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DISTRICT HEATING WITH SLOWPOKE ENERGY SYSTEMS

by

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Abstract

Nuclear energy is the only proven alternative to coal as the world strives to find substitutes for the dwindling reserves of oil and natural gas. However, to meet the demand projections nuclear technology must be used in energy sectors beyond its traditional role in electricity generation. The application of nuclear heat to district and distributed heating systems is now considered the next most important energy contribution of nuclear technology for many countries in the northern hemisphere.

The SLOWPOKE Energy System, a benign nuclear heat source designed to supply 10 thermal megawatts in the form of hot water for local heating systems in buildings and institutions, is at the forefront of these developments. A demonstration unit has been constructed in Canada and is currently undergoing an extensive test program. Because the nuclear heat source is small, operates at atmospheric pressure, and produces hot water below 100°C, intrinsic safety features will permit minimum operator attention and allow the heat source to be located close to the load and hence to people. In this way, a SLOWPOKE Energy System can be considered much like the oil- or coal-fired furnace it is designed to replace.

The low capital investment requirements, coupled with a high degree of localization, even for the first unit, are seen as attractive features for the implementation of SLOWPOKE Energy Systems in many countries.

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THE NEED FOR NUCLEAR HEATING

The increasing demand for economic and reliable energy supply is driven both by the growth in the world's population and by the essential role that energy plays in industrial development. With the global energy requirements expected to double over the next 40 years (1), all supply sectors will be seriously challenged in their ability to meet the demand.

All forecasts anticipate a significant expansion in the role for nuclear energy (2), with some predicting that energy from the nuclear fission process will grow from its current contribution of 5% to satisfying over 50% of the world's primary energy requirements by the year 2050 (3). Since electricity contributes approximately 30% of the energy requirements of many countries, meeting these supply targets means that nuclear energy must be used in energy sectors beyond its traditional role in electricity generation (4).

Building heating is now considered the next important energy sector to which nuclear technology can be applied. Many countries in the northern hemisphere consume between 25% and 50% of their primary energy supply to satisfy their building heating requirements (5). Since the majority of the population live in urban centres, a significant fraction of the heating requirements can be satisfied by central or district heating systems. Furthermore, as the world population grows, further increases are expected in the fraction of the population living in urban environments. Consequently, several countries are now encouraging, through government policy, the introduction or expansion of municipal district heating systems. From a strategic energy planning perspective, it is important to note that this is an energy sector which can be readily served by nuclear heat sources.

Since the fundamental requirement is to supply low grade heat at 20°C, the heat source can operate at relatively low temperatures. Existing district heating systems use hot water with supply temperatures in the range 90 to 160°C, or steam with pressures typically in the range 400 to 3000 kPa. Although there are advantages and disadvantages for both techniques, experience in Eastern and Northern Europe and more recently in North America has shown that the advantages of hot water transmission far outweigh the disadvantages in most cases (6). In fact, the technological trend is towards lower temperature water distribution systems to eliminate the need for pressurized systems.

In specifying a nuclear heat source to provide the energy required to heat the water, existing power reactor technology is neither required nor is it appropriate. Instead, the nuclear system can operate at atmospheric pressure thereby eliminating much of the complexity that is associated with the production of high pressure and high temperature steam that is needed for electricity generation.

An analysis of the annual load curves for stand-alone heating systems in buildings in several countries has concluded that a nuclear heating system satisfying approximately 50% of the peak heat demand and used in a base load capacity could provide up to 90% of the annual heat requirements. By using a low capital cost, fossil fired boiler to satisfy the peaking requirements and acting as a backup to the more capital intensive nuclear heat source, the overall system redundancy can be met at a cost which is competitive with fossil fuels.

For those countries with district heating networks which interconnect several load centres with a series of heat sources (much like established electrical grids), the potential for nuclear heating is even more attractive. In such cases, the nuclear heat source can be operated with much higher load factors, satisfying not only the base load requirements for heating but acting also as a source of heat for domestic hot water. In such circumstances, load factors of 80% can be expected with a corresponding improvement in the economic advantages.

Thus, in assessing the need for nuclear heating, three important points can be made:

- the potential contribution of nuclear technology to satisfying the heating requirements of many countries must be considered as significant as that already being achieved by nuclear electricity generation;
- the application of nuclear technology to this energy sector offers countries that are currently dependent on imported fossil fuels, such as the Republic of South Korea, an opportunity to increase their fuel security in this important energy demand sector; and
- although nuclear heating can offer savings over traditional fossil fuelled heat sources for individual heating systems, there are significant additional advantages that can be realized in applying the technology to municipal district heating networks.

