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ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

NUCLEAR TECHNOLOGIES FOR LOCAL ENERGY SYSTEMS: CANADIAN PROGRESS

TECHNIQUES NUCLÉAIRES DES SYSTÉMES ÉNERGÉTIQUES LOCAUX: AVANCEMENT DES TRAVAUX AU CANADA

F.N. McDONNELL and G.F. LYNCH

Prepared for presentation at the 7th Pacific Basin Nuclear Conference San Diego, California 1990 March 4-8

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario K0J 1J0

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RÉSUMÉ

Afin de pouvoir exploiter toutes les possibilités de l'énergie nucléaire en tant que solution de rechange sûre et peu coûteuse aux combustibles fossiles, on doit trouver des applications dans des domaines autres que ceux qui sont actuellement l'apanage des grandes centrales nucléaires et mettre au point des types de réacteurs appropriés.

Le programme canadien d'étude des filières de production d'énergie locale est à l'avant-garde de ces travaux. Ce programme fait appel à la simplicité de conception et aux faibles puissances volumique et spécifique, utilise des processus naturels et des systèmes passifs et réduit l'intervention des opérateurs. Le premier produit, le Système énergétique SLOWPOKE, est une source de chaleur de 10 MW prévue spécialement pour produire de l'eau chaude destinée à satisfaire les besoins des systèmes de chauffage locaux des complexes immobiliers, des établissements et des réseaux de chauffage urbain municipaux. Un réacteur de démonstration construit à l'Établissement de recherches nucléaires de Whiteshell au Manitoba fait l'objet d'un programme d'essais intensif depuis son entrée en exploitation en juillet 1987. La conception du réacteur de taille commerciale de 10 MW, fondée sur les connaissances acquises au cours de la conception, de la construction, du processus d'obtention des permis et des essais d'exploitation de cette installation, est bien avancée, et EACL est prête à s'engager dans la construction de la première installation commerciale.

La démonstration technique du concept est importante, mais on est conscient qu'un autre élément crucial est l'accueil favorable par le public et les organismes réglementaires des petits systèmes nucléaires dans les zones urbaines. Le processus décisionnel par lequel une agglomération s'engage à construire un système énergétique SLOWPOKE fait ressortir avec acuité l'appréhension actuelle du public vis à vis des techniques nucléaires.

Ce sera là le plus grand obstacle à surmonter pour tout nouveau projet nucléaire au début des années 90. Toutefois, l'idée de plus en plus répandue que l'énergie nucléaire constitue une source d'énergie durable qui est sûre, économique et douce pour l'environnement, facilitera finalement le processus d'approbation.

Quand le système énergétique SLOWPOKE aura fait ses preuves, le chemin sera ouvert à toute une série de petits réacteurs pouvant satisfaire d'autres besoins d'énergie locaux. Grâce à ces nouveaux produits, les pays en voie de développement n'ayant ni les ressources ni l'infrastructure nécessaires pour se lancer dans un programme d'énergie nucléaire de grande envergure pourront bénéficier des avantages de l'énergie nucléaire.

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ABSTRACT

If nuclear energy is to realize its full potential as a safe and cost-effective alternative to fossil fuels, applications beyond those that are currently being serviced by large, central nuclear power stations must be identified and appropriate reactors developed.

The Canadian program on reactor systems for local energy supply is at the forefront of these developments. This program emphasizes design simplicity, low-power density and fuel rating, reliance on natural processes, passive systems, and reduces reliance on operator action. The first product, the SLOWPOKE Energy System, is a 10 MW heat source specifically designed to provide hot water to satisfy the needs of local heating systems for building complexes, institutions and municipal district heating systems. A demonstration heating reactor has been constructed at the Whiteshell Nuclear Research Establishment in Manitoba and has been undergoing an extensive test program since first operation in 1987 July. Based on the knowledge learned from the design, construction, licensing and operational testing of this facility, the design of the 10 MW commercial-size unit is well advanced, and Atomic Energy of Canada Limited is prepared to commit the construction of the first commercial unit.

Although the technological demonstration of the concept is important, it is recognized that another crucial element is the public and regulatory acceptance of small nuclear systems in urban areas. The decision by a community to commit the construction of a SLOWPOKE Energy System brings to a sharp focus the current public apprehension about nuclear technologies.

