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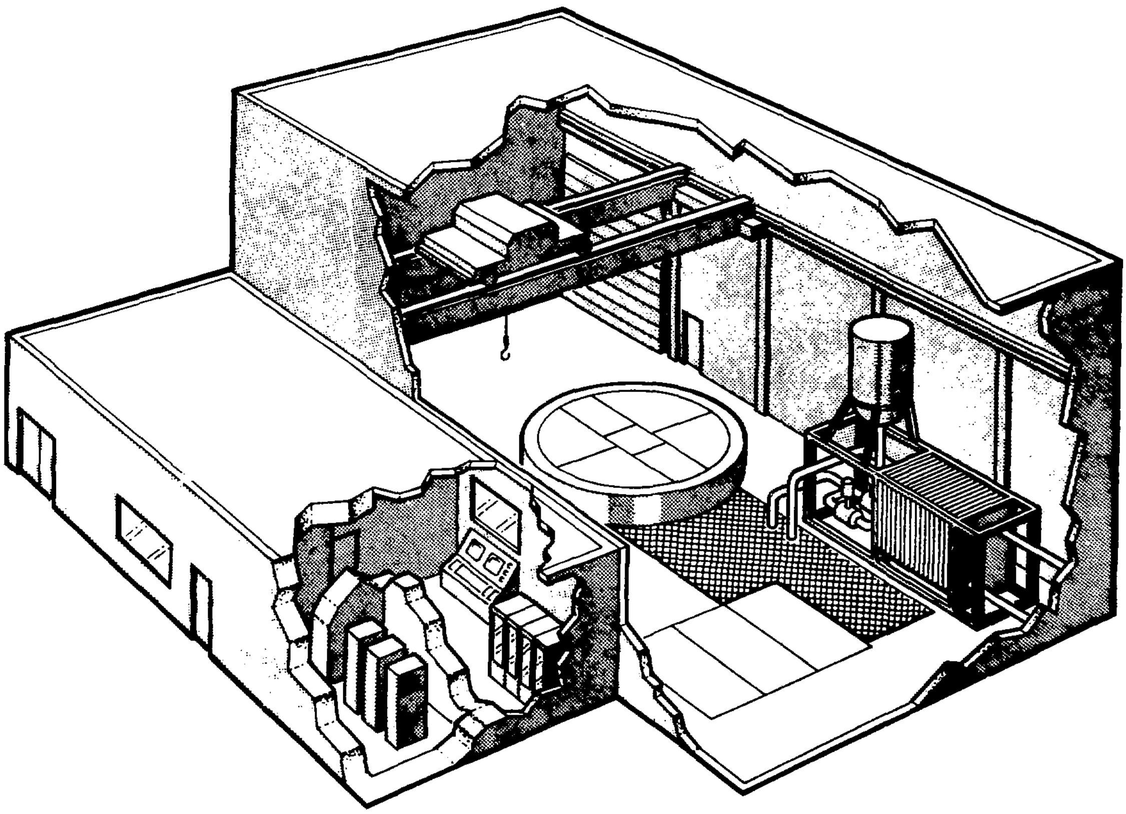
Design of SES-10 Nuclear Reactor for District Heating

AECL-10222



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Design of SES-10 Nuclear Reactor for District Heating

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by J.M. Cuttler

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Conception du réacteur nucléaire SES-10 adaptée au chauffage urbain

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par J.M. Cuttler

Résumé

Les réacteurs SES-10 sont des réacteurs de type piscine non pressurisé de 10MW (puissance nominale) conçus pour servir de source d'énergie à des systèmes de chauffage urbain; ils sont économiques et non polluants. L'eau est chauffée à une température maximum de 85°C. Des systèmes de chauffage classiques apportant le complément d'énergie nécessaire durant les périodes de pointe ou d'entretien.

