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SMALL REACTOR OPERATING MODE

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Abstract

There is a potential need for small reactors in the future for applications such as district heating, electricity production at remote sites, and desalination. Nuclear power can provide these at low cost and with insignificant pollution. The economies required by the small scale application, and/or the remote location, require a review of the size and location of the operating staff. Current concepts range all the way from reactors which are fully automatic, and need no local attention for days or weeks, to those with reduced local staff. In general the less dependent a reactor is on local human intervention, the greater its dependence on intrinsic safety features such as passive decay heat removal, low-stored energy and limited reactivity speed and depth in the control systems. A case study of the design and licensing of the SLOWPOKE Energy System heating reactor is presented.

1. CLIENT REQUIREMENTS

Small commercial reactors must satisfy three very different "clients". The most obvious client is the customer who uses the product–he demands safety, reliability, and acceptable costs. These demands become technical requirements on the design. The second client group is the general public, who must balance the real benefits of the facility with their perception of the risk. Often the function provided by a small reactor can also be provided by a competitive technology, such as natural gas for space heating or oil for desalination. The advantage provided by a nuclear source must be significantly greater than the competitive technology if the reactor is small: whereas people accept electrical power reactors because of their large economic benefit, they will not do so for small commercial applications unless they are unique, or have large advantages over the competition, or are transparently safe. The third client is the regulator, who demands licensability based on national experience with which he is familiar, and an assurance that he will not be faced with contamination of a populated area as a result of an accident. All three client requirements must be met.

2. DESIGN REQUIREMENTS RELATED TO OPERATING MODE [1],[2]

Operation of a reactor requires allocation of certain responsibilities, functions and duties. In principle these are the same as for a power reactor. However the design of a small reactor may allow a different allocation, while maintaining the essential requirements of public safety, plant reliability and low cost. For example, the design may reduce the need for prompt local response, and allow operating duties either to be centralized away from the reactor, or dispensed with entirely. The latter case requires confident demonstration of inherent safety. In general, the greater the inherently-safe characteristics of the design, the easier it is to reallocate the operating responsibilities, functions and duties.

One should start by assuming that **all** of the operating responsibilities, functions and duties of a power reactor apply to a small commercial reactor. One should then assess each one in turn, asking whether it can or should be allocated to the local staff, remote staff, or handled by the machine itself due to its inherent characteristics. In other words, one does not start from a reduced staff; one derives it from the machine characteristics, siting and usage.

We now list some safety-related characteristics for small reactors which normally are present to facilitate reduced staffing. Not all are relevant to any one application; not all must be satisfied to allow reduced staffing; and each must be considered in detail for any actual case.

1. The power, and hence the fission product inventory, are generally low.
2 There is highly restricted access to, and infrequent changes to, the core. The control devices for load-following are slow-moving and stability is aided by negative reactivity coefficients.
3. All the reactor safety systems are automatic or self-actuating. Effects of failures in the safety systems are mitigated by inherent properties or self-actuating processes. Automatic initiation of a safety system cannot be easily disabled by an operator. Safety devices are testable on power, without risk of a spurious shutdown. All critical components of a safety system are fail-safe or have independent back-up. Two independent and diverse shutdown systems are provided unless automatic shutdown can be guaranteed by inherent physical or chemical properties.
4. The mechanism for removal of decay heat has the same reliability and effectiveness as an automatic safety system for a long period after shutdown. Passive decay heat removal is the usual approach.
5. The stored energy in the coolant is low. A sudden loss of coolant is prevented, usually by double barriers. Following a small loss of coolant, there is no need for an external supply of water, nor for human intervention, for a long period of time.
6. The plant can withstand (without the need for prompt intervention) credible external events typical of the environment, such as severe natural phenomena, industrial accidents in nearby facilities, and the consequential effects of natural and man-made disasters on nearby facilities. Fires within the facility either are made impossible, or cannot affect the nuclear safety, or can be handled by fire-fighting staff in nearby settlements. There are generous time allowances built into the design for such staff to arrive and be effective.
7. The primary cooling system provides significant retention of fission products released from the fuel.
8. Storage of used fuel is on site, usually in the reactor pool or vessel, so that shipments of used fuel are infrequent or absent.
9. The confinement prevents release of radioactive gases which escape from the primary cooling system in both normal operation and an accident. In general accidents do not pressurize the confinement.

These characteristics enable the plant to operate with less need for routine operator intervention or presence. It is clear from this list that the safety of such small reactors relies much more on inherent design characteristics, and (to a lesser extent) on shutdown systems, than on engineered heat removal or prompt human intervention.

