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OPERATING EXPERIENCE OF NATURAL CIRCULATION CORE COOLING IN BOILING WATER REACTORS

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ABSTRACT

General Electric (GE) has proposed an advanced boiling water reactor, the Simplified Boiling Water Reactor (SBWR), which will utilize passive, gravity-driven safety systems for emergency core coolant injection. The SBWR design includes no recirculation loops or recirculation pumps. Therefore the SBWR will operate in a natural circulation (NC) mode at full power conditions. This design poses some concerns relative to stability during startup, shutdown, and at power conditions. As a consequence, the NRC has directed personnel at several national labs to help investigate SBWR stability issues. This paper will focus on some of the preliminary findings made at the INEL. Because of the broad range of stability issues this paper will mainly focus on potential geysering instabilities during startup. The two NC designs examined in detail are the US Humboldt Bay Unit 3 BWR-1 plant and Dodewaard plant in the Netherlands. The objective of this paper will be to review operating experience of these two plants and evaluate their relevance to planned SBWR operational procedures. For completeness, experimental work with early natural circulation GE test facilities will also be briefly discussed.

BACKGROUND

The purpose of this section is to provide an overview of early research on BWR stability and its relevance to present SBWR startup design concerns. Stability was of such a concern that, the commercial introduction of BWRs was delayed until experimental data demonstrated that BWRs could be operated safely at high pressures.[1] Despite these early experimental findings, reactor stability is still a concern. There are a host of different kinds of hydrodynamic instabilities that can develop in a BWR system during both normal operation or accident conditions.[2-7] This paper will touch primarily on those aspects of stability most relevant to SBWR startup; only a qualitative discussion will be presented.

The SBWR design is a natural circulation system without benefit of recirculation loops. Natural circulation is controlled by the mean density difference between the coolant inside and outside of the core. Natural circulation driving heads may make the SBWR design less stable relative to conventional BWR designs for certain classes of transients. In general, relatively low core mass flow rates, and/or high power densities produce conditions for sustained power and flow oscillations that may cause fuel damage. Conditions that may lead to such transients are expected to include situations during start up and shut down, rod pattern changes, and ATWS events. Evidence to support the above stability concerns includes empirical observations of stability problems in conventional BWRs. Observed stability problems include the following BWR incidents:[8]

- The Spanish Santa Maria de Garona event that indicated undamped flux oscillations during start-up on December 17, 1984.
- The Italian Caorso plant that experienced two scrams due to high neutron flux oscillations during start-up and at end of cycle in 1985.

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- The American La Salle plant, where neutron flux oscillations where observed after the recirculation pumps were tripped due to a operator error on March 9, 1988.

These above incidents emphasize the need for correct design, monitoring, and operational procedures for new schemes like the SBWR. Fortunately, there is a significant amount of information for early GE BWR-1 designs and the currently operating Dodewaard reactor that will help augment understanding of stability concerns for the current SBWR design.

Experimental Background

The early BWR technology was developed primarily at Argonne National Laboratory (ANL) and the Nuclear Energy Division of the General Electric Company (GE). Kramer has documented early ANL BWR experimental programs, including the BORAX experiments, the Experimental Boiling Water Reactor (EBWR), and the Argonne Low-Power Reactor (ALPR). In addition, Kramer's studies document the SPERT experiments, GE's Vallecitos Boiling Water Reactor (VBWR) and the Dresden Nuclear Power Station. It was findings from these reactor proto-type facilities that lead to the conclusion that stable BWR/1 designs could be developed.[1]

The early test facilities demonstrated that self sustaining power and flow oscillations could be generated during off-normal operating conditions. In the case of the BORAX reactors, diverging power oscillations could be induced when system pressure was maintained near atmospheric conditions. However, when BORAX-II was pressurized to 2.07 MPa (300 psia) the power fluctuations were greatly reduced. The SPERT I reactor also confirmed the BORAX results, producing diverging power oscillations when operating near atmospheric conditions. EBWR tests performed at 4.14 MPa (600 psia) produced stable reactor operation.

VBWR was the first commercial power plant to be licensed by the U.S. Atomic Energy Commission. VBWR was also an experimental system to test various BWR concepts. This plant operated at 7.0 MPa (1000 psig), generating up to 50 MWt of power. The reactor core was approximately 0.9 m (3 ft) high and 0.9 m (3 ft) in diameter. The initial core design utilized flat plate type fuel elements; however, a variety of rodded fuel assemblies were later tested in the facility. Figure 1 presents a flow schematic of key VBWR system components and Table 1 presents a summary of key VBWR parameters.[1,9] The VBWR was constructed so that it could be operated in the following modes:

