CORE DESIGNS OF ABWR FOR PROPOSED OF THE FIRST NUCLEAR POWER PLANT IN INDONESIA

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Diterima editor 10 November 2010
Disetujui untuk publikasi 26 Januari 2011

ABSTRACT

CORE DESIGNS OF ABWR FOR PROPOSED THE FIRST OF NUCLEAR POWER PLANT IN INDONESIA. Indonesia as an archipelago has been experiencing high growth industry and energy demand due to high population growth, dynamic economic activities. The total population is around 230 million people and 75 % to the total population is living in Java. The introduction of Nuclear Power Plant on Java Bali electricity grid will be possible in 2022 for 2 GWe, using proven technology reactor like ABWR or others light water reactor with nominal power 1000 MWe. In this case, the rated thermal power for the equilibrium cycles is 3926 MWt, the cycle length is 18 month and overall capacity factor is 87 %. The designs were performed for an 872-fuel bundles ABWR core using GE-11 fuel type in an 9×9 fuel rod arrays with 2 Large Central Water Rods (LCWR). The calculations were divided into two steps; the first is to generate bundle library and the other is to make the thermal and reactivity limits satisfied for the core designs. Toshiba General Electric Bundle lattice Analysis (TGBLA) and PANACEA computer codes were used as designs tools. TGBLA is a General Electric proprietary computer code which is used to generate bundle lattice library for fuel designs. PANACEA is General Electric proprietary computer code which is used as thermal hydraulic and neutronic coupled BWR core simulator. This result of core designs describes reactivity and thermal margins i.e.; Maximum Linear Heat Generation rate (MLHGR) is lower than 14.4 kW/ft, Minimum Critical Power Ratio (MCPR) is upper than 1.25, Hot Excess Reactivity (HOTXS) is upper than 1 %Δk at BOC and 0.8 %Δk at 200 MWD/ST and Cold Shutdown Margin Reactivity (CSDM) is upper than 1 %Δk. It is concluded that the equilibrium core design using GE-11 fuel bundle type satisfies the core design objectives for the proposed of the firs Indonesia ABWR Nuclear Power Plant.

Key word: The first NPP in Indonesia, ABWR-1000 MWe, and core designs.

ABSTRAK

DESAIN TERAS PLTN ABWR UNTUK DIUSULKAN PERTAMA DIBANGUN DI INDONESIA. *Indonesia adalah sebagai negara kepulauan yang laju pertumbuhan industri, energi, penduduk dan ekonominya cukup tinggi. Pada saat ini, jumlah penduduk Indonesia ada sekitar 230 juta dan 75 % dari jumlah penduduk tersebut tinggal di Pulau Jawa. Pada tahun 2022, dimungkinkan sistem jaringan Jawa-Bali dapat menerima beban 2 unit PLTN yang teknologinya sudah teruji seperti PLTN ABWR atau PLTN air ringan lainnya yang kapasitasnya masing-masing 1 GW. Untuk itu diambilah contoh perhitungan untuk PLTN ABWR pada siklus keseimbangan dengan daya termal 3926 MWt dan lama operasi 18 bulan dan kapasitas faktornya minimum 87 %. Desain ini telah dicapai dengan jumlah bahan bakar teras 872 bundel bahan bakar tipe GE-11 yang susunannya 9×9 batang bahan bakar yang ditengahnya ditempatkan 2 bahan bakar besar tiruan yang berisi air. Ada 2 langkah perhitungan; pertama adalah menggenerasikan pustaka data bundel bahan bakar dan selanjutnya digunakan untuk analisis termal dan reaktivitas dalam teras. Desain teras menggunakan kode komputer Toshiba General Electric Bundle Lattice Analysis (TGBLA) dan PANACEA. TGBLA adalah sebuah kode komputer yang dimiliki oleh General Electric Nuclear Energy untuk menggenerasikan pustaka data dalam sistem satuan cell dalam* *setiap batang bahan bakar dalam setiap bundle. PANACEA adalah kode komputer milik General Electric yang digunakan untuk analisis thermal hydraulic dan netronik yang digabung dalam simulator PLTN BWR. Hasil desain teras menguraikan tentang karakteristik termal dan reaktivitas teras seperti; laju maksimum pembangkitan panas linier (MLHGR) adalah lebih rendah dari 14,4 kW/ft, rasio daya kritis minimum (MCPR) adalah diatas dari 1,25, Reaktivitas Panas Lebih (HOTXS) adalah lebih besar dari 1 %Δk pada BOC dan 0,8 %Δk pada 200 MWD/ST dan reaktivitas shutdown margin dingin (CSDM) adalah lebih besar dari 1 %Δk. Untuk itu dapat disimpulkan bahwa desain teras PLTN ABWR pertama untuk diusulkan dibangun pertama di Indonesia dengan menggunakan bundle bahan bakar tipe GE-11 adalah telah memenuhi persyaratan dan tujuan desain.*

Kata kunci: PLTN pertama di Indonesia, ABWR-1000 MWe, dan desain teras.