Le réacteur SES-10 est renfermé dans un bâtiment ordinaire qui comprend une piscine à double paroi creusée dans le sol. La chaleur produite par le réacteur est transportée vers les système de distribution par deux circuits, un primaire, dans lequel la circulation s'effectue naturellement par convection, et un secondaire, dans lequel la circulation est assurée par pompage. Le réacteur est tout à fait automatisé et facile d'entretien. En raison de ses nombreuses caractéristiques de sûreté active aussi bien que passive, il est possible d'obtenir un permis d'exploitation du SES-10 en milieu urbain et de donner au public toutes les explications nécessiares à son approbation. Le coeur du réacteur a une vie utile de 43 mois à un facteur de charge de 70%, et le coût de la chaleur produite s'établit à entre 2 et 2,5 cents par kWh.

Mots clés

nucléaire, chauffage, urbain, pollution, sûreté, passive, public, approbation.

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Abstract

The SES-10 units are unpressurized, pool-type nuclear reactors of 10MW rating, designed for supplying energy to hot water district heating systems, economically and without pollution. Water for heat distribution is brought to a maximum temperature of 85°C. Conventional heating units supplement the output from SES-10 units for peak load and during maintenance.

The SES-10 is housed in a low-cost building, with a double-walled pool in the ground. A naturally circulating primary system and a pumped secondary system transport heat from the reactor to the distribution system. The unit is fully automated and easy to maintain. Because of the many active and passive safety features, it is feasible to license the SES-10 for operation in a city and easy to explain it to the public for their acceptance. The core lasts approximately 43 months at a capacity factor of 70%, and the cost of heat is expected to be 2 to 2.5 cents/kWh.

Keywords

nuclear, district, heating, pollution. passive, safety, cost, public, acceptance.

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1. INTRODUCTION

The 10 MW SLOWPOKE Energy System (SES-10) is a small pool-type light water reactor, designed specifically for hot water district heating[1-6]. Readily-available UO_2 fuel, with an enrichment of 2.5%, provides 2.5 full-power years of output, or 43 months at 70% capacity factor. For simplicity, safety and low cost, the pool is not pressurized and does not boil. The control system limits the primary circuit temperature to 95°C. To isolate the heat distribution system from the primary circuit, a secondary circuit is employed, and the maximum supply temperature is 85°C.

To achieve water temperatures above 85°C, for peak loads, the reactors are operated in conjunction with conventional boilers. SES-10 units function continuously to supply the base load, and non-nuclear units are used for short-term peak-load service, or to back up a reactor during maintenance. One SES-10 unit is appropriate for a system with a peak load of approximately 35 MW. The base-load mode of operation is ideal for the SES-10 with its higher capital cost and lower fuel cost. Peak-load service is appropriate for the fossil boiler.

The reactor operates automatically to supply the required temperature, and can load-follow over the range from 0 to 10 MW. It tolerates a sudden loss of load gracefully and recovers when the load returns. If electric power is interrupted for longer than an hour, the SES-10 would shut down and operator action would be necessary to restart it.

The design of the SES-10 evolved from the 20 kW SLOWPOKE-2 research reactor[7], whose power output is inherently self-limiting by temperature effects. This led to its licensing in Canada for urban sites and unattended operation for periods up to a day. Seven of these reactors are operating in Canadian cities, and one is in Jamaica.

The SES-10 has also been designed with characteristics that allow it to be located in population centres besides existing district heating plants, taking due account of its higher power. It is to be operated like a conventional boiler, that is, with periodic inspection by heating plant operators who have received additional training for the SES-10 units. With this mode of operation, the cost of heat is expected to be 2 to 2.5 cents/kWh.

This type of product must be visibly safe to be accepted – first by the supplier of the reactor, then by the district heating company, the regulator, the reactor operators and ultimately by the people who live in the neighbourhood. All must perceive a definite benefit and the risk of an accident to be negligible.

Progress is being made toward a generic licence, which would establish a possible basis for other jurisdictions to accept the safety of operating SES-10 units in their cities[8,9]. In each case, a review of the local conditions would be necessary to confirm they are enveloped by those of the generic licence and the supporting safety analyses. If any of the envelope conditions were exceeded, further analyses would be carried out or design changes made to satisfy the criteria for acceptance.