DESCRIPTION OF THE SLOWPOKE ENERGY SYSTEM

In a major departure from traditional nuclear power technology, Atomic Energy of Canada Limited (AECL) has developed the SLOWPOKE Energy System, a nuclear heat source specially designed to meet the requirements of building, institutional and municipal heating systems.

The SLOWPOKE Energy System is a simple nuclear heat source capable of supplying 10 MW of thermal energy in water at 85°C. As shown in Figure 1, it is a pool-type reactor designed to operate at atmospheric pressure, thereby eliminating the need for a pressure vessel. Consequently, loss-of-coolant caused by depressurization is impossible.

The reactor core, coolant riser duct and the primary heat exchangers are installed in the pool, a steel-lined concrete container. This double containment of the pool water prevents loss-of-coolant caused by leakage.

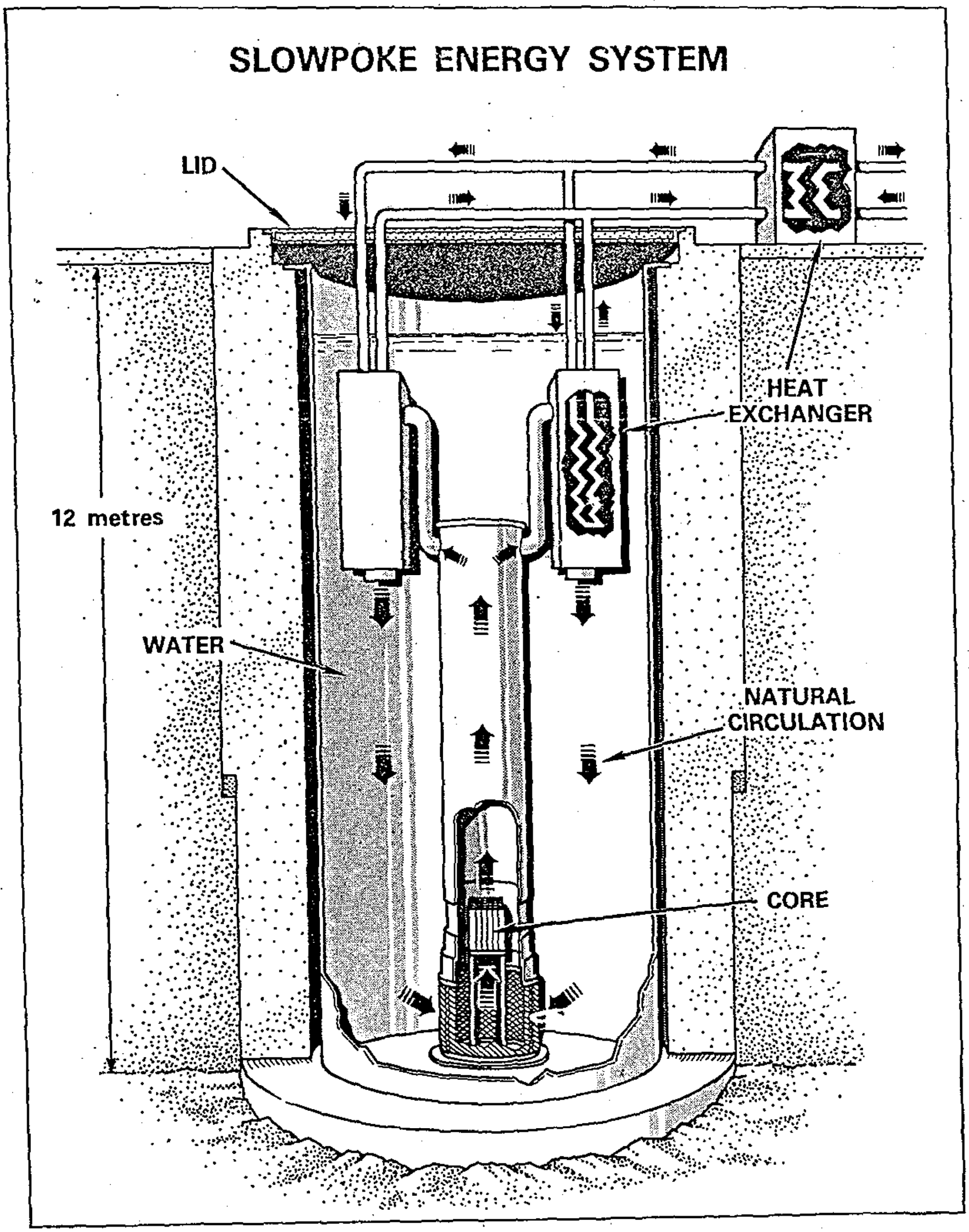

FIGURE 1: Schematic Diagram of the SLOWPOKE Energy Concept

The pool water serves as the moderator, the heat transfer medium and the shielding. Primary heat transport from the core is by natural circulation of the pool water through the plate-type heat exchangers. Natural circulation ensures core cooling without the need to depend on the reliability of pumps or the integrity of electrical supply for the pump motors.

The secondary circuit delivers the heat to the distribution system by way of the secondary heat exchanger. Thermal power is measured in the secondary circuit for the purpose of metering.

To compensate for fuel burnup, absorber plates are used for periodic core reactivity adjustments by the licensed operator. In addition, absorbers under computer control are used for load following. The rate of removal of all absorbers is limited by the speeds of their electric motors and by a timer requiring manual reset. The use of a fully redundant control system reduces the probability of unwanted shutdowns.

In the event of loss of secondary flow such as a power interruption to the pumps, the large pool volume delays core temperature rise. As a result, thermal transients extend over many hours. This factor, combined with unique design features that limit reactivity change rates to very low values, eliminates the need for the fast acting shutdown systems that are essential for pressurized power reactors.

A liquid absorber system can shut the reactor down over a period of five minutes. Gadolinium nitrate solution flows into the pool by gravity alone, through two temperature actuated valves.

The pool water is continuously pumped through ion exchange columns to maintain water chemistry and to control corrosion. The ion exchange columns can also remove fission products from defective fuel and gadolinium nitrate should the liquid absorber shutdown system be actuated.

The reactor pool is covered by an insulated lid, enclosing a gas space over the pool. The air and water vapour are continuously circulated through a purification system and hydrogen recombiner. After filtering and monitoring, a small fraction of the circulating cover gas is vented by way of the building ventilation exhaust system.

