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Design of Feedwater Heaters for the AM600 Turbine Island

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Abstract: The Advanced Modern 600 MWe (AM600) project represents the conceptual mechanical design and layout of a Nuclear Power Plant (NPP) Turbine Island intended to address challenges associated with emerging markets interested in nuclear power. The biggest challenge relates to project financing and the subsidiary issue of maintaining the construction schedule. To address that challenge in part, the AM600 is designed with a single cylinder low pressure turbine rotor matched to a condenser module. The module integrates all low pressure Feedwater Heaters (FWHs) into the condenser neck. This study investigates the design and sizing of a single string of FWHs to demonstrate proof-of-concept of the AM600 design. Specifically, the condenser is designed as a factory fabricated module which includes the installed low pressure FWHs along with major piping and valving. The analysis and design summarized here demonstrate that using industry standards and guidelines, along with accepted engineering practices, the AM600 can accommodate a modular condenser design while allowing for continued operation with an FWH Out-of-Service (OOS).

Key words: AM600, FWH, HEI, medium size reactor, NPP, PEPSE, OOS, TEMA, Turbine Island.

Abbreviations and Acronyms

AC	Alternating Current
AM600	Advanced Modern 600 MWe
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
bar-g	10^5 Pa (gauge)
BWG	British Wire Gauge
CBP	Condensate Booster Pump
DC	Drain Cooler
DCV	Drain Control Valve
EDC	External Drain Cooler
ES	Extraction Steam (System)
fps	feet per second
FFT	Final Feedwater Temperature
FWH	Feedwater Heater
HDT	Heater Drain Tank
HEI	Heat Exchange Institute
HP	High Pressure
hr	hour
in	inch
kg	kilogram
ksi	10^3 pounds (force) per square inch
LP	Low Pressure
m	meter
mm	millimeter
MOV	Motor Operated Valve
MPa	10^6 Pa
MVSD	Mechanical Variable Speed Drive
MWe	MegaWatt electrical
MWt	MegaWatt thermal
NPP	Nuclear Power Plant
OOS	Out-of-Service
P	Pressure
Pa	Pascal (= 1 N/m^2)
PEPSE®	(Heat balance software from Scientech)
psig	pounds (force) per square inch (gauge)
PWR	Pressurized Water Reactor
s	second
S/G	Steam Generator
SGFP	Steam Generator Feedwater Pump
T	Temperature
T/G	Turbine-Generator
TEMA	Tubular Exchanger Manufacturers Association
VWO	Valves Wide Opened

Nomenclature

C_v	(valve) flow coefficient
P	Differential Pressure
$P_{allowable}$	(valve) differential pressure associated with

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	flashing
K_m	(valve) pressure recovery factor
P_1	(valve) inlet pressure
P_c	critical pressure for water (= 22.064 MPa)
P_v	(valve) inlet vapor pressure
Q	(valve) volumetric flow rate
r_c	critical pressure ratio factor
S_h	allowable stress at temperature

1. Introduction

This paper investigates the design configuration and sizing of the Low-Pressure (LP) and High Pressure (HP) FeedWater Heaters (FWHs) for the Advanced Modern 600 (AM600) turbine cycle [1], a Turbine Island design to be coupled with a medium sized nuclear reactor plant.

The AM600 is unique to Pressurized Water Reactor (PWR) plants in that it is designed for a medium sized reactor but has a single LP turbine rotor. This in turn dictates a single string of FWHs, similar to designs for small to medium sized fossil units.

The number of LP FWH strings is determined by the number of LP turbine cylinders. Until now, for nuclear units, this has resulted in either two (2) or three (3) strings of LP FWHs. In these designs, for the FWH Out-Of-Service (OOS) condition (e.g., tube failure), the entire string associated with that FWH is isolated, and the unit then operates with partial bypass flow around the remaining string(s). Under this abnormal operating condition, the remaining string(s) is typically designed to operate with 120% to 150% of the normal tubeside flow (However, in practice, the actual flow is limited as the reactor operates with reduced power until the FWH OOS is returned to service).

For the AM600, the four (4) LP FWHs are all to be located in the condenser neck (Fig. 1), placing a constraint on the diameter of the heaters. The two HP FWHs will be located at a lower level in the turbine building between the Steam Generator Feed Pumps (SGFPs) and the steam tunnel. The purpose for the current study is to determine optimal LP and HP FWH sizes which balance: (i) the maximum allowed power levels with an individual LP or HP FWH OOS, with (ii) constraints associated with FWH size (diameter) (i.e., as determined by the dimensions of the tube bundle coupled with shell side clearance to the bundle).

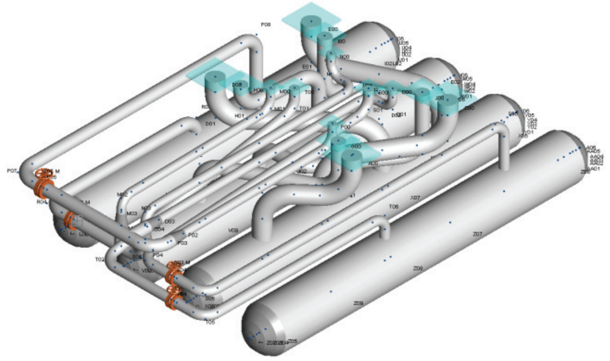

Fig. 1 AM600 LP FWH arrangement in the condenser neck.