2. HEAT TRANSPORT

Figure 1 illustrates the concept of district heating with the SES-10 nuclear reactor. Two heat transport circuits are used, a primary and a secondary.

Primary flow is by natural circulation, providing assured transfer of heat from the fuel elements to the water in the core. The warm water rises through the reactor module and the riser duct into two in-pool heat exchangers where it is cooled by the secondary circuit. The primary flow from the heat exchangers descends to the inlet plenum where it reenters the reactor module. The pool is 5.8 m diameter and 14 m deep.

The power level of the reactor is regulated to keep the water leaving the heat exchangers at a fixed temperature of 75°C. At full power (10 MW), the water rising from the core is at 95°C, and the flow is 120 kg/s. The control system automatically reduces the reactor power if the core outlet temperature exceeds 95°C or if the temperature rise across the core is greater than 20°C. The temperature of the stagnant water above the heat exchangers is between 75 and 95°C, depending on the power level.

Two 50% pumps maintain a constant flow of 120 kg/s in the secondary circuit. The pressure is 350 kPa(g) after the pumps. At full power, the water enters the primary heat exchangers at 70°C and leaves at 90°C. The SES-10 control system regulates the flow bypassing the secondary heat exchanger in order to heat the distribution system flow to the temperature setpoint specified by the district heating plant.

The district heating system is connected at the secondary heat exchanger. Fossil or electric boilers are used to supplement the heat from a SES-10 unit for peak loads or when the unit is shutdown for maintenance.

The pool water purification system maintains pool water purity and pH within the required limits. It removes dissolved material to control the concentration of radioactivity from oxidation of stainless steel structures and from a potential fuel sheath defect. The system consists of a pump, a cooler, a recuperator, two filters, an ion-exchange column and a chemical addition tank. The cooler can provide adequate shutdown cooling to maintain the pool at its 75°C temperature.

The hydrogen accumulating in the cover gas, from the radiolytic decomposition of pool water, is recombined passively using modular screens, coated with a patented wet-proof catalyst.

3. REACTOR

The reactor module is arranged in four sections: the inlet plenum, the core, the lower outlet plenum and the upper outlet. The inlet plenum screens the incoming flow and distributes it uniformly into the core. The core structure supports the 32 fuel bundles with low impedance to the flow. The lower outlet plenum accommodates the movement of the absorbers rods, and the upper plenum guides the flow into the riser duct, leading to the heat exchangers. A hatch is located at the top of the module for access to refuel the core.

The elements in the square fuel bundles contain pellets of uranium-dioxide, enriched to 2.5% U^{235}. The average power density at full power is only 9 kW/kgU. The average fuel temperature is also low, approximately 265°C, which is important for achieving high fuel reliability.

A burnable absorber compensates for fuel burnup, to obtain a fuel lifetime of 2.5 full-power years. At a capacity factor of 6100 hours per year, the complete fuel charge is replaced every 43 months. Each used-fuel charge is held in the pool for at least a year and is normally removed when the reactor is next refuelled.

The absorber rods are shared by the control system and the first safety shutdown system, which are otherwise separate and independent. The reactor is controlled by slowly raising or lowering the rods using electric motors. Before the reactor can start up, the rods are raised in symmetrical banks by the control system, to the required elevation, to poise the shutdown system. When this safety system trips, it interrupts current in the electromagnets, releasing the rods to fall into the core by gravity.

4. MONITORING AND CONTROL

4.1 Computer System

Figure 2 shows the configuration of the monitoring and control system. Inputs from approximately 100 sensors and contacts are fed to both computers of a dual, redundant control system, designed for very high reliability. A "watchdog" monitor, connected to each control computer, detects and alarms when its computer is impaired. Computer #1 and computer #2 both operate as if each is controlling the plant, but watchdog #1 automatically disconnects the outputs from computer #1 and connects them to computer #2, allowing the reactor to continue operating while computer #1 is being repaired. If both watchdogs alarm, the SES-10 automatically shuts down.

