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SMALL NUCLEAR REACTOR SAFETY DESIGN REQUIREMENTS FOR AUTONOMOUS OPERATION

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Abstract

Small nuclear power reactors offer compelling safety advantages in terms of the limited consequences that can arise from major accident events and the enhanced ability to use reliable, passive means to eliminate their occurrence by design. Accordingly, for some small reactor designs featuring a high degree of safety autonomy, it may be possible to delineate a "safety envelope" for a given set of reactor circumstances within which safe reactor operation can be guaranteed without outside intervention for time periods of practical significance (i.e., days or weeks). The capability to operate a small reactor without the need for highly skilled technical staff permanently present, but with continuous remote monitoring, would aid the economic case for small reactors, simplify their use in remote regions and enhance safety by limiting the potential for accidents initiated by inappropriate operator action.

This paper considers some of the technical design options and issues associated with the use of small power reactors in an autonomous mode for limited periods. The focus is on systems that are suitable for a variety of applications, producing steam for electricity generation, district heating, water desalination and/or marine propulsion. Near-term prospects at low power levels favour the use of pressurized, light-water-cooled reactor designs, among which those having an integral core arrangement appear to offer cost and passive-safety advantages. Small integral pressurized water reactors have been studied in many countries, including the test operation of prototype systems.

1. INTRODUCTION

For more than fifty years, nuclear power reactor technology has evolved to meet the needs of its customers, providing concentrated, competitive energy sources for large-scale energy consumers, particularly electrical utility grids, as well as compact propulsion systems for military vessels, icebreakers and a few merchant ships. This evolution has progressed toward larger reactor units to benefit from economy of scale. The nuclear safety of present-day, large nuclear generating stations (about 1 GW_e or 3 GW_t) depends on active, engineered systems, supported by a complex infrastructure, highly trained personnel and rigid regulatory oversight.

Future growth in the application of nuclear reactor technology, besides addressing the need for electricity in today's developing economies, may come from more-widespread "secondary" energy markets involving smaller reactor units (typically less than 100 MW_t) for district heating, water desalination and small-scale electricity generation in remote areas. A large number of such applications may become attractive, provided nuclear energy generating costs for small-scale systems are competitive with alternate energy sources without compromising safety and reliability.

Significant cost savings can likely be obtained for small power reactors through design simplification and standardization, up-front or "type" reactor licensing, shortened construction schedules, and shop fabrication of major components. However, the "fixed" cost components for essential equipment, such as nuclear instrumentation, and minimum staffing requirements will represent a larger fraction of their generating cost.

Consequently, small reactor designs having features that allow operation with reduced crew size are favoured. Such operation requires a greater level of safety autonomy, that is, the reactor would have to achieve a safe, stable end state by passive means for all realistic upset scenarios without operator assistance and it would have to provide a sufficient response time for any eventual intervention using off-site resources.

To attract a sufficient level of global economic activity to warrant the development of a new small reactor power supply, a flexible design is required that addresses a wide range of applications for both heat and electricity. While unpressurized pool-type reactors are an attractive option for many applications requiring low-temperature hot water for residential district heating, the need to generate electricity with acceptable thermodynamic efficiency using proven, affordable technology, at present, requires higher temperature systems that produce steam.

Therefore, the near-term development of small power reactors (< 100 MW_t) would likely be based on pressurized light water reactor (PWR) technology using conventional steam turbogenerators to produce electricity. This development would involve low technical risk since it would share component technology and global experience from the large power reactor programs.

Among the PWR concepts, the integral PWR (or IPWR), in which the steam generator is contained within the reactor pressure vessel (RPV), emerges as a strong candidate for a simplified, low-cost, compact nuclear power source in the low power range, yet incorporating enhanced passive safety features. Accordingly, this paper considers the safety requirements for the autonomous operation of small power reactors with particular reference to IPWRs.

2. GENERAL REQUIREMENTS FOR SMALL POWER REACTORS

Some important factors to consider in the selection of a small nuclear power reactor technology are:

(i) **Technical Feasibility and Appropriateness.** The technology selected must be well suited to the intended application and the required operating performance should lie conservatively within the envelope of proven performance in similar systems. To gain customer acceptance, reduce project risk and resolve generic licensing issues, it is essential that the technology be proven through the construction, licensing and test operation of prototype systems. The investment cost of such demonstration is likely affordable for a small reactor unit and would be expected to support hundreds of carbon-copy application units. The supplier of the technology must also have a proven track record for product support, as the facility lifetime will be 25-50 years.

(ii) **Safety.** The radiological hazard presented by a small nuclear power reactor is one or more orders of magnitude lower than that presented by a large power reactor by virtue of the former's low fission product inventory. Low power levels and power densities also place much less demanding performance response requirements on safety systems. Nevertheless, not all reactor hazards scale with power output, so that the design must still address the well known nuclear safety design principle of Defence In Depth, satisfy the Single Failure Criterion, and provide adequate redundancy, independence, diversity, and physical separation for achieving the safety functions. Also, the special safety systems must be designed to be fail-safe to the extent possible. A long response time prior to required operator intervention is essential.

In general, the collective risk to society from the operation of a set of $\boldsymbol{n}$ identical, small power reactors, each delivering the same lifetime energy output $\boldsymbol{e}$, but to different populations $\boldsymbol{p_i}$, must be shown to be less than that from the operation of one large reactor of energy output $\boldsymbol{E = ne}$ to a population $\boldsymbol{P = \sum_i p_i}$ in similar circumstances.

(iii) **Licensability.** There is a strong need for an up-front "type" reactor licence from the nuclear regulator that separates the power supply technology from the specific site location and the intended application. The development of a global small reactor market would be fostered greatly by the establishment of streamlined reactor licensing requirements and uniform acceptance criteria based on international consensus, as revisiting the same issues in each local jurisdiction would not be cost effective.

Existing power reactor regulations in local jurisdictions have evolved in support of specific technologies as required, and may not be entirely applicable or appropriate for alternate technologies and small systems. For example, Canadian power reactor regulations were established for the distinctive CANDU pressurized heavy water reactor system and have prescriptive requirements for dual, independent safety shutdown systems that are completely separate from the regulating system. As such, these regulations are not directly applicable to existing LWR designs.

