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Design of the AM600 Turbine-Generator for NPPs in Emerging Markets

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1. Introduction

Analysis of global electric markets indicates that the current and near term capacity of electrical grids for many developing countries (e.g., Bangladesh, Kenya, Vietnam, Malaysia) is insufficient to reliably incorporate Nuclear Power Plants (NPPs) with large unit sizes (e.g., >1000 MWe). Thus a modern NPP design with a smaller output (~600 MWe) is of interest. To address conditions for such markets, the 'AM600' Turbine-Generator (T/G) design proposed here represents a 600 MWe design which is robust and supports a simplified steam cycle. In this paper, preliminary analysis related to: (i) the T/G steam flow path, and (ii) the turbine cycle heat balance is examined. The proposed shaftline starts with a determination of the number of flows, followed by a determination of the number of high and low pressure stages, followed by heat balance analysis.

2. Target Markets

Currently it is common for Nuclear Steam Supply System (NSSS) vendors to offer large reactor plants in the range of 1200 to 1600 MWe per unit. To fulfil the growing energy needs of developing countries and emerging markets, smaller reactors are better suited to ensure grid stability and to avoid torsional resonance. This has been identified within the US DOE Global Nuclear Energy Partnership (GNEP) initiative as one of the key elements, "*Grid-Appropriate Reactors*," needed to enable worldwide expansion of the peaceful use of nuclear power [1].

In these markets, small reactors have attractive characteristics relative to large reactors in two specific areas. In the first area, large sized reactor plants have a capacity relative to the overall grid load flow which is large (e.g., >10%) [2]. Trip of such a large unit would severely challenge grid stability possibly resulting in total blackout of the grid.

In the second area (e.g., for countries with large seasonal variation in hydropower inputs), grid frequency is known to vary significantly beyond the recommended range for nuclear T/Gs. In such an environment, a T/G shaftline with natural frequencies near the critical two-times line frequency may enter into synchronous excitation with ever present negative sequence currents. For these markets, a stiff shaftline with a minimal number of natural frequencies below 150 Hz is called for.

3. Heat Sink Evaluation

The T/G design first requires a determination of the number of low pressure turbine cylinders. This in turn requires an estimate of the necessary exhaust area. The ideal exhaust area is based on optimized exhaust velocity, a function of the exhaust mass flow rate and condenser backpressure.

To determine the target range of condenser backpressures for the AM600, a representative list of candidate countries (i.e., which have either planned, or are constructing a NPP), has been selected from emerging market regions in order to determine heat sink parameters. The countries considered here are all located in equatorial regions and include: Egypt, Bangladesh, Vietnam, Kenya, Nigeria, Malaysia and Indonesia, as seen in Figure 1 and Table I.

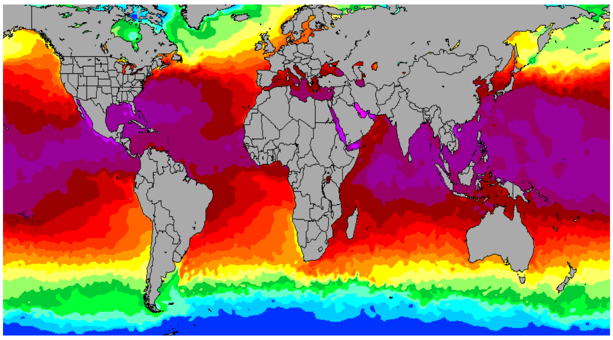

Fig.1. Ocean water temperature as recorded on 15th Aug 2015. Temperatures vary from high at the equator (purple) to low at the poles (blue). Courtesy of ©World Sea Temperature.

Table I: Yearly Average Sea Water Temperatures for NPP Candidate Sites

Country	City	Annual Average Seawater Temperature	
		°C	°F
Egypt	Marsá Maţrūḩ	22.0	71.5
Bangladesh	Chittagong	25.7	78.3
Vietnam	Cam Ranh	26.9	80.4
Kenya	Shimoni	27.5	81.5
Nigeria	Brass	27.5	81.7
Malaysia	Batu Pahat	28.9	84.2
Indonesia	Tegal	29.1	84.1

Condenser hotwell temperatures are then estimated using Equation 1 below [3], and results are shown in Table II.

$$t_c = t_{ri} + \Delta t + \delta t \quad (1)$$

where:

t_c is condenser hotwell temperature

t_{ri} is cooling water entrance temperature

Δt is circulating water range (10-12 °C)