Each control computer checks the signals for rationality and produces alarms for those which are out of range. Important measurements are made with redundant sensors, and each computer performs spreadchecks before accepting such signals for median selection or averaging. The major items controlled are the absorber motors and the bypass flow valves. Control is based on temperature. In addition to controlling the SES-10, the control computers provide video displays of plant variables such as reactor power, temperatures, rod positions, etc. This design utilizes the same basic design approach and fault-tolerant characteristics which have been thoroughly proven in CANDU power reactors for many years.

The system employs a third computer to collect data from the control computers, at two-minute intervals. This computer also receives buffered signals from the first safety shutdown system. All the data is stored, and the operator can select any variable for a video display of its historical trend. The data-logging computer automatically transmits its data every eight hours to a central SES operations office which monitors many SES-10 units in a region. Such a transmission is also triggered by an important alarm or by a request from the operations office.

4.2 Operation

To achieve a low operating cost and to reduce the likelihood of human error, the SES-10 is automated. The unit is simple to operate and monitor using the computer system. There are a few non-computer handswitches and panel displays. A pushbutton is provided to trip safety shutdown system #1. There are no manual controls to raise absorber rods, but the SES operator can disconnect autocontrol causing the rods to drive fully in, to shut the reactor down.

To start up the SES-10, the Senior Operator enters the command to poise the first safety shutdown system, and the computer raises the absorber rods to the required elevation. Then the Senior Operator keys in the instruction to heat the pool to 75°C. When the reactor reaches the hot state, he may key in the command to load-follow. The pumps of the secondary circuit are then switched on. The computer now reduces the bypass flow, and begins to supply energy to the heat distribution system, to raise its temperature to the value specified by the heating plant's control system. The computer then adjusts reactor power in order to maintain the temperature of the water leaving the heat exchangers at the 75°C setpoint. The bypass flow is continuously adjusted to suit the system conditions. Because of the large mass of water in the pool, the SES-10 can readily cope with and recover from any credible transient, including a sudden loss of full load.

4.3 Operating Plan

Because of the simplicity, reliability, automation and safety of the SES-10, the need for prompt operator action is relatively small. The unit is designed on the basis of the on-site SES operator responding within two hours to important alarms or any credible hazard, such as high temperature, radiation, fire, intrusion, etc. The only operator action in an abnormal situation is to push the trip button of shutdown system #1. The SES operator is responsible for the conventional safety, but his duties also include verifying that automatic action has occurred correctly after a control system shutdown or a reactor trip has been signalled. On an alarm, he would investigate and contact the Senior Operator at the central SES operations office.

The Senior Operator is licensed and responsible for the nuclear safety of the SES units in a region. His duties include all the tasks associated with the operation of the nuclear portion of the plant, such as start-up, core-loading changes, trend monitoring, accident diagnosis and recovery, and providing direction to on-site SES operators. He cannot remotely control the reactor, but he can remotely monitor all SES variables and alarms, and he can remotely trip the reactor.

5. SAFETY PROVISIONS

The basic safety requirements are shutdown, heat removal and containment of radioactivity. The safety measures are simple and mainly inherent or passive. They provide comprehensive protection for people and for the environment, making the SES-10 an environmentally attractive means of district heating.

5.1 Shutdown

As discussed in Section 4, the SES-10 employs a very reliable control system to regulate reactor power to meet load demands and remain within operating limits. If certain alarms occur, such as fire or radiation, the reactor will shut down automatically.

If the control system should fail in an unsafe manner such that reactor power or temperature exceed prescribed limits, an independent safety shutdown system will automatically release the absorber rods to fall under gravity and shut the reactor down. This safety system is monitored continuously and tested to ensure that its unavailability is less than 10^{-3}, or less than 8.8 hours per year.

These systems are in turn backed up by an independent and passive means of shutdown, based on the release of a liquid absorber, on high reactor temperature. The inherent limit on the rate of power increase and the natural circulation flow combine to make this protection effective against high power excursions as well. The control system and the two independent means of emergency shutdown provide adequate assurance of safe shutdown.

