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Original Article

AM600: A New Look at the Nuclear Steam Cycle

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ABSTRACT

Many developing countries considering the introduction of nuclear power find that large-scale reactor plants in the range of 1,000 MWe to 1,600 MWe are not grid appropriate for their current circumstance. By contrast, small modular reactors are generally too small to make significant contributions toward rapidly growing electricity demand and to date have not been demonstrated. This paper proposes a radically simplified re-design for the nuclear steam cycle for a medium-sized reactor plant in the range of 600 MWe. Historically, balance of plant designs for units of this size have emphasized reliability and efficiency. It will be demonstrated here that advances over the past 50 years in component design, materials, and fabrication techniques allow both of these goals to be met with a less complex design. A disciplined approach to reduce component count will result in substantial benefits in the life cycle cost of the units. Specifically, fabrication, transportation, construction, operations, and maintenance costs and expenses can all see significant reductions. In addition, the design described here can also be expected to significantly reduce both construction duration and operational requirements for maintenance and inspections.

Introduction

This paper critically examines the design configuration and sizing of the conventional nuclear steam cycle for light-water reactor (LWR) plants in relation to current technology and markets. Originally, the nuclear steam cycle was adopted and adapted from contemporaneous fossil steam cycles. Design of early commercial-scale nuclear steam cycles was conducted in the 1950s and 1960s based on the technology and knowledge available at that time.

As these designs evolved, the focus of designers was concentrated in two areas: (a) reliability and (b) efficiency. Historically, new-build nuclear units were almost exclusively designed for regulated or national markets with attendant strong growth in electricity consumption. In addition, nuclear power production costs were considered to be on par with those for coal-fired units. With these principal considerations, there was no strong incentive to economize the designs (i.e., to trade reliability and/or efficiency for reduced capital cost or for simplicity in operations and maintenance). In the modern

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world economy, new markets for nuclear power have unique characteristics that were not present in the past. Here, using new priorities related to current markets, a radical and yet evolutionary re-design of the 600-MWe class nuclear steam cycle is developed and compared with more conventional designs from the past.

Background

Of the 444 [1] nuclear power plants (NPPs) currently in commercial operation, essentially all operate by converting heat from controlled nuclear fission into electrical power using the Rankine cycle [2]. Steam at moderately high pressures and temperatures is generated [in either steam generators (S/G) or the reactor vessel] and converted to electricity using conventional steam turbine–generator (T/G) sets. Thermal efficiency is improved by using regenerative heating of feedwater and by drying and reheating steam before passing it to the low-pressure turbine (LPT) sections.

The nuclear steam cycle for these units typically addressed reliability by including redundant components in the design and flexibility in certain bypass arrangements to ensure high availability and capacity factors. By examination of the USA fleet, it can be found that the steam cycle configurations for the 99 operating units vary widely with almost as many configurations as there are units. For example, the two-unit Calvert Cliffs station, with essentially identical nuclear steam supply system (NSSS) design has two markedly different turbine cycles. The two units at the D.C. Cook station share similar steam conditions and flows but again were built with two widely differing steam cycles.

Despite this, from recent data reported by the American Nuclear Society [3], the median 3-year capacity factor for the USA fleet for the years 2013–2015 was 90.4% with the top and bottom quartiles pegging in at 92.8% and 87.2%, respectively. These very commendable figures indicate that the operating fleet (average age 36 years and median age 38 [4]) is “not getting older, it is getting better.”

Data as cited in the previous section indicate that mature nuclear units can be operated very efficiently despite a very wide variation in designs and levels of component redundancy. Above the hue and cry in the popular blogs for “new nuclear fission technology” (e.g., Generation IV, prism, traveling wave, or thorium reactors), these data strongly buttress the continued reliance on the unit size and technology used for modern day LWR plants.

By contrast, overnight capital costs for new-build nuclear units are either (i) not competitive in developed markets with significant gas, hydro, and wind resources, or (ii) not easily financed for emerging markets.

Target market analysis

Traditional markets

From a world perspective, low prices for fossil fuels combined with the lack of an international consensus on a durable, binding CO_2 emissions tax would seem to indicate that the traditional export market for large-scale NPPs such as the Korean APR1400 (advanced power reactor 1400) [5] (Fig. 1) is limited in the near term as discussed in the following sections.

Globally, the top 25 national economies generate approximately 80% of world economic output as measured by gross domestic product [6]. A simplistic and prima facie analysis of these countries with regard to NPP export potential indicates that these markets are generally closed to outside NSSS vendors as follows:

- Favorable to established domestic NSSS vendors, mostly closed to outside vendors (Canada, China, France, Japan, Russia, South Korea).
- Competition from cheap coal, gas, hydro, or wind resources (Australia, Brazil, China, Canada, Saudi Arabia, USA).
- Competition from subsidized wind and solar energies (Germany, Spain, USA).
- Legislated or announced ban, phase out, or phasedown of nuclear power (France, Germany, Italy, Sweden, Switzerland, Taiwan).
- Post-Fukushima angst (France, Germany, Japan, Netherlands, Taiwan).
- Cost concerns with new build (United Kingdom).
- Announced new build (Turkey).
- Lack of financial resources (Argentina, Mexico, Nigeria, Indonesia, Spain).

Emerging markets

For the various reasons listed in the previous section, most of the top world economies are not currently in the market for deployment of large-scale NPPs. However, many smaller emerging economies may find that the pursuit of domestic nuclear power infrastructure is attractive from consideration of both the diversification of energy supply and as a national economic development strategy. Countries that fall into this category include Bangladesh, Chile, Columbia, Egypt, Indonesia, Malaysia/Singapore, Peru, Poland, South Africa, Thailand, and Vietnam.

The year-round average load flow on the electrical grids in these countries ranges from 5,000 MWe (Peru) to 30,000 MWe (South Africa). Considering that not all of the load flow may be on a single integrated grid, using International

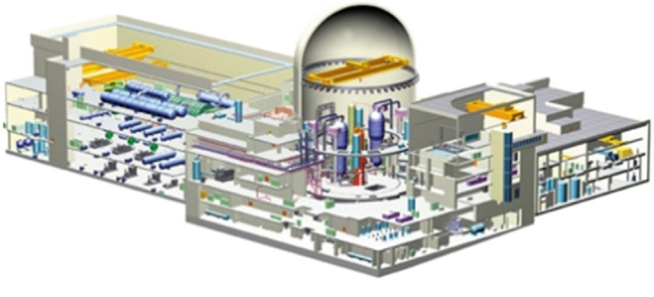


Fig. 1 – Advanced Power Reactor 1400 (APR1400).