A goal of the SLOWPOKE Energy System design was to fully automate all essential systems, thus allowing the unit to be operated for extended periods of time without an operator in the reactor building. Essential instruments will be monitored at one or more remote locations and a licensed operator will always be on call, either by telephone or personal paging system. A single remote monitoring centre could manage the heating and ventilating requirements of many building complexes in a number of towns, cities or regions. Local staff would be responsible for maintaining and testing equipment and responding to specific alarm conditions. It is anticipated that these local responsibilities can be undertaken by the existing heating plant staff. Although the local staff will have the authority to shut the reactor down in the event of an abnormal condition being observed, a licensed operator has to be present for startup.

SAFETY PRINCIPLES

One of the fundamental driving forces of the design is the safety philosophy. The primary goal is to meet all Canadian regulatory requirements in a manner that permits unattended operation with remote monitoring for periods of weeks or longer. Meeting the regulatory requirements implies system diversity and a rigorous defence in depth of the overall safety analysis.

The two main objectives of the safety design are to:

- limit the release of radioactive fission products under all circumstances to an acceptable level; and
- ensure that for any event there is a sufficiently low probability of damage to the fuel, structures and equipment that could lead to significant radiation exposure to plant personnel or members of the general public.

To meet these objectives it is essential that:

- the reactor can be safely shut down and maintained shutdown under all circumstances;
- the reactor core is adequately cooled at all times; and
- radioactive releases are not only maintained within regulatory limits but are also kept as low as reasonably achievable.

These requirements are achieved by inherent safety features, engineered control systems, operating conditions and administrative practices.

Of fundamental importance is the fission product inventory. By restricting the power level to 10 MWt, this inventory is small, being less than 0.3% of that in most of the existing power reactors. A combination of low fission product inventory and the important inherent safety characteristics of SLOWPOKE ensures that adequate safety is readily achievable.

Much of the fission product inventory is held up by the uranium oxide, diffusion resistant, ceramic fuel. A small fraction of the volatile material is released to the gas gap between the fuel and the Zircaloy sheath. Power reactor fuel sheaths have been designed to withstand the stresses resulting from the fuel expansion, fission gas release and the mechanical loads applied during refueling. Advantage has been taken of the wealth of experience during the design and manufacture of SLOWPOKE fuel. Moreover, since the fuel is operating at much lower temperatures and pressures, adequate sheath integrity is thus assured.

