INIS-mf--13074

NL91C0889

RESULTS OF A COMPARISON STUDY OF ADVANCED REACTORS

A report by a working group of
PINK PROGRAMME I

June 1991

RESULTS OF
A COMPARISON STUDY OF ADVANCED REACTORS

A report by a working group of
PINK PROGRAMME I

June 1991

nucon

ECN

KEMA

The working group of PINK PROGRAMME I for this task consisted of:

K.G. Bueno de Mesquita (NUCON)
W. Gout (NUCON)
J.A. Heil (ECN)
R.H.J. Tanke (KEMA)
F. Geevers (KEMA)

Inquiries: telephone (0) 8885 82 30

CONTENTS

LIST of FIGURES

1. INTRODUCTION

At present there are more than 400 nuclear power reactors with more than 300 GWe capacity in commercial operation, and almost one hundred are under construction. Most of these reactors are light water reactors (LWRs), the majority of which are pressurized water reactors (PWRs). The remaining non-LWRs consist of a variety of types, such as heavy water reactors (mainly CANDUs), light-water-cooled graphite-moderated reactors, gas-cooled graphite-moderated reactors, and liquid-metal-cooled fast reactors.
These reactors generate approximately one-sixth of the total electricity in the world. Over 5000 reactor-years of operating experience has been accumulated until now.
The availability of nuclear power plants to produce electricity has been increasing steadily over the past years and has surpassed 70% now.

Development stages

Like other technologies, reactor technology is continuously evolving. Over the last four decades several basic reactor designs have emerged, some of them have resulted in commercially attractive designs. Departing from current reactor technology three development stages or generations can be distinguished, each representing a period of five to eight years to full commercial utilization.

The first stage reactor designs comprise the so-called evolutionary light water reactors. These are large (900-1400 MWe) reactors, satisfying near-term needs. Their design is based on proven technology. AECL also follows the evolutionary development line in their CANDU reactors, in a power range up to 900 MWe. The main commercialized product lines are:

ABWR	General Electric / Toshiba / Hitachi / Tepco
APWR	Westinghouse
BWR90	ABB
CE 80+	ABB (originally Combustion Engineering)
CANDU6/900	AECL
Konvoi	Siemens / KWU
N4	Framatome

The economic goals in these first stage designs are met by standardization (series), and by scale (large size). Safety is enhanced by improvement of the safety systems and devices, increased automation and improved man-machine interface. The American vendors are seeking certification of their evolutionary designs by the USNRC within one or two years. These evolutionary designs are being developed and promoted by companies with an established home market.

The second stage of reactor design development, so-called advanced reactors, features increased use of passive safety systems and simplification. The aimed goals of improved safety and economics have resulted in designs in the power range of 300-700 MWe. The designs include:

SBWR	General Electric and others
AP600	Westinghouse and others
SIR	ABB / Rolls Royce / AEA Technology / SWEC
CANDU3	AECL

In the CANDU3 design the possibility to utilize slightly enriched uranium is kept open. This design modification needs thorough reconsideration of the safety concept.

The third stage reactor designs (sometimes referred to as inherently safe) also show extensive use of passive safety systems and features, as well as further simplification. Whether these safety features and simplifications will appear to be attainable or just represent the reflection of an immaturity of the designs can not be judged yet. Examples of these designs are:

PIUS	(process inherent ultimate safety) - ABB design
MHTGR	(modular high temperature gas cooled reactor) - Separate and joint developments by ABB, Siemens / KWU and General Atomics Technology

PINK study

The PINK programme is a 4-year programme of five parties involved in nuclear energy in the Netherlands to coordinate their efforts to intensify the nuclear competence of the industry, the utilities and the research and engineering companies. The parties involved are: GKN (operator of the Dodewaard Plant), KEMA (Research Institute of the Netherlands' Utilities), ECN (Netherlands Energy Research Foundation), NUCON (Engineering & Contracting Company), and IRI (Interfaculty Reactor Institute of the Delft University of Technology). This programme is sponsored by the Ministry of Economic Affairs.

The PINK programme consists of five parts. This report pertains to part I of the programme: comparison study of advanced reactors concerning the above mentioned four second-stage designs: SBWR, AP600, SIR and CANDU3. The objective of the current study is to compare these advanced reactor designs in order to provide comprehensive information for the PINK steering committee that is useful in the selection process of a design for further study and development work. The SBWR was included in this study mainly for reference purposes, since it was already decided some years ago to actively participate in design and development work on this reactor, being performed by an international group of companies coordinated by General Electric.

Recently NPI (joint-venture between Siemens/KWU and Framatome) announced the development of an advanced reactor type. At the start of this study, insufficient information was available to include this design in the comparison study.

Study approach

The work described in this report was undertaken by a joint study team of KEMA, ECN, and NUCON staff. Based on the study objectives, the study team prepared a list of important items to be covered in the 'Comparison Study of Advanced Reactors'. This list was sent to the programme managers of the four reactor design groups (General Electric, AEA Technology, Westinghouse, and AECL) with the request to provide documentation, enabling a thorough understanding of the design and a fair comparison. The main items selected are the safety characteristics, proven technology, Netherlands' requirements, commercial aspects / Netherlands' participation, fuel cycle/waste, and cost comparison. They appear as the titles of the chapters 3 to 8 in this report. A relatively large part of the comparison study was devoted to the safety characteristics. The four reactor design groups responded with large documentation packages, containing reports with varying levels of detail, depending on the status of the development programme. Part of the documentation was provided under separate proprietary agreements.

2. GENERAL DESCRIPTION OF THE REACTOR DESIGNS

In this chapter the main features of the four reactors are highlighted.

Description of the SBWR

The Simplified Boiling Water Reactor is a 600 MWe class reactor, which uses natural circulation and passive features to minimize dependence on mechanical components and operator action. In case of an emergency, the reactor vessel is depressurized and cooling water flows by gravity from an elevated pool into the reactor vessel. No operator action is needed to activate this automatic safeguard. A passive containment cooling system uses natural convection to provide long-term cooling capability.

Key simplification features include:
The natural-circulation system simplifies the design by eliminating the recirculation pumps, system logic and control, jet pumps, pipe supports, hangers, shock suppressors, pumping electrical loads, and large liquid break LOCA risk. This results in reduced inservice inspection, personnel exposure and maintenance.

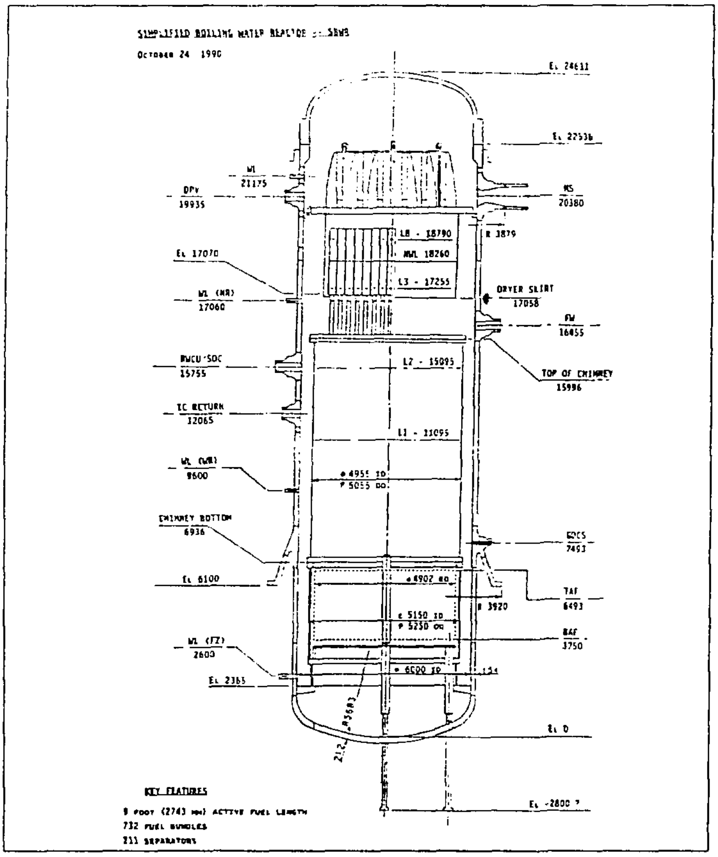

Figure 2.1 SBWR Reactor Pressure Vessel Boundary

Figure 2.1 shows the reactor vessel and all major elevations and nozzle locations which have been integrated with the containment and reactor building arrangement. The primary containment vessel, which encloses the reactor pressure vessel and its related cooling and servicing systems, is a reinforced concrete structure with a leak-tight steel liner and a design pressure of 4.9 bar. The drywell design temperature is 171°C.