Atomic Energy Agency guidelines [7] most of these countries currently have electrical grids that are too small to consider implementation of the largest-scale NPPs (e.g., in the range of 1,000 MWe to 1,600 MWe). Rather, a smaller reactor sized on the order of 600 MWe is more grid appropriate. This size is typical of those reactors first constructed in the USA, Japan, Canada, Korea, the Czech Republic, Hungary, the Netherlands, Belgium, Brazil, Taiwan, Slovakia, Sweden, Mexico, and others. In fact, there are currently approximately 75 operating reactors, which fall into the range of 450 MWe to 700 MWe [1].

As another consideration, with the exception of Poland, most all of these countries are located in tropical or subtropical zones falling within 30° of the Equator. This means that available heat-sink temperatures typically are confined to an annual range of 21–30°C.

In addition, all of these countries operate with a grid frequency of 50 Hz. When the following three factors for these candidate countries are combined, a simplified T/G design can be considered:

- High heat-sink temperatures/condenser backpressures
- Electrical grids operating at 50 Hz
- Recent development of longer last-stage turbine blades.

In summary, emerging market countries may find that a medium-sized reactor plant with a simplified balance of plant (BOP) design is attractive when compared with either large-size units (with high capital costs and long lead times) or small modular reactors (with limited capacity per unit). Design considerations for a modern nuclear steam cycle for a medium-sized, conventional LWR plant slated for deployment in countries with limited expertise and infrastructure in power generation are addressed in the remainder of this paper.

Technology developments

Since the construction of medium-sized NPPs built in the 1960s through 1980s, there have been many advances in understanding design requirements and in materials, design, and manufacturing technology for major BOP components. Handling of wet steam throughout the nuclear steam cycle presents special challenges, which were not recognized or fully understood in the early designs. From a thermodynamic efficiency and reliability perspective, turbine designers did not have sufficient knowledge to adequately address moisture management in the steam flow path. For BOP components and piping systems, plant designers did not appreciate potential degradation associated with flow accelerated corrosion (FAC) in pressure boundary components fabricated from carbon steel [i.e., when challenged by extremely low chromium content (e.g., <0.02%) and also subjected to highly turbulent flows].

Subsequently, operational and maintenance challenges at operating plants have been addressed through equipment replacement and plant modifications. Experience and changes to materials and design ensured that many chronic issues were minimized or eliminated. Plant changes have also permitted some improvement to plant efficiency through better design (primarily in the turbine steam flow path). Specific areas of improvement that are incorporated into the design concepts considered here are described in the following sections.

High-pressure turbine steam flow path

Turbine blading in the high-pressure nuclear steam turbine has seen significant advances in relation to the efficient handling of wet steam (i.e., moisture management). For example, one vendor conducted detailed experimental investigation and study to improve understanding of the mechanisms of moisture loss (e.g., nucleation, thermodynamic, and mechanical). When coupled with advanced three-dimensional design and machining capabilities, a significant improvement in the efficiency of the high-pressure turbine (HPT) steam flow path was made possible [8]. Further improvements to efficiency can be achieved for NPPs sized up to 1,000 MWe by specification of a single-flow HPT section, permitting longer blading with smaller end losses and reduced leakage.

Moisture separator reheater

Moisture separator reheaters (MSRs) have seen substantial design improvements resulting in increased reliability and thermodynamic efficiency [9]. On the design side, the “double chevron” design approach has now been widely adopted, permitting substantially improved moisture removal.

Reheater bundle design has also evolved to minimize pressure drop and approach temperature with significant benefits to heat rate. Modern shell-side design now addresses FAC concerns ensuring long life for new-build MSRs.

Low-pressure turbine steam flow path

Again, lessons learned from the study of moisture in wet steam turbines have permitted an overall improvement in turbine efficiency and reliability. Improved materials and designs (e.g., curved axial entry fir tree root attachment, or “CAEFTR”) when combined with a better understanding of torsional vibration and fatigue have also permitted the design of substantially longer last-stage blading (or L-0 blading). These two advances and others permit improved efficiency for the medium-size NPP steam flow path [10].

Last-stage blading (L-0)

The biggest improvement in LPT efficiency has taken place in the design of the L-0 blading. Advances include (a) improved materials (e.g., high-strength steel, titanium), (b) a better understanding of the aerodynamic flow field, and (c) studied design approaches to stationary and rotating blade geometry (e.g., forced vortex, lean, sweep, and flow path contouring with variation in impulse and reaction contributions along the length of a complex blade geometry) [11]. Innovative work such as this has resulted in a substantial increase in exhaust area per end and energy recovery in the last stage. The LPT design considered here models the efficiency which can be achieved with these design improvements.

Main generator design

In this area, operating experience has brought certain chronic but rather mundane aging issues to the attention of designers. To mention a few, these include (a) stator bar leakage, (b) end turn vibration fretting, (c) core heating, (d) stator bar wedging issues, (e) dusting, (f) hydrogen leaks, and (g) coupling fatigue cracking.

For the most part, vendors have addressed these issues and for the latest designs, main generator units can be expected to operate with high reliability and low maintenance requirements.

The one area of significant change is the emergence of the static exciter. For new build, the design specification would be expected to call for a static exciter design with a "smart" digital voltage regulator and turbine supervisory system. These changes and associated improvements in digital instrumentation and control systems are expected to improve reliability and industrial safety (e.g., overspeed protection, prevention of turbine water induction, torsional vibration monitoring), and to ensure robust response to a wide range of grid transients.

