REACTOR TYPES FOR THE FUTURE

by

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SUMMARY

The factors impacting a utility's choice of reactor for commercial exploitation are discussed. Concepts available in time frames of 5, 10 and 20 years are considered. It is concluded that future programmes are likely to be based on a relatively small number of largely pre-licensed turnkey station designs. The near future is likely to be dominated by light water reactors. The Westinghouse AP600 design is briefly described as an example of a soon to be available advanced design.

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INTRODUCTION

The last twenty five years have seen a remarkable growth in the production of nuclear electricity. Although the building of power plants has now paused, it appears that the world's limited fossil fuel supplies, coupled with a more rational view of the relative environmental impacts of alternative energy sources, is likely to assure a healthy long term future for nuclear power.

All new technologies appear to start life with a wealth of concepts, suppliers and models. As a technology matures, its increasing sophistication and cost of development means that new designs can only be economically developed by spreading first time engineering costs over a substantial number of units. This leads to a drift from a situation where each large developed country supports a number of vendors to a situation where only handful of suppliers exist on the world scene. This trend has been very evident in the areas of automobiles, aeroplanes and sophisticated electronics, and is emerging in the nuclear field.

In the case of nuclear power plants, the cost of developing and licensing an entire station design means that the practice of individual utilities or architect engineers developing their own unique station designs around an "off the shelf" nuclear steam supply system is also almost certainly doomed and that in future standardisation is likely to extend to the station.

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It would appear that for nuclear power to fully realise its potential it is necessary for the international community to agree a sensible unified set of safety requirements. This would mean that a developed design could be rapidly and simply licensed for a particular application with new safety work being limited essentially to site related matters. Commercial pressures, nationalism and the "not invented here" syndrome will make the agreement of such a process very difficult. Failing this it would appear sensible for utilities to limit consideration to systems where a reference design exists which is locally licensable with essentially no modification.

The next twenty five years are therefore likely to be characterised by the worldwide application of a relatively small number of largely pre-licensed nuclear station designs.

This paper discusses the criteria impacting the choice of reactor for a given application and the application of these factors to the main reactor types currently available or under development.

CHOOSING A REACTOR

Factors To Be Considered

In order for a reactor design to be considered for construction it must first and foremost be "accceptably" safe. Although there is currently a profusion of derived requirements and guidelines which are applied to achieve this objective, there is a reasonable international consensus as to what constitutes a sensible probabalistic risk target. Most designs currently being offered on the world market by major vendors are likely to meet, or at least come close to, this target when assessed on a reasonable basis. This does not mean that these designs would meet the specific national safety requirements designed to achieve these objectives.

Secondly, the cost per kilowatt hour of electricity must be competitive. Competitiveness may be biased by considerations such as the environment and balance of payment issues. Costs of construction for identical plants may differ widely between countries depending on such factors as labour costs, working practices and, where local content is important, on the local cost and availability of components.

The reliability and availability of the plant must be such as to provide an acceptable security of supply, given the plant's size and local network conditions. The largest plants are acceptable only on relatively large stable networks.

The above factors are, of course, all inter-related. For example, an increase in the complexity of safety systems in order to meet enhanced licensing requirements may impact the cost per kilowatt hour through reduced availability and increased design software and construction time, as well as directly through capital cost.

Total station financing requirements, coupled with all of the above, should be such as render the station financially attractive or at least acceptable. The criteria applied to make this judgement will depend on the local financial environment and on whether the utility is government financed or privately financed.