The containment is shown in figure 2.2. The containment system utilizes the pressure suppression concept to condense the initial release of LOCA blowdown energy in the suppression pool. Long-term safety grade decay heat removal after a LOCA is accomplished using isolation condensers.

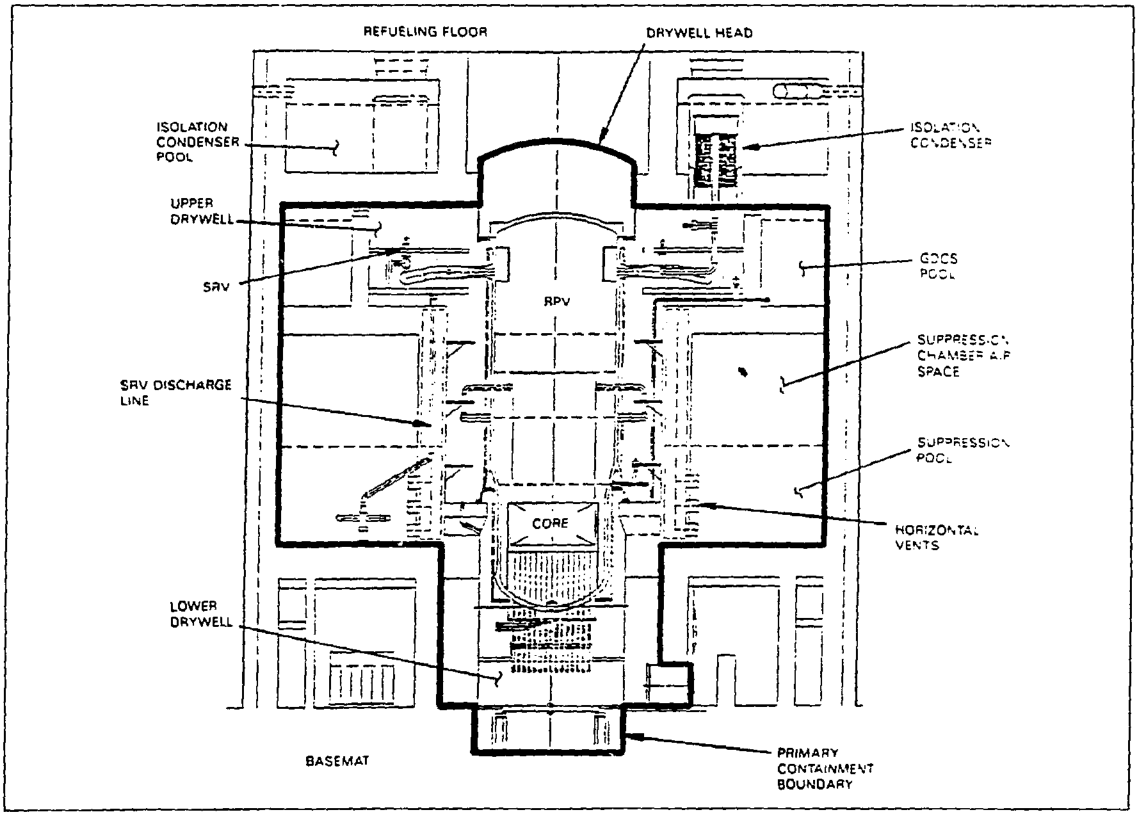

Figure 2.2 SBWR Containment Boundary

Description of the SIR

The Safe Integral Reactor is called integral, because all primary system components (reactor core, pressurizer, reactor coolant pumps and steam generators) are contained in one single reactor pressure vessel. The core is cooled and moderated by unborated water. The safety systems are primarily passive, relying on natural circulation and the large heat capacity of the inventories of the primary circuit, the suppression tank, and the condensing pool.
The SIR is a highly standardized concept of a modularized 1000 MWth reactor unit (320 MWe), normally configured as a twin plant (640 MWe total). The primary system (see figure 2.3) is arranged with the reactor core mounted centrally, down low in the reactor pressure vessel to enhance the natural circulation capability of the system for decay heat removal, and to take full advantage of a large primary coolant inventory under LOCA conditions.

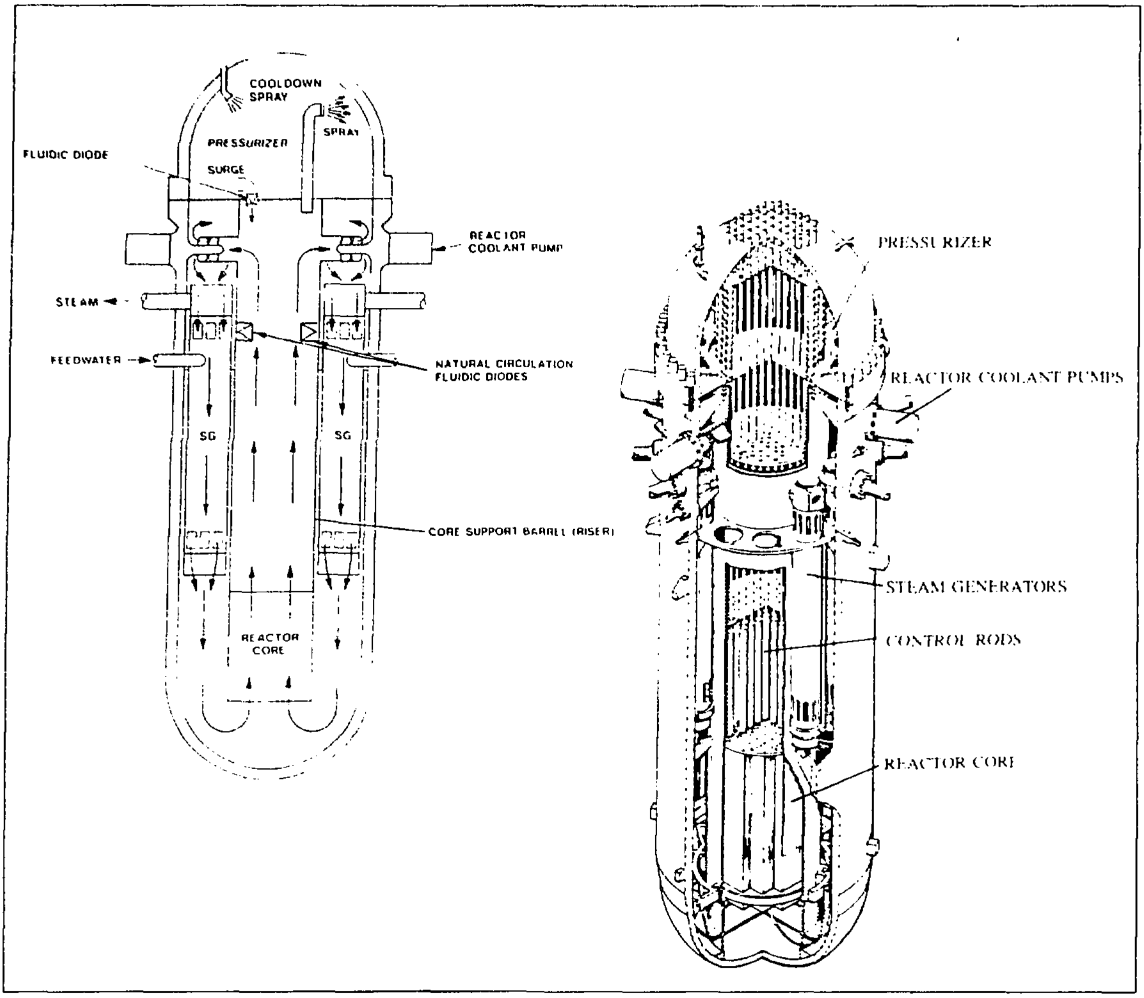

Figure 2.3 SIR, Safe Integral Reactor

Due to the large amount of water between the core and vessel the fast neutron fluence to the reactor vessel is low (1×10^{-4} of a conventional PWR).
The SIR reactor is enclosed in a pressure suppression type containment in which the reactor vessel compartment is connected with 8 steel suppression tanks by steel venting ducts (see figure 2.4).
The containment is designed to accommodate pressures up to 3.4 bar and temperatures of 171 °C.
The concept of pressure suppression instead of the so-called large dry containment (typical for standard PWR plants) is possible because of the absence of large primary components and cooling pipes in the reactor vessel compartment.
The finned exterior surfaces of the pressure suppression tanks are air cooled by natural circulation; these tanks are housed within two reinforced concrete structures which have outside air intake and discharge provisions for circulating ambient air.