Configuration

The proposed design configuration for the various components and systems considered here is provided in the following section:

Turbine–generator shaftline

As mentioned earlier, for the targeted emerging markets the combination of (a) high heat-sink temperatures, (b) a 50-Hz grid system, and (c) development of long L-0 blading by all major wet steam turbine vendors permits a major simplification of the T/G design without sacrificing thermal efficiency. Specifically, the proposed half-speed T/G shaftline employs (a) a single-flow HPT (as previously applied at Ft. Calhoun, Monticello, North Anna, and Surry) and (b) a single cylinder, two-flow LPT design with an exhaust area similar to that of a proven 63-in. L-0 blade design. This configuration permits great simplification throughout the BOP system layout as detailed in the remaining subsections here without sacrificing heat rate due to insufficient LPT exhaust area. The turbine cycle based on this concept is termed the "AM600" (or advanced modern 600 MWe design). The impact on the thermodynamic efficiency of these design decisions is examined under the "Heat Balance/Heat Rate" section.

The main generator is proposed as conventional design with water cooling of stator bars and hydrogen cooling of the rotor. Excitation is by static exciter.

Moisture separator reheater

Two horizontally oriented MSRs are considered in the design (one on each side of the T/G shaftline). The MSR design is conventional assuming a single stage of reheat. A second stage of reheat would improve thermal performance of the cycle but at the expense of lower overnight cost and simplicity in operations and maintenance. Therefore, in keeping with the design philosophy here, only a single stage of reheat is considered. Finally, the modern configuration using side entry to the LPT casing for the hot reheat piping is assumed, simplifying the "tops off" inspections of the LPT section.

Low-pressure feedwater heaters

The AM600 employs a single string of low-pressure feedwater heaters (LP FWHs). This is made possible by specification of a single LPT cylinder. When using two or three LPT cylinders, to balance extractions and minimize routing distances for extraction steam (ES) lines, the first two LP FWHs are typically placed in *each* condenser section. With additional space below the longer rotor required for a single LPT cylinder, design studies indicate that it is possible to include all four LP FWHs in the condenser neck (Fig. 2).

Mitsubishi Heavy Industries, Ltd. (now Mitsubishi Hitachi Power Systems) has proposed similar configurations in the past [12]. In addition to layout and equipment-sizing studies, preliminary ES pipe routing and stress and support analysis conducted as part of AM600 research indicates that such an arrangement can be achieved.

For LP FWH Numbers 3 and 4, it is necessary for the ES piping to leave and re-enter the condenser shell so that necessary nonreturn and block isolation valving can be installed in maintenance-accessible spaces.

With this arrangement, it is considered possible to shop fabricate the entire condenser module including LP FWHs, condensate piping and valving, and ES piping and valving. The ES piping could be fully shop fabricated with "cut lines" strategically placed for field fit to the installed LPT nozzles. A prefabricated condenser module is expected to greatly simplify field construction in the turbine building.

High-pressure feedwater heaters

The two HP FWHs are conventional horizontal U-tube design. Both the LP FWHs and the HP FWHs will be designed to

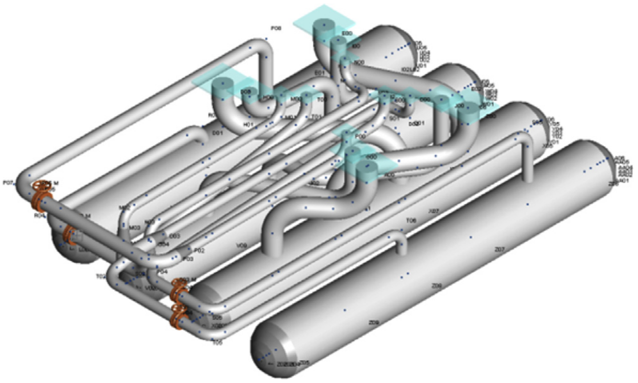


Fig. 2 – Low pressure (LP) feedwater heater (FWH) arrangement (Condenser Neck).

Table 1 – Main turbine component comparison.

	PINGP Units 1 and 2	AM600	APR1400
HPT			
No. of HPT cylinders/rotors	1	1	1
No. of flows	2	1	2
No. of extraction nozzles	2	1	4
No. of stages (including control)	10 [a]	5 [b]	7 [b]
No. of rotating blades (estimated)	~1,800	<600	~1,200
LPT			
No. of LPT cylinders/rotors	2	1	3
No. of flows	4	2	6
No. of extraction nozzles	12	8	24
No. of stages	11 [a]	7 [b]	6 [b]
No. of rotating blades (estimated)	~3,800	<1,300	~3,700
Overall			
No. of extraction nozzles	14	9	28
Total no. of rotating blades	~5,400	<1,900	~4,900
No. of shaftline journals	10	6	8
No. of thrust bearings	1	1	1
Overall T/G length (estimated)	~50 m	~38 m	~68 m

AM600, Advanced Modern 600 (MWe NPP); APR1400, Advanced Power Reactor 1400; HPT, high-pressure turbine; LPT, low-pressure turbine; PINGP, Prairie Island Nuclear Generating Plant; T/G, turbine/generator.

[a] Reaction style.

[b] Impulse style.

handle "overload" conditions (i.e., with FWH out-of-service) in terms of tube bundle surface area, perimeter shell clearances, support plate spacing, and shell-side nozzle dimensions to allow for the maximum permissible power level for this condition.

Configuration summary

The AM600 configuration described here results in substantial simplification of the nuclear steam cycle with an attendant reduction in component count. A reduced number of components also results in a rather significant cascading of cost savings in (a) turbine building dimensions, (b) associated piping and pipe supports, (c) valving, (d) instrumentation and controls, and (e) electrical support systems. These cascading effects were often not critically examined when heat balance engineers added such "nice to have" features as multiple points of drain forwarding, two stages of MSR reheat, and others without careful consideration of life cycle costs for these items.

The Prairie Island Nuclear Generating Plant Units 1 and 2 (or PINGP) are taken as the reference station. With the start of commercial operations in 1973 (Unit 1) and 1974 (Unit 2), these units each employ a double-flow HPT and two double-flow LPTs. Originally rated at 1,650 MWt, the PINGP units have since been uprated to 1,677 MWt. The LPT steam flow path was replaced in the 1990s. The steam cycle employs (a) five points of feedwater heating, (b) a single stage of reheat, and (c) drain forwarding, and is typical of designs from this time.

Table 1 provides a comparison of the T/G arrangement for the AM600 and PINGP Units 1 and 2. Compared are number of rotors, number of flows, number of stages, number of extractions, and so on. In addition, for further reference, comparison is included to a large-scale NPP, in this case the APR1400.

