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ATOMIC ENERGY OF CANADA LIMITED

ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

NEW DEVELOPMENTS IN SMALL REACTORS: AN INVESTMENT IN THE FUTURE

PROGRÈS RÉALISÉS DANS LE DOMAINE DES PETITS RÉACTEURS : UN INVESTISSEMENT DANS L'AVENIR

F.N. McDONNELL, K.S. KOZIER, D.A. MENELEY and A. REED

Prepared for presentation at the 1990 CNA Annual Conference Toronto, Ontario 1990 June 3-6

Chalk River Laboratories

Laboratoires de Chalk River

Chalk River, Ontario K0J 1J0

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RÉSUMÉ

Depuis la découverte de la fission nucléaire il y a cinquante ans, l'énergie nucléaire a joué un rôle de plus en plus important dans l'approvisionnement énergétique à l'échelle mondiale. Lors de la récente Conférence mondiale de l'énergie qui s'est tenue à Montréal en septembre 1989, les experts se sont mis d'accord pour déclarer que l'énergie nucléaire continuera à faire partie intégrante de l'éventail énergétique de l'avenir.

La demande de sources sûres et économiques d'approvisionnement en énergie augmente en raison de l'accroissement de la population mondiale et du rôle essentiel de l'énergie dans le développement industriel. On s'attend que les besoins énergétiques mondiaux doublent au cours des quarante prochaines années, et les compagnies d'électricité auront beaucoup de difficulté à répondre à la demande. L'utilisation efficace de l'énergie deviendra alors très importante.

L'industrialisation et le développement économique se manifestent par le phénomène d'urbanisation. Les citadins consomment, par personne, beaucoup plus d'énergie que leurs voisins ruraux. Par conséquent, on reconnaît maintenant qu'il faudra trouver des sources d'énergie concentrées qui sont douces pour l'environnement et établir des réseaux de distribution efficaces pour satisfaire la demande d'énergie urbaine. Parmi les différentes sources d'énergie possibles, l'énergie nucléaire répond tout à fait à ces critères, étant une source concentrée que l'on peut exploiter tout en respectant l'environnement. La production d'électricité d'origine nucléaire fait appel à des techniques éprouvées qui conduisent à d'autres applictions.

Afin d'assurer l'exploitation maximale de l'énergie nucléaire en tant que solution de rechange aux énergies fossiles, on doit élargir le champ d'application actuel et aller au delà des grandes centrales nucléaires, c'est-à-dire investir dans le futur en offrant des réacteurs spécialement étudiés et de plus petite taille.

On met effectivement au point de nouveaux réacteurs de plus petite taille qui permettront de satisfaire la demande prévue et dont les caractéristiques répondent aux attentes actuelles du public, c'est-à-dire un minimum d'impact sur l'environnement. Ces nouveaux réacteurs, dont la puissance est comprise dans la plage de 10 à 1000 MW(t), sont actuellement à l'étude dans plusieurs pays dont le Canada, les États-Unis, le Royaume-Uni, la Chine et l'Union soviétique.

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ABSTRACT

During the fifty years since nuclear fission was discovered, nuclear energy has emerged to play an increasingly important role in meeting global energy needs. At the recent World Energy Conference in Montreal, 1989 September, experts agreed that nuclear power will continue to be an essential part of the future energy mix.

The demand for economic and reliable energy sources is driven by the growth in the world's population and the essential role energy plays in industrial development. Global energy requirements, expected to double over the next 40 years, 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. 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 that paves the way for other applications.

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 appropriately designed and sized reactors developed as an investment in the future.

To meet this potential, new small reactor concepts are being developed to satisfy the expected energy demands, while also displaying characteristics that address current public concerns for providing minimal environmental impact. Concepts ranging in size from 10 MW(t) to 1000 MW(t) are being pursued in a number of countries, including Canada, the USA, the UK, China and the USSR.

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THE NEED FOR SMALL REACTORS

If small reactor concepts are to play a role in meeting some of the world's energy needs, the safety and licensing challenges of urban siting must be faced through the use of intrinsic safety features such as passive decay heat removal, low stored energy, and limited reactivity speed and depth in the control systems. The challenge of public perception must be met by clearly presenting the characteristics of small reactors in terms of size and transparent safety in design and operation.