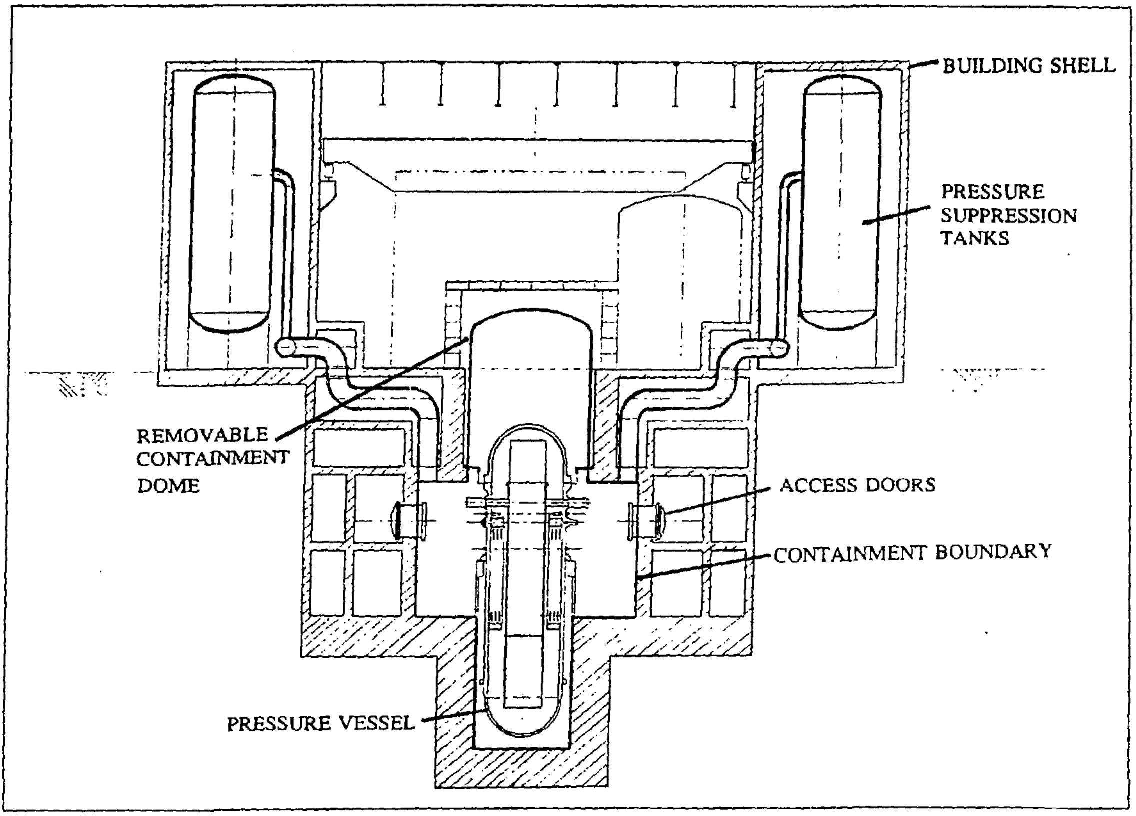

Figure 2.4 The containment and Reinforced Concrete Structures of SIR

Description of the AP600

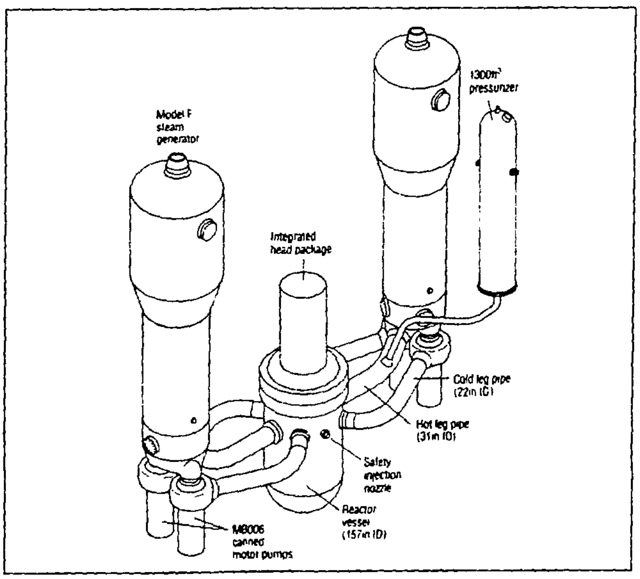

Figure 2.5 Primary System of AP600

The Advanced Passive 600 is a 600 MWe class pressurized water reactor. Simplification has been the major theme in the development resulting in a reduction of components and piping in comparison with a two loop reference PWR of Westinghouse with the same rating.

The AP600 relies upon passive safety features (natural circulation and gravity) and a compact symmetrical configuration of the reactor coolant system. Combined with application of leak-before-break criteria, this results in simple supports for the primary and secondary components, facilitating inspection and maintenance.

The primary system is configured with two identical main coolant loops.

The lay-out of the primary system is depicted in figure 2.5.

The AP600 reactor with primary components and piping is enclosed in a steel containment (single barrier) with a design pressure of 4.1 bar. This steel containment is surrounded by a shield building

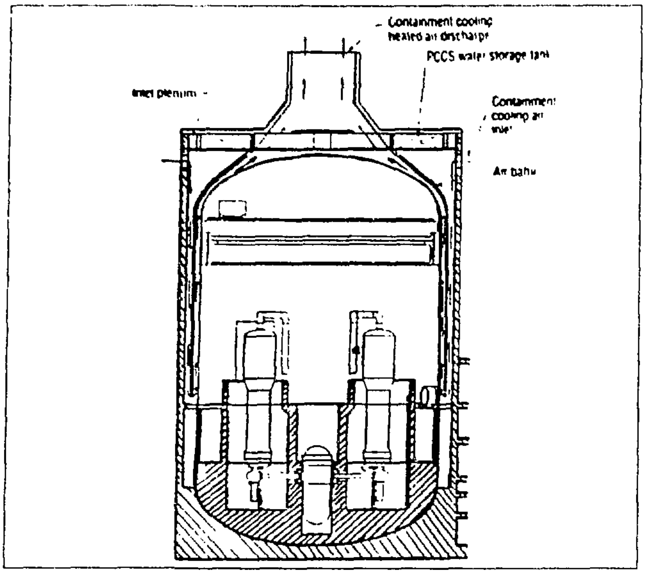

Figure 2.6 The Containment and Shield Building of AP600

which - in conjunction with the steel containment and the air baffle - acts as a natural convection cooling system. Natural circulation air cooling is assisted by the gravity drain of water out of the passive containment cooling system water storage tanks located in the top of the shield building. At the top of the shield building the containment cooling air inlets are placed and the containment cooling heated air discharge chimney gives the shield building a characteristic view (see figure 2.6).

Description of the CANDU3

The present CANada Deuterium Uranium designs have three specific features which distinguish them from the other types under consideration in this study:

- the use of natural uranium fuel in place of enriched fuel,
- the use of heavy water as moderator and as coolant in separate circuits, in place of normal water in one combined circuit,
- the use of pressure tubes in place of a reactor pressure vessel.

The presently commercially available heavy water reactors are developed by AECL. There is a wide variety of plants, single units as well as multiple ones. The evaluation of the experience gathered by utilities, constructors and designers has led to the development of standardized designs of which the CANDU3 (450 MWe) is the smallest.