Different Approaches

Historically there has been a trend to satisfy ever stricter safety requirements by adding more safety systems and increasing their complexity. The consequent increases in plant costs have been partially offset by moving to higher outputs. These large plants require very careful design in order to assure that their complexity does not lead to a significant reduction in availability. Also, great care has to be exercised in the design of the operator interface and in the training of the operators in order to assure that the operator is properly in command of his complex plant. In this respect it is interesting to note firstly that operator error, or lack of operator understanding, has been a major factor in all of the world's most serious nuclear accidents, (ie - Windscale, Three Mile Island, and Chernobyl) and that the simpler 2 loop plants have availabilities which are consistently an average of 10% above their larger cousins. (Ref 1)

In recent years, a number of vendors have undertaken design studies for plants which use a different approach to safety systems. The intent has been to use passive phenomena such as natural circulation and gravity to provide safety functions, rather than to rely on active systems requiring power supplies and control systems. The resulting simplification has led to reduced capital costs and shortened construction times. The phenomena employed generally result in plant size limitations. (Ref 2)

Some of these 'passive' designs, such as the Westinghouse AP600 (See Appendix) are evolutionary in nature and utilise existing components in a revised configuration. These will not require a prototype. (Ref 17) Others such as PIUS and SIR use more revolutionary features such as concrete pressure vessels and steam generators located within the pressure vessel. It is clear that the revolutionary concepts will require the construction and operation of a prototype in order to establish their viability.

Future buyers of power plants will, therefore, be faced with the choice between two design populations with broadly similar generating costs. The one made up of large relatively complex designs and the other of smaller relatively simple designs. These smaller simplified designs are gaining in popularity particularly in the United States. In the author's view nuclear 're-entry' in the United States will probably occur in the middle 1990s and will probably be based on smaller simplified designs.

CURRENT AND FUTURE OPTIONS

An attempt has been made to survey the major designs currently available on the world market and which appear to have a significant chance of being exploited in the near term. The list has been limited to those designs which have been widely accepted on the world market and excludes for example the British AGR which has not been applied outside Britain, or Comecon designs which are limited to the Comecon countries.

The designs currently enjoying wide international acceptance are listed in Table 1.

TABLE 1

REACTOR DESIGNS CURRENTLY ENJOYING WIDE INTERNATIONAL ACCEPTANCE

Design Concept	Major Vendor	Size Range Currently Offered MWe	Approx No in Operation or Under Construction
PWR	Westinghouse, Framatome, Combustion Eng/ ABB, KWU Babcock & Wilcox, Mitsubishi	600 to 1450	200
BWR	GE, ABB, KWU Toshiba, Hitachi	800 to 1250	100
PHWR	AECL, KWU	300 to 900	35

Any attempt to assess which major designs will be available for international commercial application within the next ten years is bound to be judgemental. Table 2 provides the author's view based on information available to him at the time of writing. No claim is made that it is complete. It is accepted that other judgements are possible. (Ref 3,4)

TABLE 2

REACTOR DESIGNS LIKELY TO BE COMMERCIALLY ON OFFER BEFORE 2000 AD

Design	Vendor	Size MWe	Features/Comments
Passive LWRs			
AP600	W/Mitsubishi	600 (2 loop) 900 (3 loop)	(Ref 5,6,7,8,9,10) 4 loop version possible See Appendix
SBWR	GE	600	5,6 (Ref 11)
Active LWRs			
APWR	W/Mitsubishi	1000 1350	1,2,3,4 (Ref 12)
System 80+	GE/ABB	1300	1,2,4 PWR
?	NPI(Framatome & KWU)	?	International PWR Model to be announced (Ref 13)
ABWR	GE/Toshiba/ Hitachi	1350	TEPCO has ordered 2 units 1,2 (Ref 14)

Notes: See Page 7.