- Natural circulation, direct cycle

TABLE 1. VBWR PLANT SUMMARY

Rated Thermal Power - MW	50
Designed By	General Electric
Built by	Bechtel Corporation
Coolant Pressure - MPa (psig)	7.0 (1000)
Core Inlet Temperature - °C (°F)	283 (542)
Core Outlet Temperature - °C (°F)	286 (547)
Core Flow Rate - m^3/s (gpm)	1.14 (18000.)
Core Flow Area - m^2 (in^2)	0.084 (130.)
Active Fuel Length - m (in)	0.94 (37.)
Number of Fuel Assemblies	102
Heat Flux - W/m^2 (BTU/ft^2hr)	552 (175000.)
Power Density - kW/l	53.
Heat Transfer Area - m^2 (ft^2)	57.6 (620.)
Vessel Height - m (ft)	6.09 (19.98)
Vessel Diameter - m (ft)	2.3 (7.5)

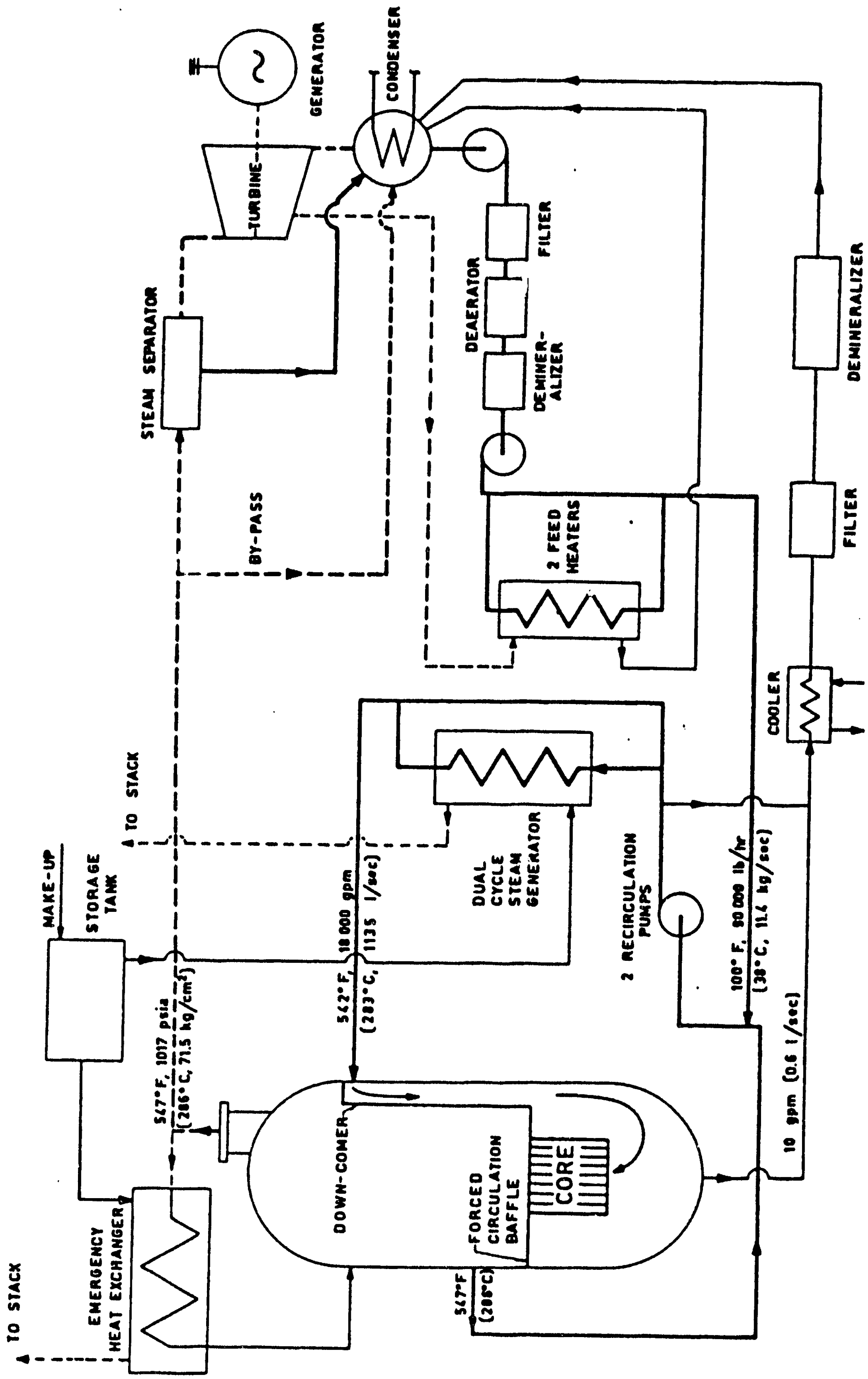

FIGURE 1: VBWR PLANT SCHEMATIC.