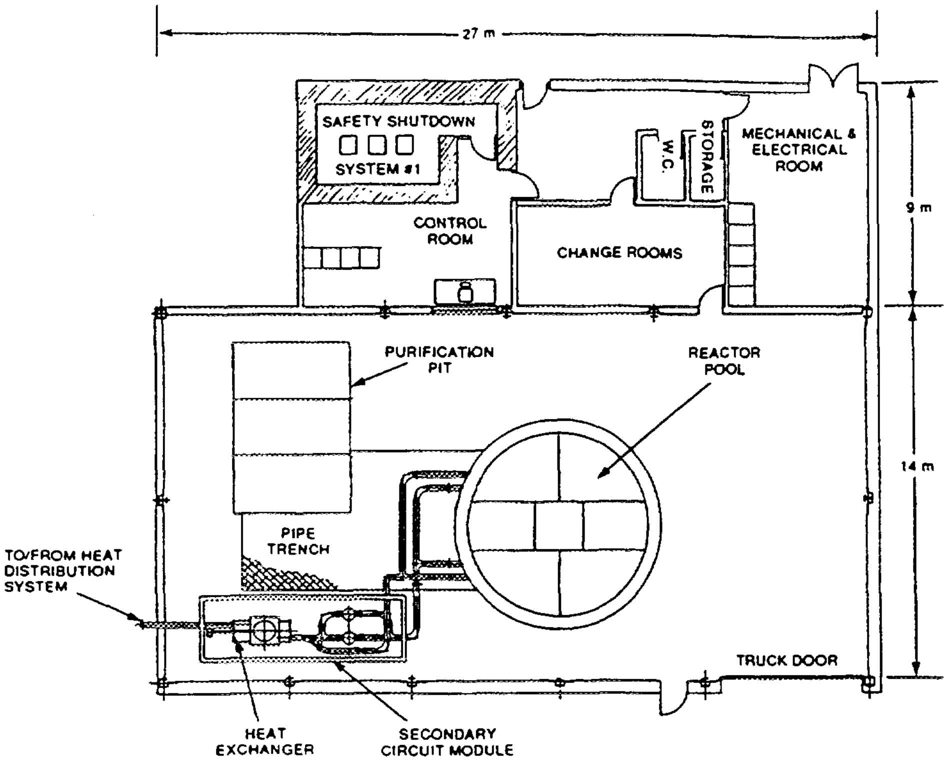
It is the emphasis on accident prevention through inherent characteristics which permits both urban siting and remotely-monitored operation. They are not new concepts by themselves–both have been accepted for a number of years in Canada for the 20 kW SLOWPOKE-2 research reactors, on the basis of an inherent design characteristic: because of the limited amount of reactivity available to the control system, and the negative temperature coefficients of reactivity, they do not need *any* engineered shutdown system, and can *therefore* be left unattended for periods of up to 24 hours. The SLOWPOKE Energy Systems 10 MW heating reactor retains many passive safety characteristics–for example, decay heat removal is passive–but because it operates at higher power, it requires an engineered shutdown mechanism and in fact is provided with two separate, independent, and diverse shutdown systems, to eliminate the potential of failure to shutdown for an abnormal event. This redundancy reflects a philosophy pioneered by CANDU nuclear generating stations.

3. SMALL HEATING REACTOR DESIGN EXAMPLE [2]

To illustrate how the small reactor safety principles discussed in Section 2 are incorporated in a design concept, the Canadian SES-10 heating reactor will be used as an example. The main protection against a major release of radioactivity from the 10 MW core is the fuel itself. By restricting the maximum fuel temperature in normal operation and in accidents, most of the fission products are retained within the uranium oxide pellets, and only a small fraction of the fission product gases escape to the narrow gap between the ceramic pellets and the metal sheath. If the sheath should fail, iodine would remain in the large volume of pool water and a small quantity of radioactive xenon and krypton could escape to the cover gas above the pool surface where it would be retained by the confinement barrier. The ultimate release to the environment from a single sheath failure would be well within regulatory limits for normal operation.