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Notes

1. Designed to EPRI requirements document
2. Improved 4 train safeguards in rationalised layout
3. Spectral shift as an option
4. Radial neutron reflector
5. Simplified systems emphasising passive principles
6. Modular construction, pre-fabricated factory modules, short construction period

Currently many new reactor types and advanced variants of existing designs are being proposed for development. Some of the non LWR types make the claim that no containment building is required. In the case of the HTR, this claim is based on the good high temperature fission product retention properties of the ceramic fuel spheres. In the case of the liquid metal cooled fast reactors the case is made that the guard vessel and head closure device achieve the same retention of radioactive materials as the high pressure containment structures used on light water reactors. In the United States NRC is currently discussing this and is expected to make a statement later this year. NRC is also considering whether to require remotely sited prototypes for non LWR advanced designs. This would raise a major hurdle for these designs in the United States. Table 3 lists a selection of advanced designs which may become commercially available within the next 20 years. (Refs 3,4,15,16,17)

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TABLE 3

SELECTION OF ADVANCED REACTOR CONCEPTS CURRENTLY CONSIDERED FOR DEVELOPMENT

Name	Power	Principle Features	Potential Vendors
PIUS	640 (350)	Process Inherent Ultimately Safe PWR. Primary Circuit surrounded by a tank of borated water	ABB
SIR	320	PWR Safe Integral Reactor. Steam generators & pressuriser contained in reactor pressure vessel	Rolls Royce & Ass ABB/Combustion
MHTGR	550	Modular High Temperature Gas Reactor (4 modules)	General Atomics
PRISM	1400	Modular liquid metal fast reactor	General Electric and others

CONCLUSIONS

The magnitude of the investment in a nuclear power plant and the long term nature of that investment necessitates a prudent and cautious approach to the choice of design. The development of new concepts can be expected to be the province of government financed groups or of consortia of utilities. All but the largest government backed utilities can be expected to select either a proven design or a design which represents a cautious evolutionary step forward from an existing design.

The majority of the world's nuclear electricity has to date been generated by light water reactors. Serious generic issues such as the stress corrosion cracking of recirculating pipes and steam generator corrosion came to light only after some years of operation. These are now understood and under control. Given the many hundreds of years of reactor operation which we now have behind us we can be rather confident in the basic integrity of the light water reactor technology.

Exciting new fast reactor and high temperature gas reactor concepts show the potential for economic application in the future, but it will be many years before a prudent utility will be able to realistically select one of these as the basis for a programme.

Some small 'passive' light water reactors based on an evolutionary technology have progressed well into the design and licensing process. However, they are not likely to be available as serious options for construction starts before the mid 1990s.

In the short term, we can expect plant orders to be largely limited to existing light water reactor designs or modest developments of existing designs.

In the intermediate term, say from the middle 1990s until early in the next century, we can expect small passive light water reactors to emerge as serious options. Currently there is every indication that they will be economically competitive with the larger more conventional designs and that they will have special advantages. These include short construction periods, more manageable financing requirements, ease of maintenance and simplicity of operation. They are likely to prove very popular particularly with the small and medium sized utilities. A second step is likely to be the progression to larger versions of the passive designs, and the ability of a concept to support such an enlargement may be an important factor in its success. Large utilities, particularly those with government financial backing may prefer to continue to build the large conventional units.

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The menu of plant designs available to utilities in the longer term, say five to ten years into the next century, will almost certainly continue to contain active and passive light water reactors as popular options. These may be supplemented by one or more of the technologies currently waiting in the wings, such as the fast reactor, high temperature gas reactor or revolutionary light water reactor. Experience suggests that their arrival on the scene will be later than we currently anticipate. Certainly, the world's future nuclear programmes will be based on only a limited number of standardised and highly developed station designs.

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APPENDIX

The Westinghouse Advanced Passive 600 MWe Plant (AP600)

BACKGROUND

The development of the AP600 began in 1985 with the Electric Power Research Institute (EPRI) Small Plant Study, and continued under the US Department of Energy (DoE) technology programme in support of advanced light water reactor. (Ref 2)

The top level objectives were to:-

- Provide a very high degree of public safety (Ref 6)
- Provide a greatly simplified plant in order to simplify operation and to reduce costs
- Use experience based systems and components so as to assure that a plant prototype will not be required
- Use modularisation and other design features to permit a short construction period
- Minimise the impact on the environment