This will be the major challenge for any new nuclear project as we enter the 1990s. However, the increased recognition that nuclear energy offers a sustainable energy source that is safe, economically competitive and environmentally acceptable, will ultimately facilitate the adoption process.

Once the SLOWPOKE Energy System has been proven, the door will be open for a range of small reactor systems that can meet other local energy needs. Through these developments, the benefits of nuclear energy could become available to those developing countries that have neither the infrastructure nor the resources to embark on a full-scale nuclear power program.

Local Energy Systems Business Unit
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1. STRATEGIC IMPORTANCE OF NUCLEAR HEATING

The demand for economic and reliable energy sources is driven by the growth in the world's population and the essential role which energy plays in industrial development. Global energy requirements, expected to double over the next 40 years (1), will seriously challenge suppliers in their ability to meet the demand. Ultimately, efficient energy utilization will become singularly important.

Industrialization and economic development manifest themselves in urbanization. Urban dwellers consume significantly more energy per capita compared with their rural neighbours (2). Consequently, concentrated and environmentally acceptable energy sources, combined with efficient distribution systems, are now recognized as essential to meet urban energy demands. In considering the alternatives that will meet these requirements, nuclear energy qualifies as both a concentrated and environmentally benign source. Nuclear electricity generation is a mature technology which we believe paves the way for nuclear heating application.

A substantial part of the energy load in cities provides thermal energy for heating buildings and their accompanying hot-water supply. District heating systems are considered an appropriate form of technology to supply energy to a significant part of this energy sector.

Over the last 30 years, hot water has demonstrated its economic superiority over steam as the preferred heat distribution medium for the residential market (3). Recent development programs now focus on the trend to lower-temperature water systems.

In determining the hot-water heat sources, energy sustainability and environmental acceptability are now emphasized in addition to the cost effectiveness of energy supply. Economic development and protection of the environment must go hand in hand. However, with the increasing energy demand has come increased pollution, in the form of acid gas and greenhouse gases, caused mainly by the combustion of fossil fuels. Governments and, more importantly, the general public are beginning to recognize this as the major environmental problem facing the world as we move toward the next century (4,5).

Nuclear energy meets the challenges of sustainability and environmental acceptability not only for electricity generation but also for space heating applications. It can compete economically with current fossil fuel prices and can be readily accommodated into existing district heating networks, provided the nuclear heat source is appropriately sized and specifically designed to meet the technical requirements of this application.

For these reasons, Atomic Energy of Canada Limited (AECL) has been collaborating with a number of potential users in evaluating the prospects for nuclear heating and assessing the appropriateness of the SLOWPOKE Energy System (6) in this application. The results confirmed that these systems offer the prospects of a significant reduction in the long-term dependence on fossil fuels. In addition, many economically attractive sites for immediate implementation have been identified world-wide.

To meet the heating needs of building complexes, institutions and municipal district heating systems, small nuclear reactors in the tens of MW range are best suited. The development of cost-effective small nuclear heat sources and their widespread adoption will establish the basis for a range of applications to meet local energy needs. Through these developments the benefits of nuclear technology will be available to those countries with a need and capability of adapting this simpler technology. We consider this technology of strategic importance to many Pacific Basin countries. Although the current application is for heating, this current technological achievement will establish the basis for application to stand-alone electricity generators, desalination and air conditioning.

2. A ROLE FOR DISTRICT HEATING

District heating, the heating of many buildings from a central heat source, fulfills the requirement of efficient energy utilization and distribution in an urban environment. The advantages of district heating are becoming more important with the current emphasis on sustainable development (7). In contrast to heating and cooling buildings using individual systems, district heating and cooling offers benefits consistent with the new emphasis. These benefits are:

(i) higher efficiency in the use of fuel, especially in the case of cogeneration systems;

(ii) reduced local and global pollution because of item (i) and improved pollution control for larger systems;

(iii) greater flexibility in the use of fuel, with the ability to optimize the use of fuels in systems with several different heat sources;

(iv) reduced cost of delivered energy; and

(v) more reliable and convenient energy supply to the building owners.