δt is minimum temperature difference (3-5 °C)

Table II: Yearly Average Estimated Condenser Temperatures and Pressures for NPP Candidate Sites

Country	Average Seawater Temperature	Average Hotwell Temperature	Average Condenser Pressure
	°C	°C	in-HgA
Egypt	22.0	36.0	1.75
Bangladesh	25.7	39.7	2.14
Vietnam	26.9	40.9	2.28
Kenya	27.5	41.5	2.36
Nigeria	27.5	41.5	2.36
Malaysia	28.9	42.9	2.54
Indonesia	29.1	43.1	2.57

From these results an upper bound condenser backpressure of 2.7 in-Hg has been selected. Similar analysis yields a lower bound backpressure of 1.3 in-HgA (i.e., for Egypt). Egypt is an outlier in the target country list with lower winter heat sink temperatures. For other countries, a minimum backpressure of 2 in-HgA is more appropriate. (Note that a backpressure range of 2 to 3 in-HgA is consistent with NPP operations in Taiwan [4], which has a similar latitude to the countries considered here). This range, 1.3 to 2.7 in-HgA, then serves as input to the determination of required exhaust area.

4. AM600 Turbine-Generator

The conceptual T/G design developed here is termed the 'AM600', or 'Advanced Modern 600 MWe' machine. The first order of business is to establish the number of high pressure and low pressure flows.

4.1 Number of High Pressure Turbine Flows

The AM600 High Pressure Turbine (HPT) is selected as a single-flow machine consistent with historical practice in the U.S. (e.g., Ft. Calhoun, Monticello). In addition, recent nuclear retrofit experience with larger sized units converted the existing design from a two-flow to single-flow HPT with an indication of increased efficiency (e.g., Surry 1,2, North Anna 1,2 [5]).

A single-flow machine is understood to offer higher efficiency due to longer blading, with each stage handling double the flow a of a two-flow machine. This longer blading reduces end losses, improving overall efficiency. In addition, there may also be some reduction in inlet and exhaust bowl losses.

4.2 Number of Low Pressure Turbine Flows

Historically, for half-speed nuclear steam turbines, the number of Low Pressure Turbine (LPT) flows has been set to either four (4) (e.g., for units ranging for 500 to 1000 MWe) or six (6) (e.g., for units ranging from 800 to 1500 MWe). For these units, exhaust area was limited by the available lengths of last stage blading, or 'L-0' blading. The 38-in L-0 design from General Electric and 44-in L-0 design from Westinghouse were typical of historical vendor offerings.

In this regard, it is important to note that the U.S. and associated markets (e.g., nuclear programs in Canada, Korea, and Taiwan) operate with a grid frequency of 60 Hz. The emerging markets considered here universally operate at 50 Hz. At this lower frequency, the lower rotational speed of the T/G (i.e., 1500 rpm) permits the design of longer L-0 blading. This increases the exhaust area per end. In practice, developments over the past two decades of longer L-0 blading make it possible to consider a two-flow LPT for the AM600. (In the public literature, more than one T/G vendor suggests design of a two-flow machine to interface with a smaller NSSS. However, to the knowledge of the authors, no such machines in the 600 MWe class have been built or ordered to date).

Considering the range of backpressures determined in the previous section, and the projected mass flow rate for the exhaust flow, the volumetric flow rate can be coupled with the exhaust area per end for identified L-0 blading in the literature to produce the following plot.

Fig. 2 illustrates that there are a number of L-0 designs for the 50 Hz market which are either commercially available or in advanced development with sufficient exhaust area to make a single cylinder, two-flow LPT a good selection for the AM600.