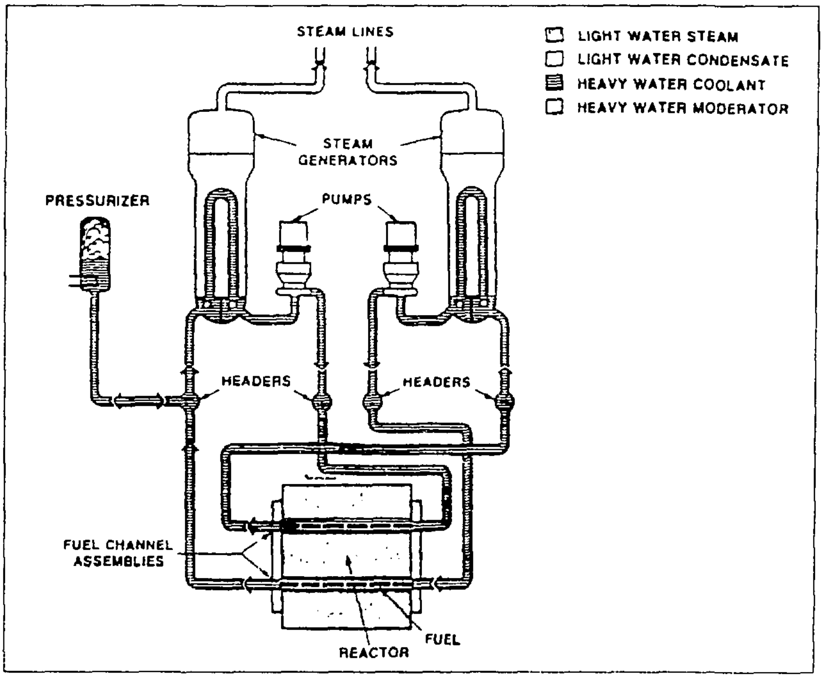

Figure 2.7 Heat Transport System of CANDU3

The reactor is a horizontally oriented cylindrical tank (calandria), filled with heavy water at low temperature and low pressure. The calandria is penetrated by 232 horizontal tubes from the circular front side to the circular back side. Each tube contains a pressurized and hot coolant tube, which is thermally insulated from its surrounding. Twelve fuel elements, each consisting of 37 fuel elements are positioned inside each pressure tube.

The pressure tubes are split up in two sections, section 1 and section 2, each with an inlet header at the back side and an outlet header at the front side. The pressure of this primary circuit is controlled by a pressurizer, which is electrically heated. Figure 2.7 provides a simplified overall flow diagram.

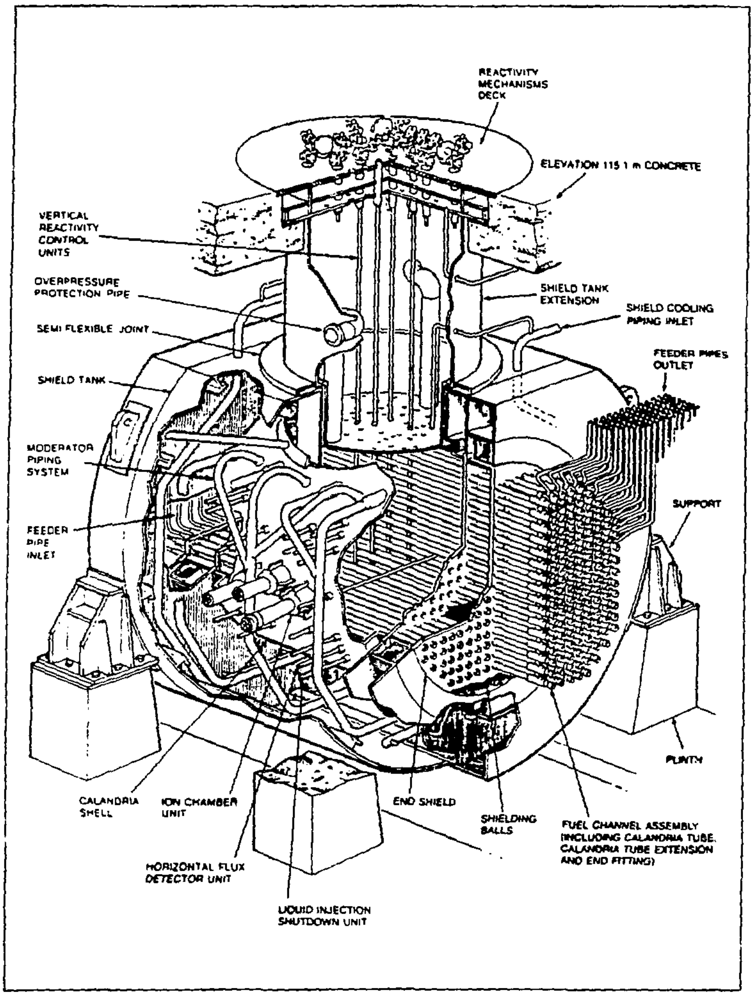

Figure 2.8 CANDU3 Calandria/Reactor Assembly

Figure 2.8 shows the calandria in some detail. The calandria and end shields are housed in a cylindrical steel tank (with an extension for reactivity control mechanisms at the top of the cylinder) filled with light water, augmented with steel balls in some areas.

The reactor building is a steel-lined vertical cylinder with a semi hemisphere top. The reactor building contains the nuclear steam supply components, including various auxiliary systems. Figure 2.9 shows a cross section of this reactor building. The main components are indicated. The containment is provided with a steel liner, which enhances the leaktightness of the building. The design pressure is 3 bar.

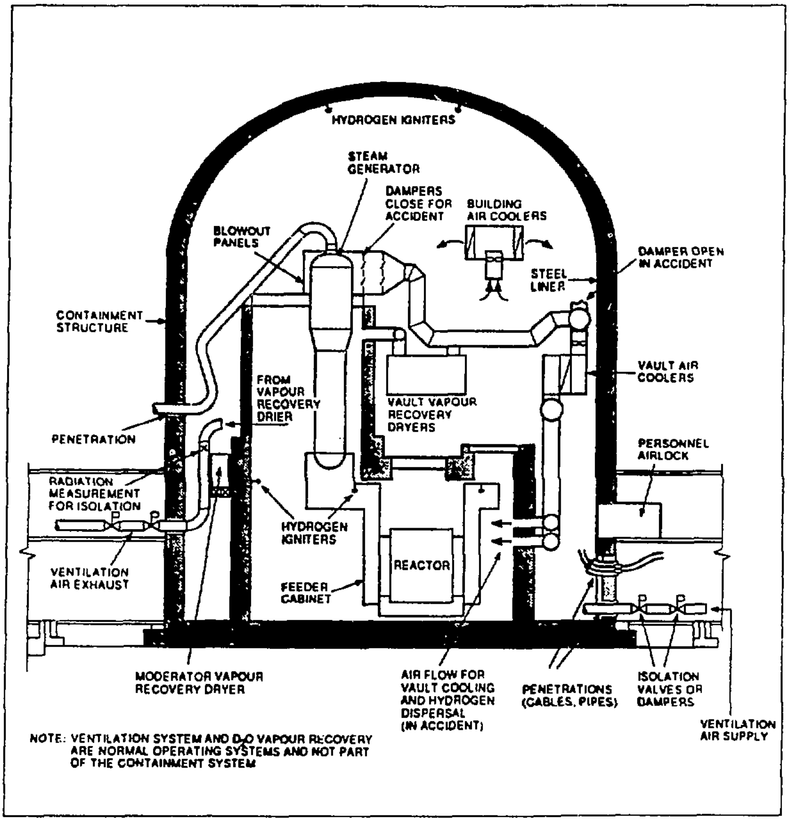

Figure 2.9 Cross Section Reactor Building of CANDU3

3. SAFETY CHARACTERISTICS

In this chapter the most important safety features and the behaviour of the four reactors under accident situations are compared. Passive safety systems are identified and forgivingness is described and compared. Results of the preliminary probabilistic safety analyses are presented.

Passive safety

Nuclear power plants have to be designed, constructed and operated such that the radioactive inventory is retained within a succession of physical barriers. Active and/or passive measures have to be taken to ensure that these barriers will function properly both during normal operation and during an accident.

According to the EPRI (Electric Power Research Institute) definition, a safety system is called passive if it primarily employs passive means (i.e. natural circulation, gravity, stored energy) for essential safety functions; the use of active components in the system is limited to valves, controls and instrumentation. 'Inherent' safety refers to basic choices in the design of the reactor (e.g. the choice of the materials) to assure through the 'laws of nature' that a potential hazard will not pose a safety concern. It implies that an inherently safe system is the ultimate form of a passive system. In contrast, one may call human action the ultimate form of an active system.

Some components which are called passive are : batteries and accumulators but also vessels and pipes. Examples of active systems are pumps and diesel-generators. As a rule, it is expected that the more use is made of passive safety features the more safe the system is.

A reactor is called passively safe if the power control, the core-cooling, the heat dissipation and the containment integrity are guaranteed by passive safety features. It must however be noted that a passively safe reactor is not by nature more safe than one which uses active safety systems.

Description of the main safety features

In order to compare the behaviour of the four reactors the main safety features are illustrated by describing how the four important safety functions (reactivity control, emergency core cooling, decay heat removal, and containment integrity) are fulfilled under accident conditions. Reactivity behaviour is discussed in a separate section. Figures 3.1 through 3.4 present the flow diagrammes of the four plants, showing the most important safety features.