2. AM600 Motivation

The AM600 is a design concept for the Turbine Island of a PWR unit which addresses several issues related to economical, reliable, and efficient design for Nuclear Power Plants (NPPs) intended for emerging markets. As described previously [1], the AM600 turbine island is designed to produce power in the range of 600 to 700 MWe when paired with an NSSS which supplies ~1,800 to 2,000 MWt. Specifically, the AM600 addresses the following design elements for the targeted markets:

- an overall design which emphasizes simplicity, easy maintenance, and reliability for “newcomer” countries to nuclear power,
- reduced component count with simplified system and component designs to be compatible with domestic maintenance capabilities,
- an electrical output compatible with smaller electrical grids and load flows, and
- a simplified turbine-generator (T/G) shaft-line which is robust in relation to torsional vibration associated with an electrical grid which may experience: (i) seasonal frequency drift, and (ii) frequent large electrical disturbances.

3. Background and AM600 Challenges

3.1 Feedwater Heater Design Configuration

FWHs are used to affect regenerative heating in the power generating Rankine cycle, improving thermal efficiency. Heater design is most typically of the standard shell and tube configuration consisting of a tube bundle inside a cylindrical shell [2]. Condensed steam from the condenser hotwell is pumped through a series of FWHs for preheating prior to introduction to the steam generator. The condensate or feedwater is directed to flow through the tube side while extraction steam from various stages in the main turbine is introduced to the shellside to condense on the outside of the tubes [3].

To further improve cycle efficiency, the steam entering the FWH shell is completely condensed, and before leaving the shell, this condensed steam is subcooled by passing through a "drain cooler" section, transferring additional heat to the condensate. Thus NPPs use a "two-zone" FWH design with a condensing zone and drain cooler zone (see Fig. 2). The tubing is configured in the U-tube bundle arrangement. This approach simplifies the design and fabricating steps, and avoids the need for floating heads for high temperature heaters. Note that some tubes are omitted at the center of the bundle to permit the installation of the air removal channel.

3.2 Feedwater Layout

In passing from the first to the last FWH, the condensate temperature is increased in steps by the increasing pressure and temperature on the shell side of each heater in sequence. The source of heat is steam extracted from various locations along the turbine steam flow path. The lowest pressure FWHs work at low pressures—and hence high volumes of steam flow. To minimize the piping lengths and pressure drop for routing the steam from the turbine nozzles to the FWH shellside nozzles, these heaters are typically located directly below the LP turbine exhaust flange in the condenser "neck". In conventional designs, the first two (2) LP FWHs are located at this position for each condenser shell.

The AM600 design considers placing all four (4) low pressure FWHs in the neck region, and thus a "proof of concept" study is needed to ensure there is sufficient space for this equipment without compromising other functions of the condenser (e.g., exhaust steam flow velocities, turbine-generator foundation design, extraction steam line routing). Sizing for the LP FWH shell diameters is the first step in this process.

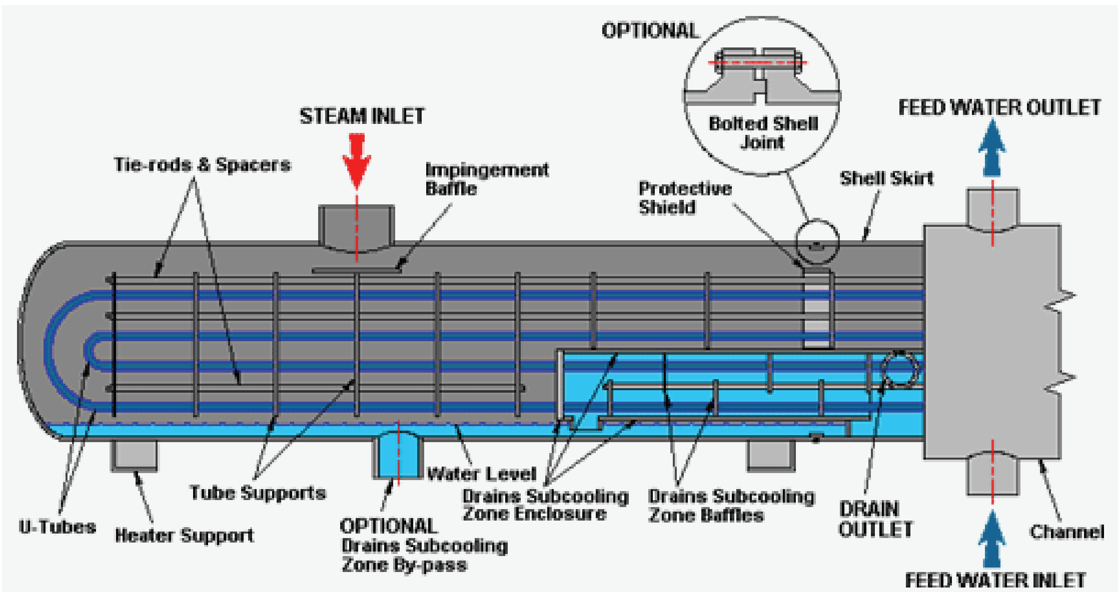

Fig. 2 Two-zone feedwater heater.