Another crucial element is the public and regulatory acceptance of small nuclear systems. Small reactors will bring nuclear technology close to the public, not as remote megaprojects but as small energy systems located close to the loads of the people they serve. This implies that not only must the safety and environmental issues be thoroughly reviewed by technical experts, they must also be expressed in a manner that can be understood by individuals who have limited or no technical knowledge.

This is the dilemma currently facing not only Canada but also many countries as they approach nuclear project decisions. Proponents must address the emotional issues currently associated with nuclear projects with processes that are designed to assess the ecological impact, safety aspects and economics in a logical and formal manner. Effective public information programs, strongly supported by the government, will be essential to emphasize the fact that nuclear energy meets the challenges of sustainability and environmental acceptability.

In the final analysis, small reactors must also be able to meet fossil fuel and competitive fuel prices. The challenge facing small reactor designers is the need to minimize unit energy costs so that they are acceptable relative to larger (i.e., more powerful) plants. How is it possible to overcome the traditional, and often inherent, economies of scale that favour larger and larger plants? Probably the most promising approach is to increase the number of identical reactor units produced so that advantage can be taken of modern series production techniques for the fabrication of standardized nuclear plant components. Also, unit energy costs will decrease significantly as multiple small reactor modules are added at a single application site.

Recent trends within the nuclear industry are fostering conditions that would encourage the establishment of a viable small reactor market. For example, international industrial consortia are being formed to address global reactor markets rather than the largely indigenous and closed national markets of the past. Also, there has been some consolidation of the multitude of competing technical concepts proposed as "super-safe" reactor designs, and only a few are proceeding to prototype tests. Notably, the process of "up-front" or "generic" reactor licensing is making progress in Canada, the USA and elsewhere.

CURRENT DEVELOPMENTS AND STATUS

The rationale for developing small nuclear reactors throughout the world arises from considering a number of factors, such as the potential market, economic competitiveness, safety, public and regulatory acceptability.

With these factors in mind, organizations in several countries are pursuing the development of small power reactors for a diverse range of applications, from the traditional role of generating electricity for domestic and industrial use to small satellite-borne reactors.

A brief overview and examples of typical small reactor developments in several countries are provided in the following sections.

ELECTRICITY GENERATION

The generation of electricity for utility grids is the traditional market for nuclear reactors. On a worldwide basis this is provided by the LWR (light-water reactor), the HWR (heavy-water reactor) and gas-cooled reactors. Small reactor designs of both the PWR (pressurized-water reactor) and BWR (boiling-water reactor) types have been proposed to serve the needs of small utilities or developing countries that desire smaller increments to grid capacity. A partial list of proposed LWR small reactor concepts (<1000 MW(t)) for electricity generation is given in Table 1. The CANDU 3 HWR is the subject of a companion paper in this session by D.S. Lawson and G.L. Brooks and will not be discussed further in this paper.

TABLE 1

Small LWRs (<1000 MW(t)) for Electricity Generation

Name	Designer Country	Thermal Power MW(t)	Electrical Output MW(e)
		PWRs	
SIR	USA, UK	1000	320
MS-300	Japan	950	300
ISER	Japan	645	210
		BWRs	
TOSBWR-900P	Japan	900	310
SBWR-200	West Germany	630	200

In addition to the concepts in Table 1, electricity-producing designs have been proposed based on the PIUS (Process Inherent Ultimate Safety) concept, in which a deep pool of water provides natural pressurization of the water in the fuelled reactor core. An example which fits within the size range considered is the GEYSER-GTEC proposed in Switzerland, which could produce 1-10 MW(e).

A common theme of the small LWRs is increased emphasis on simple, passive safety systems, usually involving natural coolant circulation. Several of these designs are of the integral type, in which the complete primary coolant circuit is contained within the reactor vessel.