It is often stated that small reactors should achieve more stringent safety standards than larger units, such as a core melt frequency of $< 10^{-6}$ per year, since their benefit to society is less than that of large reactors.

(iv) **Cost Effectiveness.** Maximum use should be made of high-quality, mass-produced components for large power reactors, such as standard fuel assemblies that are widely available on a commercial basis, e.g., having Zircaloy-clad UO_2 rods with $< 5\%$ ^{235}U enrichment. The overall design should be as simple and as compact as possible to minimize radiation shielding mass and cost, as well as reactor containment and building size and cost.

On-site nuclear infrastructure costs must be minimized, including operating and maintenance staff. In particular, on-site activities and facilities associated with core refuelling, fuel handling and transport, and high-level radioactive waste management should be minimized and simplified; for example, through the use of long-life reactor cores (e.g., as in Rolls-Royce & Associates submarine reactors [1]), the accommodation of spent fuel within the RPV, or the transport of the entire reactor with its containment as a sealed unit to a qualified, central nuclear maintenance facility (e.g., for barge-mounted or marine propulsion systems).

(v) **Public, Investor and Political Acceptability.** Public perceptions of risk are such that the consequences of severe reactor accidents in large power reactors are not generally considered acceptable despite technical assurances that their probabilities of occurrence are very low. In contrast, with a large number of identical small reactors it may be possible to have acceptable consequences to otherwise severe accident events in individual units and lower total consequences despite a greater frequency of occurrence as a result of the large number of units. Improved acceptability may require convincing demonstration to average citizens that a self-evident improvement in safety practice relative to existing large reactors has been achieved.

Even when the safety risk of accidents is limited, the financial burden posed by events such as at Three Mile Island may carry unacceptable risk for investors. Financial exposure would be greatly reduced for utilities operating multiple small units.

Cross-border radioactive contamination associated with the Chernobyl reactor accident has left an indelible impression that nuclear safety is a transnational, global concern, despite its general implementation and regulation on a national basis. Consequently, local political acceptability of reactor technology would be encouraged if the technology were developed and implemented with multinational participation and broad application to a variety of environments (e.g., urban, remote, Arctic, tropical, desert, etc.).

(vi) **Reliability and Maintainability.** High reliability is essential in remote locations where skilled technical resources may be unavailable or very expensive and high availability is necessary to maximize the load factor for cost effectiveness. Accordingly, the design must be simple with a minimum number of auxiliary systems and critical components. Also, it should be tolerant of the failure of individual components, perhaps by the incorporation of factory-installed, redundant spares.

(vii) **Flexibility.** Potential applications for small nuclear reactor systems span a large range:

- electric power generation for small, isolated grid systems, or barge-mounted units,
- heat production for medium- and large-capacity water desalination systems,
- process steam generation for chemical plants and industrial applications, such as heavy oil recovery,
- residential district heating (e.g., low-temperature hot water district heating systems),
- combined systems (cogeneration) for electric power generation plus district heating or water desalination,
- propulsion of large, fast merchant ships, such as container ships and crude oil carriers, or icebreakers, and
- propulsion of small submarines and submersibles for oceanographic research, industrial support such as for off-shore oil drilling platforms, and cargo transport.

3. AUTONOMOUS REACTOR OPERATION

The technical feasibility of autonomous reactor operation has been demonstrated by the successful operation of Russian space satellites powered by small nuclear reactors for periods of up to one year. However, terrestrial power reactors operate in a cost-competitive, public environment and are subject to different regulations that have largely evolved in support of the commercial nuclear power industry with a focus on large generating stations.

From a technical safety perspective, the operation of small nuclear power reactors in a self-governing mode without the continuous attendance of highly skilled operators seems feasible for some reactor designs in well defined situations of limited duration.

Autonomous reactor operation does not mean that the reactor would not be supervised. The physical state of the reactor would be monitored continuously with transmission of essential data to a central station that would observe and record the behaviour of several units simultaneously. The monitoring station might be located at some distance from the actual plant and would be continuously staffed by trained personnel with ready access to the required expertise. Certain safety functions such as reactor shutdown would be possible to initiate remotely, but other actions like reactor restart would require the physical presence of a licensed operator at the reactor site.

A local representative would carry out any instructions received from the central monitoring station and could also serve as an initial contact point for local citizens, should a need arise. Simple, fail-safe means would be provided for the local representative to place the reactor in a safe shutdown state at any time. For example, the local representative would have access to a reactor trip button from outside the reactor room that disrupts electrical power to the control rods allowing them to drop into the core by gravity.

The time interval during which the reactor could be left in autonomous operation would depend on design details and operating needs. For example, periodic operator action would be needed to keep the primary cooling water chemistry from drifting beyond acceptable limits. If need be, a timer clock could be used to initiate reactor shutdown automatically if it is not reset by an operator at the required maintenance intervals.

At present, only a few very-low-power research reactors are licensed by nuclear regulatory authorities for unattended operation with remote monitoring and only for short durations. A good example is the unpressurized 20-kW_t SLOWPOKE-2 [2] research reactor which is licensed by the Atomic Energy Control Board (AECB) in Canada for operation at full power for up to 24 hours with no one in the reactor building and with the reactor room locked. The SLOWPOKE units are located in conventional buildings in high-density population, urban environments such as at the University of Toronto in downtown Toronto. Two TRIGA research reactors have similarly been licensed in other countries for unattended operation [3].

Extending the regime of autonomous reactor operation to higher power levels and to longer operating periods is a significant technical challenge, yet progress to this end seems achievable. For example, an important goal in the plans to develop the 10-MW_t SES-10 (SLOWPOKE Energy System) [4] dedicated heating reactor was to demonstrate the capability to operate for extended periods without an operator in the reactor room, but remotely monitored at all times.