- Forced circulation, direct cycle
- Natural circulation, dual cycle
- Forced circulation, dual cycle

Experience gained with VBWR showed stable operation could be maintained during all modes of operation and during normal plant evolutions (i.e. start-up, load follows, full power). However, during power operation, the natural circulation mode was less stable than the forced circulation mode. This difference is attributed to the smaller driving head under natural circulation conditions.

One of the present concerns relative to the SBWR design is the possibility of geysering instabilities. This type of instability is most likely to occur during start-up. Manipulation of the control rods is critical in this operation because the NC BWR is heated by fission energy under low temperature conditions until NC becomes fully developed. Geysering is induced when liquid in a fuel channel is suddenly vaporized, producing a large slug of vapor which grows due to a decrease in hydrostatic head as it moves up the fuel channel. The expanding vapor slug clears liquid from the top of the flow channel. Upon exiting the fuel channel, the vapor slug mixes with subcooled liquid in the upper plenum and is condensed. Subcooled water then reenters the channel and the cycle is repeated. Experiments performed by the Hitachi corporation confirmed the potential for geysering instabilities in the SBWR design.[10]

NC PLANT DESIGNS AND OPERATING HISTORIES

This section discusses the NC plant designs of and the operational experience gained from the Humboldt Bay and Dodewaard commercial power reactors. These reactors were first generation GE BWRs with Dodewaard being located in the Netherlands and Humboldt Bay in the U.S. These early low power reactors were researched to study both the range of variation in designs and their similarity with the proposed SBWR design. The operating practices of each plant were also reviewed to help identify potential problems associated with natural circulation. Finally, a review of the licensing event reports (LERs) was performed for each plant in order to gain insight into potential problem areas that may be inherent to the passive natural circulation core cooling, such as geysering or thermal stratification.

Humboldt Bay

The Humboldt Bay Unit 3 Nuclear Power Plant was designed to generate 63 MW of net electrical power, employing a natural circulation BWR/1 design.[11-15] The plant is located near Eureka, California and was operated by the Pacific Gas and Electric Company. Humboldt Bay Units 1 and 2 are conventional oil and natural gas power plants located at the same site. Key parameters for Humboldt Bay Unit 3 are provided in Table 2. Key flow paths for Humboldt Bay are presented in Figure 2.[9] The plant began operation on February 16, 1963 and was shutdown on July 1, 1983.The Humboldt Bay Unit 3 plant employed a direct-cycle, natural circulation design with internal separation. The bottom entry control rods were cruciform in shape, and were hydraulically actuated. Individual fuel rods consisted of 0.0107 m (0.420 in) diameter fuel pellets stacked in a Zr-2 tube. Primary separation of water from steam was by free surface or gravity forces. Steam from the chimney was passed through impingement (screen or corrugated plate) type dryers with the discharged steam having 0.1% or less moisture content. In the event the turbine was off line, steam could be bypassed directly to the condenser hot well. If the condenser vacuum was lost, steam could be diverted to an emergency isolation condenser. The secondary side of the isolation condenser was vented directly to the atmosphere and there was sufficient secondary inventory for eight hours of shutdown decay energy removal.

The Humboldt Bay design took advantage of the operating experience gained from the EBWR, VBWR, and Dresden 1 units.[16] In many respects, the stability design philosophy of Humboldt Bay was similar to the forced convection Dresden 1 plant. The Humboldt Bay plant:

- Was designed to operate at relatively high pressures 7.13 MPa (1020 psig) where geysering instabilities are unlikely to develop.
- Design incorporated a relatively long fuel thermal time constant to maintain stability.
- Used reliable level and pressure control systems.

The above design strategy ensured a negative overall power coefficient over the entire range of operating conditions. A number of built in safeguards against accidents were incorporated into the plant design; these include:

- The core design ensured that the reactor will tend to shut itself down upon a potentially dangerous increase in its power -- that is, an increase in fuel temperature or steam void volume provided a negative reactivity feedback.

TABLE 2. KEY PARAMETERS FOR THE HUMBOLDT BAY UNIT 3 STATION

Rated Thermal Power - MW	165[a]
Designed By	General Electric
Built by	Bechtel Corporation
Coolant Pressure - MPa (psig)	7.13 (1020.)
Feedwater Inlet Temperature - °C (°F)	134 (273)
Core Inlet Temperature - °C (°F)	280 (537)
Core Outlet Temperature - °C (°F)	287 (549)
Core Flow Rate - kg/s (lbm/hr)	1.57×10^3 (12.5×10^6)
Flow Area per Assembly - m^2 (in^2)	0.0080 (12.4)
Steam Flow Rate - kg/s (lbm/hr)	73.6 (584000.)
Average Core Exit Quality	0.063
Active Fuel Length - m (ft)	2.0 (6.5)
Number of Assemblies	172
Number of Fuel Rods per Assembly	49
Average Heat Flux - W/m^2 (BTU/ft^2hr)	2.54×10^5 (80600.)
Average Core Volume Power Density - kW/l	27.
Core Heat Transfer Area - m^2 (ft^2)	625. (6726.)
Core Diameter - m (ft)	2.0 (6.5)
Chimney height - m (ft)	3.1 (10.2)
Vessel Height - m (ft)	13 (42)
Vessel Inside Diameter - m (ft)	3 (10)

a. Later upgraded to 200 MWt before shutting down.