INTRODUCTION

Indonesia as an archipelago has been experiencing high growth industry and energy demand due to high population growth, dynamic economic activities. The total population is around 210 million people and 75 % to the total population is living in Java. The introduction of Nuclear Power Plant on Java Bali electricity grid will be possible in 2022 for 2 GWe, using proven technology reactor like ABWR or others light water reactor with nominal power 1000 MWe [1,2,3].

Advanced Boiling Water Reactor (ABWR) evolves as one of the contemporary, most advanced, commercially available nuclear power reactors and has been installed and operated successfully at full power in Japan [4]. ABWR will also be installed in Taiwan [5] and is being considered as one of the most possible nuclear power reactor selections in Indonesia.

Studies to assess the feasibility of installing an ABWR for power generation in Indonesia are ongoing [6]. This paper describes the ABWR core designs recently developed specifically feasibility studies of the proposed first Indonesia nuclear power reactor and the associated spectral shift effect due to gradual core flow increase near the end of cycle (EOC) on these ABWR core designs.

The initial cores of Kashiwazaki-6 and -7 ABWRs in Japan were designed to operate on 13-months fuel cycle and utilized an older commercially standard GE9 type fuel bundle configuration, consisting of an 8×8 fuel rod array with 60 fuel rods and one large central water rod [7]. The ABWR cores for the Indonesia feasibility studies were designed to operate on an optimized 18 month fuel cycle and utilized a more technically advanced, but still standard, and commercially licensed GE11 fuel bundle design, consisting of a 9×9 fuel rod array with 74 fuel rods and two central water rods.

FUEL DESIGN SYSTEM (FDS)

The first functions of the Fuel Design System (FDS) is provide a nuclear heat generation source for the Composite Nuclear System (CNS) by producing thermal energy at power levels up to licensed conditions over the specified cycle energy increment. The second FDS is provide for transfer of this thermal energy to the reactor coolant while remaining within thermal limits and compliance with all safety requirements under normal and transient conditions. The third FDS is provide for regulation of thermal power output by means of control blade movement.

Unlike other plant systems, the core design is subject to routine change each cycle of operation. A complete description of the IABWR core design and operation is included in the following section. System level design requirements for the FDS consist primarily of functional, performance and procedural constraints on cycle specific design work. The following describes the FDS outputs.

The FDS system level design includes the required nuclear and thermal hydraulic characteristics of and operational constraints on the reactor core, and limit with the interfacing systems, necessary to provide for the safe, reliable and continuous generation and removal of thermal energy from the nuclear fuel at levels up to and including full licensed power, the regulation of this thermal power output to accommodate normal plant load variation, as well as for the rapid seduction of power required for certain abnormal operating transients.

The results of the detailed nuclear design of the core and fuel are fuel bundle average enrichments, enrichment and gadolonia distribution within the fuel bundle, location of each bundle within the core, selection of acceptable control rod patterns for a given power/flow operating condition, calculation of those nuclear performance parameters which effect the transient and stability of the core. These design results for the equilibrium cycle of the IABWR are presented in this report.

CORE DESIGN BASIC/CRITERIA

A set of fuel licensing acceptance criteria has been established for evaluating fuel designs and for determining the applicability of generic analyses to these designs. Fuel design compliance with the fuel licensing acceptance criteria constitutes USNRC acceptance and approval of the fuel design for initial core and reload applications without specific USNRC review. The fuel licensing acceptance criteria are presented in the Table 1, Table 2 and Table 3.