Beyond component count, two distinct and very significant advantages are evident. One is the length of the T/G shaftline. This permits a complete redesign of the turbine building, with attendant savings in concrete and steel and in routing distances for piping, electrical cables, heating ventilating and air conditioning (HVAC) ductwork, etc. The other advantage is the very large reduction in the number of turbine blades, which will greatly simplify and reduce the resources needed for inspections.

Table 2 provides a comparison of the number of large-pressure vessels included in the BOP design.

Not identified in the previous section, the AM600 design includes full flow (pre)filter and demineralizer vessels to adequately address control of water chemistry. Many early pressurized water reactor (PWR) units did not consider full flow systems and later performed plant modifications to "back fit" this essential capability. The modern day consensus approach to water chemistry for new design is (pre)filtering followed by deep bed demineralization. Because this capability is considered to be critical to overall plant health [13–15], it is not included when analyzing a reduction in component count for new build.

Table 3 provides a tabulation of large bore valve count. A reduction in the number of FWHs will generally result in a reduction in the number of large bore valves. Similarly, a single LPT cylinder will require fewer intercept valves and have fewer extractions.

The number of nonreturn valves in ES lines is estimated for the AM600. This number will depend on whether extraction lines are first combined with the valve installed on the combined lines or installed on lines from each end of the turbine. It

Table 2 – Large-pressure vessel count.

Description	PINGP Units 1 and 2	AM600	APR1400
MSR vessels	2	2	2
M/S drain tanks	2	2	2
Reheater drain tanks	2	2	4
Deaerator vessels	–	–	1
FWH and deaerator: drain tanks	1	–	2
FWHs: two zone	8	6	15
FWHs: condensing zone only	2	–	–
External drain coolers	2	–	–
Condenser zones	2	1	3
Total: large-pressure vessels	21	13	29

AM600, Advanced Modern 600 (MWe NPP); APR1400, Advanced Power Reactor 1400; FWH, feedwater heater; M/S, moisture separator (section of MSR); MSR, Moisture separation reheater; PINGP, Prairie Island Nuclear Generating Plant.

Table 3 – Large bore valve count (steam side, approximate).

Description	PINGP Units 1 and 2	AM600	APR1400
Main steam, extraction steam			
No. of turbine stop	2	4	4
No. of turbine throttle	4	4	4
No. of combined intercept	4	2	6
No. of cross-around relief	4	4	6
No. of reheating steam throttle	2	2	4
No. of ES nonreturn	6	5	10
No. of ES block	6	5	10
Total large bore valve count	28	26	44

AM600, Advanced Modern 600 (MWe NPP); APR1400, Advanced Power Reactor 1400; ES, extraction steam; PINGP, Prairie Island Nuclear Generating Plant.

will also depend on turbine vendor analysis of overspeed transients, FWH shell-side inventories, and the allowable overspeed.

Valving which is independent of the turbine arrangement (e.g., main steam isolation valves, main steam safety valves, atmospheric dump valves), is not included in the tabulation.

Figs. 3A and 3B illustrate differences on the steam side of conventional design versus the AM600 (i.e., main steam and ES systems).

Overall, Tables 1–3 indicate the very substantial reduction in component and subcomponent count for the AM600. From the number of turbine cylinders/rotors (33% reduction), extraction nozzles (36% reduction), turbine blades (65% reduction), pressure vessels (38% reduction), and large bore valves (4% reduction), the component count alone points toward a much simplified and lower cost design. Beyond the simple component count is the rather substantial savings in building volume and support system requirements [upstream electrical (cables, breakers, relays, etc.), HVAC, insulation systems, instrumentation and controls, and so on]. Finally, in construction, operations, and maintenance, additional cost savings and simplifications are likewise expected.

Simplified operations and maintenance

The configuration outlined in the previous section will result in simplifications across the board. Design and layout will be simplified particularly with upfront vendor input for design of the condenser module and other aspects of the layout.

Operations and operations training will be greatly simplified. Confusion between physical plant locations of equipment and parallel components is minimized.

Routine outage inspections can be coordinated with tight outage schedules for an 18-month or 24-month fuel cycle. Staffing requirements will be reduced with tops-off inspections of the LPT reduced by 50%. Similarly, with a 6-year interval for eddy current inspections of FWH tube bundles, the number of inspections will likewise be reduced by 50% requiring no more than two FWHs to be opened within any given outage. In addition, with proper specification of FWH shell material (i.e., FAC resistant), shell-side wall thickness measurements can practically be eliminated.

Heat balance/heat rate

Salient aspects of heat balance modeling for the AM600 are detailed here. Component performance and design parameters are consistent with modern day vendor offerings and with measured performance at operating units. Specific modeling results are presented on the AM600 valves wide-opened heat balance diagram provided as Appendix 1.

Steam conditions

The NSSS is modeled as a PWR with T_{cold}, T_{hot}, the S/G approach temperature, and leaving steam pressure and moisture similar to conditions which are guaranteed for the APR1400. The cycle can just as easily be modeled for boiling water reactor conditions with slightly higher steam pressures and temperatures. Pressure drop from the S/G dome to the HPT stop valve inlet is taken as 6% of the upstream pressure. Pressure drop across the turbine stop valves and turbine throttle valves is taken as 2% for each valve position.

HPT modeling

The HPT is modeled with modern day efficiencies for wet steam with a single-flow arrangement and a single extraction serving HP FWH Number 6.