- Two separate and independent reactor shutdown systems were provided. One system utilized the reactor control rods for fast automatic shutdown. The second system was an emergency backup of the first that provided injection of borated liquid.
- Three separate and independent systems for cooling the reactor were provided. The main power system cooled the reactor under design operating conditions using the turbine and main condenser. The second system used an emergency condenser to cool the reactor following a scram. Finally, the third system injected cooling water through a spray ring above the core to prevent fuel damage following loss of RPV liquid inventory.

Startup and Stability Testing. Start-up to full power could either be initiated from hot or cold zero power conditions. Initiation from cold power occurred following refueling or maintenance operations that required the reactor to be shutdown for an extended period of time. From an initially cold state, reactor criticality was achieved through control rod withdrawal. As the reactor reached 10^{-2} of full power, boiling began and void formation caused natural circulation flow rates to increase. After initial criticality, the control rods were further withdrawn until a period of about 30 s or longer was obtained. This period was maintained until the heating rate was established to bring the reactor coolant temperature up by some prescribed rate.

A summary of the cold start-up procedure is as follows:

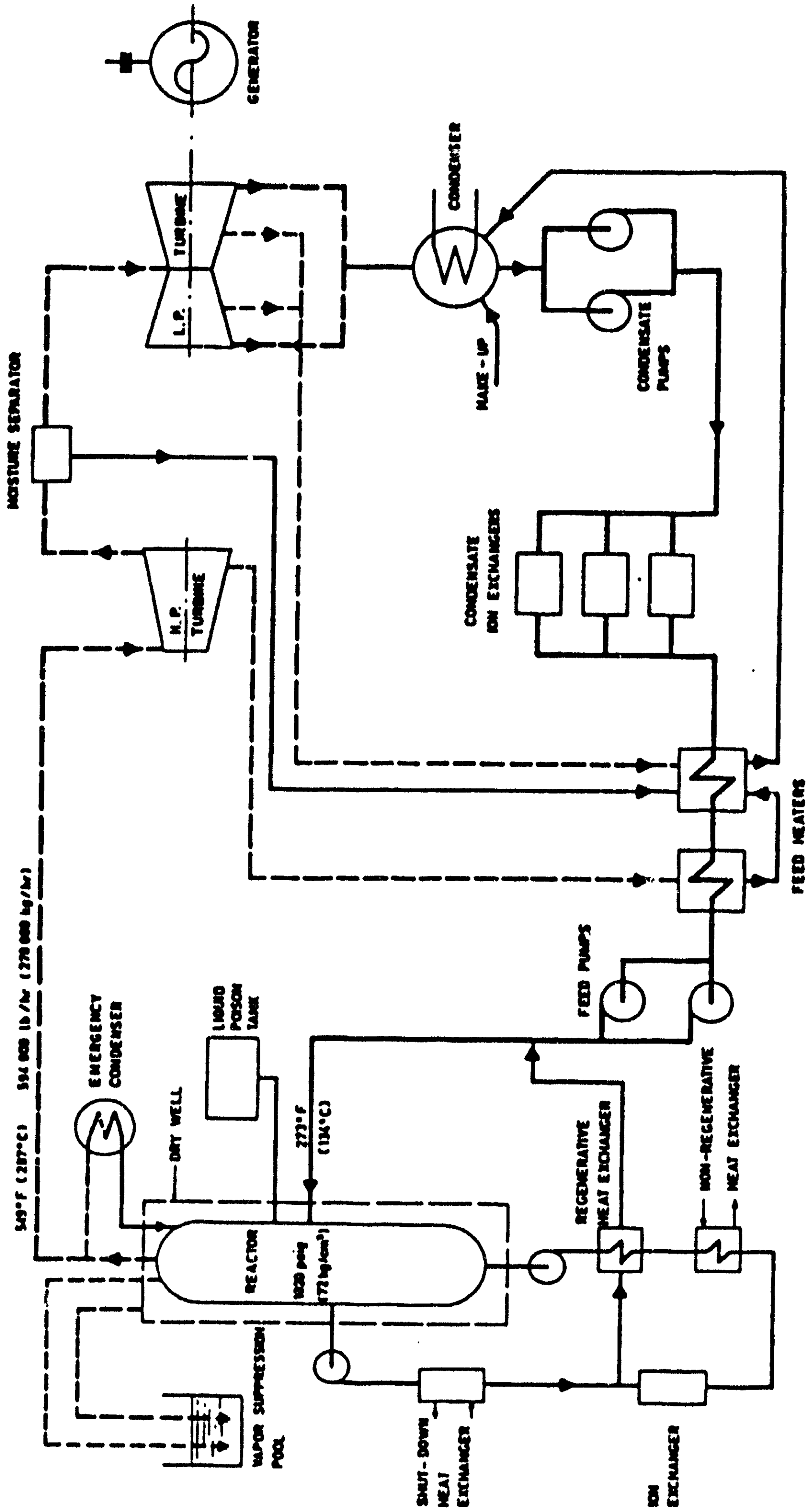

FIGURE 2: HUMBOLDT BAY FLOW DIAGRAM.