Table 1. Performance requirements [7]

No	Parameters	Value
1	Power rating, MWe	1356 (Equilibrium cycle) 1000 (Initial cycle)
2	Thermal rating, MWt	3926 (Equilibrium cycle) 2895 (Initial cycle)
3	Refueling interval, days	547.5
4	Outage time, days	45
5	Operating cycle length, days	502.5
6	Operating capacity factor, %	95
7	Effective Full Power Days (EFPD)	477.4
8	Overall capacity factor, %	87.2
9	Target cycle energy, MWD	1,874,272.4 (Equilibrium cycle) 1,382,073.0 (Initial cycle)
10	Core fuel mass, MT ST MT ST	150.57 (Equilibrium cycle) 165.85 (Equilibrium cycle) 154.72 (Initial cycle) 170.42 (Initial cycle)
11	Cycle exposure, MWD/MT	12,454 (Equilibrium cycle)

ISSN 1411–240X
Nomor : 266/AU1/P2MBI/05/2010

	MWD/ST MWD/MT MWD/ST	11,301 (Equilibrium cycle) 8,937 (Initial cycle) 8,110 (Initial cycle)

Table 2. Interface requirements [7]

No	Parameters	Value
1	Core configuration: • Number of bundles • Number of control rods • Control rod notch, inches • Power density, kW/l	 872 193 3 49.6 (Equilibrium cycle) 36.6 (Initial cycle)
2	Core Flow: • 100 % Rated core flow, Mlb/hr • 85 % Rated core flow, Mlb/hr • Transient and stability requirements	 115.1 96.71 Separate report

Table 3. Design requirements [7]

No	Parameters	Value
1	Cold shutdown margin (CSDM) one strongest stuck rod, % Δk	1
2	Maximum linear heat generation rate (MLHGR), kW/ft	14.4
3	Minimum critical power ratio (MCPR) for operating limit	1.25
	Exposure limit: Maximum pellet exposure, GWD/MT GWD/ST Maximum bundle residence time, years Maximum batch average discharge exposure, GWD/MT GWD/ST Target batch average discharge exposure, GWD/MT GWD/ST	 70.0 63.5 7.5 50.0 45.4 38.0 34.5
4	Minimum hot excess reactivity margin at BOC, % Δk	1
5	Minimum hot excess reactivity margin at 200 MWD/ST,% Δk	0.8
6	Nuclear design allowance for thermal limits at operating conditions with rod patterns: MLHGR design allowance, % MCPR design allowance, %	 10 (Equilibrium) 20 (Initial) 7 (Equilibrium) 14 (Initial)

FUEL AND CORE DESIGN METHODS

The fuel designs employed TGBLA [8,9], which is a neutron transport and diffusion coupled lattice design computer program. TGBLA uses mainly ENDF/B-V cross-section library, uses integral transport theory methods to solve for cell neutron spectra in thermal, resonance and fast energy range, and uses leakage-dependent diffusion theory methods to solve for lattice kinf. and power distribution. In general, The TGBLA solution techniques begin with the generation of thermal broad group neutron cross sections for all homogenized fuel rod cells and external region in a bundle. In thermal energy range, rod-by-rod thermal spectra are calculated by a method similar to the THERMOS formalism. The major difference is that neutron leakage from rod to rod is taken into account. The leakage is determined by diffusion theory and is fed into the thermal spectrum calculation. Iterations between diffusion theory and thermal spectrum calculations are carried out to determine accurate, spatially dependent, thermal cross sections.

Five fuel lattices which consist in the difference enrichments, Gad concentrations, 0 %, 40 % and 60 % void fractions in two assembly types were designed using TGBLA for ABWR cores. Axially, each assembly type is composed of a thin bottom natural uranium blanket, a lower lattice spanning up to 2/3 of the active core, an upper lattice containing eight rod-vanished regions, and a thin top natural uranium blanket. In the assembly type 1, the lower lattice (9×9 array) contains 14 Gd rods, 60 UO_2 rods, and two large water rods and the upper lattice contains 12 Gd rods, 54 UO_2 rods, two large water rods, and eight rod-vanished regions. In the assembly type 2, the lower lattice (9×9 array) contains 13 Gd rods, 61 UO_2 rods, and two large water rods and the upper lattice contains 11 Gd rods, 55 UO_2 rods, two large water rods, and eight rod-vanished regions. The Gd weight percent in the Gd rods are varied axially to optimize the axial power shape. The highest U-235 enrichment in the design is 4.9 weight percent.

