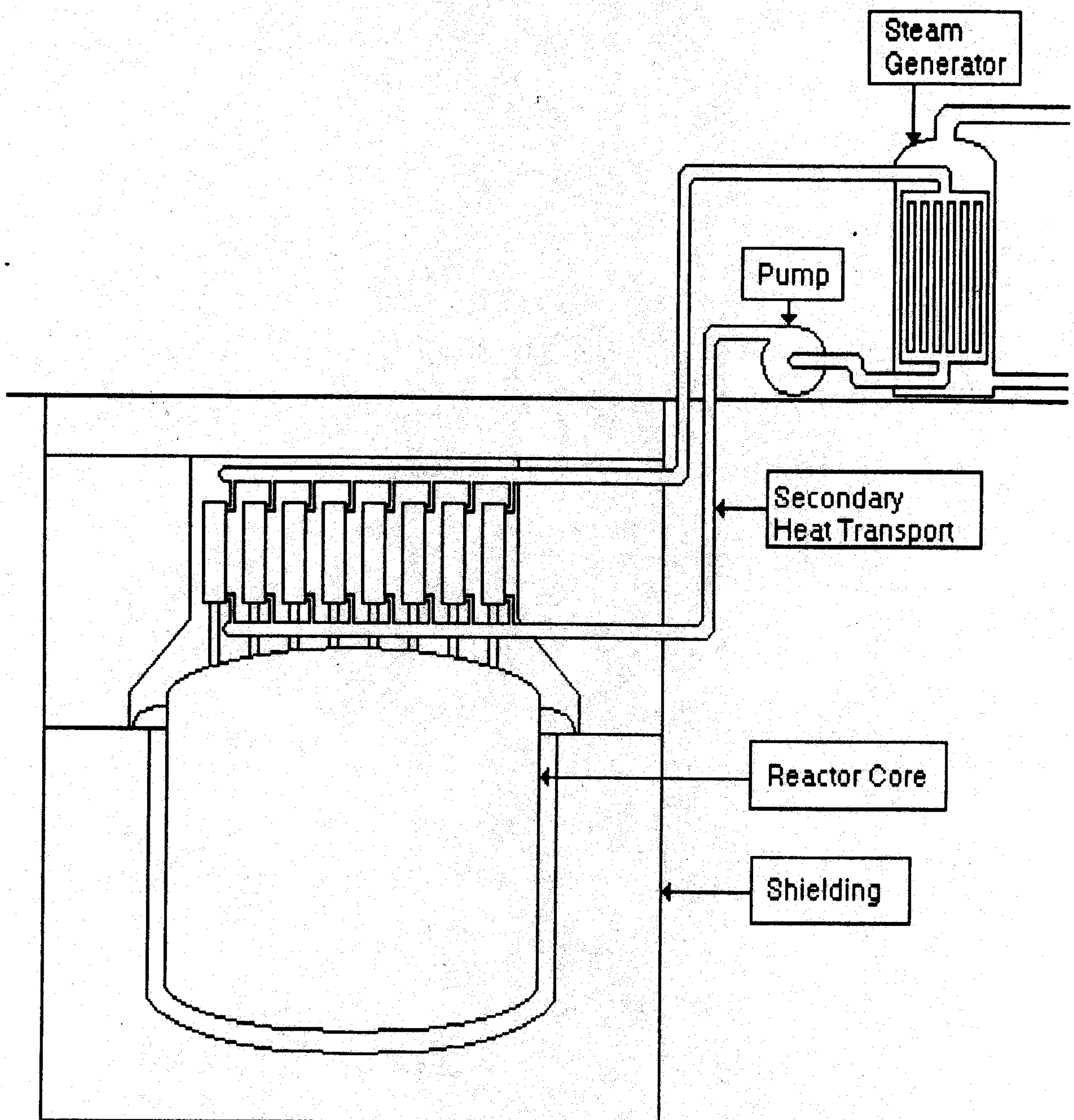

FIGURE 5: Schematic of a 2400-kW(t) Nuclear Battery for Steam Generation

the proven "huff-and-puff" recovery process, which requires high-pressure injection steam of 80% quality. In situ recovery programs, such as the Esso Cold Lake project, are proceeding in gradual phases using natural gas to produce steam. In the past, AECL has evaluated the use of a large, organic-cooled reactor station to supply the required energy [14,15,16].