SBWR

Decay heat removal

Decay heat in an isolation situation is removed by redundant isolation condensers situated in an isolation condenser pool above the reactor vessel. This passive system, in which the steam flows by natural circulation, has been used satisfactorily in earlier BWR designs. It keeps the reactor vessel pressure below the setpoint of the safety relief valves. The steam is diverted to the isolation condensers through valves actively actuated (by the reactor protection system). Condensed steam is returned to the vessel and this ensures that the core remains covered. There is no need to open safety relief valves or remove water from the reactor vessel. Each isolation condenser is designed to remove the full decay heat.

Emergency core cooling

Emergency core cooling in case of a LOCA is primarily provided by conventional emergency systems. In case these systems do not function properly, the gravity-driven core cooling system is activated. This system is, in conjunction with the automatic depressurization valves, capable of passively injecting large volumes of water into the depressurized reactor vessel to keep the core covered with water throughout the event.
After the reactor is depressurized, flow from the gravity-driven system water pools refills the reactor vessel to the minimum water level a few meters above the core.

Containment integrity

The SBWR utilizes a passive containment cooling system that provides a three-day cooling capability using natural convection. No operator intervention is necessary. The decay heat inside the containment is removed by the passive containment cooling system to the condenser pool and ultimately to the atmosphere.

Safe Integral Reactor (SIR)

Decay heat removal

Decay heat is removed in an accident situation by the secondary condenser system, consisting of four condensers in a natural convection pool. Natural circulation is used to circulate the coolant in the condenser loop and through the secondary side of the steam generators within the reactor vessel. Except for automatic initiation opening and closing valves, there are no active components. No operator intervention is required for at least 72 hours; refilling of the secondary condensing pool may be necessary after this period.

Emergency core cooling

The emergency cooling injection system consists of a steam injector taking suction from the suppression tanks and injecting coolant into the pressure vessel downcomer near the top of the steam generator. The steam injector is a passive device which uses a jet of high pressure steam to accelerate cold water from a low pressure source and thus create a high dynamic pressure. Two independent emergency cooling injection trains are provided.

The safety depressurization system consists of two sets of pipes and valves connecting the primary system to the suppression tanks. This allows the primary system to be depressurized and coolant to drain by gravity from the suppression tanks to the reactor vessel. The safety depressurization system may also be used in conjunction with make-up systems in a feed and bleed mode. The safety depressurization system is manually initiated. Manual operation of the depressurization system is not required until after 72 hours for postulated events.

Containment integrity

The SIR utilizes a passive containment system that provides a 72 hours cooling capability using natural convection of the ambient air as the ultimate heat sink. The suppression pools, in fact 8 tanks, have a finned exterior surface to promote heat transfer to the environment and are housed within a reinforced concrete structure.

AP600

Decay heat removal

Three heat exchangers (3 x 50%) have been provided for the removal of the decay heat in an incident situation: they are placed inside the refuelling water storage tank. Natural circulation is used to circulate the coolant from the primary system to the heat-exchanger. Heat from the refuelling water storage tank is dissipated into the containment.

Emergency core cooling

Emergency core cooling is primarily provided by conventional systems. In case these systems do not function accumulators (1 of 2) and high-pressure make-up tanks (1 of 2) will inject borated water into the primary system. Injection from the high pressure tanks is based on gravity-flow.

Containment integrity

The AP600 has a leak-tight steel lined reactor building, a so called 'dry containment'. The outside of the reactor building is surrounded by a concrete structure, which provides a cooling path for the containment cooling. Cold air is drawn from the environment and is heated up by the containment, through which the air circulation will be forced in a natural way. On the top of the outside structure the air is discharged back to the environment. In the beginning the cooling of the containment is supported by gravity-flow water, which is stored in a separate storage tank on the top of the outside structure. Additionally the containment can be sprayed internally with borated water, which is stored in accumulators outside the containment. No operator intervention is necessary within the first 72 hours after the accident.

CANDU3

Although all CANDU-types have some safety features which one may call 'passive' or even 'inherent', the CANDU3 has no passive solutions for three of the four main safety functions: decay heat removal, emergency core cooling, containment integrity.

Decay heat removal

Normal heat removal paths include the steam generators which are supplied by two feedwater trains. Should all normal heat removal paths be lost and the emergency core cooling system not function, the residual heat is rejected to the moderator system, which is capable of cooling away 5% of the nominal power. It is a low-pressure system that relies on forced circulation of heavy water.