5.2 Heat Removal

Several hours after a shutdown from full power, the rate of decay heat production in the reactor core declines below 50 kW. If electric power were unavailable to transfer this energy to the load, the primary system would heat up, but boiling would not occur due to the inherent 50 kW rate of heat loss from the pool (at 100°C) to the ground.

5.3 Radioactivity

The sources of radioactivity are the activated water and the activated structures in the pool, and the potential release of fission products from the fuel. The likelihood of a defect in the fuel elements is less than one in 50 years of normal operation and, in this event, the radioactivity released would be very small. It is very unlikely that a fuel bundle would be dropped underwater while refuelling during a shutdown. However, if it did occur, the radioactivity released would still be very small.

The large, deep pool of water with its double walls would retain nearly all of this radioactivity, and it would eventually be captured in the filters and ion-exchange resin. Only radioactive gases would reach the cover gas space at the surface, and these would be retained during operation by the sealed pool cover and the gasholders which adjust passively to accommodate volume variations. Releases of radioactive gases from a shutdown reactor in the open pool during maintenance are negligible.

A core load of used fuel is removed from the pool in four batches using the used fuel transport packaging which accommodates eight bundles at a time. Any spills of potentially contaminated water during maintenance are collected in the liquid waste holding tank. When the tank is full, the contents are sampled and purified (if necessary) before discharge. Solid wastes, such as filters and ion exchange resin, are removed in a suitable transport packaging to a licensed radioactive waste disposal site.

The SES-10 has area radiation monitors, a gaseous effluent monitor, a hand and foot contamination monitor and portable survey meters.

5.4 Protection from Hazards

Comprehensive analyses have been carried out on a full range of hazards, and the reactor has been designed to avoid or withstand them. For example, the entire reactor pool and the provisions for emergency shutdown have been qualified to withstand a design basis earthquake with a maximum horizontal acceleration of 0.3 g[10], and they are protected against debris from a design basis tornado.

An external monitoring station, protected from hazards, is provided to allow the operator to monitor the state of the reactor, and to shut it down in the event of a hazard which prevents access to the control room, such as a large fire.

6. BUILDING

An industrial-type building, constructed to local building codes, houses the SES-10. The interaction between the concrete pool structure and the soil is taken into account when designing the site-specific foundation to be qualified for the design basis earthquake. The plan view and side elevation are shown in Figures 3 and 4. The building can be located near an existing plant.

For radiation zoning, the auxiliary rooms are classified as Zone 1 and the reactor room is Zone 2. The reactor pool and the purification pit are Zone 3. The shielding is adequate to meet the SES-10 design target of less than 0.05 mSv/year for the most exposed public group (those standing at the side of the building). In addition, the target for all design basis accidents in that the most exposed member of the public receives less than 0.1 mSv. This is much less than the level of natural background radiation, typically 1 to 2 mSv/year.

7. DESIGN FEATURES FOR SAFETY

Economic viability is necessary but not sufficient for acceptance of nuclear district heating. The safety of the design must be obvious to every stakeholder.

To achieve a very high degree of confidence that the SES-10 will shut down when necessary, it has a reliable control system and two independent safety shutdown systems. In addition, the design has the following inherent/passive features:

- negative fuel and coolant temperature coefficients of reactivity to limit reactor power
- negative coolant void coefficient of reactivity to limit reactor power
- natural circulation flow through the core to remove heat at all power levels
- safety shutdown systems driven by natural forces
- primary circuit at atmospheric pressure
- large (340 m^3), 14 m deep underground pool of water enables the SES-10 to tolerate a sudden loss of load and retain radioactivity from a potential fuel sheath defect
- passive removal of decay heat through the pool walls to ground
- inherent limit on rod speed prevents fast power changes
- low fuel rating and low fuel temperature for good retention of radioactivity in the fuel
- sealed reactor pool cover and passive gasholders to delay the escape of gases
- passive recombination of hydrogen from radiolysis
- double containment of pool water
- thick, reinforced-concrete pool cover protects reactor against intruders, tornado debris and other hazards

8. MAINTENANCE

The SES-10 is designed for easy maintenance. There are few systems to look after and most of the equipment and controls are similar to those found in conventional heating plants. Some of the maintenance, such as replacing a power transformer or a pump in the secondary circuit, can be performed by the SES operator who operates the district heating plant and the non-reactor portions of the SES-10. Special jobs, such as replacing an absorber rod motor, require personnel from the central SES operations office.