These advantages are well known to users of district heating systems. For example, the International District Heating and Cooling Association was formed in 1909 to facilitate the exchange of technical, operational and management information, mainly among North American users. One vehicle for this exchange and for the promotion of district heating is the publication of information from system operators (8). In Europe, where the variety of indigenous fuels has been limited, district heating has had generally greater acceptance. Use in Scandinavian countries is extensive (9). In Denmark, 42 percent of buildings are supplied by heat distribution systems. The Western European countries with the largest connected heating capacities are Germany with 36 GW, Sweden with 26 GW, France with 16 GW and Denmark with 15 GW. Use in Eastern Europe is also extensive, especially in Czechoslovakia, Hungary, Poland and the USSR.

3. PERFORMANCE REQUIREMENTS

To meet the needs for heating buildings, a heat source must have a number of important features.

(i) It must have appropriate capacity to supply groups of buildings or to fit into a district heating system. An appropriate unit size for many applications is 10 MW, as single or multiple units.

(ii) It must deliver heat at a temperature appropriate to the building heating system. Steam and hot water in the range 50-150°C is in line with the current trend to lower-temperature hot-water distribution systems.

(iii) It must be capable of being sited close to urban loads. As with combustion units, a nuclear heat source must be safe.

(iv) It must be economical, which means having acceptable capital, operating and fuelling costs.

4. THE SLOWPOKE ENERGY SYSTEM

The SLOWPOKE Energy System, developed by Atomic Energy of Canada Limited, is a 10 MW heat source specifically designed to satisfy the needs of local heating systems in building complexes, institutions and municipal district heating systems.

Although the technical and licensing criteria for the application of nuclear technology to this important energy sector are still evolving, it is clear the existing power reactor technology is neither required nor appropriate (6). A low-temperature nuclear heat source in the 5-20 MW range offers the best prospects for supplying the hot water required for the existing heating systems.

A. System Description

The SLOWPOKE Energy System is a simple nuclear heat source capable of supplying 10 MW of thermal energy in water at 85°C. At this power level, a SLOWPOKE Energy System can heat 150 000 square metres of floor area or approximately 1 500 individual apartments with an inflation-resistant fuel source. As shown in Figure 1, it is a pool-type reactor designed to operate at atmospheric pressure, thus eliminating the need for a nuclear 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 contained inside a steel-lined concrete vault. Double containment of the pool water prevents loss-of-coolant caused by leakage.

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

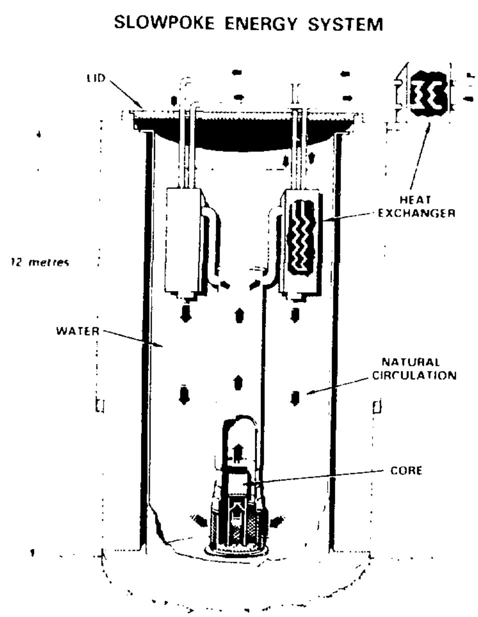

FIGURE 1: SCHEMATIC DIAGRAM OF THE SLOWPOKE HEATING REACTOR CONCEPT

The secondary circuit delivers heat to the distribution system by way of the secondary heat exchanger. Thermal power is then measured in the secondary circuit, for the purpose of metering and calibrating the instrumentation in the primary circuit.

Absorbers under computer control are used for load following. Periodic adjustments of these absorbers, by a licensed operator, compensates for fuel burnup. The rate of removal of absorbers is limited by the speeds of their electric motors. Use of a fully redundant control system reduces the probability of unwanted shutdown to an acceptable level.