- Beginning at atmospheric conditions, the reactor was brought critical by control rod withdrawal following a prescribed withdrawal pattern.
- The power was adjusted once criticality was reached to maintain a coolant temperature rise of no more that 83 °C/hr (150 °F/hr).
- The turbine was rolled once the system pressure was above 2.5 MPa (350 psig).
- The electrical load demand was increased by withdrawing control rods to meet grid load demands. The electrical load was limited to 5 MWe and reactor power to 20 MWt until the reactor reached operating pressure of 7.13 MPa (1020 psig).

Stability testing was part of a power operation test program for Humboldt Bay Unit 1 that commenced after initial fuel loading and criticality had been completed. The stability test program was done over a range of powers. Step changes in power resulted in small oscillations that were rapidly damped out. Other system wide stability tests were also performed and no self sustaining oscillations were observed. Step changes were induced by rapid movement of the control rods which change power by 5-10% or by sudden pressure regulator set point changes. Results of these stability tests also reinforced the results from operating experience of Dresden, VBWR and EBWR that for normal plant operating conditions (full power and high pressure) the plant exhibits a stable response to random perturbations.

In the course of performing the power operation test program, undamped oscillations were induced during carryover and carryunder tests.[14] These tests were performed at 40, 80, 125, 145 and 165 MWt. In some tests the level in the vessel was raised above normal level to 1.3 m (4.2 ft) above the chimney. These oscillations occurred at 145 MWt and had amplitudes of about 10 MW. These power oscillations were relatively small compared to full power and were suppressed when the vessel level was reduced to within the normal operating range. As long as the water level was maintained in the normal operating range this problem was suppressed.

Dodewaard

The Dodewaard reactor is a small 183 MWt natural circulation BWR/1 located in the Netherlands.[17-22] Table 3 presents key plant parameters and Figure 3 presents a flow schematic of the plant[9]. Dodewaard was designed by GE and was built by the Dutch industry from 1965-1968. Initial start-up of the reactor was in 1968. Since then the plant has been continuously operating. Systematic research has been performed at the Dodewaard plant over the last ten years to evaluate BWR stability and stability monitoring techniques. The only other known natural circulation BWR operating at this time is the Melekess VK-50 BWR in the former Soviet Union.

The reactor consists of 164 rectangular fuel assemblies. Each assembly consists of 35 fuel rods contained in a 6x6 rectangular lattice. Thirty seven control rod assemblies which can be positioned at 23 fixed axial positions are used to control the magnitude and shape of the core power distribution. The control rods are cruciform in shape. Individual fuel rods consist of 0.01145 m (0.45 in) diameter fuel pellets stacked in Zr-2 tubing.

Located above the top of the core, are 45 chimney channels. These channels effectively cover the top of the core and help to enhance steam separation. Primary separation of water from steam is by free surface or gravity forces. This separation begins at the top of the chimney columns. Steam from the chimney is passed through an internal vessel steam separator and then to the turbine. Feedwater is injected into the vessel via spargers to ensure uniform flow into the downcomer region. This liquid mixes with the return-saturated liquid from the separator region. At the bottom of the downcomer, the water flows through the shroud, into the lower plenum region, and then upwards through holes in the fuel support plates into the fuel region.

In the event the turbine is off line, steam can be bypassed directly to the condenser hot well. If the condenser vacuum is lost, steam can be diverted to an emergency IC. The IC has the capacity to dissipate 6% of the normal full load reactor power. This system has a return line going to the RPV downcomer. The IC is driven by natural circulation with steam flowing from the RPV, condensing on the tube side of the heat exchanger, and returning by gravity to the RPV. The ECC system consists of high pressure and low pressure systems to recover core liquid inventory. The high pressure system is defined as the liquid return flow from the IC. The low pressure system is pump driven and is automatically activated when the RPV pressure drops to 1.5 MPa (220 psia).