There appears to be a plausible degree of technical fit of base-loaded Nuclear Batteries for this type of application in that a single in situ recovery well requires roughly 6 MW(t) of steam for about 0.9 full-power years spread over eight calendar years. A cluster of twenty wells is at present fed from a single satellite station. Siting of Nuclear Batteries close to the wellhead should help alleviate steam distribution needs.

In situ recovery of bitumen is very energy-intensive and requires about 6.8 GJ/m^3. The total resource that is recoverable by this method in Alberta is estimated to be 23 x 10^9 m^3, or about 22% of the world's total recoverable petroleum resources. The total energy necessary to extract this bitumen is equivalent to the lifetime output from about 140 000 Nuclear Batteries. Clearly, no single energy source technology would be capable of supplying all of this energy and some mix will be required, particularly as natural gas prices increase.

7. R&D PROGRESS

Significant technical progress has been made over the past several years to support the viability of the Nuclear Battery reactor power supply concept. Notably, the basic reactor physics features of the system have been confirmed by LANL in a full-scale mockup of the 20-kW(e) core that achieved first criticality in 1987 July [17,18]. A series of low-power core neutronics tests were successfully completed by LANL last year, including a measurement of the core temperature reactivity coefficient up to about 70°C.

At WNRE, our core design efforts have concentrated largely on improving the economic prospects for commercial-scale units and establishing burnable neutron poisons as a plausible means of enhancing their passive safety.

In hardware development programs at WNRE, a 1-kW(e) REMCOM (Remote Communications) [19] toluene organic Rankine cycle engine was commissioned and operated with a propane heat source. This demonstration-scale unit was operated for a total of 784 h, including 465 h in a single continuous run with a simulated remote startup. It is now being converted to an electrically heated configuration that will permit the determination of its conversion efficiency as a function of its operating state while providing data on toluene thermal degradation rates. Toluene thermal decomposition data have already been obtained over a wide range of conditions in static-capsule and flowing-loop tests. Decomposition experiments concerning gamma radiolysis have been conducted with static capsules and are being extended now to flowing-loop tests.

The heat pipe program at LANL successfully demonstrated the heat transport performance required for the 20-kW(e) core using a full-scale stainless steel/potassium heat pipe with a knurled interior surface. A similar knurled heat pipe, but constructed from a low neutron-absorbing zirconium alloy, was made to transport about 10 kW(t) at 500°C in a carbon block in experiments at WNRE. Work at WNRE with composite wick structures in sub-scale heat pipes has demonstrated superior axial heat transport performance in comparison with knurled-tube designs. Notably, an axial heat flux about 20% greater than the average required for a commercial Nuclear Battery unit has been achieved and further improvements are anticipated.

An experiment to study graphite oxidation under conditions that roughly simulate an air ingress accident in the Nuclear Battery was also performed. A small, electrically heated graphite block was consumed over a six-week period at temperatures progressively increased from 600 to 800°C, without observing a temperature runaway.

A full-scale toluene vaporizer test loop, including a stainless steel/potassium heat pipe, is now being commissioned as the next important hardware development step.

The near-term goal of the R&D support program is to demonstrate the overall technical feasibility of the Nuclear Battery concept in a non-nuclear, but otherwise comprehensive, test. Thus, plans are now under way to build a single-heat-pipe integrated test facility that will look much like Figure 2, except it will use electric resistance heaters instead of nuclear fuel rods.

8. CONCLUSION

The Nuclear Battery high-temperature power-source concept has evolved over the past four years from the consideration of special-use projects at low-power levels into a commercial-scale unit capable of delivering either 600 kW of electricity or 2400 kW of high-grade steam heat for 15 full-power years. This evolution has been accomplished without compromising the Nuclear Battery's technical feasibility or its superior passive safety features. Broad-based domestic applications for village electricity and for industrial steam production have been identified that are in the long-term Canadian national interest and are sufficiently large to justify the further development and demonstration of the concept.

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