The design team, which is led and managed by Westinghouse includes Bechtel, Burns and Roe, Avondale Shipyards (experts in modular design) and Chicago Bridge and Iron. To date, over 300,000 hours of work have been performed. (Ref 5)

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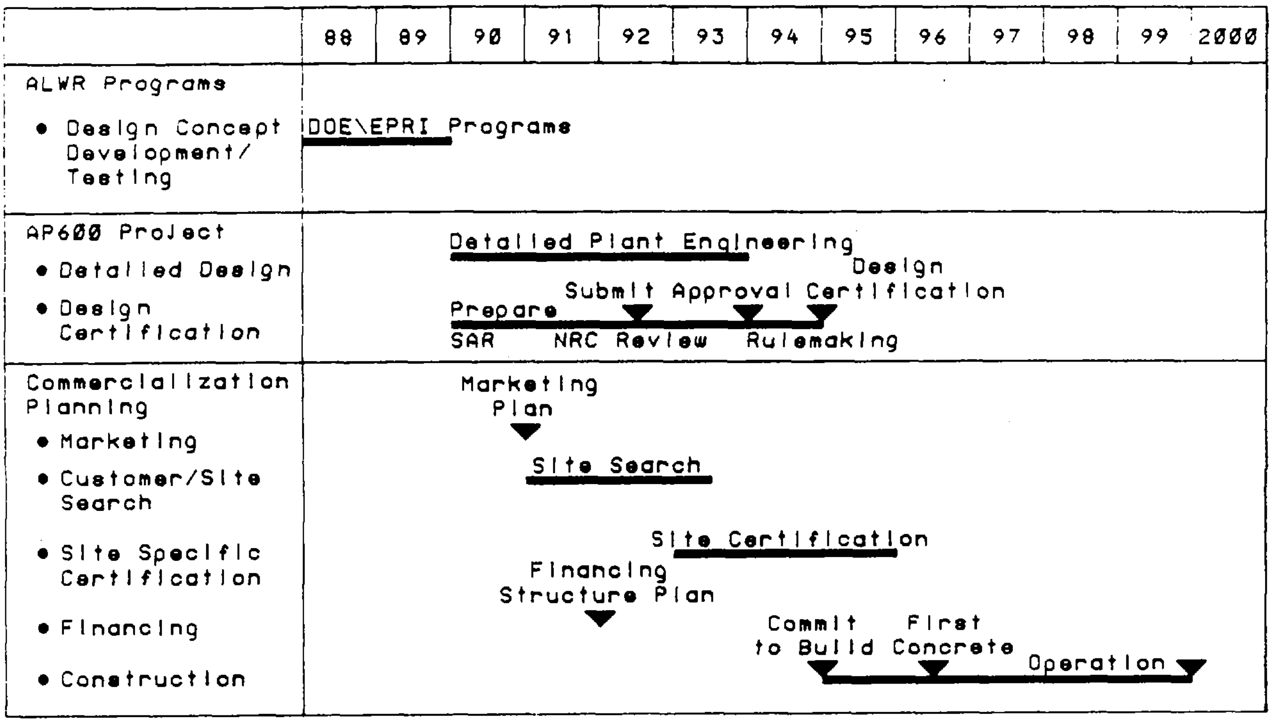
PROGRAMME

Westinghouse have stated their intention to have a plant on line and producing power before the end of the century. The programme to achieve this is shown in figure 1.

Fig 1



It is believed that subsequent stations would be on line within five years of order placement. The first one and a half years would be used for site licensing and preparation, and for the ordering of long lead materials. It would then require three years to construct the plant and a further six months to commission it.

The design process is backed by an extensive test programme which is esssentially completed.