Start-Up Procedures and Stability Testing. The reactor heatup and pressurization procedure for the Dodewaard plant start-up is similar to the planned procedures for the SBWR.[10] Cold start up is initiated at a refueling water temperature of approximately 60 °C (140 °F). The initial coolant heat up is done with the reactor shutdown cooling system or decay power. When the coolant reaches saturation conditions of 100 °C (212 °F) the reactor is brought to

TABLE 3. KEY PARAMETERS FOR THE DODEWAARD STATION

Rated Thermal Power - MW	183
Designed By	GE
Built By	NVGKN
Coolant Pressure - MPa (psig)	7.5 (1073)
Feedwater Temperature - °C (°F)	138.4 (281)
Core Inlet Temperature - °C (°F)	286 (547)
Core Outlet Temperature - °C (°F)	291 (556)
Total Core Flow Rate - kg/s (lbm/hr)	1.25×10^{3} (9.9×10^{6})
Coolant Flow Area per Assembly - m^2 (in^2)	6.96×10^{-3} (10.8)
Steam Flow Rate - kg/s (lbm/hr)	84 (6.7×10^{5})
Average Core Exit Quality	0.075
Active Fuel Length - m (ft)	1.8 (6)
Number of Assemblies	164
Number of Fuel Rods per Assembly	35
Average Heat Flux - W/m^2 (BTU/ft^2hr)	3.67×10^{5} (1.16x105)
Average Core Volume Power Density - kW/l	38.4
Core Heat Transfer Area - m^2 (ft^2)	436.2 (4695)
Core diameter - m (ft)	1.8 (6)
Chimney Height - m (ft)	3.048 (10.0)
Vessel Height - m (ft)	12.090 (39.7)
Vessel Inside Diameter - m (ft)	2.8 (9.2)

critical conditions; the power and pressure are then slowly increased to full load conditions. Reactor heatup rate is then controlled at rate of 45 (113) to 55 °C (131 °F) per hour with the control rod system. During the course of plant startup no unstable oscillations have been observed during the Dodewaard operational history. However, in the early development of Dodewaard start-up procedures, thermal stratification was identified as one potential problem.[21,22] That is, there was a tendency for colder water to accumulate in the lower plenum region as the fluid in the core region became progressively hotter. At the onset of core boiling, the recirculation rate is increased which may cause sudden entrainment of subcooled water trapped in the lower plenum. Sudden entrainment would convect this liquid into the core region which would trigger a power increase and attendant unstable flow/power oscillations.

Because of this problem, a couple of countermeasures have been formulated to ensure that adequate mixing between liquid in the lower plenum and downcomer region developed during start-up. One countermeasure, developed at Dodewaard employs the use of a bottom drain line, lower plenum junction for draining stagnant cold water out of the lower head before significant boiling occurs. The drained fluid was recirculated back into the vessel downcomer. This countermeasure is not without its own risks, since the probable frequency of a bottom line break is increased. An alternate countermeasure against lower plenum stratification suggested by staff at Dodewaard is to open the main steam line valves at low pressure to induce early bulk boiling. This will increase the recirculation rate and reduce stratification in the lower head. However, this reduction in pressure increases the chances of geysering.