The inherent safety features of the SLOWPOKE Energy System design include a negative fuel temperature reactivity coefficient and negative coolant temperature and void reactivity coefficients, both of which attenuate power transients following loss-of-regulation. In addition, the primary heat transport system is a natural circulating system requiring no external power source to maintain coolant flow through the core during operation or shutdown.

The engineered systems include:

- the robust fuel;
- a double containment pool with no penetrations;
- a large pool volume to mitigate the consequences of any transients;
- slow reactivity addition rates;
- a fully redundant control system; and
- separate and diverse shutdown systems dedicated to safety.

The normally accepted codes and standards have been used for the design and fabrication of components and systems. A quality assurance program has been instituted for all aspects of the commercial installations.

TECHNOLOGICAL DEMONSTRATION

The SLOWPOKE heating reactor concept has the advantage of a sound technological base. For over 20 years Atomic Energy of Canada Limited has been involved in the development of small nuclear reactors. This program has led to the progressive evolution of the SLOWPOKE concept. The first product was the SLOWPOKE Research Reactor which was first introduced in 1972 and remains part of the AECL product line.

SLOWPOKE Research Reactors

The SLOWPOKE Research Reactor is a low cost, pool-type reactor producing a thermal neutron flux of 10^{12} $n.cm^{-2}.s^{-1}$ in the beryllium reflector surrounding the core. It is used primarily for neutron activation analysis and as a university teaching and research tool. Since the startup of the prototype in 1970 at the Chalk River Nuclear Laboratories, eight units have been installed.

The SLOWPOKE Research Reactor has a high degree of inherent safety, arising from the negative temperature and void coefficients of reactivity, limited maximum excess reactivity and restricted access to the core by users. As a result, the reactor does not require an automatic shutdown system, neutron ionization chambers or low power startup instrumentation. The reactor is controlled by a single motor-driven absorber rod responding to a self-powered neutron detector.

The seven units which are operating in Canada have accumulated over 70 reactor-years of reliable operation. All the units are located in urban areas. They are the only reactors in the world to be licensed for unattended operation for periods up to 72 hours.

SLOWPOKE Demonstration Heating Reactor

The realization that many of the key design criteria of the research reactor are the same as those required for a nuclear heat source, led the developers to optimize the reactor for heat production rather than producing neutrons while retaining the essential safety features of the concept. This work culminated in the decision to construct and operate the SLOWPOKE demonstration heating reactor at AECL's laboratory facilities at the Whiteshell Nuclear Research Establishment, Manitoba.

Construction of the demonstrator started in the spring of 1985 and the reactor started operation on 1987 July 15. The SLOWPOKE Demonstration Reactor is designed to operate at 2 MWt and incorporates the key technical features of the research reactor. The primary purpose in designing, constructing and testing this facility is to validate, in a very demonstrative way, that the technical, economic and safety criteria for the nuclear heating reactor concept can in fact be met. A photograph of the facility taken during the final stages of commissioning is shown in Figure 2.

The reactor physics and transient test programs have already been completed successfully, the thermalhydraulics confirmation program is underway and the long term program to confirm the fuel capability will be concluded with defect tests that are currently scheduled for the end of current core life in 1990. In addition, a comprehensive data base on reactor performance is being compiled. This includes the analyses of drainage tiles under the concrete pool structure and the ventilation system to confirm the effectiveness of the systems that are designed to control all possible releases to the environment.

The SLOWPOKE Demonstration Reactor is a unique facility designed to confirm in a very practical way that the criteria for a nuclear heating system can be satisfied. Through this program, the ability of the SLOWPOKE concept to meet the demands of the urban heating marketplace is being demonstrated.

The SLOWPOKE Energy System

Based on the lessons learned from the design, construction, licensing and operation of the SLOWPOKE Demonstration Reactor, the design of the 10 MW commercial size unit is well advanced. The conceptual design is complete and the detailed design of all systems is actively being pursued. A parallel component development and testing program has been implemented for those systems that have been changed from the Demonstrator.