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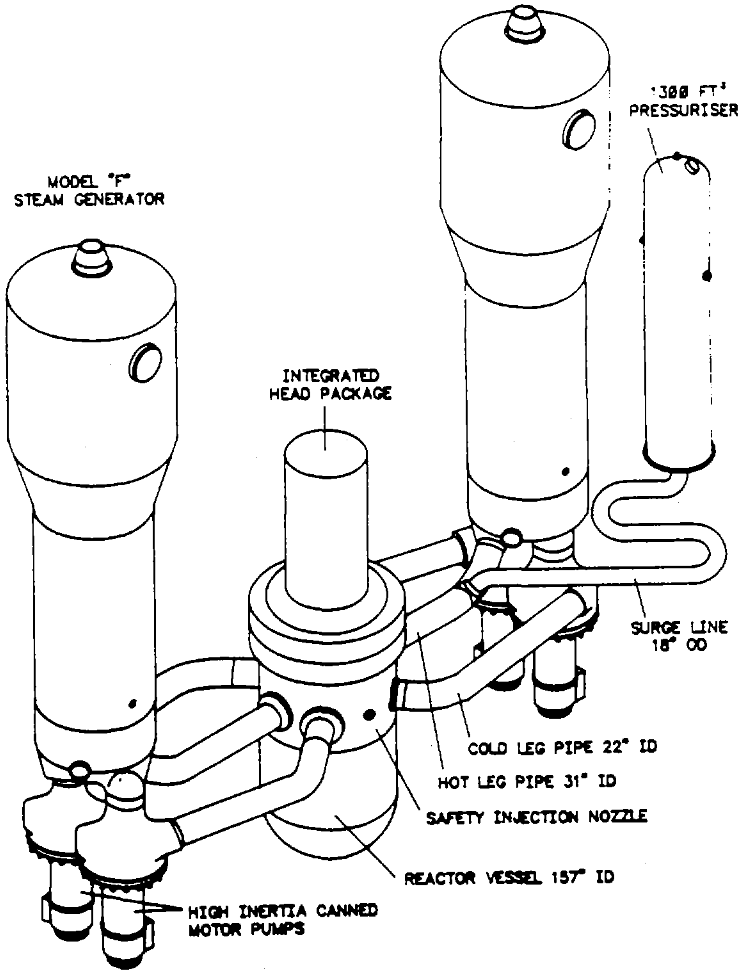
DESIGN FEATURES

Reactor Coolant System

The Reactor Coolant System is shown in Figure 2. It incorporates a vessel similar in design to that used on the conventional three loop plants, such as Koeberg and two model F steam generators. The steam generators are identical to those used on modern Westinghouse plants, such as Sizewell, except that their outlet plenum is modified to accommodate two high inertia canned rotor pumps. The latter are of a design for which a very high experience base exists. A rather large pressuriser is provided. (Ref 7)

Fig 2



The core consists of 145 assemblies of standard Westinghouse OFA design. It is surrounded by a neutron reflector. The linear heat rating is 12.6KW/m or about 70% of that of a modern 2 loop plant such as Napot Point. The vessel fluence is reduced by a factor of about four to 2 x 10^{19} for a 60 year design life. The plant incorporates a hydroball in core flux mapping system which has permitted the deletion of the bottom penetrations in the reactor pressure vessel.