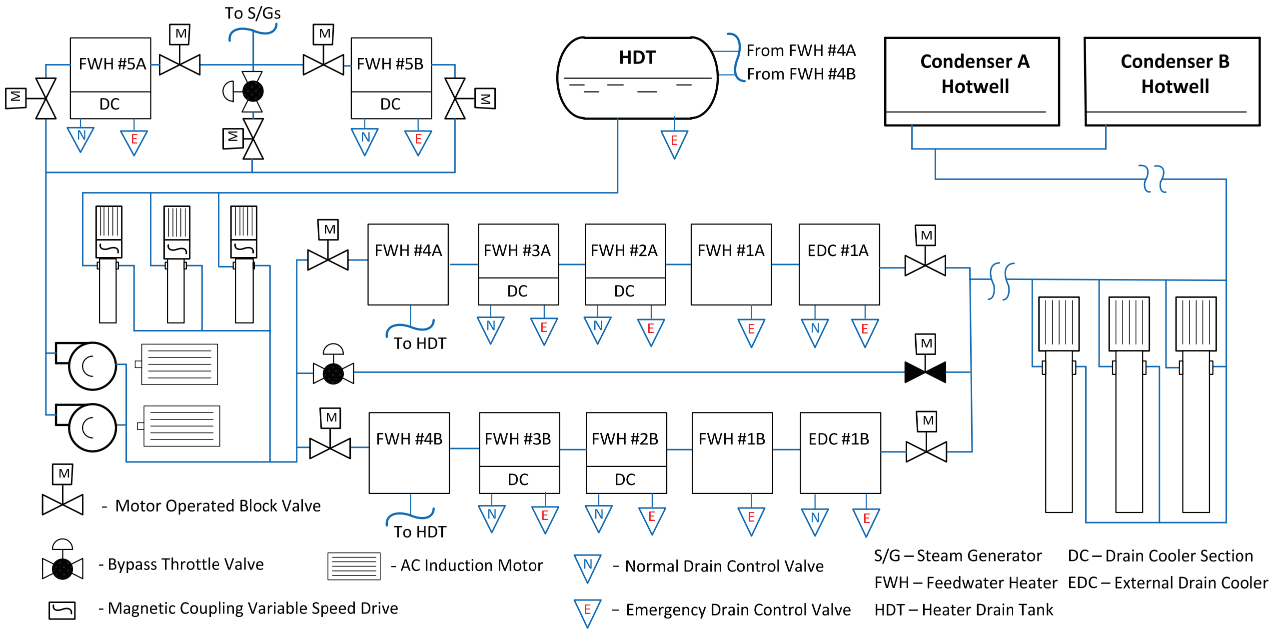

Fig. 3a Conventional two string design with bypass.

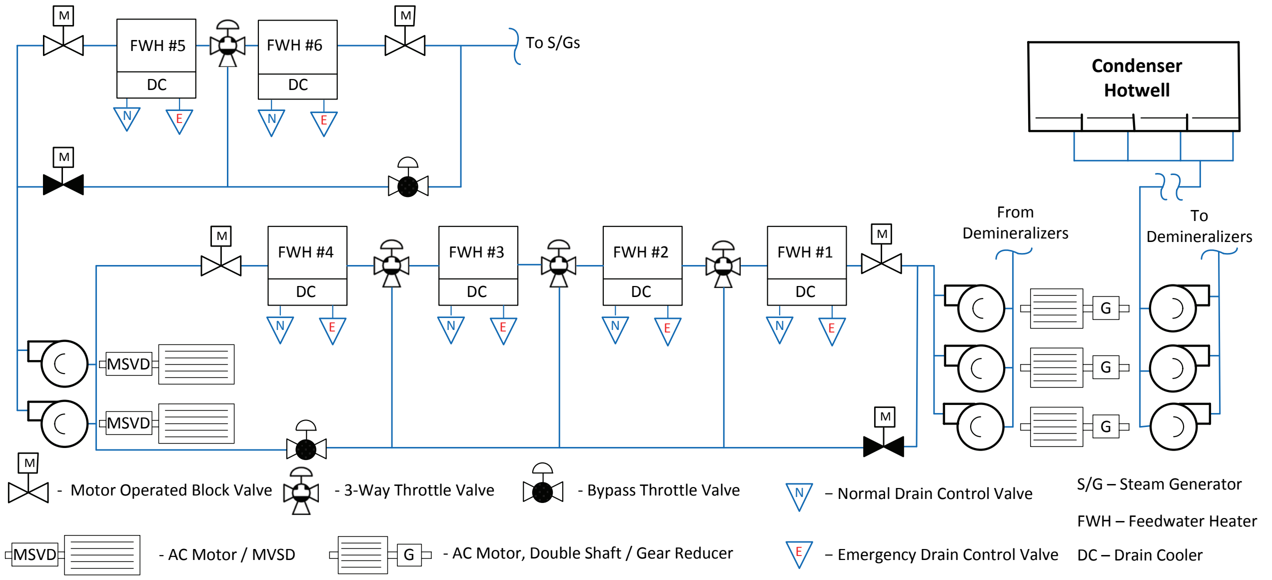

Fig. 3b AM600 single string design with bypass.

3.3 Feedwater Heater Out-of-Service (OOS)

In conventional design, in the event of an FWH Out-of-Service (OOS) (e.g., tube leak, malfunctioning drain control valve), the plant remains on-line by isolating the affected FWH "string" and opening the "bypass" line for partial bypass flow around all the heaters in that string. The standard design using two (2) strings of FWHs is illustrated in Fig. 3a.

The AM600, however, is designed with only a single string of FWHs. To permit the unit to remain online while isolating only the affected FWH, the design incorporates the conventional bypass line, but also includes a three-way valve between each of the heaters. This permits re-routing of condensate flow to allow the desired isolation. The AM600 arrangement for the single string of FWHs is depicted in Fig. 3b.

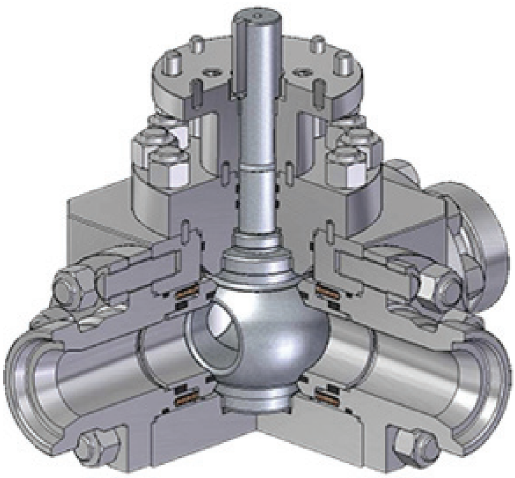

Fig. 4 Three-way metal seated ball valve—FWH bypass.