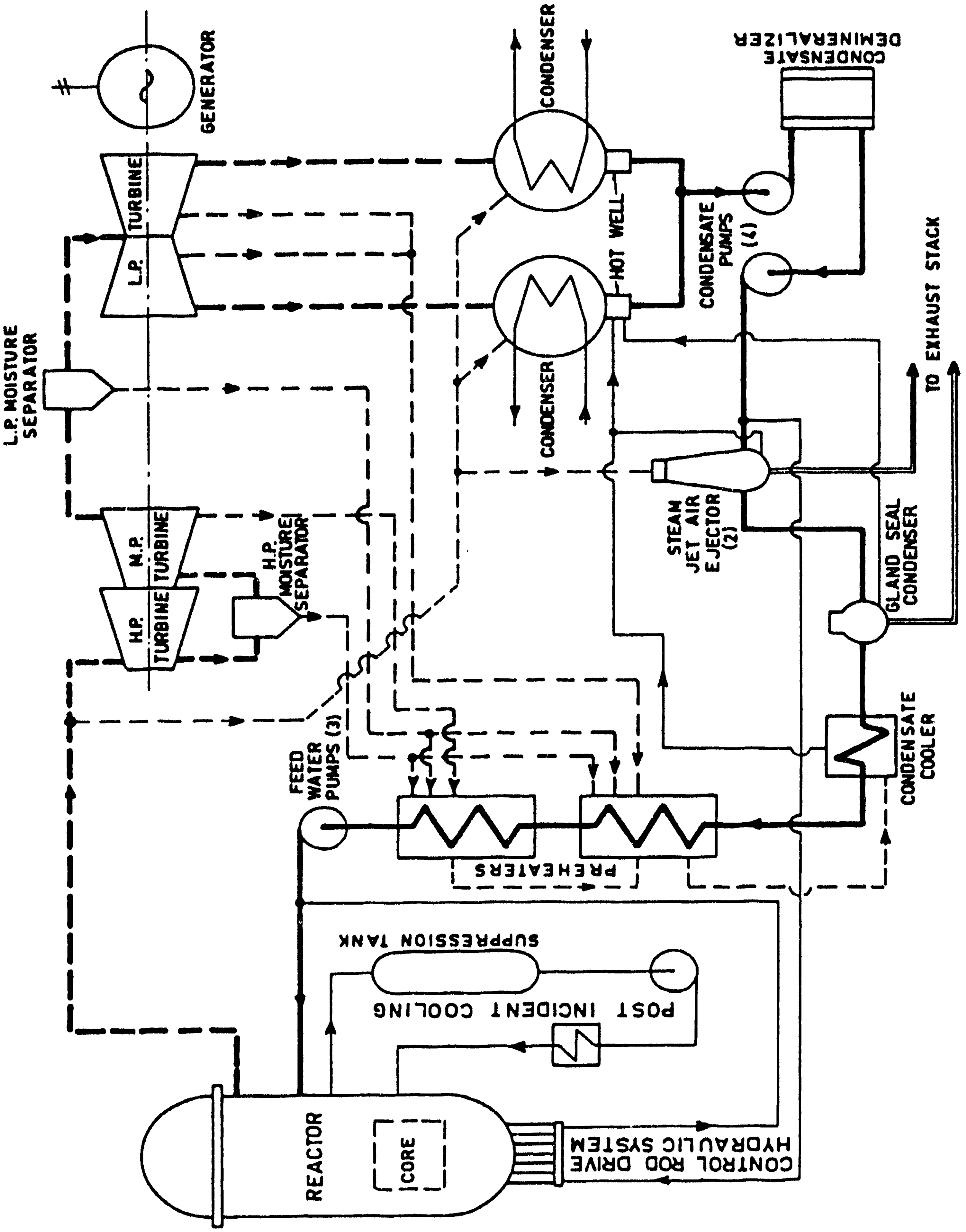

FIGURE 3: DODEWAARD FLOW DIAGRAM.

State-of-the-art stability measurement techniques have been used at Dodewaard. These methods are applicable for identifying potential instability problems in the SBWR design. Stability testing at Dodewaard included investigating reactor kinetic stability, thermal-hydraulic stability, and total-plant stability. Standard testing techniques were similar to those first used at Humboldt Bay. A more recent technique employing noise analysis from both neutron detector and thermocouple signals was employed.[18] Noise analysis relies on a data processing methods that filter out signals that characterize unstable flow patterns in the RPV. Stability tests at Dodewaard have shown this plant operates with a very large margin to instability. It was concluded by KEMA personnel that the Dodewaard reactor is a highly self-regulating system, due in large part to natural circulation. This self regulation feature has been demonstrated by conducting tests with the pressure and feedwater control systems switched off for several hours while the reactor power level was perturbed with control rod movements.

APPLICABILITY OF OPERATING EXPERIENCE TO SBWR

The Simplified Boiling Water Reactor is a 2000 MWt advanced reactor design proposed by General Electric.[10] The SBWR design uses passively driven safety features such as a passive containment cooling system (PCCS) and a gravity-driven cooling system (GDCS). The reactor design is a natural circulation, direct cycle nuclear power plant with vessel internal separation. The natural circulation design simplifies plant operation and reduces capital equipment expenditure through elimination of the recirculation pump loops. Natural circulation in the RPV is driven by the mean density difference between coolant in the downcomer and that in the core-chimney region. A tall chimney section is used to enhance natural circulation flow.

Start-up procedures

Specific SBWR standard operating procedures were considered by GE to be beyond the scope of their SSAR. However, some representative information for typical operation was provided in sections related to component descriptions and safety features. The following is a summary of what was documented in the SBWR SSAR regarding startup operating procedures. The reactor heatup and pressurization procedure during a typical startup from cold conditions involves the following steps:

- First, the reactor water is heated to 80 °C (176 °F). Two electric immersion heaters in the reactor shutdown cooling (SDC) system provide heating capability during this phase especially during initial start-up when there is little to no decay heat. Then the reactor pressure is maintained at 356 mm (14 in) Hg vacuum for deaeration operation.
- After the deaeration operation, the reactor is made critical by withdrawing the control rods in a prescribed pattern.
- The reactor heatup is performed by withdrawing control rods. A heatup rate of less than 55.6 °C/hr (100 °F/hr) is maintained by controlling the reactor power with control rods. Initially, the reactor power is kept low and then gradually increased up to 1 to 2% of rated power during heatup period.
- Typically, the reactor absolute pressure is near 0.1 MPa (14.5 psia) when the reactor power starts to increase. The reactor pressure increases correspondingly with the reactor vessel heatup rate. Initially, the reactor pressure is controlled by the main steam drain line valves and later by the turbine bypass valve.
- After the reactor pressure reaches the rated pressure, the reactor power is increased to the rated power.