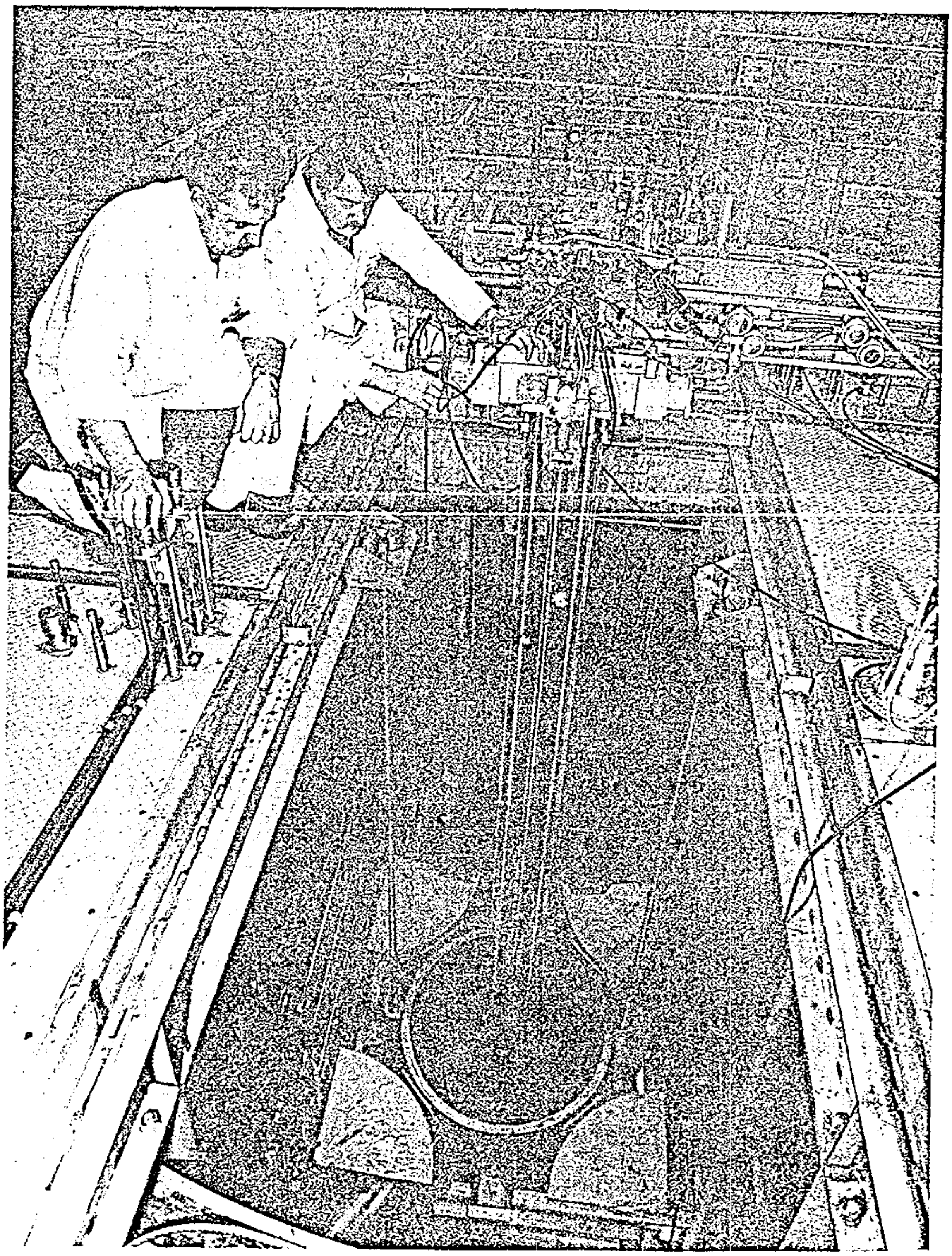

FIGURE 2: Photograph of the SLOWPOKE Demonstration Reactor at Atomic Energy of Canada Limited's Laboratories at the Whiteshell Nuclear Research Establishment, Manitoba

The 10 MW SLOWPOKE Energy System can be housed in a separate building or building extension that measures 10 x 15 metres, as shown in Figure 3. The reactor core and safety systems are being designed to remain fully functional during and after seismic events in Canada, Europe and Asia.

During the design process, particular attention is being paid to partitioning the various systems into separate modules to facilitate off-site manufacturing and testing. This approach is also convenient for joint overseas projects where local manufacturers will be supplying much of the plant. In fact, since the manufacturing technology that is required is not as sophisticated as the high-temperature and high-pressure engineering needed for conventional nuclear power stations, a high degree of local content can be achieved even for the first unit in most countries.