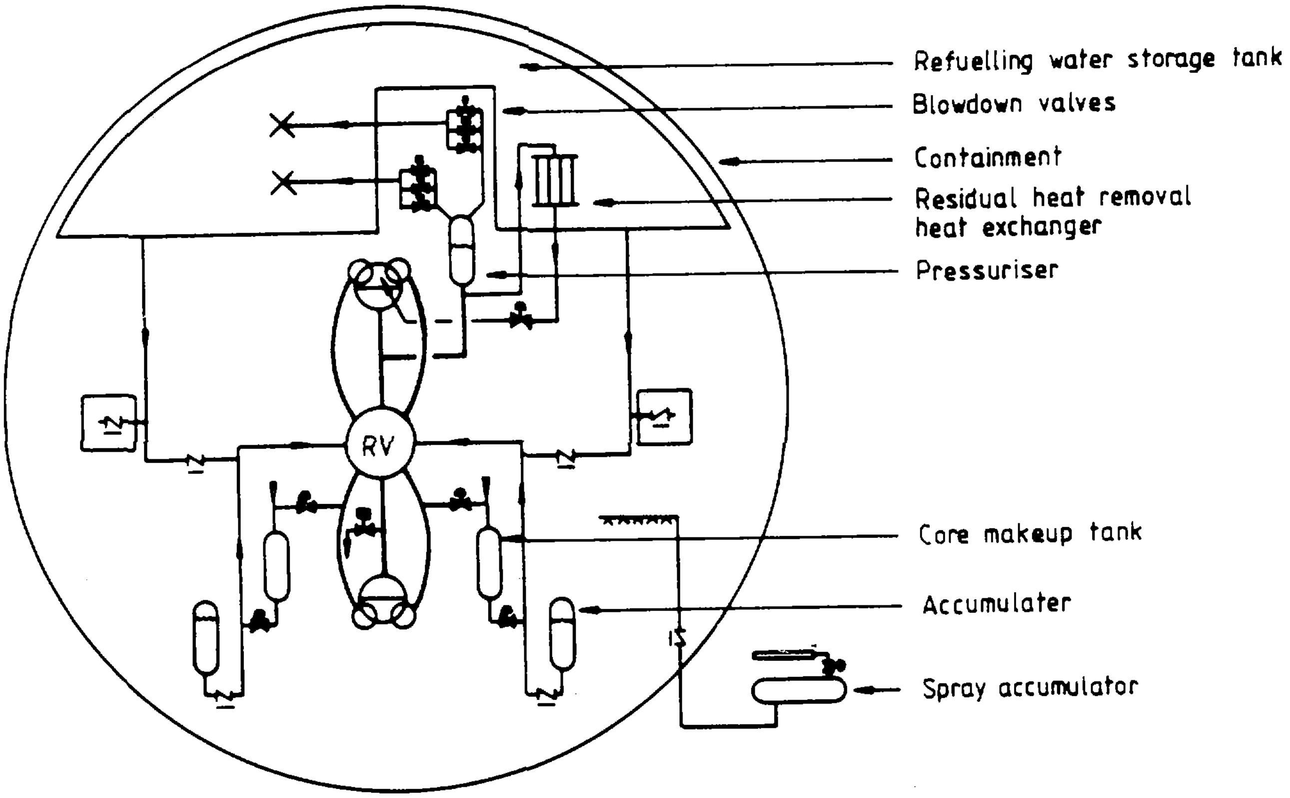
Engineered Safety Features

The AP600 uses passive engineered safeguards. Space prevents other than a brief description of the major principles employed.

Short term, the In Containment Refuelling Water Storage Tank (IRWST) provides the heat sink. In the longer term the atmosphere is used as the ultimate heat sink with heat removal by natural convention from the containment.