Additionally, several, much-larger advanced light water reactor (LWR) designs, such as the 1000-MW_t Safe Integral Reactor (SIR) [5], claim that no operator action would be required for up to 72 hours following any design basis accident event. Also, the reactors on nuclear submarines routinely operate for patrol periods of about 70 days without outside assistance.

Of course, autonomous operation for extended periods would require that any essential functions normally provided by technical staff, such as instrument calibration or testing the availability of safety systems, would either have to be performed automatically by remote means or not be required for the duration of autonomous operation. Thus, cost savings from reducing staff requirements may be offset to some degree by the need for additional monitoring instrumentation.

Conceptually, the nuclear safety risk presented by a 10-MW_t pressurized water reactor may not be much different from that presented by a 10-MW_t unpressurized pool-type reactor, provided adequate cooling provisions are available to absorb the additional stored thermal energy in the former system when required. However, for pressurized systems, additional regulatory issues arise as a result of existing regulations for the autonomous operation of non-nuclear steam heating plants.

For example, the Power Engineer's Act [6] for the Province of Manitoba in Canada, although it does not apply to nuclear plants licensed by the AECB, allows for the operation of certain steam plants without constant supervision for periods not exceeding 72 hours with written authorization from the provincial Minister of Labour. However, such operation is permitted only for small systems up to a power level of 500 kW_t and a pressure of up to 1030 kPa, provided the boiler is installed in an unoccupied building, is equipped with a full set of safety controls and an approved visual readout system, and the plant and each safety device are tested by a power engineer of the class required.

Additional regulatory considerations and possible design limitations would arise from Non Proliferation Treaty (NPT) related safeguards requirements for significant quantities of fissionable materials and physical security requirements to restrict entry to controlled areas to authorized personnel and maintain adequate surveillance.

Implementation of autonomous operation of a specific reactor system would likely proceed gradually, following a prolonged period of supervised operation to demonstrate appropriate safety behaviour.

4. THE NUCLEAR SAFETY ENVELOPE

Reactor operation involves a continuum of operating states that can be grouped into several bands as shown in Figure 1. The lowest region corresponds to the safe shutdown state. It is followed by a transition zone in which the major plant physical variables, such as temperature and pressure, change during reactor start-up. The next state represents normal power operation. The passage from the shutdown state to normal power operation requires the presence of a qualified reactor operator, but the reverse transition can be performed locally or remotely by deliberate intervention or automatically through actuation of safety trip systems.

Above the normal power operation state is a band representing abnormal operation. The transition to this state could result from the drift of a physical variable, a component failure, or some internal or external initiating event. Operation in the abnormal state does not imply an immediate safety hazard, but it indicates a potential threat to one of the three fundamental reactor safety functions (control, cooling and containment) should further degradation occur. Consequently, alarm notification would occur locally and at the remote monitoring station. Failure to restore normal operation within a specified time period would initiate automatic reactor shutdown.

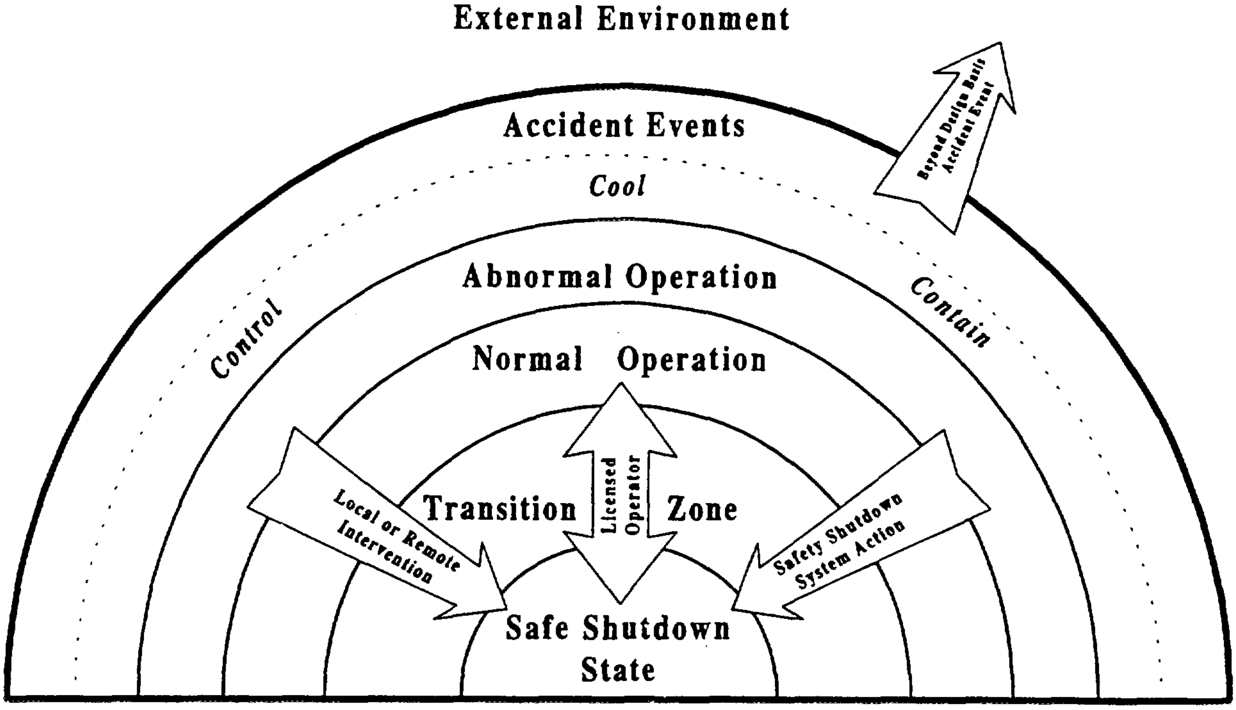

Figure 1. Nuclear Safety Envelope for Autonomous Reactor Operation

The next band corresponds to accidents that directly impact the three safety functions and are not arrested or mitigated by the built-in safety systems, such as reactor trip. Proper application of Defence In Depth may still prevent releases to the environment. However, a trained nuclear accident response team would be dispatched from the central monitoring station.