The maintenance plan consists of: 1) daily inspections by the SES operator, 2) monthly tests and calibrations by the Senior Operator from the central SES operations office, 3) annual shutdown for absorber adjustments, replacement of filters and resin, inspections, tests and other preventative maintenance and 4) refuelling after 2.5 full-power years of operation.

Component failure can occur at any time. Most of these will be detected by the monitoring and control system. Important components and sensors are redundant, allowing ample time for skilled personnel to come and replace failed items. Most of the items requiring maintenance are readily accessible, and repairs can be made without a shutdown. Replacing an absorber rod drive unit, however, would require a brief shutdown.

9. EXPERIENCE

The conceptual design of the SES-10 has been completed. The safety analyses of the conceptual design has been completed and issued to the Canadian regulatory agency for review. The detailed design has been completed for the reactor module, the heat transport systems and the safety systems.

The detailed design of the building, foundation and concrete pool structure will depend on the characteristics of the specific site.

The design process, including the computer software development, has followed a quality assurance program to achieve a high degree of confidence in the design. Experienced and capable designers were employed, and their work was documented and formally verified.

A prototype of the heating reactor was built at Whiteshell Laboratories and operated at power levels up to 1 MW, to verify physics, fuel, thermalhydraulics and control simulation codes. Fuel bundles were tested in flow rigs. A mockup of the entire SES-10 core, complete with absorber rods, was built and shake-tested to demonstrate the rods would not be affected by a 0.3 g design basis earthquake. The passive hydrogen recombiner was tested in a containment simulation chamber. Software was developed and validated for the computer system. Tests have been planned for the rod drive mechanism, the safety shutdown systems and for the fuel handling tools.

10. CONCLUSION

The SES-10 is simple, safe and low in cost. The design of this product is nearing completion, and its licensing is proceeding in parallel.

This nuclear unit is an attractive alternative to conventional boilers for heating plant owners who are concerned about the reliable supply of economical fuel and the public reaction to the health hazard of releasing polluting gases in the neighbourhood. For a typical site with a hot-water district heating system already in place, the cost of the heat is expected to be 2 to 2.5 cents/kWh.

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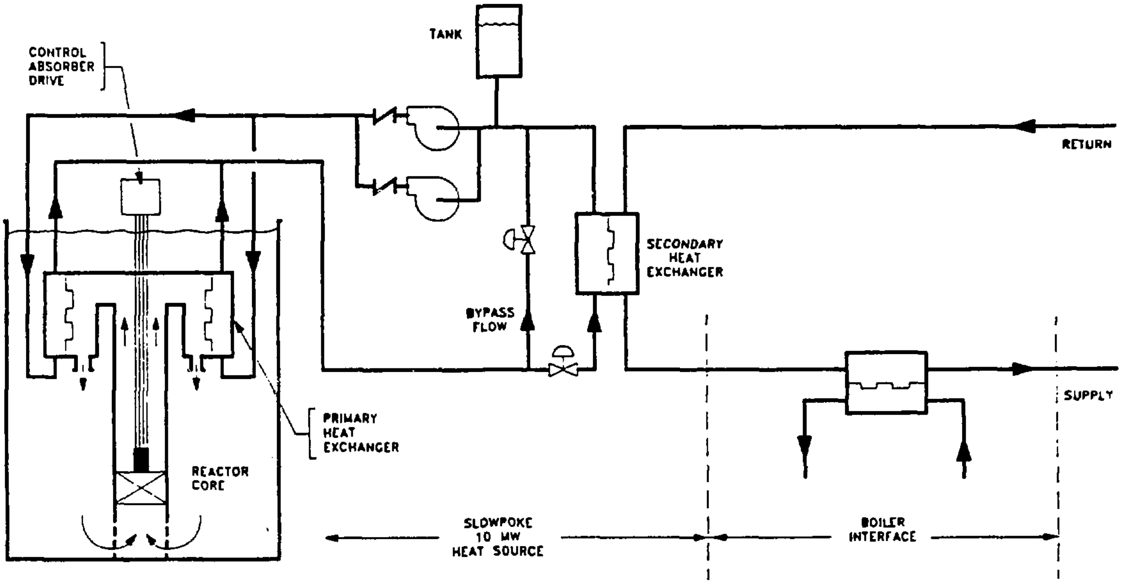