During startup the core inlet subcooling is expected to be low. The SDC system is designed to provide up to 25.2 l/s (400 gpm) of flow out of the bottom head. Coolant is returned to the RPV by the feedwater line. This mass flow rate is judged by GE staff to be sufficient to minimize lower plenum temperature stratification. The SDC also helps to maintain the correct vessel level during power increases. When boiling starts, voiding in the core and RPV chimney regions will generate a NC head that is sufficiently large to drive core flows that further mix subcooled water in the lower plenum with the heated core liquid. Even with no core boiling, the core inlet subcooling is expected to be low because of the recirculation of reactor coolant via the SDC line. At progressively higher power levels, subcooling stability requirements become more complex. Recent experimental data indicates that, for higher powers, inlet subcooling may either improve or degrade system stability.[23,24]

Comparison of SBWR With Earlier NC BWRs

Presented in Table 4 are key comparisons of SBWR design parameters with a standard BWR/6, Dodewaard, and Humboldt Bay. The referenced BWR/6 is included to enhance understanding of forced versus NC BWR design. For instance, NC BWRs have a relatively large chimney section relative to forced circulation BWRs. This chimney section is required to generate sufficient hydrostatic head to drive NC at 100% power. Consequently, density wave feedback, geysering phenomena, and overall plant stability may be fundamentally different between a NC BWR and a forced flow BWR which operate at similar power levels and have a similar core design.

With regard to NC BWR differences, a three-way comparison of the parameters in Table 4 indicates that there are significant quantitative differences despite the fact that each system is qualitatively the same. The SBWR has a much larger chimney height, larger subcooling, longer fuel, a different instrumentation configuration, different contro. systems, and a higher power relative to Humboldt Bay and Dodewaard. Because of the smaller NC driving heads in Dodewaard and Humboldt Bay there is substantially less subcooling in these smaller reactors. Moreover, both Dodewaard and Humboldt Bay have substantially shorter cores. These geometric differences are expected to change the SBWR stability margin relative to Dodewaard or Humboldt Bay. The taller chimney of the SBWR will provide a greater natural circulation driving head, tending to improve reactor stability at full power conditions. This is born out by design studies that indicate larger chimney heights improve the stability response.[25,26] However, during startup under certain circumstances, too long a chimney can reduce stability.[27] In addition, increased subcooling, longer fuel length and higher power densities may tend to adversely affect overall stability reactor stability. Also geometric differences between the SBWR design and the early NC BWR-1 plants may play a role in temperature stratification response in the RPV. A taller SBWR chimney is expected to significantly change the vessel mixing dynamics. However, analytical investigations will need to be conducted to evaluate whether these combined differences will enhance or degrade overall SBWR stability relative to Dodewaard or Humboldt Bay. There are other key parameters such as the fuel thermal time constant that may play a critical role in differences in stability. There was not sufficient information to make comparisons for these parameters. Finally, the control system technology for the SBWR will be significantly different than what is presently in Dodewaard or Humboldt Bay. These differences must be quantified to determine how overall SBWR plant stability is affected.

CONCLUSIONS

From the above comparisons, it was determined that the SBWR is qualitatively similar to Humboldt Bay and Dodewaard reactors. As previously noted, Dodewaard start-up data was judged by GE to be applicable to formulating SBWR start-up procedures. However, the SBWR is

TABLE 4. COMPARISON OF SBWR WITH OTHER RELEVANT REACTOR CONFIGURATIONS

Comparison of Properties	BWR/6	SBWR	Dodewaard	Humboldt Bay[a]
Rated Thermal Power (MWt)	3840	2000	183	165
Cycle Type	Direct	Direct	Direct	Direct
Recirculation	Forced	NC	NC	NC
Power Density (kW/l)	50	41.5	38.4	27
Active Fuel Length (m)	3.81	2.74	1.8	2.0
Chimney Length (m)	2.1	9.05	3.048	2.0
Number of Assemblies	800	732	164	172
Average Core Exit Quality	0.15	0.14	0.075	0.063
Average Bundle Power (MW)	4.8	2.7	1.1	0.96
Core ΔP (kPa)	172	48	31	31[b]
Fuel Array	9 by 9	8 by 8	6 by 6	7 by 7
Core Inlet Subcooling (kJ/kg)	70	46.5	21	28

a. Humboldt Bay is currently shutdown.

b. Estimated.

quantitatively different relative to the smaller Humboldt Bay and Dodewaard reactors. Modes of instability that could appear in a SBWR may have fundamentally different quantitative characteristics because of the larger chimney elevation, higher power densities, etc. In general, the taller SBWR chimney is expected to improve stability while the increased subcooling, higher power density and longer core region are expected to adversely affect reactor stability. Further research is necessary to quantify the impact of these combined effects on stability.

ACKNOWLEDGEMENTS

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