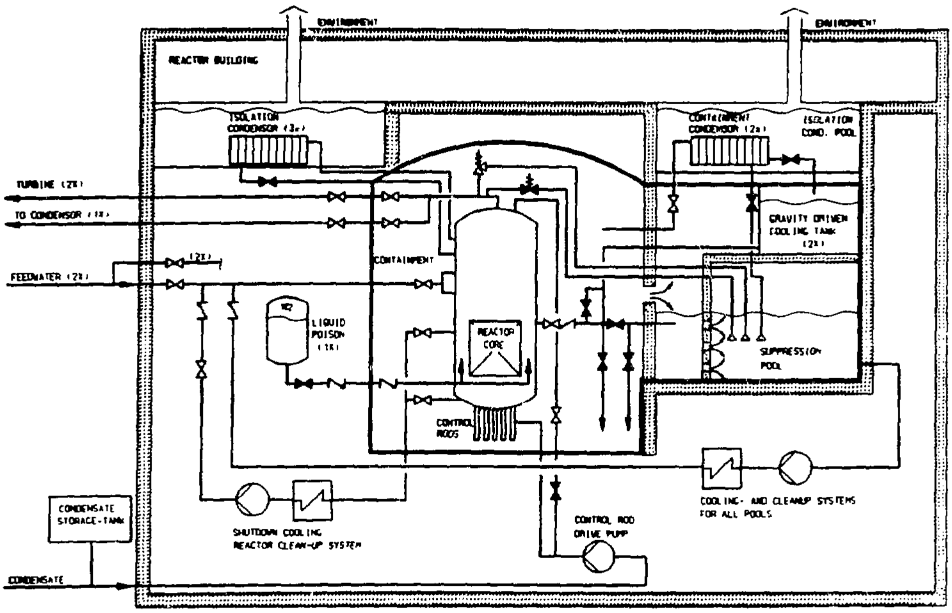

Figure 3.1 SBWR Primary-, Heat Removal-, and Safety Systems

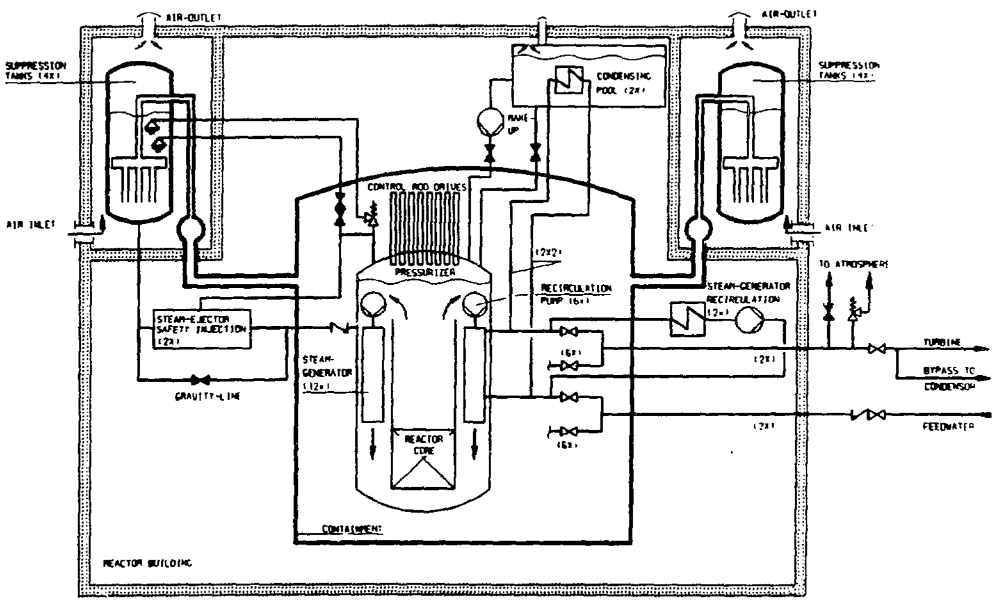

Figure 3.2 SIR Primary-, Heat Removal-, and Safety Systems

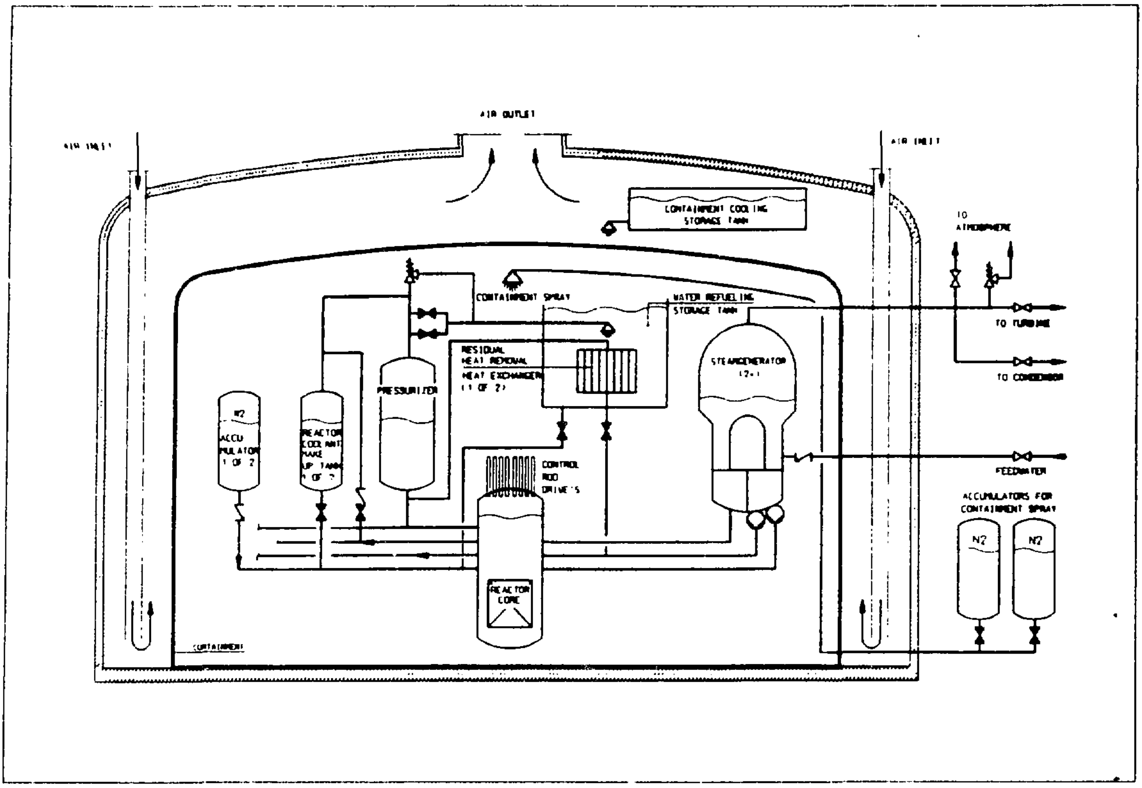

Figure 3.3 AP600 Primary-, Heat Removal-, and Safety Systems

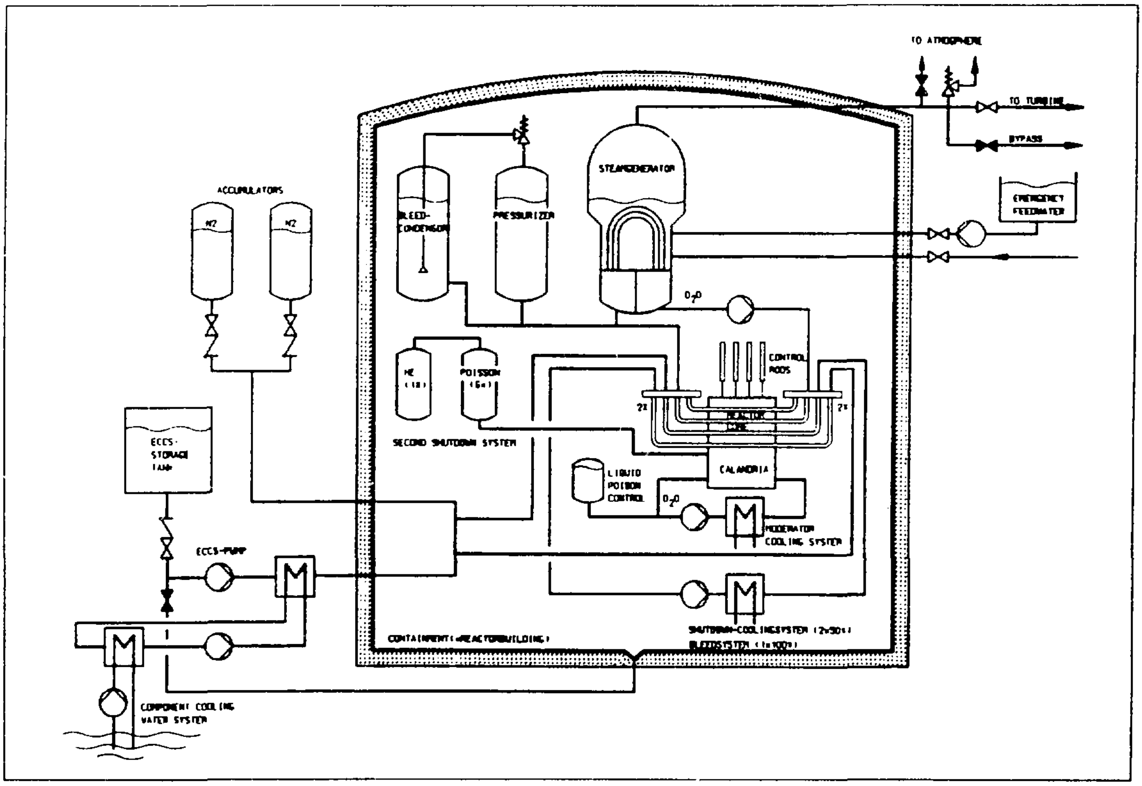

Figure 3.4 CANDU3 Primary-, Heat Removal-, and Safety Systems

Emergency core cooling

The emergency core cooling system removes residual and decay heat from the reactor following a failure of the heat transport system pressure boundary. It is divided into two parts: short-term injection and long-term recirculation. Short-term injection consists of two stages: high- and low pressure. During the high pressure stage, (light) water from accumulator tanks is injected into the heat transport system by pressurized gas. At low pressure (light) water is injected from a tank using the emergency core cooling pumps. When the water supply is completely depleted, long-term operation begins by recirculating a mixture of heavy- and light water from the reactor building floor back into the heat transport system via the heat-exchangers and pumps. The recirculation of water depends in all cases on the proper functioning of pumps and valves and on the control system which activates them.

Containment integrity

The CANDU3 has a leak-tight steel-lined reactor building, a so called dry containment. It is designed to withstand an internal overpressure of 2.0 bar. The pressure-rise inside the containment of the CANDU, due to steam and hydrogen generation is limited by air-coolers.

Reactivity aspects of the four reactors

Reactivity coefficients

All reactors have a negative fuel-temperature-coefficient (Doppler-coefficient) which causes a reactivity decrease upon a fuel-temperature increase. This, in turn, limits the fuel-temperature and thus forms a reactivity control mechanism which may be called inherently safe. The Doppler coefficient of LWRs is considerably more negative than that of the CANDU, which implies that in an LWR a higher reactivity-addition can be coped with.
The coolant-temperature coefficient including density effects is positive for the CANDU3; this means that the reactivity additions following transients are amplified by the powe, increase. The coolant-void coefficient is positive for the CANDU during operation, which implies that upon coolant loss and failure of the shut-down system, the power may increase rapidly. This coefficient is negative for LWRs.

Stability

The power distribution in LWRs is stable because of the negative fuel-temperature and coolant-temperature coefficients. Due to the on-line refuelling and the use of natural (or slightly enriched) uranium, CANDU reactors have only a small overreactivity as compared to LWRs. In addition, the generation time of the neutrons is considerably longer than with ordinary LWRs. These two features cause nuclear transients to be relatively slow; they can be controlled relatively easy. The CANDU3 has more margin than LWR-types in this respect. The CANDU however, requires a continuously working control system with local detectors, because of the positive coolant coefficients.

Shut-down reactivity

The SBWR can be brought into the cold shut-down condition by insertion of the control rods. Even a failure of the most reactive control rod does not alter this. A second shut-down system provides for the suppletion of boron in the reactor. The control rods of the SIR are capable to effectuate a complete shutdown without boron addition. The AP600's control rod insertion is less effective and extra boron has to be supplied. The reactor control rod system of the CANDU3 has a relatively small capacity, but can still shut down the reactor for all events except loss of coolant (because of the positive coolant and moderator temperature coefficients). Shutdown system #1 and #2 have a large capacity compared to the required reactivity for shutdown.