The upper, open-ended band represents low-probability severe reactor accidents with consequences beyond the facility boundary. It is not expected that any off-site evacuation of the public would be needed under any circumstances for small power reactors, however, minor releases of radioactivity within the specified regulatory limits may occur. The accident response team would secure the site, restore a safe, contained shutdown state, and perform any required cleanup.

Autonomous reactor operation requires that the reactor is in the normal operating state and that the transition to an accident which may lead to a potential release to the environment is sufficiently long for the response team to arrive and take appropriate action. In essence, the presence or absence of staff at the site should have no bearing on the progression of any foreseeable event for an extended period exceeding the authorized period of autonomous operation.

5. REACTOR SAFETY FUNCTIONS

A robust safety envelope requires appropriate attention to the design of the three fundamental safety functions, such that firm limits are imposed on the possible consequences of a wide range of accident events.

5.1 REACTOR CONTROL

Autonomous reactor operation requires intrinsic self-regulation of reactor power. This behaviour can be obtained by negative reactivity feedback such as that provided promptly by Doppler broadening of neutron absorption resonances in ^{238}U resulting from increased fuel temperature, and quickly by effects associated with coolant temperature increases and density decreases (i.e., negative void coefficient), and fuel thermal expansion. However, adequate safety consideration would also have to be given to possible reactivity insertion transients initiated by overcooling events.

In certain exceptional cases, such as for UZrH-type fuel used in TRIGA reactors, intrinsic protection can also be provided against large, rapid reactivity insertion transients, as might occur during control rod withdrawal at cold reactor start-up. In most cases, however, such protection can only be achieved by placing a conservative upper bound on the maximum excess reactivity that could be made available at any given instant. For example, for the SLOWPOKE-2 research reactor, the maximum credible excess reactivity is only about 3.9 mk [2], so that the worst-case reactivity insertion transient that could occur under any circumstance is well below prompt critical (about 8.0 mk for SLOWPOKE-2) and is limited to a value that can be demonstrated to produce acceptable transient behaviour.

For reactors that normally operate at higher power levels, burnable neutron poisons are an appropriate means to help provide the reactivity needed to compensate for long-term fuel depletion. Burnable poisons are an effective way to limit the amount of reactivity that needs to be supplied by movable control devices, provided the poisons are retained in the core with the fuel under all reactor conditions.

However, power reactors require significant amounts of reactivity (i.e., well above the amount needed to go prompt critical if added suddenly) that must be provided by movable control absorber devices (or removable poison dissolved in the primary coolant) under the direction of a licensed operator and following approved procedures during reactor start-up and the transition to equilibrium full-power operation. This positive reactivity is needed to compensate for losses associated with increased core temperature, reduced coolant density including bubble void formation, and equilibrium fission product poison loads, especially ^{135}Xe. Consequently, it is only possible to limit the amount of reactivity that could theoretically be inserted to small, intrinsically safe values when the reactor is already in the normal full-power operating mode with all movable control devices very near their maximum withdrawal positions (and when the dissolved poison concentration is close to zero).

During the specified autonomous operation interval, the control absorber devices could be kept at their maximum withdrawn positions (but available to drop into the core on safety system command). Operation in this manner would ensure that the maximum possible reactivity insertion rate would be limited by the maximum rate at which changes could be made to the physical state of the core, especially coolant temperature and density. Provided such changes are limited in magnitude and can only be introduced relatively slowly, it may be possible to demonstrate that the self-regulating characteristics of the reactor will ensure that any transient overpower is limited to acceptable values and that the stable end-state that is established does not exceed safety limits (e.g., RPV design pressure).

If, for example, the secondary system load demand is also constant during this interval, the primary coolant temperature and pressure would vary only gradually in response to the depletion of fuel (and burnable poison). The only noticeable effect would then be a correspondingly small change of performance output, such as modified energy conversion efficiency. Consequently, near-base-load thermal power reactor operation would support nuclear safety in this circumstance, whereas significant load-following operation could introduce larger perturbations through associated coolant temperature and xenon transient effects that might induce a reactor trip, without control rod movement.

A qualified reactor operator would make small adjustments to the control absorber mechanical stop positions on a routine, periodic basis, but without physical access to the control rods, similar to the procedures presently used with submarine reactors. Care in the mechanical and electrical design of control rods and their drive mechanisms is essential to ensure fail-safe operation and to prevent inadvertent rod withdrawal events and the development of possible rod ejection forces from pressure gradients under any circumstances.

A safety shutdown system would be provided to insert negative reactivity rapidly by dropping the control rods into the core (Note: in the Canadian regulatory environment, dropping the control rods might not be credited as a safety system action since the rods are not physically separate from the control system and are, therefore, used for two purposes). This system would be triggered by abnormal signals for several core parameters, but particularly including neutron flux values and their rate of change. An additional independent shutdown system involving poison (boron) injection would likely be provided, but might be initiated manually.

Safety analysis would need to address the potential for reactivity insertion transients initiated by overcooling events, such as steam outlet header rupture and inadvertent primary pump start-up. Systems relying completely on natural circulation cooling have intrinsic protection against the latter accident event.

5.2 CORE COOLING

The provision of adequate cooling of the reactor core for an extended period of autonomous operation imposes additional safety design requirements to ensure that the core always stays covered by coolant. Thus, a sufficiently large inventory of coolant must be available to absorb the heat generated by the fuel and a means provided to deliver it to the core during postulated accident events that disrupt the normal heat transport pathways.

Design features that enhance the ability to cool the core include:

- a low power density to provide a large fuel heat transfer surface area and a large temperature margin to fuel failure,
- a large primary coolant inventory to provide a slow response to transients,
- relatively low primary system operating temperature and pressure to provide large safety margins, reduced stored thermal energy and slower response to Loss Of Coolant Accident (LOCA) events,
- a thermalhydraulic arrangement that facilitates natural coolant circulation while avoiding the potential formation of vapour-lock flow barriers,
- a passive decay heat removal system, particularly one that does not require active initiation, and
- limitation of LOCA events by using only small diameter piping penetrations on the RPV and locating them well above the top of the reactor core.