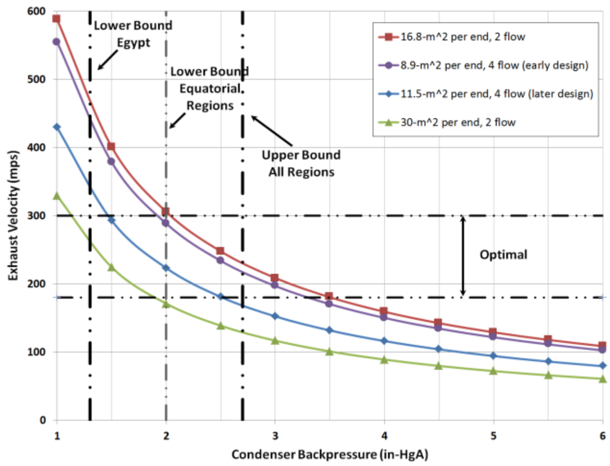

Fig.2. Exhaust velocity, number of flows, and L-0

It is expected that exhaust velocities within the targeted backpressure range can be adjusted to either match that for the historical four (4) flow design (e.g., using the GE 38-in L-0 at 8.9 to 11.5 m^2) or to be higher or lower than the historical design (i.e., the 16.8-m^2 design can produce higher velocities, while the 30-m^2 design can produce lower velocities).

From the evaluation above, it is clear that an LPT with a two-flow design can accommodate the expected exhaust flow for the AM600 with good thermodynamic efficiency. This design is expected to have benefits from reduced capital cost, reduced inspections, and in particular, a stiffer shaftline. These benefits more than outweigh any benefit from improved thermal efficiency (i.e., for a four-flow machine) for markets with a minimum backpressure of 2 in-HgA. Thus, the AM600 is designed with a two-flow LPT. Detailed design will be the responsibility of individual T/G vendors.

For the heat balance analysis presented here, the estimated Expansion Line End Point (ELEP), exhaust loss, and Used Energy End Point (UEEP) are based on available L-0 blade design.

4.3 Stage Design

The steam flow path performance is based on similar sized T/G units currently in operation. HPT stage efficiency is based on existing designs for wet steam. In general, for internal LPT stages (i.e., not L-0), a two-flow machine with modern design should have higher efficiency than found in existing four-flow units due to higher flows per stage and lower end losses. The L-0 design is based on stated performance for similar designs and exhaust velocities. Utilizing Cotton stage group efficiency charts [6], optimal pressure ratios for the HP and LP turbine stages have been determined in Fig. 3.

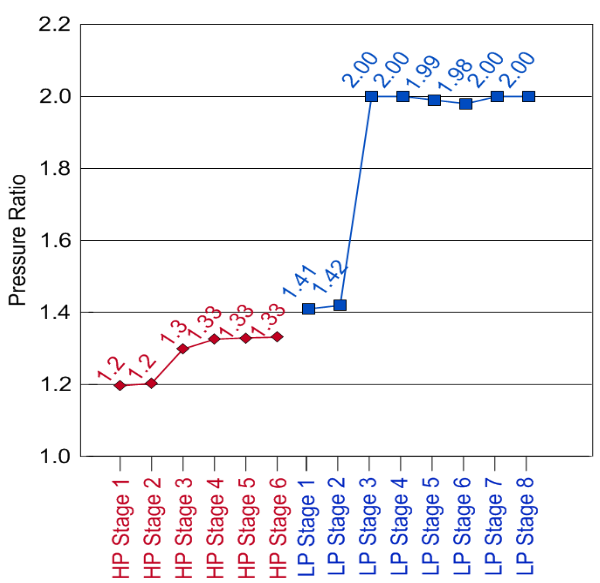

Fig.3. HPT and LPT stage pressure ratios.

4.4 Low Pressure Rotor Design and Challenges

The AM600 LPT rotor conceptual design is developed using CATIA V5 graphical software [7], as seen in Fig 4, and its parameters are shown in Table III.

Table III: Proposed AM600 LPT rotor features

Component	units	AM600 Rotor (welded drum)
Mass (monoblock)	tonnes	270
Mass (welded drum)	tonnes	175
Journal diameter	mm	760
Rotor diameter	mm	2020
L-0 Blade Length	mm	1600
Rotor Length	mm	13100

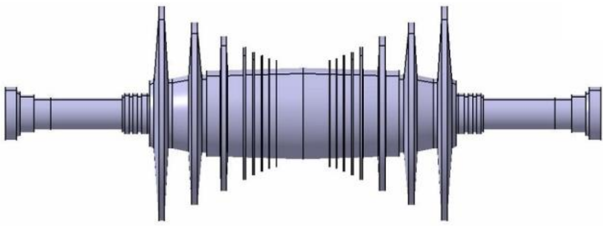

Fig.4. AM600 Rotor 3D dimension executed using CATIA V5.