Fig. 4 provides a cutaway drawing for the type of three-way valve intended for this service.

Thus the AM600 design presents unique challenges as related to equipment layout and cycle design which are further explored here.

4. Methodology

4.1 AM600 Turbine Cycle Heat Balance

As a first step, steam cycle parameters for the base case and for FWH OOS service conditions are established and presented in Table 1. Analysis is performed using the PEPSE® program [4]. The standard AM600 model developed for design of the T/G steam flow path was used for the following case set.

Steam cycle parameters developed using the PEPSE® program were then used as design input for the follow-on analyses reported here.

4.2 Tubeside Design

Tubeside design was developed using the following steps.

(1) Tubing Specification—Determine the fabrication method for tubes and the tube material.

(2) Design Conditions (P, T)—Determine tubeside design pressure and temperature using heat balance and hydraulic analysis results.

(3) Allowable Stress—Using the design temperature, establish the allowable tube hoop stress (S_h) using Code values [5].

(4) Tube Diameter—Determine tube nominal diameter based on accepted engineering practice.

(5) Minimum Bend Radius—Establish the minimum bend radius for U-tubes based on accepted engineering practice.

(6) Tube Minimum Wall—Determine tube minimum wall using Code equations for hoop stress [5] with allowance for handling in the factory (i.e., adequate stiffness to limit sag and potential damage during tube insertion into cage).

(7) Required No. of Tubes—Determine the number of required tubes using: (i) volumetric flow rates from VWO heat balance results, (ii) industry guidelines from the Heat Exchange Institute (HEI) [6], and (iii) tube plugging margin per accepted engineering practice the results obtained are reported in Table 2.

(8) Tube Arrangement—Establish the tube arrangement using guidance from the Tubular Exchangers

Table 1 AM600 FWH OOS design conditions.

Case[a]	FWH OOS	LP OOS	HP OOS	Operating power[b]	% Bypass flow
1	N/A	-	-	VWO	N/A
2a	No. 1	✓	-	100%	30%
2b	No. 2	✓	-	100%	30%
2c	No. 3	✓	-	100%	30%
2d	No. 4	✓	-	100%	30%
2e	No. 5	-	✓	100%	30%
2f	No. 6	-	✓	100%	30%

a: The PEPSE® heat balance diagram for Case 2c is provided here as Attachment 1.

b: VWO = 1,982.4 MWt NSSS, 100% = 1,943.7 MWt NSSS.

Table 2 FWH Tube Count[a, b].

FWH No.	Average density (kg/m^3)	Volumetric flowrate (m^3/s)	Required tubes[c] (#)	Required tubes w/5% margin (#)
1	984.8	1.15	1,608	1,688
2	967.1	1.17	1,637	1,719
3	945.6	1.20	1,675	1,758
4	919.7	1.23	1,722	1,808
5	889.1	1.27	2,965	3,114
6	846.3	1.34	3,116	3,271

a: Mass flowrate for all FWHs is 4.071×10^6 kg/hr.

b: Flow area per tube is 2.343×10^{-4} m^2 for 3/4-in, 20 BWG LP FWH tubing and 1.407×10^{-4} m^2 for 5/8-in, 18 BWG HP FWH tubing.

c: Volumetric flow rate divided by flow area per tube divided by HEI velocity limit (3.048 m/s).

Manufacturers Association (TEMA) [7] with a tube pitch selected within the range of industry accepted practice.

(9) Tube Bundle Diameter—determine the "effective" bundle diameter from the results of Steps 7 and 8.

The bundle diameter from Step 9 is then combined with the shell clearance dimensions and other allowances to determine the installed shell diameter (as further described below). Note that the limiting tubeside flow condition occurs for the VWO case (see Section 5).

The AM600 design is not constrained by FWH tube length or the corresponding shell or overall FWH length. Tube length can be appropriately sized to account for required heat transfer in the condensing zone (i.e., achieve desired terminal temperature difference) and drain cooler zone (i.e., achieve desired drain cooler approach temperature). This tube length will not impact the design of the condenser neck for LP FWHs and will not infringe on available space for layout of the HP FWHs. Therefore, tube length and heat transfer surface area are not addressed here.

The analysis described above then establishes the necessary and sufficient tubeside and bundle arrangement information for input to the determination of shell diameter.

4.3 Shellside Design

Next, shellside design was developed using the following steps.

(1) Extraction Steam Flow—Determine the volumetric extraction steam flow rates to the shellside from the PEPSE® analysis (Case 1: VWO).

(2) Steam Inlet Nozzle Specification—Determine the number and size (diameter) of shellside inlet steam nozzles using: (i) industry guidelines from HEI [6], and (ii) accepted engineering practice for the maximum diameter for extraction steam piping and nozzles and for steam distribution along the length of the shell for very low pressure steam.

(3) Bundle to Shell Clearance—Determine top of tube bundle to shell clearance as the maximum of the following: (i) ¼ of the inlet nozzle inside diameter (per HEI [6]), (ii) clearance needed to meet steam escape velocity guidelines from HEI [6] (see below), or (iii) 150 mm (industry practice).

(4) Shellside Wall and Insulation Thickness—Estimate shell wall and insulation thickness.

(5) Installed Shell Diameter—Determine installed shell diameter as the sum of: (i) the tube bundle diameter, (ii) the tube bundle-to-shell clearance dimensions (top and bottom), (iii) twice the shell wall thickness, and (iv) twice the insulation thickness.