INDUSTRIAL PROCESS APPLICATIONS

High-temperature reactors (HTRs) involving graphite core structures and helium coolant offer the prospect of addressing process heat applications in addition to electricity generation. Examples of proposed applications include water desalination, coal gasification, bitumen extraction from oil sands, crude oil refining, aluminum oxide production, and thermochemical water splitting (hydrogen production).

The HTR designs may be classified into two basic types based on their use of either prismatic block construction or beds of graphite fuel pebbles. The principal example of the former type is the MHTGR (modular high-temperature gas-cooled reactor) proposed by General Atomics, which produces 350 MW(t). The main example of a small pebble-bed design is the HTR-MODUL proposed by Siemens/Interatom, which produces 200 MW(t). In addition to the USA and European HTR programs, similar design concepts are being actively pursued in the USSR and Japan.

A unique safety feature common to all HTR designs is their use of tiny TRISO (triply isotropic) coated fuel particles. This fuel type offers extraordinary resistance to the release of hazardous fission products up to temperatures of 1600°C.

MARINE REACTORS

Several hundred small reactors are in use today as the prime power source for military submarines and surface vessels (mainly aircraft carriers) and for several ice-breakers in the USSR. Such extensive use reflects the unsurpassed technical and economic performance of nuclear power for these purposes. The vast majority of these reactors are of the PWR type, although a few have been liquid-metal-cooled designs.

Commercial marine nuclear propulsion has been attempted in the past, the main examples being the USS Savannah and the Otto Hahn, but with limited success. The advent of new and safer small reactor designs will likely trigger renewed interest in this potentially large market.

Another possible application for marine reactors is to service off-shore oil platforms, such as barge-mounted units, and commercial submarines. A recent endeavour in the latter area is the AMPS reactor concept proposed by ECS of Canada, spanning a power range from 100 to 1700 kW(e).

SPACE REACTORS

Undoubtedly, the most technically demanding environment in which to produce power is the vacuum of space. For this reason, mankind's excursions beyond earth have been limited to power levels of less than about 15 kW(e). Even the Freedom manned space station will only extend this level to about 75 kW(e), using large solar arrays that require extensive use of reboost propellent to overcome the atmospheric drag in low earth orbit.

Nuclear reactors are the space power technology of choice at high-power levels and for long-duration missions. They are particularly appropriate for unmanned missions and deep space probes far from the sun, or when combined with ion thrusters for mass-efficient nuclear-electric propulsion. Small reactors will also likely be used when mankind returns to establish a base on the moon or visits Mars. An important safety aspect of unused nuclear reactors is that they pose no radiological hazard on the launchpad.

To date, the USSR has launched dozens of space reactors for military radar reconnaissance satellites. The reactor is based on a compact, liquid-metal-cooled concept, known as TOPAZ, which features a novel, in-core thermionic conversion system that produces several kW(e). In contrast, the USA has launched only one space reactor, SNAP-10A, in 1965, which produced 500 W(e) for about 43 days. However, the USA has recently revitalized its interest in space reactor technology and is actively developing a more-powerful system known as the SP-100. This unit uses a compact, liquid-metal-cooled, fast reactor core and will produce 100 kW(e) for seven full-power years when combined with a passive thermoelectric conversion system.

SMALL HEATING REACTORS

A substantial part of the energy load in urban centres is for supplying heat to buildings through district heating systems.

In determining the heat sources, nuclear energy meets the challenges of sustainability and environmental acceptability, provided it is economical and is appropriately sized and designed to meet the technical requirements of the specific application.

THE SLOWPOKE HEATING REACTOR

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 1500 individual apartments with an inflation-resistant fuel source. 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 dependability of pumps or the integrity of electrical supply for pump motors.

The secondary circuit delivers heat to the building distribution system by way of the secondary heat exchanger. Pool water is continuously pumped through ion exchange columns to maintain water chemistry and control corrosion. 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.

The goal of the 10 MW SLOWPOKE Energy System (SES-10) design is to fully automate all essential systems, thus allowing the unit to be operated for extended periods of time without a licensed operator in the reactor building.

The SES-10 can be housed in a separate building or building extension that measures 10 x 15 metres, as shown in Figure 1. The reactor core and safety systems are being designed to remain fully functional during and after seismic events.