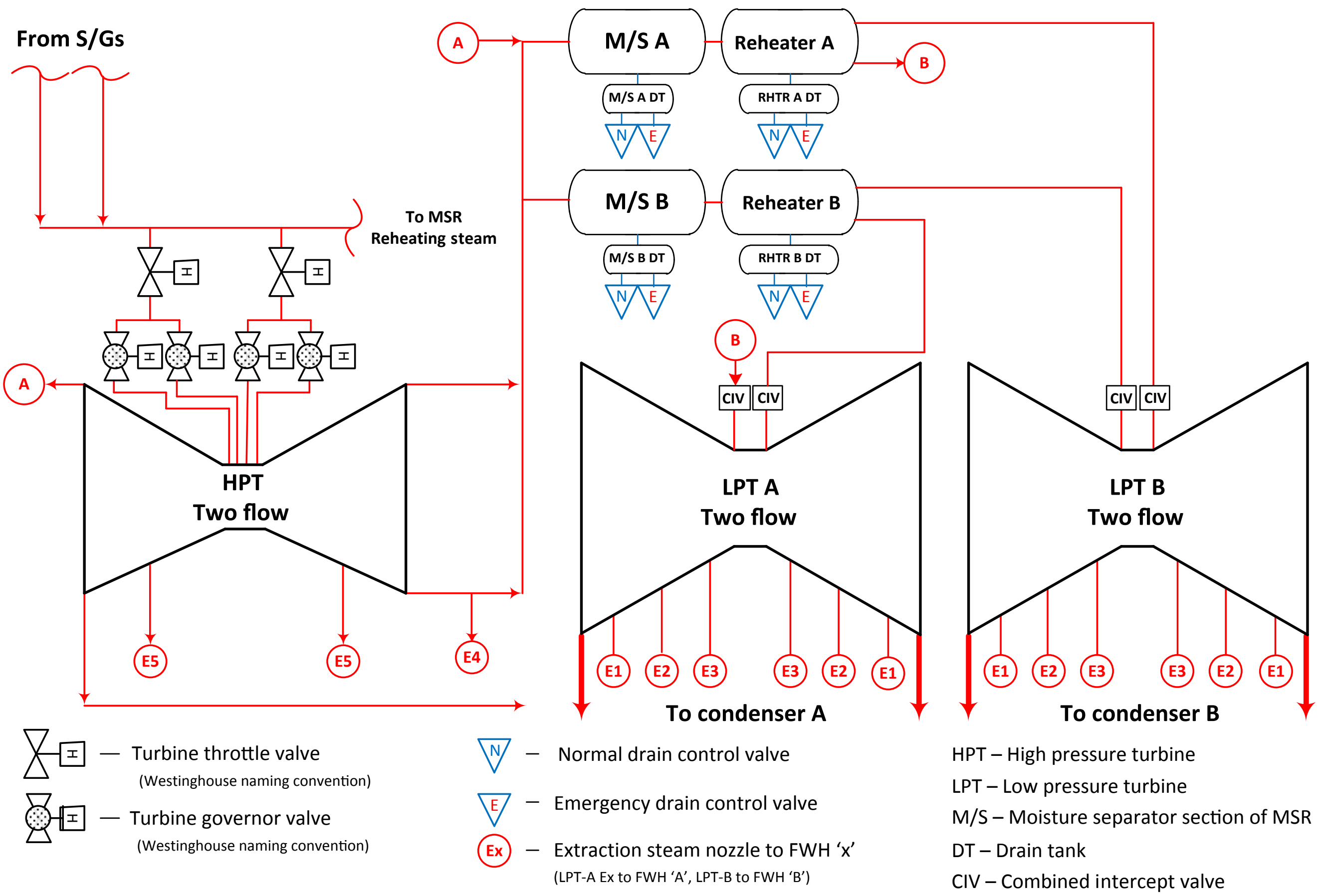
Cross-around and MSR modeling

Total pressure drop for cross-around from the HPT exhaust to the LPT inlet (downstream of the combined intercept valves) is modeled as 6% of the HPT exhaust bowl pressure. Steam supply to HP FWH Number 5 is taken from the cold reheat cross-around piping. Moisture separation efficiency is taken as 99%. The total temperature difference in the reheater bundles is modeled as 5.6°C comparable to current offerings.

LPT modeling

The operating fleet of wet steam turbines encompasses a wide range of cross-around pressures (approximately 5.5 bar to approximately 20 bar). Based on various studies, the optimal range is considered to be 11 bar to 15 bar. For the AM600 modeled here, the cross-around pressure is set toward the higher end of this range to minimize cross-around piping and component sizing. The overall heat rate is not particularly sensitive to cross-around pressure in this range. Lower cross-around pressures penalize efficiency through higher pressure drop and higher exiting moisture from the HPT. Higher cross-around pressures result in shorter LPT blading for the inlet stages resulting in higher end and leakage losses. Here, use of

(A) Conventional Configuration (PINGP)



(B) Proposed Configuration (AM600)