5.3 FISSION PRODUCT CONTAINMENT

Defence in depth requires the provision of multiple barriers to the release of hazardous fission by-products from the fuel. In general, these barriers include the fuel matrix itself (UO_2), the fuel cladding, the primary heat transport circuit boundary and a surrounding containment structure. Autonomous reactor operation for a specified time interval requires that all containment barriers are initially intact and that no events are foreseen that could compromise barrier integrity within this duration.

Concerning the fuel cladding containment barrier, special mention must be made of the high-temperature ceramic cladding used with TRISO coated-particle fuel that provides excellent containment behaviour in high temperature gas cooled reactors, even though fuel based on this principle is not presently applicable to PWRs. A similar subdivision of the fuel cladding containment is found in the CARAMEL-type [7] fuel plates used in certain French research reactors.

The primary cooling circuit in a PWR is a high-integrity, pressure-resistant system that will contain any fission products released from the fuel in an accident until the internal pressure exceeds the values that would actuate the pressure relief devices. A simple, compact primary system will be easier to qualify and inspect and to protect from seismic events and external hazards. The RPV penetrations should be as few as possible and of small diameter. All primary system openings would be kept sealed for the duration of autonomous operation.

A small power reactor would have a separate containment structure acting as an additional, leak-tight barrier to the release of fission products to the environment and capable of withstanding the excess pressure that would develop during a design-basis LOCA event in the primary system.

6. THE INTEGRAL PRESSURIZED WATER REACTOR (IPWR)

6.1 THE INTEGRAL REACTOR DESIGN PRINCIPLE

In an ***integral*** or "unitized" reactor configuration, all the primary coolant is kept in the same vessel as the reactor core and the primary-to-secondary heat exchanger or steam generator is immersed in the primary coolant. The discussion of integral reactors in this paper is limited to reactors with primary cooling systems that are sealed in a reactor pressure vessel (RPV), that operate at a pressure significantly above one atmosphere and that use light water as coolant.

A wide range of IPWR core concepts have been studied based on technology from both large PWRs, which typically operate with the primary system pressure at 15-16 MPa with no bulk boiling in the core, and large Boiling Water Reactors (BWRs), which usually operate at a lower pressure of 7 MPa with substantial boiling. Some of the main technological differences arise in the fuel assemblies, which are enclosed in flow boxes in BWRs and use an open-lattice arrangement in PWRs, and the control absorbers, which typically use cruciform control blades in BWRs and rod clusters in PWRs.

Many IPWR designs are neither pure PWRs or pure BWRs, but combine features of both systems as discussed in reference 8 for the specific case of the KWU-NHR 200-MW_t district heating reactor. However, BWR-based designs that use bulk boiling are sensitive to coolant density fluctuations and are generally considered unsuitable for mobile applications, such as marine propulsion. A listing of many of the proposed IPWR designs and their intended applications is provided in Table 1 and discussed briefly in Section 7.

6.2 ORIGIN OF THE IPWR CONCEPT

The IPWR concept is an outgrowth of widespread interest in commercial nuclear ship propulsion in the late 1950s and early 1960s. Economic evaluations of commercial marine propulsion reactor designs based on several distinctly different reactor concepts (e.g., loop-type PWR, gas-cooled, organic-cooled, etc.) concluded that none were competitive at that time with conventional fossil-fuelled propulsion systems, at least in sizes up to 20-30,000 shp (shaft horsepower).

The search for a plant design with reduced capital cost naturally led to a simplification of reactor design by merging the heat exchanger and RPV components to minimize the amount and complexity of the interconnecting piping and thereby achieve a more compact, lighter system. These considerations gave rise to the 60-MW_t Vulcain reactor concept, which originated at BelgoNucléaire in Belgium in 1959 and grew into a joint Anglo-Belgian research program with the participation of the UKAEA (United Kingdom Atomic Energy Authority).

Concerning the choice of design basis for Vulcain, reference 9 notes:

> "... the integral concept, in which the major components of the primary circuit are incorporated in the reactor vessel, was regarded as essential for significant improvement in terms of weight and cost."

In the United States meanwhile, the Babcock & Wilcox Company (B&W) began looking at an integral reactor concept called the Integral Boiler Reactor, also in 1959 [10]. These studies evolved into an integral reactor design concept in 1962 known as CNSG-I (Consolidated Nuclear Steam Generator) based on evaluations of cost, weight and size of the various alternatives. The CNSG-I design formed the basis for the FDR reactor [11] for the German NS Otto Hahn merchant nuclear ship project which was built by a B&W-Interatom consortium between 1964 and 1968.

6.3 GENERIC IPWR DESCRIPTION

In the ideal IPWR system, all the primary reactor cooling system components including the pumps (if required) and pressurizer are incorporated within the single primary reactor pressure vessel. A simplified drawing of a generic low-power IPWR concept that uses natural circulation without any primary pumps is shown in Figure 2.

The natural-circulation IPWR design shown in Figure 2 is similar in its basic operation to small, pool-type natural-circulation reactors, like SES-10. The main difference is the higher operating temperature and pressure of the IPWR and its enclosure within an RPV and a pressure-retaining containment vessel as a result.

Reactor Core

The reactor core of an IPWR generally uses proven technology from loop-type PWRs or BWRs to minimize cost. Typically, the fuel assemblies are square arrays of Zircaloy-4-clad, enriched UO_2 (< 5% ^{235}U) fuel rods with some burnable poison rod (Gd_2O_3) positions.