The use of factory fabricated modules contributes to the short construction time of one year that is proposed for the commercial units.

The SLOWPOKE Energy System is a benign nuclear heat source with many intrinsic safety features which make it one of the safest nuclear energy sources ever constructed. This allows the system to be operated with minimum operator attention and facilitates the licensing of the system close to the load in urban areas.

ECONOMIC ANALYSIS

The analysis of the competitiveness of the SLOWPOKE Energy System relative to conventional fossil fuels or other nuclear heating concepts must include the capital investment, the fuel costs, the operating and maintenance requirements and load factor.

The capital cost of a SLOWPOKE Energy System in Canada is in the range $5 M to $7 M, Canadian, (3000 to 4200 million Korean won) (7), depending on the nature of the site. This is, of course, significantly lower than the capital investment required for a conventional nuclear electric power station such as a CANDU or a PWR. However, it is also very important to note that the capital investment in terms of $/MW of thermal energy is also significantly lower. This is the result of many factors including the elimination of the complexity of pressurized systems and the very short construction time. This leads to the conclusion that dedicated nuclear heating systems, such as SLOWPOKE, are economically competitive even with large nuclear co-generation plants.

The low capital cost, when combined with the low operating expenses resulting from unattended operation, results in the unit energy cost of heat from a SLOWPOKE Energy System being as low as $0.02 per kilowatt-hour, Canadian, (12 won per kilowatt-hour) for a unit built in Canada with a load factor as low as 50%. This total unit energy cost includes the capital, fuel, operating and maintenance, spent fuel management and the decommissioning of the facility at the end of its useful life. The economic analysis is based on a 25 year amortization period for the capital and a 5% discount factor.