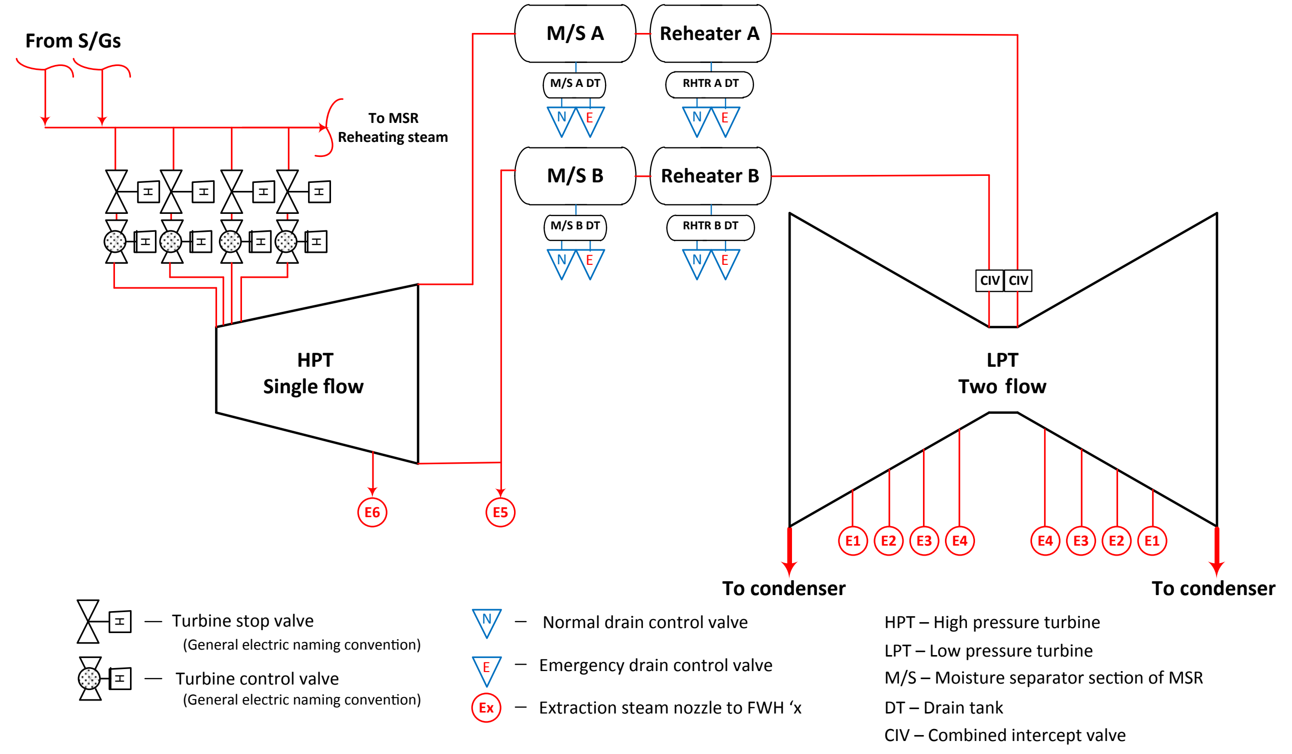


Fig. 3 – Comparison of conventional configuration with proposed AM600 (steam side).

a two-flow LPT arrangement doubles the volumetric flows to each path allowing for longer entry blades, thus reducing end and leakage losses. Overall, higher cross-around pressures are expected to be optimal, pending detailed vendor review.

The LPT is modeled with modern day efficiencies for wet steam. Moisture removal is considered consistent with current vendor designs for the wet stage groups.

Stage group efficiency and exhaust loss

Stage group efficiency, exhaust loss, and "inferred" Baumann coefficient are present in Table 4. The achievable dry efficiency is based on recent vendor offerings for fossil cycles and the "dry" portions of nuclear LPTs.

Condenser performance

The condenser backpressure for summer conditions is set to 66 mm-HgA (2.6 in-HgA). Circulating water approach temperature is set to 4°C as representative.

Power train pumps

Enthalpy and pressure rise across power train pumps are representative but not based on any specific pump curve. Similarly, pressure drop in the condensate and feedwater systems (including across FWHs) is representative but not calculated.

Table 4 – AM600 turbine: modeled efficiency, exhaust loss.[a]

	ε_{dry} [a]	ε_{wet} [b]	Baumann coefficient (%/%)
HPT			
Control stage	89	88.1	0.5
First stage group	91	88.9	0.5
Second stage group	91	87.7	0.5
Third stage group	89	84.1	0.5
LPT			
First stage group	93	93.0	N/A [c]
Second stage group	93	92.7	0.877
Third stage group	94	91.9	0.877
Forth stage group	93	87.4	0.877
Exhaust stage	87	78.5 [d]	0.877
L-0		Loss	
Exhaust velocity (m/s)	–	~200	–
ELEP (kJ/kg)	–	2,296.9	–
Exhaust Loss (kJ/kg)	–	23.3	–
UEEP (kJ/kg)	–	2,320.2	–

AM600, Advanced Modern 600 (MWe NPP); ELEP, expansion line end point; HPT, high-pressure turbine; LPT, low-pressure turbine; UEEP, used energy end point.

[a] Based on survey of recent vendor offerings.

[b] Dry efficiency minus average moisture times Baumann coefficient.

[c] Superheated.

[d] To ELEP.

FWH performance

Thermal performance for FWHs is set to standard industry values of 2.8°C for terminal temperature difference and 5.6°C for drain cooler approach. As described earlier, the FWHs are oversized to allow for higher core power levels with an FWH out-of-service. Therefore, performance is expected to be slightly better than these values.

ES line pressure drop

The pressure drop from the interstage extraction point in the turbine shell to the FWH shell is varied by extraction to model industry experience with calculated pressure drops. Typical heat balance modeling might assume 3% pressure drop leaving the turbine and 5% pressure drop in the extraction lines. Computed pressure drop for operating plants indicates lower values for HP FWHs and higher values for LP FWHs, particularly for FWH Number 1. Modeled pressure drop (total – turbine casing plus piping system) for FWH Numbers 1–6 is 20%, 10%, 7%, 5%, 5%, and 3%, respectively.

Heat recovery

Heat recovery for sealing steam, S/G blowdown, the generator stator water, hydrogen coolers, and lube oil coolers is included in the models but these (minor) flows are isolated for the analysis here.

Generator losses

Generator fixed losses are taken as 0.32%. Generator variable losses when operating with a power factor of 0.85 are taken as 1%.

Heat balance summary

With the modeling assumptions outlined earlier and results provided according to Appendix 1, the design performance of the AM600 (with conservative performance modeling) compares favorably with similar-scale LWRs constructed in the 1970s and 1980s as indicated in Table 5. This primarily reflects efforts by vendors to improve the design of the steam flow path and in L-0 blading, which permits adequate exhaust area with a single LPT cylinder.

Efficiency could be improved by adding complexity to the steam cycle such as use of two stages of reheat or application of heater drain forwarding. These approaches are omitted to maintain simplicity of design, construction, operations, maintenance, and inspections. With a high-efficiency steam flow path as modeled here, the benefit to heat rate of these options is reduced from that for a less efficient turbine steam flow path.

By contrast, heat must be rejected from certain services such as generator stator water and hydrogen cooling, T/G lubricating oil, and S/G blowdown. It is possible to design heat recovery systems for these services (to improve heat rate)

Table 5 – T/G summary: input, output, and heat rate.

Description	PINGP Units 1 and 2	AM600	APR1400
NSSS input (MWt)	1,690.0	1,857.5	4,001.9
Condenser backpressure (mm-HgA)	66 [a]	66	66
Gross generator output (MWe)	573.2 [a,b,c]	648.6 [c,d]	1,425.3 [d,e]
Gross heat rate (kJ/kW-h)	10,615	10,311	10,107
Gross efficiency (%)	33.9	34.9	35.6

AM600, Advanced Modern 600 (MWe NPP); APR1400, Advanced Power Reactor 1400; LPT, low-pressure turbine; NSSS, nuclear steam supply system; PINGP, Prairie Island Nuclear Generating Plant; T/G, turbine/generator.

[a] Interpolated.

[b] Provided with retrofit LPT in the 1990s.

[c] Motor-driven feedwater pump.