(6) FWH OOS Steam Inlet Velocity—Perform a confirmatory check of the shellside steam inlet nozzle velocities for the FWH OOS heat balance conditions (Cases 2a through 2f).

(7) FWH OOS Steam Escape Velocity—Complete confirmatory checks by examining the shellside steam escape velocities (as defined by HEI) for the FWH

OOS heat balance conditions (Cases 2a through 2f).

(8) FWH OOS Drain Cooler Flow—Determine drain cooler shellside volumetric flow rates for FWH OOS conditions to determine if OOS conditions are limiting for inlet window velocity and baffle plate spacing.

(9) FWH OOS Drain Control Valve Sizing—Determine required drain control valve capacity for FWH OOS conditions and compare to the required capacity for VWO conditions. Determine if oversized valves are required.

4.4 Other

Operation with an FWH OOS will see a reduction in the final feedwater temperature. This will result in an impact on the interface to the NSSS including considerations related to: (i) reactivity, and (ii) S/G structural and thermal-hydraulic design. Here, the change in final feedwater temperature from the PEPSE® heat balance analysis is reported.

5. Tubeside Design Analysis and Results

Unlike conventional designs, the limiting flow for the design of the AM600 LP and HP FWH tubeside occurs with all FWHs in service. The maximum volumetric flow rates through the tube side of the AM600 LP and HP FWHs occur at full power with maximum Final Feedwater Temperature (FFT) (i.e., minimum enthalpy rise in the Steam Generators (S/Gs)). The volumetric flow rates are then based on the VWO heat balance mass flow rates, pressures, and enthalpies.

With an FWH OOS, heat transfer surface area will be removed from service, impairing overall regenerative heating of the condensate and feedwater, slightly reducing the final feedwater temperature. For such bypass conditions, the enthalpy rise in the secondary side of the S/Gs will increase, and the mass and volumetric flow rates will decrease (with or without bypass). Thus, the total tube flow area can be based on the VWO condition.

For illustration of the bypass arrangement and tubeside flows used in the turbine cycle heat balance analysis, Fig. 5a depicts isolation and bypass flows for LP FWH No. 3 OOS while Fig. 5b illustrates isolation and bypass flows for HP FWH No. 5 OOS.

5.1 Tube Material Selection (Steps 1, 2, 3)

Within the nuclear industry, a consensus has emerged on material selection for FWH tubing. Specifically, ASTM A688 TP304 [8], Dual Rated seam welded stainless steel tubing is specified giving a good balance of strength, corrosion resistance, and ductility. This material is also easily inspected using conventional eddy current probes. This is the material specification applied for the design of the AM600 FWH tube bundles.

The tubeside design temperature for LP FWHs is determined as 175 ^{o}C (~350 ^{o}F) resulting in a maximum allowable stress of 99.5 MPa (14.4 ksi). For the HP FWHs, the design temperature is 250 ^{o}C (~480 ^{o}F) giving a maximum allowable stress of 90.0 MPa (13.1 ksi).

Note that attention is required to obtain quality tubing which meets the Code requirements above but which goes beyond the explicit specifications from the ASTM. A good set of guidelines is provided elsewhere [9].

5.2 Tubeside Design Parameters (Steps 4, 5, 6)

For the LP FWH tubing, the design pressure is established in the hydraulic analysis as 65 bar-g (~942 psig). The industry standard specification for LP FWHs of 3/4-in tubing with an assumed wall thickness of 20 BWG. Using industry practice for a 50-mm minimum bend radius (i.e., to allow space for installation of the pass partition plate and eddy current inspections), this specification meets the required duty considered here with margin.

For the HP FWH tubing the design pressure is established in the hydraulic analysis as 135 bar-g (1,958 psig). The industry standard specification for

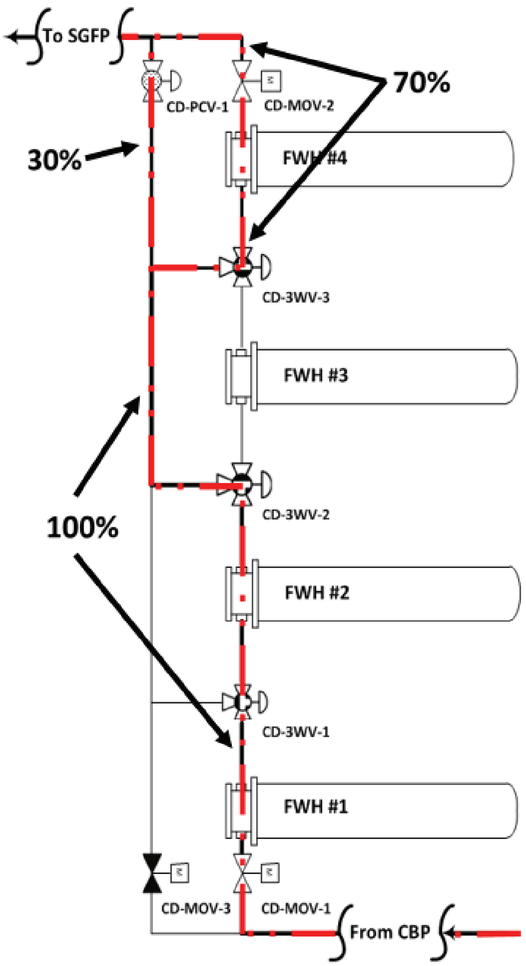

Fig. 5a LP FWH bypass flow alignment—FWH #3 OOS.