Forgivingness

An indication for the forgivingness of a reactor is its so-called grace period: the time between the initiation of a safety system (after reactor shutdown) after an incident or accident and the moment some kind of operator action is required to maintain the reactor in a safe condition. Since no human intervention is required during that period, the possibility of erroneous decisions is largely reduced; a grace period in the order of days is desirable.
The SBWR, SIR and the AP600 claim a grace period of three days. After this time relatively easy water-make-up is necessary for the SBWR containment cooling. The AP600 containment cooling is essentially a process of natural air convection and may function an indefinite period of time. In case of loss of feedwater, station blackout, and some LOCA events relatively easy water make-up is made possible for the natural circulation pool in the SIR design. The natural air convection for the suppression pools may function for an indefinite period of time.
It is claimed that the CANDU3 has a grace period of 8 hours, the time needed to boil-off the moderator and coolant water in case no make-up is possible and emergency core cooling does not function. However after this period part of the core is damaged and normal operation is only possible after a large overhaul, although off-site consequences are small.

Probabilistic Safety Assessment

Preliminary probabilistic safety assessments were performed for all four reactors in an early stage of the design. Therefore possible weaknesses found could result in design improvements. However, the numerical values found for the frequency of accident sequences and core damage frequencies should be treated with care. The core damage frequencies range from 10^{-6} to 10^{-5} per reactor-year. No firm conclusion regarding distinctions in safety can be drawn from these figures.

4. PROVEN TECHNOLOGY

The reactor concepts discussed in this report are characterized by the vendors as advanced and proven. It appeared that the various concepts are either natural steps in the development of the vendor's line or a new approach based on existing technology, materials, and know-how.
The CANDU3 resembles in many aspects the CANDU6, especially for the main components. The major distinguishing features are discussed for each reactor type.

SBWR technology

The natural circulation in the reactor vessel is new for modern BWRs; the experience of Dodewaard and Humboldt Bay is relevant, but the margins for hydraulic and neutronic stability have to be demonstrated by validated calculational tools.
The gravity driven cooling system is simple and passive, based on standard technology and confirmed by tests. The experience however is limited. The isolation condenser system is passive. There is only a limited number of confirmatory testing available.

SIR technology

The SIR design is new in many aspects. It combines features of conventional PWRs with hardware solutions normally found in BWRs. The primary system is completely contained in a single reactor pressure vessel, while the containment is of the pressure suppression type with a novel concept of eight separate steel suppression tanks. The main new components are the pressurizer, the steam generators, and the construction of the circulation pumps. An extensive test programme should confirm their reliable operation.

AP600 technology

The major differences of the AP600 compared to current PWR designs concern the design of the steam generators, and the safety systems which are primarily passive. The containment is a single steel vessel and isolates the reactor from the environment. A surrounding shield building provides a natural circulation pathway for a passive containment cooling.

CANDU3 technology

The reduction of the power of the CANDU3 (450 MWe) compared to the CANDU6 (665 MWe) has been achieved by reducing the number of components; the dimensions of the various components are essentially unchanged. The well proven 2 sided refuelling of the core has been replaced by single sided refuelling. The fuel elements are pushed out now by hydraulic forces instead of by the fresh elements. The experience gathered by pushing operation shows a reliable operation mode; the new way of operation however seems to be more vulnerable to dimensional imperfections, and the system needs further demonstration.

5. NETHERLANDS' REQUIREMENTS

Licensing requirements

Present licensing criteria are documented by the following existing rules:
1) The Netherlands' Nuclear Energy act and its decrees.
2) The Netherlands' Safety Rules (NVR, 'Nucleaire Veiligheidsregels')
   These rules are an adaptation of the IAEA NUSS Codes of Practice:
   - Nuclear Power Plant Design 50-C-D (rev. 1)
   - Nuclear Power Plant Operation 50-C-O (rev. 1)
   - Quality Assurance 50-C-QA (rev. 1)

Interpretations of the existing rules such as the IAEA NUSS Safety Guides and the recommendations of the Netherlands' Reactor Safety Committee (CRV) have a more quantitative nature and are subjected to frequent revisions. Possible criteria for risk to the population and radiological limits for population and workers in the nuclear industry are documented by: 'Premises for Risk Management' (an annex to the Dutch 'National Environmental Policy Plan'), and 'Radiation Standards Policy Document'.

Evaluation of the reactor types with respect to Netherlands' requirements

Comparison of the SBWR, the SIR, the AP600 and the CANDU3 shows that all deterministic requirements are fulfilled, except:
- double containment with depressurization between containments, and
- protection against external influences such as flooding, explosions and aircraft crash.

None of the four reactor designs includes a double containment. For the CANDU3 and the SBWR there are no fundamental problems associated with the addition of a secondary containment. For the SIR and the AP600 a double containment conflicts with the natural circulation system for containment cooling, respectively the suppression pool vessels (SIR) and the primary containment (AP600). Some of the requirements can be met by adding a safety system such as for filtered containment venting (for all four reactor types).

Utility preferences

In a government policy statement issued in 1984 a preference for reactors in the power range between 900 and 1300 MWe was stated. In the past few years evidence was gained for the competitiveness of small and medium sized reactors. It may be expected that designs in the power range of 450-700 MWe will also deserve serious consideration, provided that there will be sufficient

benefits to compensate for the less than optimal utilization of the economy of scale. A preference of utilities for European codes and standards (due to the easier selection of subcontractors) may be expected. Vendors acquainted with these codes and standards may have some advantage. In this respect, it may be assumed however that the vendors of the reactor systems in this study all have a thorough understanding of these items, so that no major preference for one or the other is expected.
This is not the case if the acquaintance of the utilities with the technology offered by vendors is discussed. One may expect a preference for an LWR because a lot of experience was gained in the operation of a BWR (Dodewaard, originating from GE) and a PWR (Borssele, delivered by Siemens/KWU). Although a new and relatively large reactor, the SBWR resembles in principal respects (e.g. natural circulation, passive isolation condensers) the Dodewaard reactor. The PWRs in this study (SIR and AP600) are based on technology which to a great extent can be found in the Borssele plant.
The CANDU3 reactor, however, deploys technology which is new for the Netherlands' utilities on essentials aspects; for example reactor control, fuel management, fuel handling, management of heavy water, waste management, in-service inspection, and management of the tritium generated in the heavy water during normal operation.
Another item which may influence the preference of the utilities is the dependence on suppliers of components, materials, inspection services etc. It is a disadvantage if there are only one or two suppliers for a resource.

6. COMMERCIAL ASPECTS / NETHERLANDS' PARTICIPATION

The selection of a second advanced nuclear reactor (besides the participation already existing in the SBWR programme) is closely related with the opportunities for Netherlands' industry, engineering services, and research institutes. The participation in the development programmes of the vendors has to fit in the long term policy of both sides.
Important features of those development programmes are the commitment of the vendors to remain in nuclear business and the assurance of sufficient support of those programmes by government and other participants given to the supplier.

Supplier development programmes

The development programmes of GE (SBWR) and of Westinghouse (AP600) are supported by DOE and EPRI. Each development programme is sponsored by DOE with an amount of 50 M$. The non-USA participants in the SBWR programme are:

- Ansaldo, ENEL and ENEA with the Italian government sponsoring
- Toshiba and Hitachi
- KEMA, ECN and NUCON with the Netherlands' government sponsoring

The SBWR programme started with GE-coordinated studies in 1982. The DOE provided essential support to this programme in 1986 and selected the conceptual design of the SBWR as a candidate for licensing in the USA in 1989. Final USNRC design certification is expected to be obtained in 1995. Commercial operation will be possible before the end of this decade.
The non-USA participants in the AP600 programme are: Ansaldo, ENEL and ENEA with the Italian government sponsoring. The AP600 programme started in 1985 and resulted in a recently completed conceptual design. The proposal to DOE to initiate the detailed design has been accepted. Final USNRC design certification is scheduled for the end of 1994. Commercial operation will be possible before the end of this decade.
The SIR programme is initiated by:

- ABB Combustion Engineering, Inc.
- AEA Technology
- Rolls Royce and Associates Limited
- Stone & Webster Engineering Corporation

The SIR team started in 1988 to develop a small passive reactor that could replace the aging Magnox plants in the UK. This programme aims for design certification by the USNRC in 1994 and aims for formal licensing by the UK Nuclear Installation Inspectorate in 1994 also.
Development support sought for the SIR programme was not awarded by DOE in 1990; further support of this programme by the British government or other participants is not yet realized. The development by ABB of SIR and other advanced reactor types (PIUS and HTR) is still subject to discussion within ABB. The question arises which programme(s) will be supported in the future.
The development of the CANDU3 reactor by AECL started in 1982 and is a logical extension of the power range supported by AECL. No other participants are involved in these developments. The construction of a CANDU3 reactor can begin by 1992. AECL has also indicated to the USNRC its intention to apply for design certification of CANDU3 in the USA. USNRC certification is aimed for by 1995.
A reasonable effort of the vendors, with considerable uncertainties for the SIR development, may be expected in their future development of the reactor types discussed in this study. All vendors have shown a high degree of willingness to cooperate with interested participants in their development programmes. The commitment of their management to remain in nuclear business is evident.