[d] Static exciter.

[e] Steam turbine-driven feedwater pump.

while retaining redundancy with service water systems without compromising the overall design philosophy promoted here.

Summary and future work

Summary

Outlined here is the conceptual design of a simplified 600-MWe nuclear steam cycle, the AM600. The design includes high thermodynamic efficiency while greatly reducing the complexity and cost of the T/G and of the supporting BOP systems and components. The simplified design is expected to show benefits in all cost centers associated with a nuclear power program including (a) reduced fabrication costs (fewer components), (b) modularized construction (factory assembly of condenser module plus fewer components for field installation, less piping, less turbine building volume, etc.), (c) simplified training for operators, (d) simplified operations (fewer alignments and transitions between alignments, fewer valves, etc.), and (e) simplified maintenance and inspections.

At the same time, little is sacrificed in the area of reliability. With exacting (best practice) skill in the specification, fabrication, inspection, installation, and maintenance/inspections of components, the BOP can be expected to perform even better than the exemplary performance recently demonstrated by the mature but aging nuclear fleet in the USA (as cited earlier).

Follow-on activities

From the technology readiness perspective, the AM600 is ready for the dance but lacks a partner. An interfacing NSSS providing approximately 1,600 MWt to approximately 1,800 MWt is required to complete the project. Finding this partner is beyond the scope of the work outlined here.

The principal design challenges in order are (a) detailed T/G shaftline and LPT rotor design, (b) detailed condenser design to fit below the single cylinder LPT, and (c) structural design of the turbine pedestal to accommodate the turbine bearings while not interfering with the four LP FWHs located in the condenser neck. These areas require expertise in wet steam turbine design, condenser steam flow modeling, and structural design for NPPs. It is hoped there is sufficient interest in the concepts detailed here to further pursue these areas, specifically for the following:

T/G shaftline design

One of the major benefits of the single-cylinder LPT design is the significant improvement in torsional stability relative to negative sequence currents. Preliminary rotordynamic analysis of a prototype AM600 shaftline indicates that torsional eigenvalues are well out of the range of frequencies which bring concerns. This is particularly important for countries with developing electrical grids where frequency control is not up to standards in mature markets. Design development/analysis of a T/G shaftline by a turbine vendor would be most welcome.

Main condenser

A big advantage of the AM600 design is the potential to build the main condenser and LP FHWs as a module. Two big challenges are available space (i.e., footprint and height) and the very large cascading drain flow which must be accommodated. Further development in this area requires participation of designers from an experienced condenser vendor and from a systems designer.

T/G foundation design

With a “clean sheet,” all aspects of T/G foundation design can be re-examined. For example, the design could incorporate a spring-damper foundation such as that employed in European NPPs using Gerb components [16]. This would reduce column dimensions, permitting more space for the condenser. The design could also consider use of levelizing jack screws to greatly simplify T/G shaftline alignment while eliminating shimming for shaft alignment during installation [17].

Conflicts of interest

The author has no conflicts of interest to declare.

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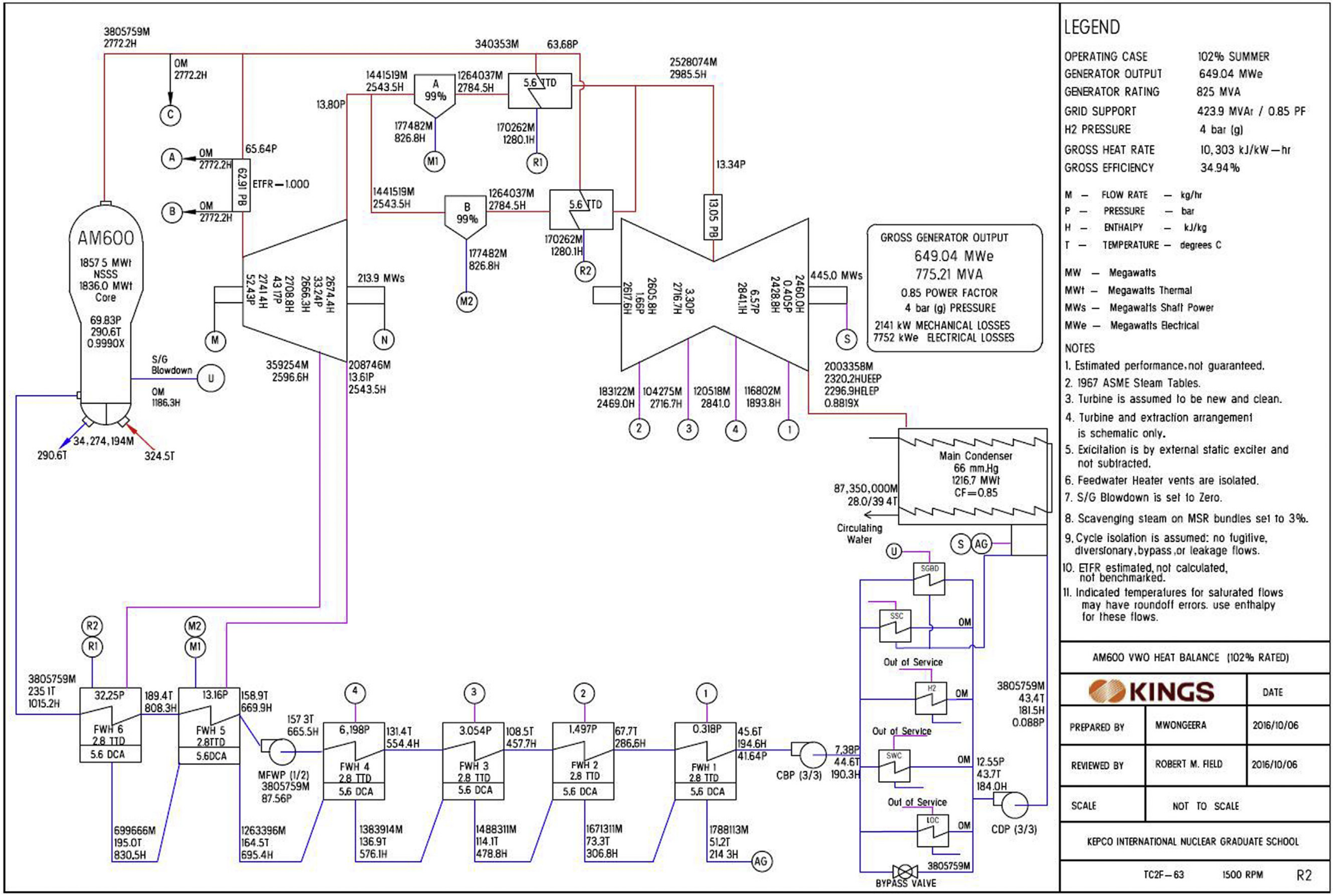
Appendix 1. Advanced Modern 600 (MWe NPP), AM600, Heat Balance (VWO: Summer).