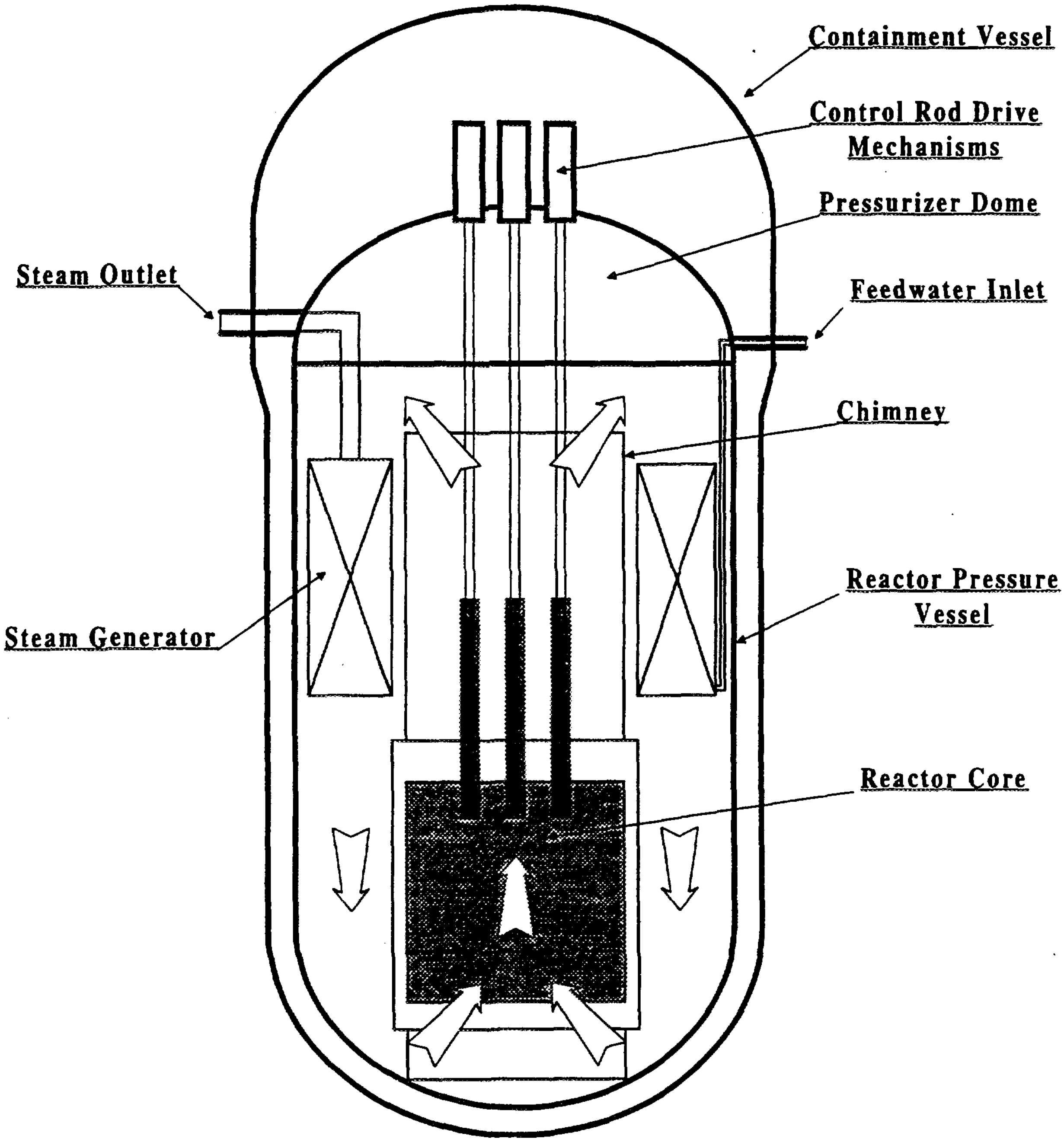

Figure 2. Natural Circulation IPWR

Control absorber rods or blades are associated with the fuel assemblies and their drive mechanisms are located on the RPV top closure head. Safety shutdown is achieved by control rod drop. A boric acid injection system is usually provided as an additional shutdown system for use in emergency situations.

Thermalhydraulic Arrangement

In a typical IPWR, light water coolant enters the base of the core, is heated as it passes upward over the fuel and continues upward through a chimney that provides flow separation from the downcomer region. Self-pressurization is achieved by providing a vapour space at the top of the vessel, such that the vapour phase is in equilibrium with the liquid phase at the core mean outlet temperature. An overpressure of inert gas may be added.

Primary coolant circulation pumps (if needed) are often located on the top RPV closure head for easy access. Primary coolant passes downward over the steam generators in the space between the chimney and the RPV wall and returns to the core inlet. Overall, the thermalhydraulic arrangement enhances natural circulation of the primary coolant.

The primary coolant circulation pumps are typically internal, canned axial pumps, of the glandless, vertical mixed-flow type. Some alternate IPWR arrangements have the pumps located on nozzles or "stems" attached to the lower portion of the RPV, as in the NS Otto Hahn design, and often in the cold leg of the primary circuit.

Two types of steam generators have been used with IPWR designs, both based on once-through designs with the secondary fluid generally on the tube side. The first type, is a helical-wound, cross-parallel-flow, Benson-type steam generator, usually divided into two or more independent sections and wound into a common packet. The second type uses multiple, vertical, straight-tube modules arranged in a circle inside the downcomer annulus.

For applications involving electricity generation, the steam generators deliver superheated steam to the turbines, eliminating the need for steam drums, driers and steam separator equipment. Since the secondary pressure is less than the primary pressure, the steam generator tubes will operate under compression, which provides added resistance to stress-induced corrosion cracking.

Control System

The control scheme for an IPWR is based on maintaining the primary pressure constant and independent of the load in a load-following mode as introduced through the steam generator. The steam generator has a very low heat capacity compared to the entire primary circuit, so that the primary pressure can be kept constant by the control system over the whole load range.

Containment

Although the RPV for an IPWR is larger than that for a loop-type PWR of the same power output, the surrounding containment structure and the reactor building that encloses it are smaller for the IPWR. Indeed, a characteristic feature of many IPWR designs is the use of "dual" pressure vessels as shown in Figure 2, where the containment vessel is close fitting and follows the contours of the RPV, providing clear evidence of Defence In Depth.

A low-volume containment structure that is closely fitted to the lower portion of the RPV ensures that the core will not become uncovered during a LOCA event.