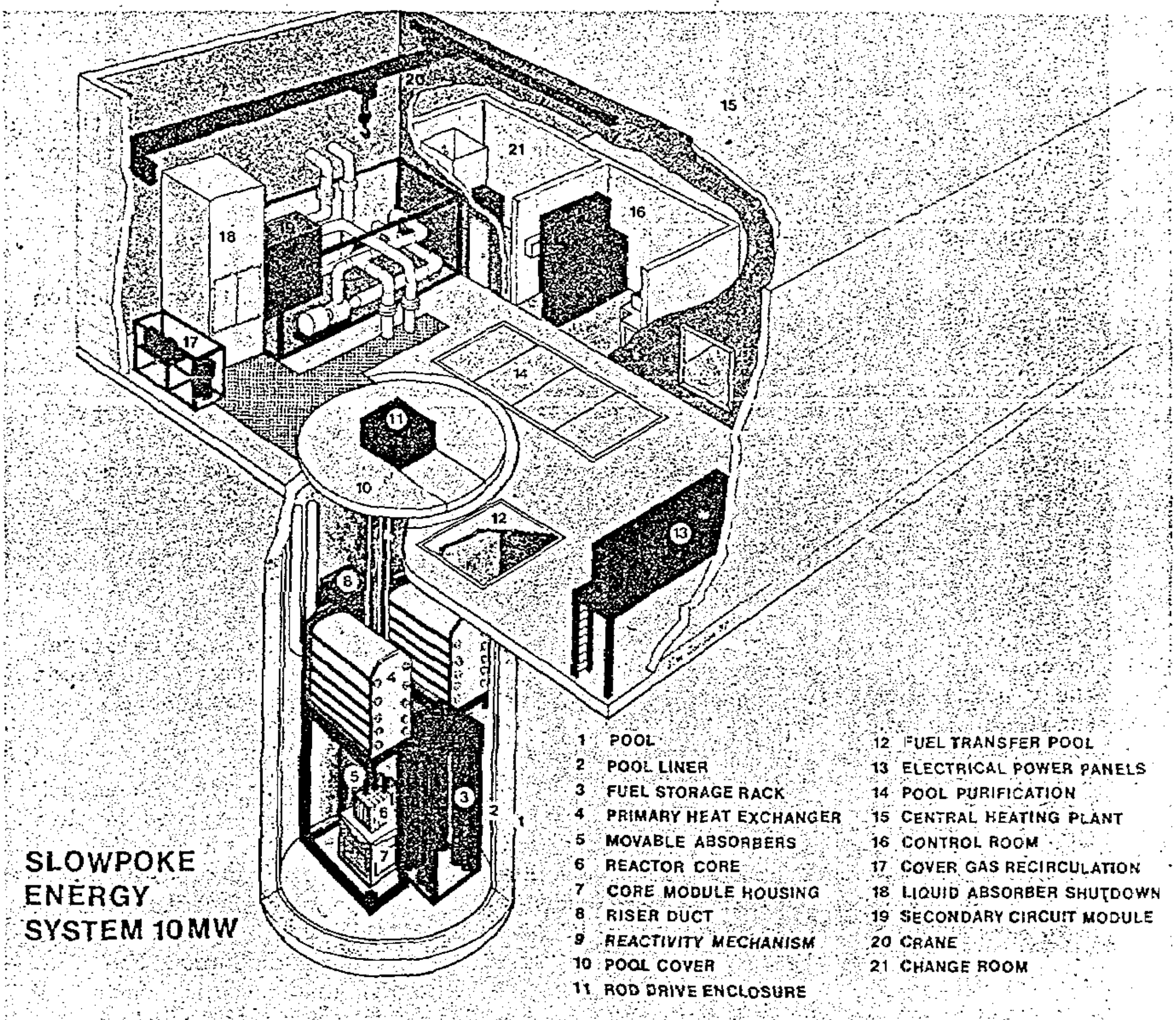

FIGURE 3: Cutaway View of the 10 MW SLOWPOKE Energy System as a Commercial Installation

The cost for the construction of units in Korea can be expected to be lower than the Canadian estimates.

Comparison with the cost of heat from fossil fuelled systems is specific to each country since it depends on government pricing policies including local taxes, subsidies, etc. Fossil fuel prices usually vary even within a country when the transportation cost of the fuel is included in the pricing formula. To overcome these regional disparities, the benchmark used for the cost of alternative fuels is the world price of crude oil. Furthermore, to eliminate potential confusion in comparing overall costs, only the variable cost of heat from oil is used - no allowance being taken for the capital cost of the oil boiler or the operating and maintenance costs. This approach is taken to permit a realistic comparison of the effect of substituting a SLOWPOKE Energy System into an existing heating system and simply displacing oil purchases.

In examining the utilization of oil in existing heating systems, two fuels predominate, namely Bunker-C and light fuel oil. A comparison of the heat cost from these fuels and the SLOWPOKE Energy System, as shown in Figure 4, confirms that not only is SLOWPOKE competitive now but the savings to be realized increase considerably as the world price of crude oil increases according to current forecasts (8).

This analysis confirms the viability of small nuclear heat sources as an economically attractive alternative to conventional heating systems in many countries including the Republic of South Korea.

PUBLIC ACCEPTANCE

In addition to financial savings and fuel security, the general public can be expected to consider the environmental impact and relative risks associated with adopting any new heating technology. Nuclear heating is no exception and, in fact, may be at a disadvantage as a result of the current image of the nuclear industry - a series of megaprojects so expensive and so complex that only governments and major utilities can understand the benefits and be prepared to finance the investment required.

The SLOWPOKE Energy System can bring nuclear technology close to the public, not as remote megaprojects, but as small energy systems located close to the people they serve. This implies that not only must the safety and environmental issues be thoroughly reviewed by technical experts but they must also be expressed in a manner that can be understood by individual members of the general public with limited or no technical knowledge.

Canada's nuclear plant approval process involves the Atomic Energy Control Board (AECB) and the Federal Environmental Assessment Review Office (FEARO). The role of each body can be generally described as relating to technical and community standards, respectively. These authorities are a good reflection of the perceptions of the public they serve. The AECB assess the safety of the reactor facility from a technical point of view.