The dimensions in Table III are used to develop the conceptual layout of the turbine building. With a single LPT cylinder, the size of the turbine building can be significantly reduced greatly decreasing construction time and installed cost. The single cylinder LPT does however, present significant challenges in the design of the main condenser. This component is constrained to a single shell located within the confines of the turbine pedestal. Development of the main condenser design and layout of associated systems and components is addressed elsewhere.

Preliminary (simplified) rotordynamic analysis of the AM600 T/G shaftline using ANSYS [8] indicates a that a stiff design with a small number of natural frequencies below 150 Hz can be achieved (i.e., for a final design which aligns with the conceptual design for the AM600.

5. AM600 Heat Balance

5.1 Configuration

Turbine cycle heat balance analysis for the AM600 is based on a conceptual design with a single-flow HPT with six stages, and a two-flow LPT with eight stages.

Final feedwater temperatures and HPT throttle pressures are similar to design values for the APR1400. Cross-around pressure is towards the high end of the traditional range (11 to 15 bar) for wet steam turbines. AM600 component list can be seen in Table IV.

Table IV: Proposed AM600 Component List

Component	AM600	Comments
HPT Cylinders	1	Single Flow
LPT Cylinders	1	Two Flow
Moisture Separators	2	Two Cross-Around Lines
Reheaters	2	Single Stage
Condenser Zones	1	Seawater Cooling
Hotwell Zones	4	-
Condenser Passes	2	-
HP Feedwater Heaters	2	Fully Cascading
LP Feedwater Heaters	4	Fully Cascading
Condensate Pumps (Radial)	3	3/3 Operating at 50% Capacity
Condensate Booster Pumps	3	3/3 Operating at 50% Capacity
Main Feedwater Pumps (Motor Driven)	2	1/2 Operating at 100% Capacity

The overriding consideration in establishing the steam cycle is reduced component count in order to reduce upfront capital outlays, simplify operations, and minimize required maintenance, testing, and inspection activities.

The starting parameters for the AM600 heat balance are taken from a historical design with six (6) points of feedwater heating (fully cascading) and two stages of reheat. It is assumed that stage group efficiencies (L-0 treated separately) for the AM600 can be made to match those from this reference design since flow per stage is approximately double for the two-flow machine. Adjustments were then made to optimize the cycle for the specific features of the AM600. In particular, temperature rise per stage of feedwater heating were levelized to maximize thermal efficiency (i.e., within constraints on optimal pressure ratios between the turbine stages).

The cycle is illustrated in the heat balance diagram, Fig. 5 below.