PANACEA receives lattice-averaged cross sections from TGBLA and solves a modified one-group diffusion equation for keff and power distribution of a BWR core [8]. The PANACEA keff preserves the fundamental mode keff of the three-group core neutron diffusion equations. PANACEA was qualified against the operating plant simulation, eigenvalue tracking, and gamma scan measurements. The principle functions of PANACEA are to calculate the core criticality along with neutron flux, power, burn-up exposure and void distributions within the core and to estimate the margins to thermal limits including the linear heat generation rate (LHGR) and critical power ratio (CPR). Adaptive options are available for adapting the solution to in-core instrumentation. In addition, an extensive set of core design analysis options are available including: power-exposure iteration, equilibrium cycle, control rod pattern development, cold critical, cold shutdown margin, rod drop, rod withdrawal error, scram and Xenon transient [9,10,11]. Two equilibrium ABWR cores, one with the flow spectral shift and the other without the flow spectral shift near EOC, were designed using PANACEA, with both operating on an 18-months cycle. The reload batch fraction is 0.3, and the number of reload fresh type-1 assemblies is about the same as that of reload fresh type-2 assemblies.

RESULTS AND DISCUSSION

The details of the equilibrium cycle core design are presented in this section. The reference core configuration of the IABWR consist of 872 bundles - 92 peripheral bundles and 780 interior bundles. The inlet orifice of the peripheral bundles is restricted in order to

ISSN 1411–240X
Nomor : 266/AU1/P2MBI/05/2010

preferentially force flow through interior high power bundles. The rated core thermal power is 3926 MWt which corresponds to a 54.1 kW/l power density.

The results of the detailed core nuclear design consist of the loading pattern, rod pattern, energy performance and demonstration of compliance with thermal, reactivity and nuclear dynamic parameter requirements. The energy utilization plan and performance criteria are described in detail in the design basis and criteria section.

The bundle average enrichments is defined by the requirements of the energy utilization plan and the neutronic efficiency of the core and fuel. Examination of the energy utilization plan reveals that the required cycle energy is quite large. This necessitates very high bundle enrichments. The number of bundles loaded is defined by the discharge exposure targets and the cycle exposure targets.

The equilibrium cycle energy performance is presented in this section. The energy utilization plan calls for a two year cycle with a 50 day refueling outage and a 98.5 % operating capacity factor. This results in an extremely large cycle energy target of 1341 GWD necessitates a high bundle enrichments in order to accommodate it. The details are presented in the Table 4.

Table 4. Core parameter design result

Parameters target	Result
Core average enrichment	3.75
Core mass, ST	165.858
Cycle energy, GWD	1894.075
Cycle exposure, GWD/ST	11.42
Batch average discharge exposure, GWD/ST	27.41
Peak pellet exposure, GWD/ST	43.35
Maximum residence time, years	7.5

The maximum linear heat generation rate (MLHGR) through the cycle is presented in Figure l, and the maximum critical power ratio (MCPR) is presented in Figure 2. Examination of the results reveals that there is in excess of 10 % margin to the 14.4 kW/ft MLHGR operating limit, but 7 % margin to the 1.40 MCPR operating limit. The fluctuations results of MLHGR and MCPR are depend on the rod pattern during cycle operation and fuel burn-up distributions. All thermal limits are satisfied.

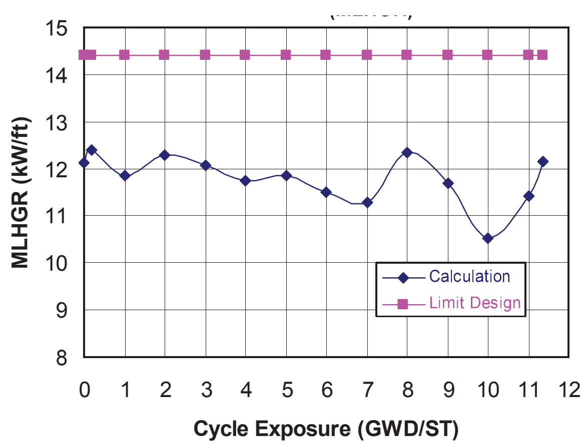

Figure 1. Maximum linear heat generation rate (MLHGR)

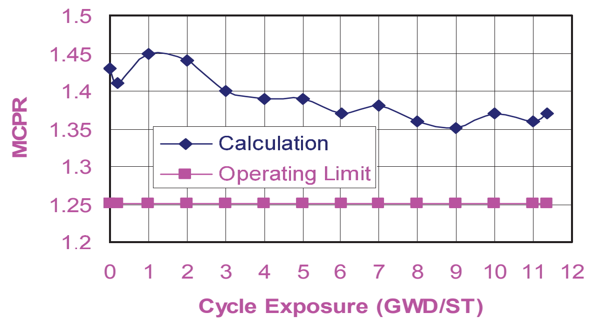

Figure 2. Minimum critical power ratio (MCPR)

As described in the design basis and criteria section, the reactivity limits that must be satisfied consist of 1% cold shutdown margin (CSDM) throughout the cycle and 1.0 % hot excess reactivity (HOTXS) at a cycle exposure of 200 MWD/ST The hot excess reactivity through the cycle is presented in Figure 3. Examination of the results shows that hot excess reactivity is flat due to the concentration gadolonia in the fuel and dummy water rod as well as burn-up exsposure. The flat hot excess reactivity is reflected in the control blade pattern summaries in that control blade movement is very small until the end of cycle. The cold shutdown margin results are presented in Figure 4. Examination of the results reveals that there is a substantial improvement in cold shutdown margin over current BWR's due to increased bundle pitch. All reactivity limit are satisfied.