COST OF HEAT ENERGY FROM VARIOUS TYPES OF FUEL

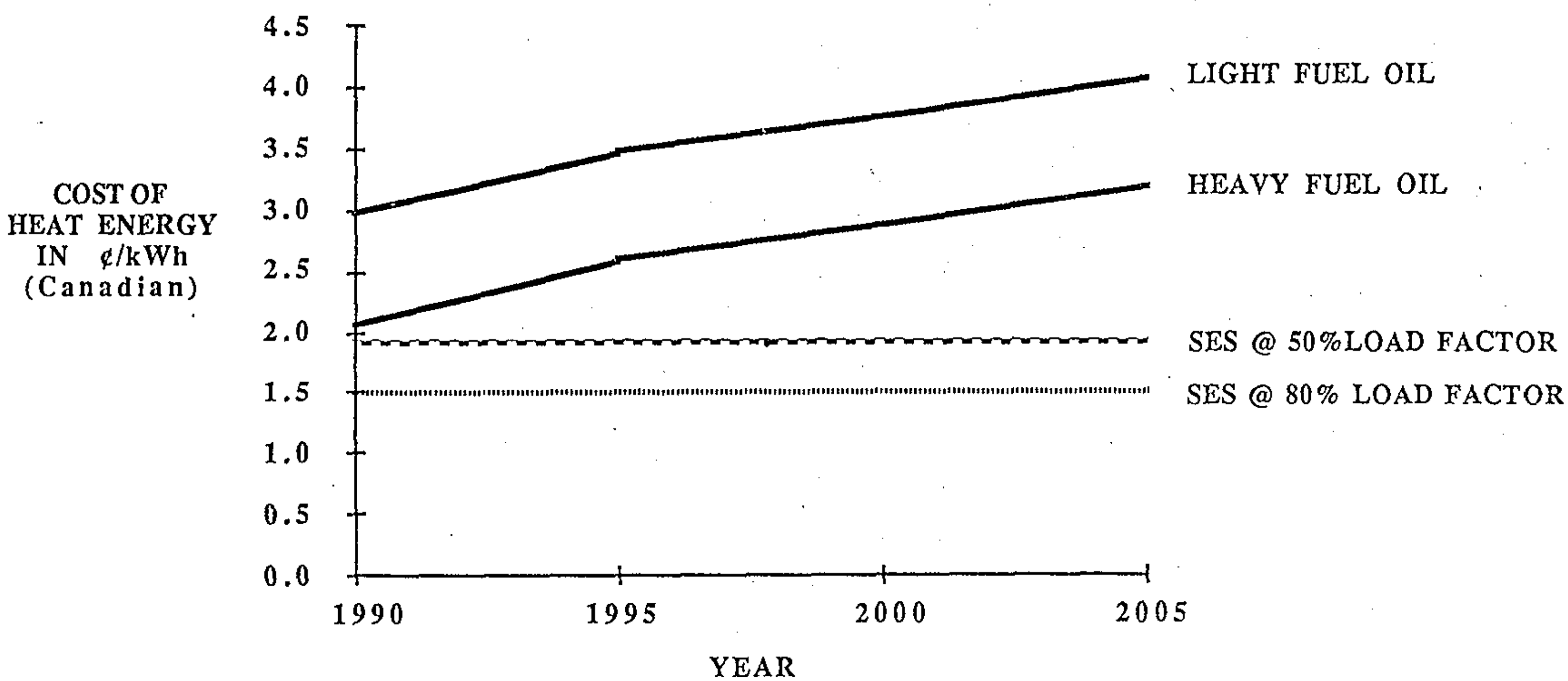

FIGURE 4: Comparison of the Variable Cost of Heat from Oil (World Price of Oil in the Range US$16-27) with the Total Cost of Heat from a SLOWPOKE Energy System

The FEARO process requires public input on siting and the industry supporters must then satisfy the public that the facility is safe.

A major consideration in the public information program is the environmental impact. The SLOWPOKE Energy System is a heat source free from the pollution problems of conventional fossil fuels, such as coal, oil or natural gas. It does not emit chemicals which contribute to urban air pollution, acid rain or to the greenhouse effect. It presents an opportunity to enhance the environment by improving the quality of air in urban areas and to reduce the global rate of increase of carbon dioxide.

Nuclear heating with simple, safe systems such as SLOWPOKE, offers the opportunity to significantly reduce the dependence on combustion fuels in urban environments.

CONCLUSIONS

The building heating market in many countries is large and is growing. Small nuclear heat sources are ideally suited to satisfy the demands of this energy sector but to be technically viable the detailed design criteria must match the application. By keeping the power level low, much of the complexity of the larger nuclear electrical generating stations can be avoided thus allowing small, safe nuclear heating systems to be economically viable.

The SLOWPOKE Energy System is a demonstrated technology that has been designed specifically for the institutional and municipal heating networks. It is a technology that offers long term energy security at stable prices for this very important energy sector.

The low capital investment requirements for a SLOWPOKE Energy System, coupled with the possibility of a relatively high degree of localization, even for the first unit, are seen as attractive features to facilitate its early adoption by those countries that are striving to relieve their dependence on imported fossil fuels.

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