GROSS GENERATOR OUTPUT
649.04 MWe
775.21 MVA
0.85 POWER FACTOR
4 bar (g) PRESSURE
2141 kW MECHANICAL LOSSES
7752 kWe ELECTRICAL LOSSES

LEGEND

OPERATING CASE	102% SUMMER
GENERATOR OUTPUT	649.04 MWe
GENERATOR RATING	825 MVA
GRID SUPPORT	423.9 MVAr / 0.85 PF
H2 PRESSURE	4 bar (g)
GROSS HEAT RATE	10,303 kJ/kW – hr
GROSS EFFICIENCY	34.94%

M – FLOW RATE – kg/hr
P – PRESSURE – bar
H – ENTHALPY – kJ/kg
T – TEMPERATURE – degrees C

MW – Megawatts
MWt – Megawatts Thermal
MWs – Megawatts Shaft Power
MWe – Megawatts Electrical

NOTES

1. Estimated performance, not guaranteed.
2. 1967 ASME Steam Tables.
3. Turbine is assumed to be new and clean.
4. Turbine and extraction arrangement is schematic only.
5. Excitation is by external static exciter and not subtracted.
6. Feedwater Heater vents are isolated.
7. S/G Blowdown is set to Zero.
8. Scavenging steam on MSR bundles set to 3%.
9. Cycle isolation is assumed: no fugitive, diversionary, bypass, or leakage flows.
10. ETFR estimated, not calculated, not benchmarked.
11. Indicated temperatures for saturated flows may have roundoff errors. use enthalpy for these flows.

AM600 VWO HEAT BALANCE (102% RATED)		
KINGS		DATE
PREPARED BY	MWONGEERA	2016/10/06
REVIEWED BY	ROBERT M. FIELD	2016/10/06
SCALE	NOT TO SCALE	
KEPCO INTERNATIONAL NUCLEAR GRADUATE SCHOOL		
TC2F – 63	1500 RPM	R2

REFERENCES

[1] International Atomic Energy Agency, PRIS [Internet], International Atomic Energy Agency, Vienna (Austria), 2016 [cited 2016 Dec 15]. Available from: https://www.iaea.org/pris/Home.aspx.

[2] Babcock & Wilcox Company, Steam, Its Generation and Use [Internet], forty-second ed., Babcock & Wilcox, New York (NY), 2016 [updated 2016 Dec 15]. Available from: http://www.babcock.com/library/pages/steam-its-generation-and-use.aspx.

[3] American Nuclear Society, Nuclear News, 2016, pp. 28–30.

[4] Scientech, Commercial Nuclear Power Plants, twenty-sixth ed., A Curtiss Wright Flow Control Company, Brea (CA), 2013.

[5] APR1400 Design Control Document Tier 2, Chapter 1, Introduction and General Description of the Plant, Korea Electric Power Corporation/Korea Hydro & Nuclear Power CO, LTD, Seoul (Korea), 2014.

[6] World Bank. World Bank GDP Data [Internet], World Bank, Washington, DC [cited 2016 Dec 15]. Available from: http://data.worldbank.org/indicator/NY.GDP.MKTP.CD/countries.

[7] International Atomic Energy Agency, IAEA Nuclear Energy Series No. NG-T-3.8: Electric Grid Reliability and Interface with Nuclear Power Plants, International Atomic Energy Agency, Vienna (Austria), 2012, pp. 23–25.

[8] D.R. Cornell, et al., Advanced Nuclear High Pressure Steam Turbine Designs: Solutions for Retrofit and New Unit Applications, General Electric Company (GE Energy), Schenectady (NY), 2006.

[9] A.L. Yarden, Turning MSRs into High-performance Items [Internet]. Neimagazine [cited 2000 May 30]. Available from: http://www.neimagazine.com/features/featureturning-msrs-into-high-performance-items/.

[10] J.I. Cofer, J.K. Reinker, W.J. Sumner, Advances in Steam Path Technology, Report No. GER-3713E, GE Power Systems, Schenectady (NY), 1996.

[11] S. Senoo, K. Asai, A. Kurosawa, G. Lee, Titanium 50-inch and 60-inch last-stage blades for steam turbines, Hitachi Review 62 (2013) 23–30.

[12] Mitsubishi Heavy Industries, Ltd, Chapter 10—steam and power conversion system, in: MUAP-DC010, Rev. 3, Design Control Document for the US-APWR, Mitsubishi Heavy Industries, Ltd, Tokyo (Japan), 2011, pp. 10.1–10.6.

[13] Electric Power Research Institute, Pressurized Water Reactor Secondary Water Chemistry Guidelines, Rev. 7, EPRI Report No. 1016555, Electric Power Research Institute, Palo Alto (CA), 2009.

[14] Electric Power Research Institute, Pressurized Water Reactor Primary Water Chemistry Guidelines, Rev. 7, EPRI Report No. 3002000505, Volumes 1 and 2, Electric Power Research Institute, Palo Alto (CA), 2014.

[15] Electric Power Research Institute, BWRVIP-10-Revision 1: BWR Vessel and Internals Project, Volume 1: BWR Water Chemistry Guidelines—Mandatory, Needed, and Good Practice Guidance and Volume 2: BWR Water Chemistry Guidelines—Technical Basis, EPRI Report No. 3002002623, Palo Alto (CA), 2016.

[16] Gerb, Elastic Support of Turbines, Gerb Vibration Control Systems, Berlin (Germany), 2011. Available from: http://www.gerb.com.

[17] Unisorb, General Catalog, Unisorb Installation Technologies, Jackson (MI), 2012. Available from: http://www.unisorb.com.