Netherlands' participation

The capability of the Netherlands' industry in supplying materials, components and engineering services is very promising, but some exceptions for delivering materials and large components must be made. AECL has explored the Netherlands' industry and questions three items specifically: the calandria, the pressure tubes, and the heavy water supply.
A high level of experience is required for the manufacturing of the calandria and the pressure tubes. For limited quantities of these components cost competitive manufacturing will be difficult. Manufacturing and processing of heavy water is expensive and will not be cost competitive for the amounts needed for a limited number of reactors.
In general manufacturing by Netherlands' industry of fuel assemblies for any reactor type is not likely, although large scale enrichment capability is present. In the past reactor vessel industry was established in the Netherlands. Due to the worldwide reduction of nuclear power plant orders, vessel manufacturing capability was terminated. It is expected that manufacturing of reactor pressure vessels will be possible again, if prospects for more orders arise. In general manufacturing of large components will be possible, although some industries may consider the efforts for manufacturing one-of-a-kind components as unacceptably high.

7. FUEL CYCLE / WASTE

Fuel

LWRs use slightly enriched uranium; the CANDU3 uses natural uranium in all bundles except for a few bundles which use slightly enriched uranium (up to 1.2% U-235). Uranium is used in the form UO_2 as hot-pressed and sintered pellets. A fraction of the fuel pellets for the LWRs contains burnable poison to control reactivity and to stabilize the power distribution of the core. The poison can be gadolinium (Gd) inserted in the fuel or boron (B) evaporated on to the pellet surface. The pellets are arranged in fuel rods made of Zircaloy; in the LWRs the fuel rods are arranged in a square pitch geometry to form a fuel element. The CANDU3 uses a different geometry: 37 fuel rods are arranged to form a cylindrical fuel bundle. Twelve fuel bundles stacked behind each other then form the so-called fuel channel.
The fuel cycle encompasses exploration of uranium and conversion from ore to uraniumhexafluoride, enrichment, fuel fabrication, reprocessing and waste disposal. The three light water reactors have virtually no differences in need for resources. The CANDU3 does not depend on enrichment facilities but needs heavy water. Large facilities for heavy water production are presently operating in Canada, India, and Argentina.
Cycle-lengths for LWRs of 24 months at full power are theoretically possible with the current fuel technology. However, it implies that with the limited enrichment and burnup almost the full core has

to be replaced, which has an economic penalty. Reactor owners normally aim to replace about one-third of the core per cycle. Therefore, a tendency exists to increase the enrichment and burnup. The CANDU3 has on-line refuelling with the reactor at full power; the equilibrium refuelling rate is about 12 fuel bundles per full power day.

Waste

The main types of waste produced are spent fuel and operational wastes. The amount of decommissioning waste is smaller than the accumulated production of the two other sources; furthermore, it is concluded that the various reactor types do not show significant differences for this aspect. The fission waste production is by nature quite similar for all reactors; however, the actual operational waste production in m^3 may vary considerably.
Due to the higher burnup (a factor of 2.5 - 4) of LWRs compared to CANDUs, LWR spent fuel contains more long-lived radionuclides and actinides. The amount and radioactivity of operational waste strongly depends on the type of materials used in the primary system, the water chemistry, and the design of the clean-up systems. The absorption of neutrons in D_2O, used as coolant and moderator in CANDU reactors, is a source of tritium production, which necessitates purification, in order to limit occupational exposure by possible leakage of tritiated heavy water. No specific data on waste production are available for the four reactors.
However, based on system characteristics, it is estimated that the total waste production will be for the

SBWR	comparable to the previous designs (BWR6, ABWR)
CANDU3	comparable to the CANDU6
AP600	slightly smaller than the previous designs of Westinghouse
SIR	slightly smaller than the AP600.

8. COST COMPARISON

Considering the economics of a power station the generating cost of a particular plant may be broadly subdivided into:

- Capital cost; which tends to dominate the generating cost of nuclear power plants (also in relation with availability)
- Fuel cycle cost
- Operating and maintenance costs
- Decommissioning costs

Economy of scale has played an important role in capital cost for nuclear power plants. A small reactor of a particular type and configuration would therefore be expected to have a higher capital cost per MWe installed than a larger reactor of identical type and configuration (roughly doubled for a 300 MWe power plant in relation to a 1200 MWe conventional single nuclear station). On the other hand a smaller nuclear station may have a number of advantages which compensate the traditional penalties of scale, such as a greater degree of factory fabrication and shorter construction times. Simplification of the design may also be of significant influence in this respect.
Construction times (first concrete to commercial operation) for the four reactors in this study range from 3 - 3.5 years. This period will have to be preceded by 1 - 1.5 years for civil works (very much site dependent). Capital costs range from 1.3 - 1.6 Million US$ per MWe installed, whereas total generating costs vary from approximately 3 - 4 US¢ per kWh. These figures compare favourably with present day costs for large nuclear power stations.

9. CONCLUSIONS AND RECOMMENDATIONS

The four reactor designs compared in this study all have characteristics that make these designs potential candidates for the Netherlands' utilities considering expansion of their nuclear generating capacity. Safety and economy are dealt with in an integrated approach leading to three designs

(SBWR, SIR and AP600) that combine simplicity with a high level of (passive) safety and performance. The CANDU3 uses primarily active safety features and is quite complex compared to the others, although less complex than the previous designs.
The comparison of the four designs was focused on six main characteristics, which were briefly described in the chapters 3 to 8. This comparison study was aimed to generate sufficient input (mainly technically oriented) for the PINK steering committee to decide which reactor design, supplementary to the SBWR, should be considered in more detail in the PINK programme. Shortly before the present study was finalized, the Ministry of Economic Affairs requested to include one or more third stage reactor designs as an extension of the PINK programme I. Therefore a recommendation for active participation in one or more reactor development programmes has been postponed.

Summary evaluation of the selected aspects

General safety characteristics: The four reactor designs have a high safety level. The CANDU3 design was ranked lower in comparison with the light water reactors because of the complexity of the reactor, the reactivity coefficients, which can be positive, and the shorter grace period. The preliminary PSAs did not offer significant differences in the evaluation. All PSAs show low core damage frequencies, in the range of 10^{-6} to 10^{-5} per reactor-year.

Proven technology: All designs, especially the CANDU3, make use of proven technology to a large extent (mostly demonstrated in their earlier designs).

Netherlands' requirements: If any of the reactors in this study were to be licensed in the Netherlands, some adaptations would be necessary. The SBWR and CANDU3 design could comply with Netherlands' requirements if the secondary containment design is adapted; this adaptation does not seem to pose fundamental design problems. The SIR and AP600 would probably require major modifications, especially regarding double containment. Acquaintance with BWR and PWR technology is largely available in the Netherlands, due to two decades of experience gained with the operation of a BWR and a PWR.

Commercial aspects / Netherlands' participation: The type of technology and manufacturing capability required for the construction of a CANDU3 are less developed in the Netherlands compared to what is needed for LWRs. The more units are planned the less the importance of this argument will be. Continuation of the SIR programme is considered to be questionable.

Fuel cycle / waste: Arguments in favour of the CANDU3 are its on-line refuelling and associated high availability. However, there is no experience in the Netherlands with the use of natural uranium and heavy water. There is a well-developed enrichment industry, whereas no heavy water production or tritium purification capability is present.
The amount of waste generated by the four types is not significantly different.

Costs: Capital cost is relatively low for all types under consideration, compared to currently built larger types. Apparently the simplification in the design pays off. Total generating costs for AP600 and SBWR (being almost equal) are higher than the estimated costs for CANDU3 and SIR (twin design). However, it is expected that the difference is mainly due to different calculating bases.