Other important safety features of the SES-10 concept (Figure 1) are listed below:

- A pool type reactor avoids the need for a nuclear pressure vessel and high pressure piping system.
- Operation below 100C and near atmospheric pressure avoids a large source of stored energy and loss of coolant by depressurization.
- Natural circulation of primary coolant in the pool avoids a loss-of-primary flow accident.
- Double containment of the pool in a steel vessel and concrete vault prevents loss of coolant by leakage. An air gap between the two containers permits both detection and control of leakage.
- Slow-moving control devices permit slow-response safety systems.
- The negative reactivity effects of coolant density and fuel temperature attenuate the power transient following control system faults.
- The large heat capacity of the pool delays the core temperature rise following loss-of-secondary coolant flow.
- The top surface of the pool is not open to the reactor building as in many pool-type reactors, but is enclosed with a steel cover plate and concrete shield. The vapour space between the pool surface and the cover plate is used to monitor and control gases released from the pool. The cover gas is confined by expandable gas bags to compensate for swell due to temperature changes.
- A mechanical shutdown system, and a second shutdown system dependent on phase change in devices installed in the fuel bundles are provided. Both systems are actuated by gravity. The first system is active and has dedicated instrumentation for detecting potentially hazardous conditions. The second system is passively triggered by the temperature of the material only.
- Long-term decay heat removal is by conduction to the ground through the concrete wall of the pool.



PLAN VIEW OF BUILDING

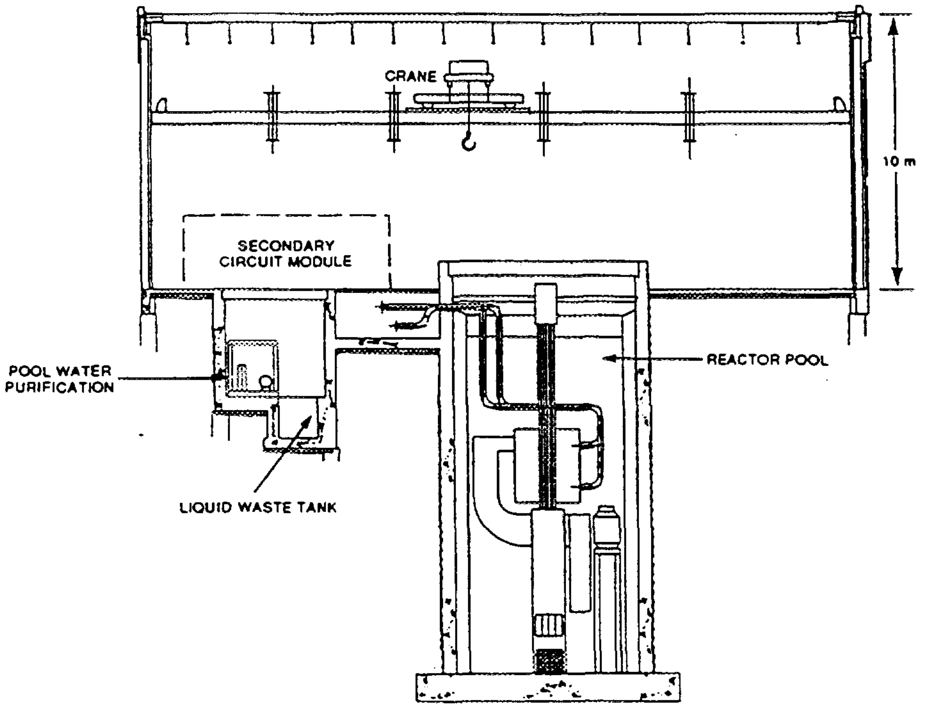


FIGURE SIDE ELEVATION OF BUILDING

4. SMALL HEATING REACTOR LICENSING EXAMPLE [3],[4],[5]

It was clear during the early design of SES-10 that licensing would be a challenge, because there were no well-established rules of licensing small reactors in any case, and SES-10 was proposed to operate in an urban environment using a unique operating concept. The operating model distinguished two types of operators: local and remote. Both had well-defined roles and responsibilities. Local operators were generally stationary engineers, charged with running the conventional heating plant and with monitoring the automatic operation of SES-10. They did not need to be in the control room all the time; they would go there periodically and be paged in case of an abnormal event. They would verify that the correct automatic action had occurred, and, if it did not, or in case of doubt, they could shut the reactor down (but not start it up). Because of the large pool, shutting the reactor down generally gives days before any further action need be taken. They, and the local fire and security staff, were also responsible for the conventional safety of the plant. The local operators would also communicate periodically, and in case of emergency, with the remote operators. They would receive specific training appropriate to these duties.

The remote operators were trained nuclear operators, periodically inspecting a remote monitoring station, which displayed all the key plant parameters, and from which these operators could diagnose an event and shut the reactor down. In case of emergency, they were summoned to the remote station by a pager initiated automatically by the monitoring computers, backed up by the local operator. Again, because the action time was days, there was no requirement for instantaneous response. The remote operators would also travel to site for skilled nuclear tasks such as refuelling or repairs to the control and safety systems. AECL and the Atomic Energy Control Board (AECB), the Canadian regulatory body, jointly agreed to consider the major issues for licensing SES-10 in advance of a formal application for a construction licence. This gave both parties the opportunity to consider the policy and concept issues posed by the design and mode of operation, so that a potential purchaser could be assured of low licensing risk.