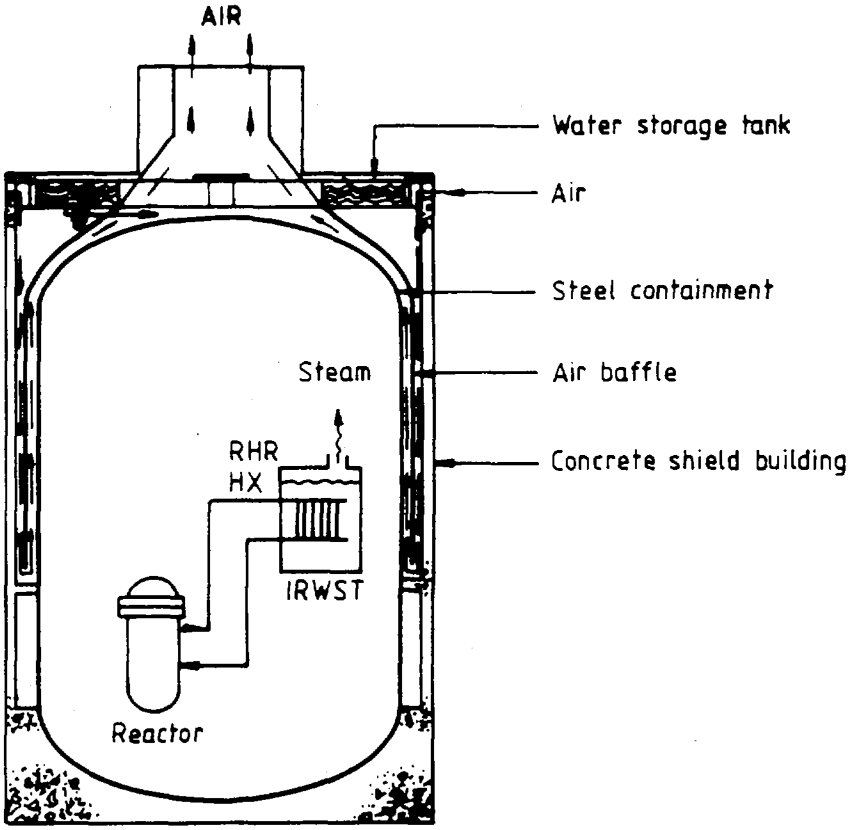
The basic arrangement of the safeguards is shown in Fig 3.

Fig 3



In the event of a station blackout decay heat removal is normally provided by steaming from the steam generators with make-up by a non-safety grade auxiliary feedwater pump, powered by a non safety grade diesel. Should this fail, the safety grade heat removal path is via natural circulation to a high pressure Residual Heat Removal (RHR) heat exchanger, which dumps heat to the IRWST. If this situation persists the IRWST will boil. Steam condenses on the inner water of the containment and drains back to the IRWST. The containment is cooled by natural convection, initially assisted by the evaporation of gravity fed cooling water as shown in Fig 4. (Ref 8)

<u>Fig 4</u>



Initially it was believed that the use of natural convection cooling of the containment as the ultimate heat sink would limit the plant's power to around 600 MWe. Test results now show that 900 MWe is certainly possible, and that 1200 MWe is probably achievable.

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Small Loss of Coolant Accidents (LOCAs) are handled by normally pressurised Core Makeup Tanks (CMTs) which drain into the reactor coolant system under gravity. For larger LOCAs the reactor coolant system is blown down via the pressuriser into the IRWST. Makeup is provided by nitrogen pressurised accumulators, the core make-up tanks and by gravity feed from the IRWST. The ultimate heat sink is again provided by the natural convection cooling of the containment. (Ref 9)

For all accident scenarios there is a requirement for only a once and for all re-alignment of some valves. After this the plant will remain safe indefinitely without any form of operator intervention.

Some indication of the simplifications achieved can be gained by the comparisons of table 4.

TABLE 4

PLANT FEATURES	STD 2 LOOP	AP600
Fuel assemblies	121	145
CRDM - Shut/Control	33	45
- Gray	0	12
Pressuriser	1000 FT3	1300 FT3
RC Pumps	2 Shaft sealed	4 canned
Pumps - Safety	24	0
- NNS	188	139
HVAC Fans	52	27
HVAC Filter Units	16	7
Valves - NSSS (>2")	512	215
- BOP (>2")	2041	1530
Pipe - NSSS (>2")	44,300 FT	11,042FT
- BOP (>2")	97,000 FT	67,000 FT
Evaporators	2	0
Diesel Generators	2 (SC)	1 (NNS)
Bldg Vol - Containment	2.7 MIL FT3	3.0 MIL FT3
- Seismic	6.7 MIL FT3	1.6 MIL FT3
- Non Seismic	6.2 MIL FT3	6.1 MIL FT3

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