In some larger IPWR designs, the containment vessel may consist of a prestressed reinforced concrete vessel with a steel liner, which eliminates the need to perform difficult welds on thick steel shells. The containment systems for large IPWRs usually include a pressure-suppression system consisting of an arrangement of condensation chambers that are partially filled with water. The advantage of a wet containment system is that the pressure increase will be lower, leading to a lower design pressure and/or smaller containment dimensions.

In certain cases, the IPWR reactor containment vessel is itself immersed in a large pool of low-temperature water that serves several functions in a simple, passive manner:

- provision of biological shielding, especially for fuel handling and storage,
- provision of an ultimate heat sink for decay heat removal from the primary circuit by natural circulation,
- pressure suppression of releases from low-probability severe accidents, and
- scrubbing/filtering of released fission products except for noble gases.

The main factor determining the required response time for operator intervention is the thermal capacity of the ultimate heat sink, i.e., the volumetric water inventory of the pool.

Reactor Auxiliary Systems

The reactor auxiliary systems are similar to those found on other PWRs and typically include: a primary water volume control and inventory system, a primary water purification system, radioactive liquid and gaseous effluent treatment systems, and a ventilation system. At low power levels, many of these systems may be required only on an intermittent basis and would be valved out during periods of autonomous operation.

6.4 IPWR ADVANTAGES

Partly as a consequence of its origins in the competitive civilian marine propulsion sphere, the IPWR design strives for simplicity, cost-effectiveness, maintainability and self-sufficiency in a compact, lightweight and rugged package. Notably, the search for economy in the IPWR design supports enhanced safety (e.g., natural circulation).

The use of self-pressurization based on nuclear heating is desirable to avoid the expense of an auxiliary electric power system, pressure control equipment and the potential for an accident event involving a break of the piping between an external pressurizer and the RPV. Also, the volume inside the RPV serving as an internal pressurizer for an IPWR tends to be larger than that for an external pressurizer with a loop-type PWR and, thus, provides a slower pressure response to transients. Moreover, the integral configuration is more comprehensible to the operator because the water level in the pressurizer always corresponds directly to the amount of water above the core.

The IPWR is amenable to shortened construction schedules because the RPV and internal components can be shop-fabricated, pre-assembled and tested under optimum conditions. In particular, the IPWR configuration eliminates the need for difficult on-site welding work on the primary system. This feature leads to improved quality assurance and reduced construction costs.

The simple, compact arrangement of the IPWR makes it easier to shield efficiently; less shielding is required as a result of the elimination of gamma sources within the primary piping and separate components of the reactor cooling system. Also, the fast neutron dose to the RPV is extremely low because there is a large water gap between the reactor core and the vessel wall. Consequently, radiation embrittlement of the RPV can be ignored. For the same reason, the RPV will present a reduced radiation hazard at reactor decommissioning.

The IPWR configuration is much easier to protect against seismic events on land or against mechanical shock loads in a marine propulsion application. Also, since the RPV has few protrusions and requires no major on-site welding work, it is well suited to siting below ground level. In turn, a low building profile would permit more aesthetic structures and ease licensing concerns for environmentally sensitive areas. Moreover, RPV location below ground provides protection against external hazards.

6.5 IPWR SAFETY ATTRIBUTES

Intrinsic LOCA Resistance

The most significant safety advantage of the integral reactor arrangement is its lack of large primary coolant pipes. The only possible primary piping connections are for coolant makeup, letdown, purification or pressure relief. Even for large IPWR designs these connections would be less than about 8 cm in inside diameter, so that the worst pipe break would produce a relatively slow depressurization. This allows more time to detect the accident and initiate the safety system response.

In addition, primary piping connections for IPWR designs are generally made as high as possible on the RPV, through the top closure head or just below the flange joint on the lower portion of the RPV, so that the core remains covered for as long as possible.

Large Primary Coolant Inventory

The IPWR has a large inventory of primary coolant that is contained entirely within the RPV and, thus, is immediately accessible to the core fuel. A large coolant inventory provides a large heat sink and a correspondingly long response time during accident events to initiate protective measures.

The large primary inventory mitigates the effects of a LOCA event by keeping the core cooled and covered during a blowdown without the activation of a safety system. In a similar manner, the large inventory also serves as a thermal energy storage or absorption medium during a loss of heat sink event, such as a sudden feedwater pipe break.

An additional advantage of a large primary coolant inventory coupled with a smaller secondary coolant inventory is that the magnitude of a cold water reactivity insertion event on primary pump start-up is greatly diminished.

Enhanced Natural Circulation and Passive Shutdown Cooling

The vertical arrangement of the steam generator above the core level permits natural circulation of the coolant through the core and a primary circuit thermalhydraulic design with low flow resistance. Also, any nucleate boiling in the core creates a pronounced buoyancy-induced enhancement of this natural convection flow. Consequently, reactor shutdown decay heat can be passively removed from the core through the steam generators entirely by natural circulation.

In addition, the IPWR configuration eliminates the multiplicity of high points that exist in some loop-type PWR piping arrangements where vapour can collect and potentially block a natural-circulation flow path.

Self-Regulation

Like other LWRs, the IPWR core arrangement has negative reactivity coefficients (i.e., coolant temperature, coolant void and fuel temperature) that promote stable power output.

However, because the IPWR operates with the coolant in the core close to the saturation temperature, a small amount of transient local overheating quickly produces a significant amount of void generation (nucleate boiling) in the core which immediately induces a large negative reactivity response. This feature reduces the core power rapidly in a loss-of-heat-sink event.

Response to Steam Generator Tube and Steam Line Rupture

Since the steam generators in an integral reactor are located inside the RPV and can be isolated individually (if there are more than one in the design), there is no need to reduce the primary system pressure in the event of a steam generator tube rupture, unlike the situation in current large loop-type PWRs.

Steam line breaks are generally not serious accidents since the small amount of secondary water boils off rapidly. The resulting reactivity transient induced by the temporarily enhanced cooling is minor because the primary coolant inventory is large.

In some IPWR designs for district heating applications, the pressure is maintained at a slightly higher value in the secondary circuit than in the primary circuit so that a breach of the heat exchanger tube would not create an immediate leakage of the primary fluid.