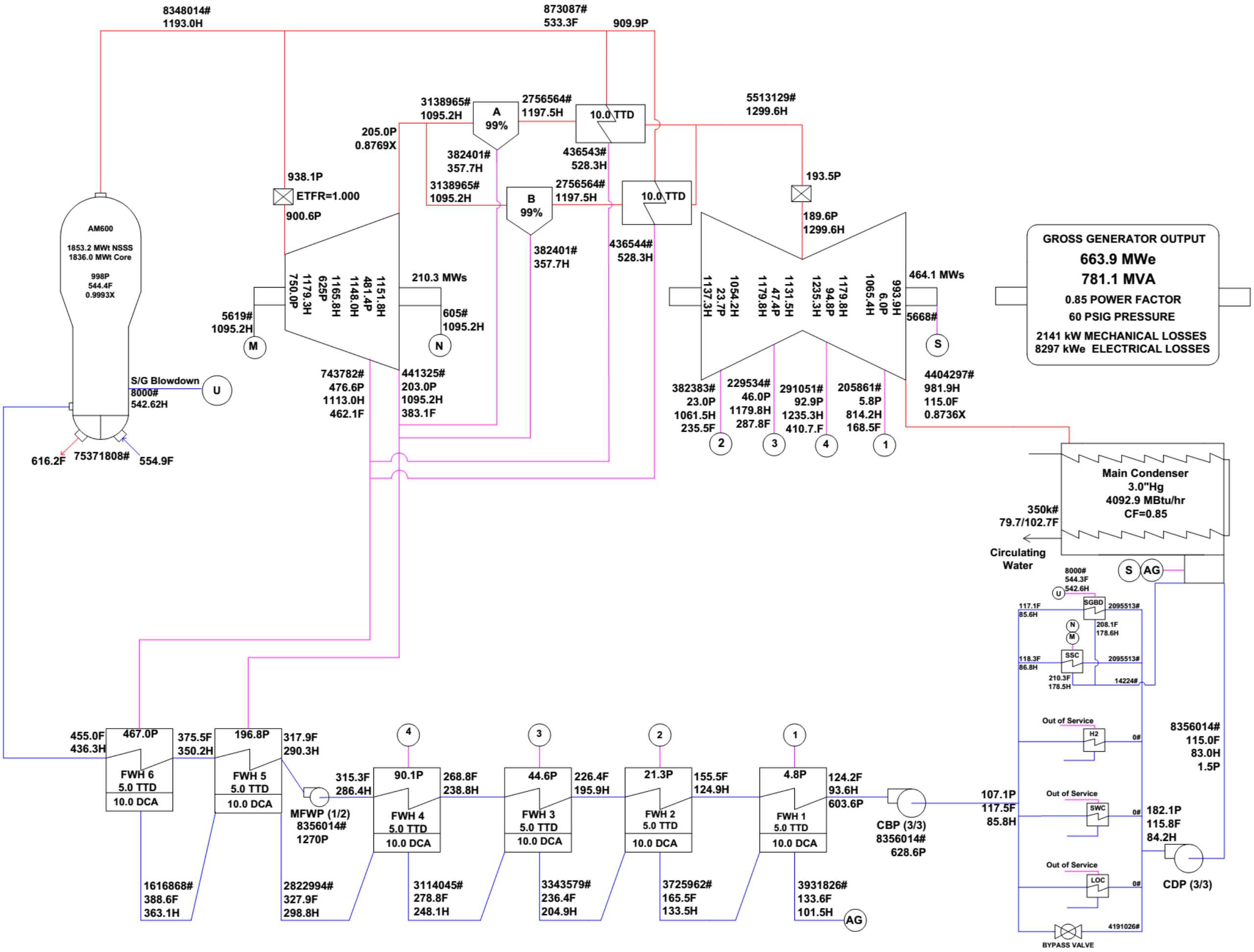

Fig.5. AM600 Heat balance diagram showing component count and arrangement.

5.2 Heat Balance Initial Parameters

The T/G will have five steam extractions as follows: one extraction in the HP Turbine, four (4) extractions in the LP turbine. The 5th point FWH will receive extraction steam from the cold reheat piping. Initial heat balance parameters are summarized in Table V.

Table V: Heat Balance Initial Parameters

Parameter	Units	AM600
Licensed Thermal Power	MWt	1800
Maximum Calculated	%	102.9
NSSS Power (Max Calc)	MWt	1853.2
S/G Dome Pressure	bar	68.8
S/G Leaving Moisture	%	0.07
S/G Leaving Enthalpy	kJ/kg	2774.9
HPT Throttle Pressure	bar	62.1
LPT CIV Inlet Pressure	bar	13.3
Reheat Mass Flow Rate	kg/hr	396,026
Final Feedwater Enthalpy	kJ/kg	1014.9
Final Feedwater Temperature	C	235.0
Feedwater Mass Flow Rate	tonnes/hr	3,790

5.3 Heat Balance Performance Indicators

Parameters in all necessary locations on the cycle have been determined and performance indicators are summarized in Table VI. The resultant efficiency is competitive with modern T/Gs for nuclear steam conditions. Equipment, installation, and operating costs can be reduced, for example for a design of MSRs with one stage of reheat.

Table VI: Heat balance performance indicators

Parameter	Units	AM600
HPT Shaft Power	MWs	210.3
LPT Shaft Power	MWs	464.1
Shaft Power to Main Generator	MWs	674.4
Gross Generator Output	MWe	663.9[1]
T/G Gross Efficiency	%	35.82[1]
T/G Gross Heat Rate	BTU/kW-hr	9524[1]

1) 3 in-HgA

6. Conclusions

The conceptual design for the AM600 T/G offers the following:

- a stiff shaftline which can offer robust performance in smaller grids lacking optimal stability relative to grid disturbances and frequency variation,
- a simplified approach to T/G fabrication, installation, operation, testing, inspections, and maintenance due to design with a single LPT cylinder while maintaining high thermal efficiency, and
- a reduced component count for MSRs, FWHs, and power train pumps and drivers (and associated support system components) resulting in lower capital outlays, simplified operations, and further reducing the maintenance, testing, and inspection burden.

Further studies are underway to refine the conceptual designs performed to date and to fully determine the optimum minimal configuration of the system while providing a competitive thermodynamic efficiency.

ACKNOWLEDGEMENTS

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