FIGURE 1 SLOWPOKE DISTRICT HEATING

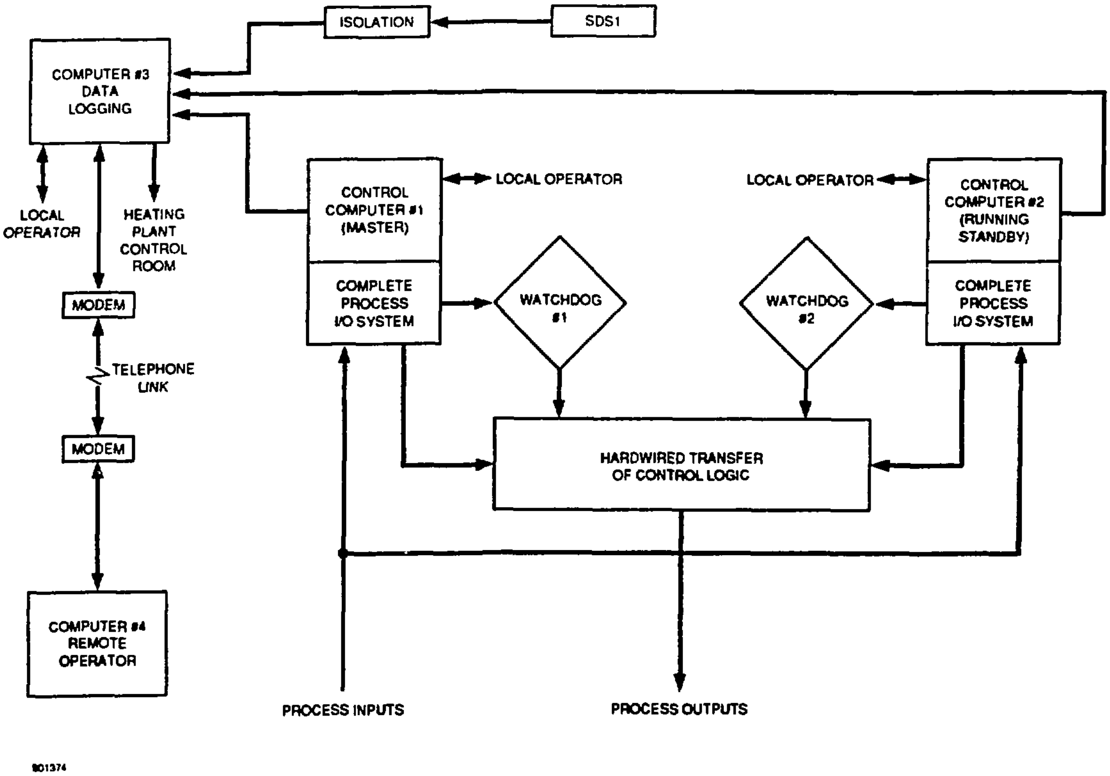

FIGURE 2 COMPUTER SYSTEM

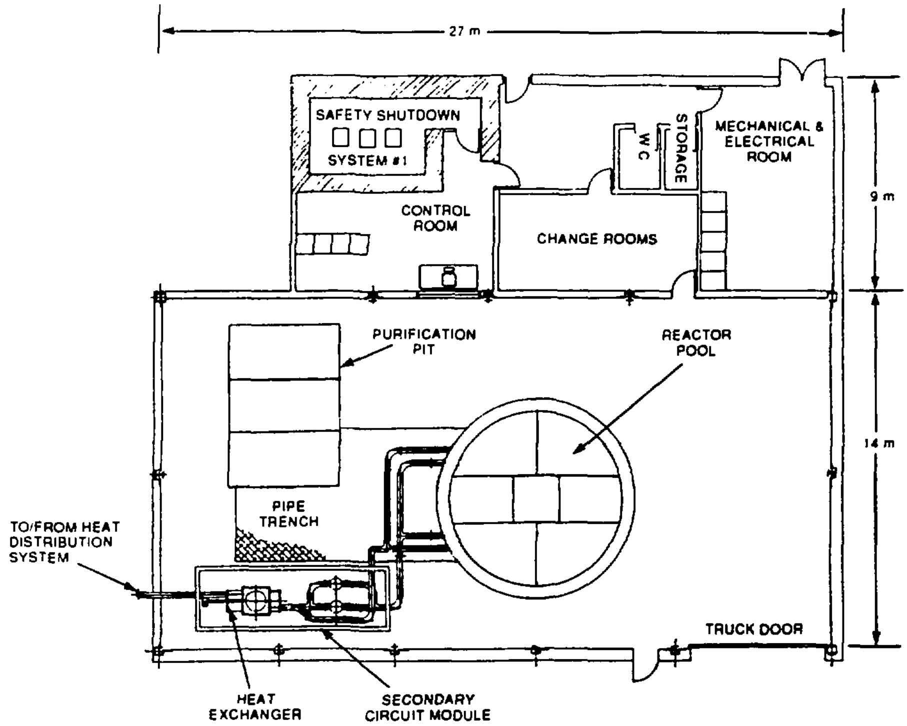