During the initial review of the design, the AECB identified ten issues to be solved in the pre-licensing review. The major ones were as follows:

1. The worth of individual control rods would be determined by the following requirements:
   a. Calculate with confidence the consequences of inadvertent rapid withdrawal of the rod, regardless of the means, *or*
   b. Show that the probability of achieving prompt criticality or very severe fuel damage due to inadvertent withdrawal was less than 10^{-6} per year, *or*
   c. Subdivide the control rods so no one rod was worth more than 5 mk[1], *or*
   d. Use some other unspecified approach to convince the AECB the design is safe.

2. Use a risk target in design which reflects the lower benefit compared to power reactors.

3. Identify those events whose likelihood is so remote that they are excluded from the design basis. (These were generally accidents such as massive structural failure, which are precluded by use of appropriate codes and standards).

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[1] 1 mk ≈ 1/6 β

4. Use two poison storage tanks to give confidence that the reliability of liquid injection of 999 times in 1000 could be achieved.

5. Define the design specifications, and their basis, for the reactor building. The AECB expected that not all events leading to fuel damage could be ruled out of the design basis.

6. A comprehensive PRA could be required to demonstrate that risk targets were met.

7. Chemical interactions which produced sudden quantities of hydrogen, or precipitate the dissolved liquid from the second shutdown system, should be considered.

8. The design specifications for the operating mode should be considered early in the review.

The major issues from AECL's point of view were #1, #8, and #5. AECL took two years to systematically address these issues and respond to the AECB.

Issue #1 required a redesign of the reactor core, to dramatically reduce the worth of individual control rods. This was achieved by increasing the number of rods (and the core size), and by the use of burnable poison in the fuel assemblies, so that the control rods held the minimum reactivity required to start up the reactor and follow the load.

Issue #2 was considered by a joint industry-AECB ad-hoc technical working group, which proposed public risk criteria appropriate to small reactors [4],[5]. AECL identified the low-probability events for Issue #3, although little debate occurred on this. Issue #4 and part of #7 were made obsolete when the liquid poison shutdown system was replaced by the passive devices in the fuel elements. Passive self-starting hydrogen recombiners were used in the cover gas space. For issue #6, a commitment was made to perform a risk assessment, as is done on other AECL small reactors and on CANDUs.

Issue #8 was dealt with at length. A senior expert, formerly in Operations in Ontario Hydro, Canada's largest nuclear utility which now operates 20 CANDUs, joined the SES-10 team, and provided the operations framework for the design. A compilation of the operating responsibilities, functions, duties and training of operators in CANDU reactors was first undertaken, to ensure that none were overlooked. Next a set of basic operating principles was extracted from these; meeting these principles was a prerequisite for sound operation in any reactor facility. Finally these principles were used in allocating all the operating functions to the local operators and the remote operators. The roles and duties of each type of operator were carefully defined, and AECL ensured that the necessary technical infrastructure would be in place at each location to support them.

On issue #5, the design was changed so that the cover gas space was no longer vented either in normal operation nor in accidents. The confinement boundary therefore consisted of the reactor pool, the cover gas enclosure, and expandable gas bags which collected gas driven from the cover gas space due to the swell of the pool water either in normal startup, or in an accident. The redundant shutdown systems, and the ability to reject decay heat to the ground, ensured that design-basis accidents would not result in pool boiling (a relief path was provided for incredible accidents).

AECB accepted the revised core design in principle, subject as is usual in the regulatory arena to detailed review. Almost a year later they accepted the operating scenario as a satisfactory basis to proceed with further development of the design, subject again to future details on the safety analysis and the operating plans. On containment, AECB recognized that the absence of energetic dispersal of fission products was as prerequisite for the containment concept to be viable, but deferred an overall conclusion until further design details were reviewed.

5. CONCLUSIONS

Reduction of operating staff, or reallocating their duties elsewhere, derives from the design concept rather than being an *a priori* feature. Such reallocation is made easier by use of inherent safety characteristics which reduce the need for prompt local action to ensure safety. Since there is little precedent for such concepts, discussions with the regulatory agencies at an early stage are essential. The SES-10 example shows that the regulatory agency was willing to consider such innovation, as long as the designer was prepared to respond in a significant way to their concerns.

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