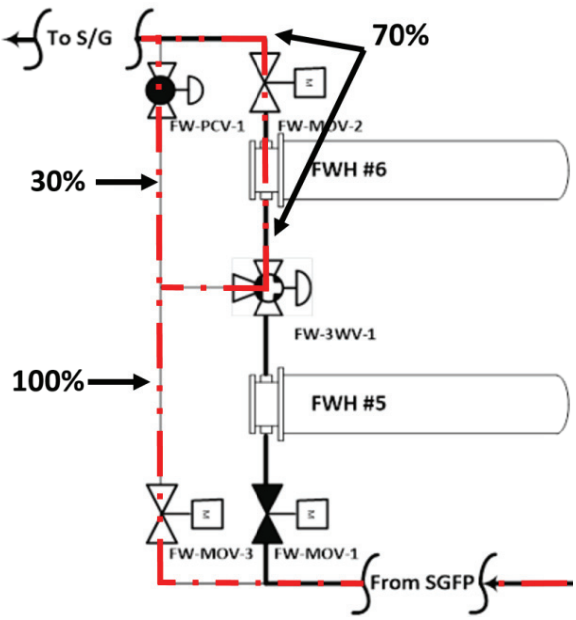

Fig. 5b HP FWH bypass flow arrangement—FWH #5 OOS.

HP FWHs of 5/8-in tubing with an assumed wall thickness of 18 BWG. Using industry practice for a 50-mm minimum bend radius as above, this specification meets the required duty while allowing longer tube support and baffle plate spacing than required for thinner tubing.

5.3 Number of Tubes (Step 7)

The required flow area for the tubeside is based on the limiting tube velocity given by HEI as 10 fps (3.048 m/s) based on the average density of entering and leaving flow [6]. The volumetric flow for design is based on the VWO heat balance. Finally, a tube plugging allowance of ~5% is then applied to the calculated number of tubes.

5.4 Tube Bundle Arrangement (Step 8)

Fig. 6 illustrates the conventional triangular pitch tube pattern used in virtually all FWHs. Tube layout is defined by the characteristic angle and the corresponding definition of the tube pitch [7]. The 30°, 45°, and 90° layouts are commonly employed but the 60° layout is not considered because it produces lower effectiveness in pressure drop to heat transfer conversion for single phase flow applications and is not generally recommended. The 30° staggered layout has the highest tube density, a very high shell side (condensing) heat transfer coefficient, and a high effectiveness of pressure drop to heat transfer conversion. Therefore, the tube layout for the AM600 FWHs was selected as the 30° triangular pitch.

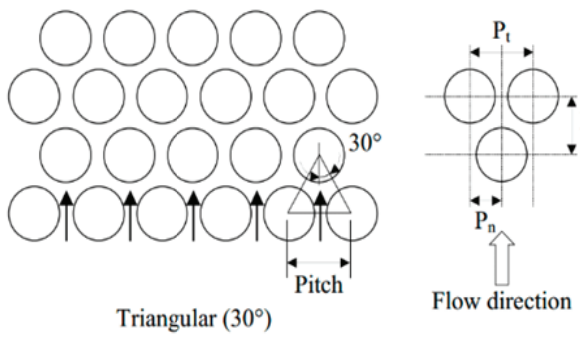

Fig. 6 Tubesheet standard pattern.

Table 3 Tube bundle effective diameter.

FWH No.	Number of tubes[a]	Enclosing circle diameter[b,c]	Center offset	Effective bundle diameter[d]
	(#)	(mm)	(mm)	(mm)
1	1,688	1,501	83	1,583
2	1,719	1,514	83	1,597
3	1,758	1,532	83	1,614
4	1,808	1,553	83	1,635
5	3,114	1,860	86	1,946
6	3,271	1,907	86	1,993

a: See Table 2.

b: Tubesheet face area per tube is 524 mm^2 for LP FWH tubing and 437 mm^2 for HP FWH tubing.

c: Enclosing circle diameter is the diameter of a circle with an area equal twice the #-tubes times tubesheet face area per tube.

d: Effective bundle diameter is equal to enclosing circle area plus center offset.

Given the selection of tube diameter above, the standard industry practice which uses a pitch-to-diameter ratio of 1.25 is applied here. This pitch provides a balance between: (i) FWH size and cost (smaller pitch), and (ii) a sufficient ligament dimension between tubesheet holes to allow for reasonable manufacturing tolerance (larger pitch).

5.5 Tube Bundle Diameter (Step 9)

For the 30° triangular pitch arrangement, the tubesheet face area occupied by each tube within the bundle is twice the area of an equilateral triangle with the length of a side equal to the tube pitch (from Fig. 6 above, the "triangle" occupies one-sixth of the area for each of three tubes. Thus each triangle occupies an area equal to one-half that is occupied by one tube).

Now the area and diameter of an "enclosing" circle for the tube bundle can be determined. This area and corresponding diameter is equal to: (i) the twice the number of tubes (U-tube arrangement), times (ii) the tubesheet area per tube.

First, the "enclosing" circle is "cut in half" and then it is offset by the effect of the minimum bend radius (or "center offset"). This is then the "effective" bundle diameter. Calculations are summarized in Table 3.

6. Shellside Design Analysis and Results

The sections below describe analysis and results for Steps 1 through 9 outlined in Section 4.3.

6.1 Shellside Nozzle Calculations (Steps 1, 2)

Heat balance conditions for Extraction Steam (ES) flow to the FWHs are taken from the PEPSE® results (mass flow rate, pressure, and enthalpy). With this data, the volumetric flow rate is calculated.

The Heat Exchange Institute [6] provides guidelines for ES nozzle velocity and these are applied here to determine the number of required nozzles and diameter for each FWH. The HEI guidelines for limiting velocity (stated using British units) are given as:

$$V < 250/\ (\text{psia})^{0.09}\ \text{ft/sec}$$

Using the heat balance data and HEI guidelines, the numbers of nozzles and sizes were established as shown in Table 4.