FIGURE 3 PLAN VIEW OF BUILDING

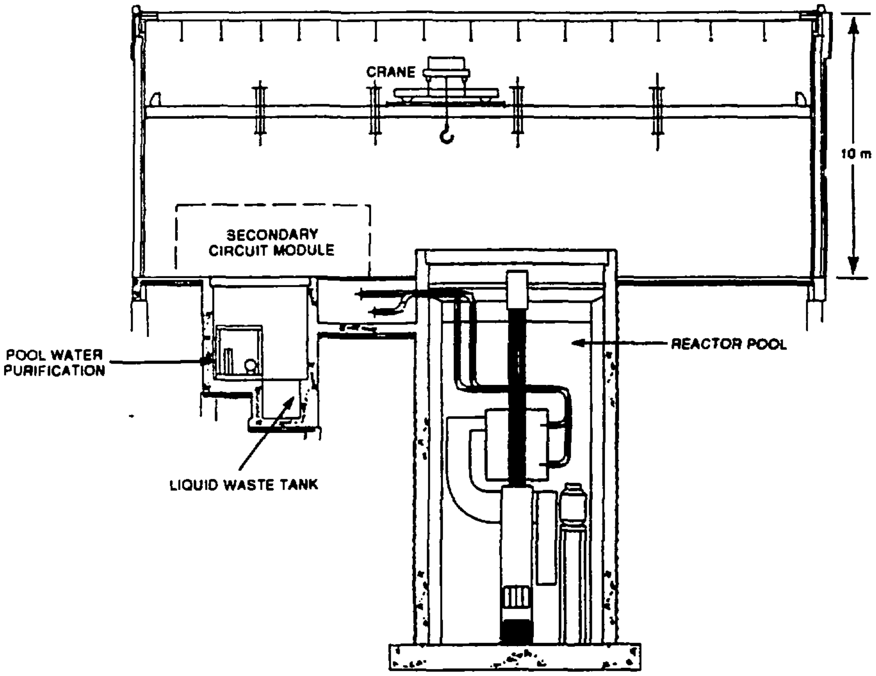

FIGURE 4 SIDE ELEVATION OF BUILDING