Should a loss of secondary flow occur, such as by a power interruption to the pumps, the large pool volume delays core temperature rise. Consequently, 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 fast-acting shutdown systems that are essential for pressurized power reactors. Two independent and diverse shutdown systems are provided.

Pool water is continuously pumped through ion exchange columns to maintain water chemistry and control corrosion. Ion exchange columns can also remove fission products from defective fuel.

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.

The goal of the 10 MW SLOWPOKE Energy System design is 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 non-critical equipment and responding to specific alarm conditions. It is anticipated that these local responsibilities can be undertaken by the existing heating plant staff. Although local staff will have the authority to shut the reactor down in the event of an abnormal condition being observed, the licensed operator is required for startup.

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 2. The reactor core and safety systems are being designed to remain fully functional during and after seismic events.

The design process paid particular attention 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. 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 for the first unit in most countries.

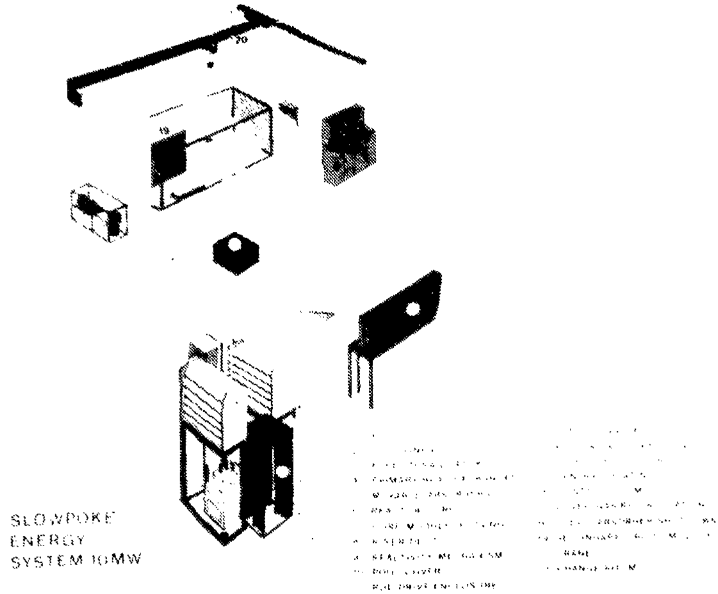

FIGURE 2: 10 MW SLOWPOKE ENERGY SYSTEM

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 safety element allows the system to be operated with minimum operator attention and facilitates the licensing of the system close to the load in urban areas. In this way, a SLOWPOKE Energy System can be considered similar to the gas- or oil-fired boiler system it is designed to replace.

B. Status of the Canadian Program

Because of the uniqueness of the design requirements for a nuclear heat source for district heating applications, it was recognized that a fundamental and thorough demonstration of the technology was required before commercial units could be committed. For this reason, AECL has constructed the SLOWPOKE demonstration heating reactor at its laboratory facilities at the Whiteshell Nuclear Research Establishment, Manitoba.

(i) Technical Demonstration

Construction of the SLOWPOKE Demonstration Reactor began in the spring of 1985 and the unit started operating on 1987 July 15. The main purpose in designing, constructing and testing this 2 MW facility is to validate, in a demonstrative way, the required technical, economic and safety criteria associated with this form of heating. The demonstrator is currently undergoing an extensive test program that will culminate with extreme transient tests and fuel performance measurements at the end of the first core life in 1991/92.

Following the test program, the reactor will be used to provide heat for buildings at the research site.

Based on the knowledge learned from the design, construction, licensing and operation of the SLOWPOKE Demonstration Reactor, the design of the 10 MW commercial-sized 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 changed from the demonstrator. On the basis of this work, AECL is prepared to commit the construction of the first commercial unit in Canada.

(ii) Regulatory and Public Acceptance

Although the technological demonstration is important, it is recognized that another crucial element is the public and regulatory acceptance of small nuclear systems in urban areas. This is very much a social challenge. SLOWPOKE Energy Systems will 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 and Provincial Environmental Assessment Review Offices. The AECB, as the official government regulatory agency, has the primary responsibility for the assessment of the safety of the reactor facility from the technical point of view.