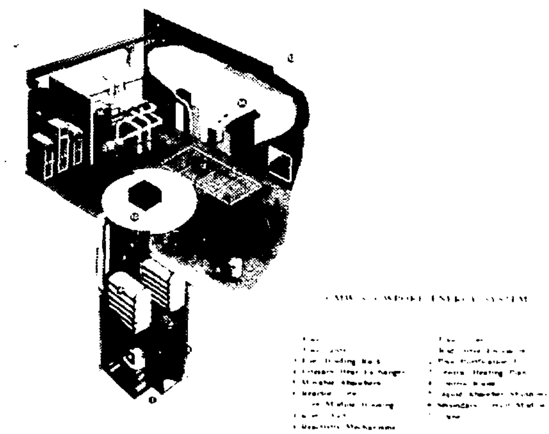

FIGURE 1: 10 MW SLOWPOKE ENERGY SYSTEM

The SLOWPOKE Energy System has benefitted from the experience gained in the design, construction and testing with the SLOWPOKE Demonstration Reactor (SDR), located at Whiteshell Laboratories. The SDR, with a power up to 2 MW, is being used to demonstrate the technology. Experiments to date have provided confidence in the concept, particularly with the validation of the thermalhydraulics and physics behaviour for conditions of similar fuel power ratings as for the SLOWPOKE Energy System.

WORLDWIDE SMALL HEATING REACTORS

Small heating reactor developments are also being pursued in several countries, many with features similar to the SES-10. The proposed designs are based on standard concepts with appropriate safety-related modifications. The exception is the GEYSER, a departure from contemporary designs in that it does not use conventional engineered safety systems or controls. Some typical examples are listed in Table 2.

TABLF 2

Small Heating Reactors

Designer Country	Reactor Name	Type
Canada	SES-10	Covered Pool Absorber Rod Control
China	THR-5	PWR Absorber Rod Control
Russia	RUTA	Covered Pool Be Reflector and Absorber Rod Control
Switzerland	Swiss Heating Reactor SHR	Pressurized BWR Absorber Rod Control
Switzerland	GEYSER	Covered Pool Chemical Control
United States (General Atomics)	TPS	Pressurized TRIGA Absorber Rod Control

The Chinese THR-5 started up in 1989 October and is currently operating at full power of 5 MW(t). It recently completed its 100-day run.

There are also a number of large nuclear plants currently in design or construction dedicated to district heating. The ACT-500 program in Gorky, USSR, is the most advanced: the twin 500 MW unit is in the latter stages of construction and will supply hot water to about half the city. Kraftwerk Union AG in the Federal Republic of Germany has designed a 100-500 MW district heating reactor. Other designs include: the THERMOS 100-200 MW French reactor; the 100-400 MW Swedish SECU reactor, a forerunner of the PIUS concept; and the 64 MW(t) TRIGA power system.

SMALL REACTOR APPLICATION IN CANADA

An opportunity to apply a small reactor concept could be provided in the near term in Saskatchewan. In 1989 May, the President of the University of Saskatchewan announced that a SLOWPOKE Energy System would be considered for the University of Saskatchewan campus in Saskatoon. The University invited Atomic Energy of Canada Limited to assess the suitability of campus buildings for SLOWPOKE Energy System heating.

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 the SLOWPOKE Energy System technology is based. In operation 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 to install the system will be based on several factors, including the outcome of the Environmental Impact Assessment process. This process for the first commercial unit is particularly important since, through public interaction and dialogue, it will bring out the environmental benefits of nuclear heating, and address the public concerns and social acceptance of this technology.

SUMMARY

While it is clear that nuclear power will continue to meet its traditional role of providing electricity generation from large central plants, an additional and major contribution can be made by small reactors in the fields of district heating, cogeneration and high-temperature process heat.

Worldwide, the market potential is attractive, and several countries have development programs in place to meet the expected demand.

With increased emphasis on sustainability and environmental acceptability in the 1990s, small nuclear reactors will also have an important role to play in a variety of new and non-traditional applications. Canada is only one of many countries pursuing small reactor options to provide flexibility in meeting future energy demands.

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