6.2 Bundle-to-Shellside Clearance (Step 3)

From Section 4.3 above, the bundle-to-shell top clearance is established as the maximum of:

- the clearance needed to meet steam escape velocity limit,
- one fourth (25%) of the inlet nozzle inside diameter, or
- 150 mm (industry practice).

The "escape velocity" is defined by HEI [6] as the steam velocity passing perpendicular to a 45° expanding cone between the shell and bundle (i.e.,

Table 4 FWH steam inlet nozzle sizing.

FWH No.	No. of ES nozzles	ES nozzle size (NPS)	VWO vs. HEI criterion
1	4	36	91%
2	2	30	103%
3	2	24	81%
4	1	24	98%
5	1	24	57%
6	1	18	86%

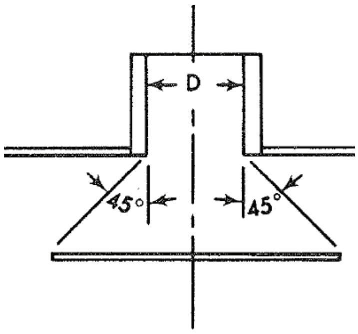

Fig. 7 HEI "truncated cone" for escape velocity.

with an upper diameter equal to the inside diameter of the steam inlet nozzle (presented in Table 4), and a lower diameter set by the expansion angle and the clearance). The geometry of the truncated cone which defines the flow area for calculation of the escape velocity is illustrated in Fig. 7.

It is considered to be a design improvement to "offset" the tube bundle within the shell to accommodate a top clearance to control steam velocity while reducing the bottom clearance to permit flooding of the bottom rows of tubes (i.e., to affect subcooling prior to enter the drain cooler) while limiting the mass of condensed steam in the heater (i.e., as related to stored energy and turbine overspeed). The bottom clearances assume successively higher clearances in FWHs with higher (cascading) drain flows (and lower stored energies).

Calculations of the bundle-to-shell top clearances for each of the three criteria along with the bottom clearances are provided in Table 5. The limiting criterion for top clearance for each FWH is underlined

For Top Clearance, Criterion 2 (one-fourth of the inlet nozzle diameter) is limiting for LP FWH Nos. 1 and 2, and the fixed minimum dimension of 150 mm is limiting for the remaining FWHs.

6.3 Installed Shell Diameter (Steps 4, 5)

Using simple estimates for hoop stress and engineering practice for the LP FWHs which normally operate at or near vacuum conditions, the LP FWH shell thickness is taken as 0.375-in (9.5-mm), for FWH No. 5, the shell thickness is taken as 0.500-in (12.7-mm), and for FWH No. 6, the thickness is taken as 1.25-in (31.8-mm).

Space constraints in the condenser neck limit insulation and lagging for LP FWHs to 25-mm. For HP FWHs, space is not limiting on diameter, and for the higher shellside temperatures for these heaters, an insulation and lagging thickness of 150-mm is assumed.

The results for tube bundle effective diameter and steam inlet nozzle sizing, for shell thickness and insulation above were used to calculate the nominal installed shell diameter and the results are provided in Table 6.

Using these dimensions, the layout of the condenser can now be completed, including layout of the condenser neck area.

6.4 Nozzle and Escape Velocity for FWH OOS (Steps 6, 7)

Next, with the clearances established, the inlet nozzle and escape steam velocities for the FWH OOS case analysis can be analyzed. Results are reported in Tables 7 and 8 for FWH OOS.

From the results presented in Tables 7 and 8, there are several cases with FWH OOS that exceed the

Table 5 Bundle-to-shell clearance (mm).

FWH No.	Top clearance Criterion 1[a] escape velocity	Criterion 2 ¼ nozzle diameter	Criterion 3 150 mm minimum	Bottom clearance (estimated)
1	126	224	150	180
2	117	185	150	160
3	75	148	150	140
4	88	148	150	120
5	54	148	150	120
6	58	108	150	120

a: The clearance for Criterion 1 is equal to the distance which produces the escape area of the 45° cone as defined per HEI (see Fig. 7) to limit the steam escape velocity to the guideline value.

Table 6 FWH installed shell diameter (mm).

FWH No.	Bundle diameter Table 3	Shell clearance Table 5 (Top)	Shell clearance Table 5 (Bottom)	Other[a]	Installed diameter
1	1583	224	180	68.5	2,056
2	1597	185	160	68.5	2,011
3	1614	150	140	68.5	1,973
4	1635	150	120	68.5	1,974
5	1946	150	120	325.4	2,542
6	1993	150	120	363.6	2,627

a: Twice shell thickness plus twice insulation thickness.

Table 7 Steam inlet nozzle velocities[a].

	FWH OOS					
FWH No.	1	2	3	4	5	6
1	OOS	159%	150%	133%	133%	133%
2	92%	OOS	178%	154%	154%	154%
3	37%	75%	OOS	121%	121%	125%
4	111%	94%	123%	OOS	132%	114%
5	117%	40%	87%	62%	OOS	64%
6	92%	91%	89%	50%	85%	OOS

a: Percent of HEI guideline (i.e., $250/(\text{psia})^{0.09}$).

Table 8 Steam escape velocities for LP FWH OOS[a].