The approach being taken for nuclear licensing for the first Canadian commercial SLOWPOKE Energy System is based on the concept of "Early-Licensing" which was originally developed for the nuclear power industry in Canada (10,11). In this way, the safety principles and licensing criteria are developed early in the project life-cycle to the extent that all basic design issues that impact on safety are resolved prior to the construction licence being issued.

Subsequent installations will then only need to address those site-related issues that impact on the safety of the facility at a particular location.

The environmental review process addresses the question of the impact of the project from an ecological and social perspective.

It is intended that a complete environmental assessment review process, including formal public hearings, will be undertaken for the first installation. Although this has an impact on the project schedule, the social acceptability of the technology is of sufficient importance to warrant a thorough review. Public endorsement of the concept of nuclear heating is essential if the technology is to contribute significantly to the nation's long-term energy needs. This requires a thorough review and explanation of the balance between the benefits to be gained from nuclear heating and the real risks relative to other heat sources. This assessment is best undertaken within the framework of the existing environmental review processes.

(iii) First Commercial Unit

Several urban locations in Canada are being assessed for their suitability for the construction of the first commercial 10 MW SLOWPOKE Energy System. In 1988 March, one of these sites, the Centre hospitalier universitaire de Sherbrooke, in the province of Quebec, announced publicly its intention to give serious consideration to the installation of a unit. As a result of detailed economic evaluation, the SLOWPOKE Energy System was found to be a competitive source of heat for the hospital. However, in 1988 December, after considerable public debate conducted mostly through the local media, and with the lack of provincial government support, the hospital was obliged to interrupt the studies. The consideration of the project was therefore stopped before the formal environmental review process could be initiated. Investigations have since been launched at a number of alternative sites suitable for the application of a SLOWPOKE Energy System.

This highlights the dilemma currently faced, not only by Canada but also by many countries as they approach nuclear project decisions. How does one address the emotional issues currently associated with a nuclear project, with processes that are designed to assess the ecological impact, safety aspects and economics in a logical and formal manner? It is unlikely that this dilemma can be resolved without an effective public information program strongly supported by the government.

An opportunity to test this view is to be found in Saskatchewan in the near term. In 1989 May, the President of the University of Saskatchewan announced that a SLOWPOKE Energy System will be considered for the University of Saskatchewan campus in Saskatoon. The University has invited AECL to assess the suitability of campus buildings for SLOWPOKE Energy System heating, and has asked the Saskatchewan Department of the Environment and Public Safety to review the environmental impact of the project.

The proposed SLOWPOKE Energy System, if approved, will serve as a commercial demonstration system to potential users and enhance the development of nuclear district heating technology.

The Saskatoon campus is already home to a SLOWPOKE research reactor on which SLOWPOKE Energy System technology is based. Operated there since 1981 by the Saskatchewan Research Council, this nuclear analytical instrument supports research in such diverse fields as medicine and mining. The SLOWPOKE Energy System would be a further development in this pioneering history.

The decision on installing the system will be based on the environmental impact assessment which includes discussions with interested groups and individuals, and technical and economic data.

C. Economic Analysis

In addition to fuel security and environmental acceptability, a fundamental consideration for any heat source is its economic competitiveness. The financial analysis should involve the initial capital investment, the fuel costs, the operating and maintenance requirements and load factor.

The capital cost of a SLOWPOKE Energy System built in Canada depends on the nature of the site (12). The capital investment, in terms of $/MW of thermal energy, is significantly lower than the equivalent cost of a nuclear system designed for electricity production. This results from many factors, including the elimination of the complex pressurized systems and a short construction time. Subsequently, dedicated nuclear heating systems can be competitive with fossil-fuelled heat sources for base-load supply of district heating systems.

The low capital cost, combined with low operating expenses arising from remote monitoring, results in the unit energy cost of heat from a SLOWPOKE Energy System being 2.3¢ per kilowatt-hour, Canadian, for a unit built in Canada with a load factor of 80 percent. This levelized 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 30-year amortization period for the capital and a 5 percent discount factor.

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. To overcome these disparities, it has been decided that the benchmark used for the cost of alternative fuels will be 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 district heating system and simply displacing fossil fuel purchases.