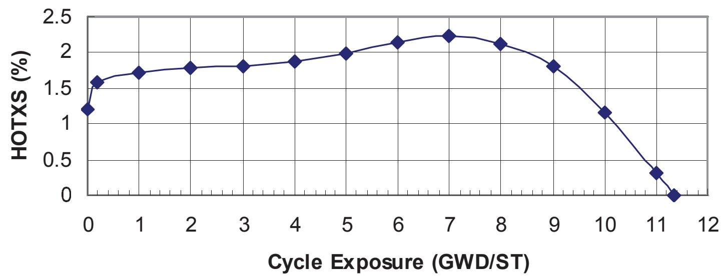

Figure 3. Hot excess reactivity (HOTXS)

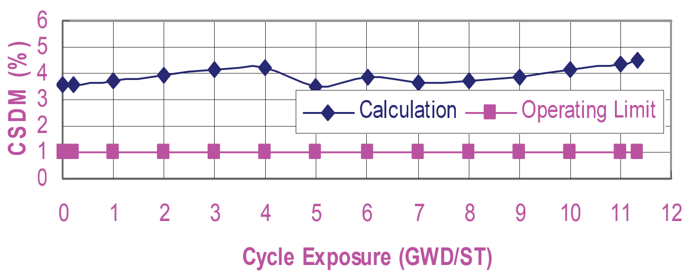

Figure 4 .Cold shutdown margin reactivity (CSDM)

ISSN 1411–240X
Nomor : 266/AU1/P2MBI/05/2010

There are a number of nuclear dynamic parameters which have limits that must be complied with in order that the design reside within the domain of bounding transient and stability analyses. These nuclear dynamic parameters consist of the moderator void reactivity coefficient and fuel Doppler reactivity coefficient as well as power reactivity coefficient are already satisfied by negative reactivity coefficient.

CONCLUSIONS

An ABWR core with the flow spectral shift and an ABWR core have been designed using GE 11 fuel to operate on an 18-months equilibrium cycle for the proposed first Indonesia nuclear power reactor. Hot excess reactivity, cold shutdown margin, and thermal limits are satisfied. It is concluded that the equilibrium core design using GE11 fuel satisfies the core design objectives for proposed IABWR.

Acknowledgments

The assistance provided by Mr. Rick Asamoto and Dr. Hadid Subki during the course of this study is appreciated.

REFERENCES

1. Indonesia Energy Outlook. Center of data and information for energy and mineral resources. Ministry of Energy and Mineral Resources Indonesia. Jakarta; 2009.
2. National Energy Policy. Presidential Regulation No. 5/2006. Jakarta; 2006.
3. Government Regulation No. 43/2006. Licensing of Nuclear Reactor; Jakarta 2006.
4. International Atomic Energy Agency – IAEA. Nuclear power reactor in the world. Vienna IAEA-RDS-2/30 - 2010 Edition, ISBN 978-92-10-105610-8; Printed IAEA July 2010.
5. David Durham. GE Hitachi nuclear energy international; new reactor construction. Pacific Basin Nuclear Conference; 2010.
6. GE-BATAN. Application of the advanced boiling water reactor to Indonesia study. Final Review; 1997.
7. EPRI. ALWR utility requirements document chapter 4 reactor systems. EPRI Palo Alto USA; 2001.
8. R.T. Chiang. TGBLA03C software design description. Nuclear Fuel Engineering Department, San Jose California; 2005
9. R.L. Crowther et. al. Advances in BWR design for extended burnup. Trans. Am.Nucl. Soc. 1982; 43: 156.

10. M. Yamamoto et. al. Development and validation of TGBLA BWR lattice physics methods. Proc. Top. Mtg. Reactor Physics and Shielding, Chicago, Illinois. 2002; 1: 364.
11. R.T. Chiang. Impact of average-leakage lattice homogenization on LWR core simulation. Trans. Am. Nucl. Soc.1995; 72: 371.