7. SURVEY OF IPWR DESIGNS

A partial listing of many of the IPWR designs and concepts that have been considered in various countries over the past 36 years is provided in Table 1 as compiled from numerous information sources.

The entries in Table 1 are arranged alphabetically according to country of origin and in ascending order according to thermal power output within each country group. In this table "multipurpose" refers to designs that have been considered for electricity generation, district heating and water desalination. For these cases, the entry listed in the "output" column usually provides typical data for hybrid applications, such as electricity (MW_e) plus district heating (MW_t) or water desalination (m^3/d).

Although Table 1 may be incomplete or contain some out-of-date information, certain observations are apparent:

(i) The IPWR concept has enjoyed a widespread level of technical interest in many countries over a long period of time. In recent years, this interest is particularly strong in Russia.

(ii) The range of applications considered is extremely broad and includes marine propulsion (particularly France and Japan, in recent years), district heating (especially China), and cogeneration or multipurpose use (Russia).

Table 1. Listing of IPWR Designs and Concepts

Country	Designation	Application	Thermal Power (MW_t)	Output	Status/Comment	Reference
Argentina	CAREM	multipurpose	-	15-150 MW_e	concept	12
Belgium/UK	Vulcain	marine propulsion	60	-	early concept	9
China	NHR-5	district heating prototype	5	-	operating, Beijing	13
	NHR-200	district heating	200	-	design being licensed	14
France	SCORE	marine propulsion, electricity	10	<2 MW_e	concept	15, 16
	CAS-48	marine propulsion:Rubis/Amethyste	48	-	~6 units operating	17
	THERMOS	district heating	100	-	concept	18
	CAP-70	electricity	-	70 MW_e	concept	19
Germany	FDR	marine propulsion: NS Otto Hahn	38	460 kW_e + 11000 shp	decommissioned	11
	IPWR-38	multipurpose	38	6.7 MW_e + 10000 m^3/d	concept	20
	IPWR-138	multipurpose	138	19.5 MW_e + 40000 m^3/d	concept	20
	KWU-NHR	district heating	200	-	concept	8
	IPWR-220	multipurpose	220	38.5 MW_e + 60000 m^3/d	concept	20
	EFDR	electricity	275	100 MW_e	concept	11
Japan	DRX	marine propulsion	0.75	150 kW_e	concept	21
	MRX	marine propulsion	100	-	concept	22
	ISER	electricity	645	210 MW_e	concept	23
	SPWR	electricity	1100-1800	350-600 MW_e	concept	23, 24
Russia/CIS	GAMMA	electricity, prototype	0.22	6.6 kW_e	operating, Moscow	25
	ELENA	district heating, electricity	3	70 kW_e	concept	25
	ABV-1.5	cogeneration	12	1.2 MW_e + 5 MW_t	concept	26
	AST-30B	district heating	30	-	concept	27
	ABV-6	multipurpose	48	12 MW_e / 6 MW_e + 14 MW_t	concept	27
	ABV	multipurpose	60	9 MW_e + 14000 m^3/d	concept	28
	ATETS-80	multipurpose	250	80 MW_e	concept	28
	AST-500M	district heating	500	-	concept	29
	ATETS-150	multipurpose	536	150 MW_e + 70000 m^3/d	concept	30
	ATETS-200	multipurpose	690	200 MW_e + 60000 m^3/d	concept	28
	B500 SKDI	electricity	1350	515 MW_e	supercritical pressure concept	31
	CHPP	cogeneration	1650	500 MW_e + 522 MW_t	concept	32
	VPBER-600	electricity	1800	630 MW_e	concept	28
Switzerland	SHR	district heating	10	-	concept	33
UK/US	SIR	electricity	1000	320 MW_e	concept	5
US	NCIR	electricity	-	10 MW_e	concept	34
	CNSG-IVa	marine propulsion	314	120000 shp	concept	10, 35
	CNSS	electricity	1200	400 MW_e	concept	36

(iii) The thermal power outputs considered in the various IPWR designs span a broad range from 0.22 to 1800 MW_t. Of the 36 reactor concepts listed, about 50% belong to a low-power category ≤ 100 MW_t, including seven very-low-power designs and concepts that are ≤ 12 MW_t.

(iv) Despite the large number of IPWR designs and concepts listed, very few have been actually constructed. The exceptions are very-low-power experimental prototype units in China and Russia (≤ 5 MW_t) and marine propulsion systems of intermediate power levels (< 50 MW_t) in France and Germany.

The very low power range ≤ 12 MW_t includes NHR-5, SCORE, DRX, GAMMA, ELENA, ABV-1.5 and SHR. All of these small IPWR designs use natural circulation of the primary coolant without pumps and incorporate passive safety features such that some degree of limited autonomous reactor operation may be achievable.

8. CONCLUSION

Small power reactors may offer attractive solutions to a wide range of energy needs provided overall costs are competitive with alternate power sources. Operation of small power reactors with limited on-site nuclear infrastructure and operating staff would reduce generating costs, if the necessary technical resources and support can be obtained from centralized sources when needed and if the cost of this external support is distributed over a large number of identical field application units. Such operation requires a small reactor design incorporating a high degree of safety autonomy, so that there is a long transition time to any state requiring operator intervention, and continuous remote supervision.

Among the existing power reactor designs capable of producing electricity and steam, the IPWR appears well suited to a wide range of applications at low power levels. Although it has been widely studied, the present implementation of IPWR designs is mainly for low-power prototypes and marine propulsion systems. At very low power levels (≤ 10 MW_t), IPWR systems using natural circulation of the primary coolant appear to be technically capable of achieving safe, autonomous operation for limited periods. However, regulatory issues arise concerning the supervision of pressurized systems of any type. Widespread use of small IPWRs with limited on-site supervision would benefit from the establishment of streamlined reactor licensing requirements and acceptance criteria based on international consensus, as well as prior experience with similar modes of operation with unpressurized pool-type reactor systems of comparable capacity. This paper reflects the personal opinions of the authors.

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