Studies have confirmed that using a SLOWPOKE Energy System as a base-load heat source in existing district heating systems in some countries can result in load factors as high as 80 percent. Consequently, load factors in the range from 50 percent to 80 percent are considered. In this way, the situation for both small and large district heating networks is represented.

Normally, both heavy fuel oil and light heating oil are used in current district heating systems. A comparison of the heat costs from heavy fuel oil and the SLOWPOKE Energy System, as shown in Figure 3, confirms that not only is SLOWPOKE competitive but the savings to be realized increase considerably as the world price of crude oil increases according to recent forecasts (13). The oil price data presented in Figure 3 is based on the assumption that the world price of crude oil will slowly rise from $17 per barrel, US, to $32 per barrel, US, in 2010. These comparisons show that the SLOWPOKE Energy System is a cost-competitive heat source.

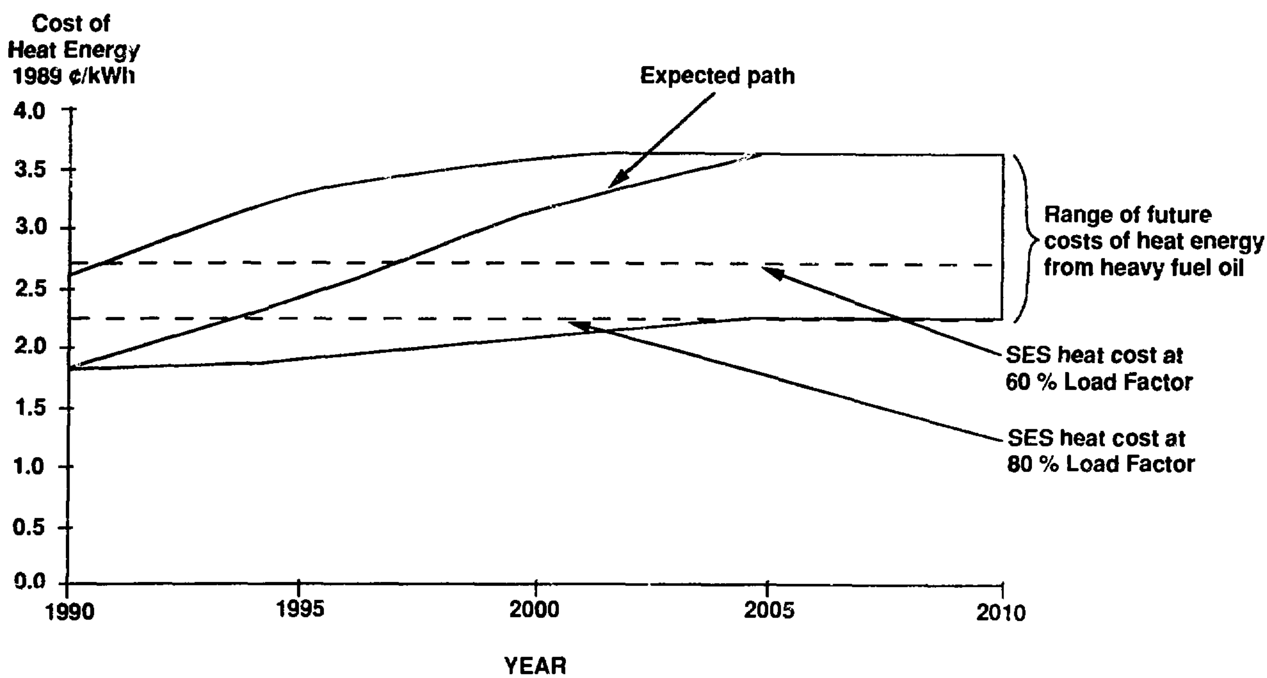

FIGURE 3: COMPARISON OF THE TOTAL COST OF HEAT ENERGY FROM SES WITH THE FUEL COMPONENT COST OF A HEAVY FUEL OIL-FIRED BOILER

5. CONCLUSION

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 both for environmental and economical reasons. Successful application of nuclear district heating will lead to many other applications of mini-reactor systems, thereby broadening the range of countries that can access the benefits of nuclear energy.

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