	FWH OOS					
FWH No.	1	2	3	4	5	6
1	OOS	90%	85%	75%	75%	75%
2	52%	OOS	100%	87%	87%	87%
3	21%	42%	OOS	67%	67%	69%
4	62%	52%	68%	OOS	73%	63%
5	65%	22%	48%	34%	OOS	36%
6	35%	34%	34%	19%	32%	OOS

a: Percent of HEI guideline (i.e., $250/(\text{psia})^{0.09}$).

guideline value for steam inlet nozzle velocity. This could be addressed by adding additional steam inlet nozzles on affected FWHs or increasing the ES line size. However, both of these options are not considered as they would compromise both the design of the turbine and complicate line routing within the condenser neck

A number of options are available to address this condition as follows:

(1) Permit Velocity above Guideline Values—The OOS condition is considered to be infrequent and of short duration, and operation with steam nozzle velocities above guideline values may pass a design review. Since the escape velocities are within the guideline values (see below), high velocities for the inlet nozzles relate to piping, nozzle, and impingement plate erosion and mechanical integrity (vibration induced fatigue). This issue can be addressed by specification of stainless steel nozzle liners and impingement plates. Further, the impingement plate attachment should be robust (to address past industry issues and the OOS challenge). Finally, a review of the ES piping for erosion issues can be made. The ES piping will be specified as alloy steel (Cr-Mo P22) with high resistance to erosion.

(2) Design Change—One cause of high steam inlet nozzle velocities is the dumping of cascading heater drains to the condenser. One option to improve heat rate and reduce the nozzle velocities is to introduce a second normal drain control valve from each Moisture Separator drain tank to the shellside of FWH No. 2. This would reduce ES steam flows and would also be a design improvement for loss of function of the normal drain control valve on either Moisture Separator drain tank.

(3) Power Reduction—Similar to standard operating practice at essentially all NPPs, reactor power could be reduced as a precautionary measure while operating with a FWH OOS.

Using a combination of the approaches outlined above, steam inlet nozzle velocity is not considered to represent a design constraint for the design of the AM600.

All cases with FWH OOS meet the escape steam velocity criteria with margin under a 30% bypass condition.

Final determination ("fine tuning") of FWH design details, operating power levels, and bypass fraction must await detailed design but results here provide assurance that short-term operation is possible for the considered operating conditions.

6.5 Shellside Drain Cooler Flows (Step 8)

Flows of condensate through the shellside of the drain cooler affect the design including sizing of the inlet window and baffle plate arrangement and spacing. While the detailed design of the drain cooler section is not performed here, a check of the ratio of OOS flows to VWO flows provides a measure of whether the design will be limiting for OOS conditions. Table 9 provides a comparison of drain cooler volumetric flow rates with isolated FWHs to the VWO flow. A percentage of less than 100% indicates that the design for FWH OOS is not limiting.

Shellside drain cooler flows slightly exceed the VWO flows by up to 12% for some cases and some heaters. It is considered that this small increase can be easily accommodated in the design stage (e.g., larger snorkel, shorter spacing of baffle plates) without adverse consequences for heater fabrication or operation.

6.6 Shell Side Drain Control Valve Capacity (Step 9)

Drain flows leaving the drain cooler section of the FWHs are either cascaded to the next lower pressure FWH shell (normal path) or directed to the main condenser (emergency path). Flow is controlled in these paths by Drain Control Valves (DCVs) to maintain proper water level in the condenser shell. The DCVs are sized to pass flow to maintain this level under all normal and abnormal operating conditions. With operating conditions corresponding to an FWH

Table 9 Drain cooler flows versus VWO flow.

	FWH OOS					
FWH No.	1	2	3	4	5	6
1	OOS	14%	25%	33%	43%	64%
2	103%	OOS	13%	24%	35%	61%
3	105%	105%	OOS	13%	26%	56%
4	111%	106%	107%	OOS	15%	51%
5	112%	108%	105%	85%	OOS	44%
6	99%	99%	98%	76%	95%	OOS

Table 10 Normal DCV required capacity vs. VWO.

	FWH OOS					
FWH No.	1	2	3	4	5	6
1	OOS	116%	23%	30%	39%	60%
2	E[a]	OOS	9%	17%	28%	50%
3	117%	E[a]	OOS	12%	26%	56%
4	131%	116%	E[a]	OOS	16%	54%
5	133%	119%	113%	E[a]	OOS	48%
6	109%	101%	100%	84%	E[a]	OOS

a: Flow is through emergency DCV for these heaters.

OOS, the capacity of these valves may be challenged. To address this potential, the required capacity for the drain control valves were investigated and presented in Table 10.

The required capacity of a drain control valve is a function of the volumetric flow rate, the fluid density, and the “allowable” pressure drop. Flow and density are based on the heat balance analysis. The allowable pressure drop is a function of the inlet pressure to the valve, the vapor pressure of the fluid, and the recovery coefficient of the valve [10]. Let required capacity be denoted as “C_v”, and from the flow relations:

$$C_{\mathrm{v}} \propto Q / [\Delta P_{\mathrm{allowable}} / SG]^{1/2}$$

$$\Delta P_{\mathrm{allowable}} = K_{\mathrm{m}} (P_1 - r_{\mathrm{c}} P_{\mathrm{v}})$$

$$r_c = 0.96 - 0.28 \cdot (P_v / P_c)^{1/2}$$

where:

C_V—valve flow coefficient

Q—volumetric flow through valve

$\Delta P_{allowable}$—pressure differential at which the flow chokes

K_m—pressure recovery factor

P_1—valve inlet pressure

r_c—critical pressure ratio factor (unitless)

P_v—vapor pressure of water at inlet temperature

P_c—critical pressure of water (22.065 MPa)

SG—specific gravity of entering fluid

It is conservative for the analysis here to assume that the valve pressure recovery coefficient is constant. With this, the required capacity for the control valve is then proportional to volumetric flow (Q) and the relation $[SG / (P_1 - r_c P_v)]^{1/2}$. P_1 is equal to the upstream pressure from the heat balance minus the pressure change due to: (i) friction in the drain cooler section, (ii) friction in the downstream piping network, and (iii) elevation head effects. These are all typically minor terms and can be estimated.

From these relations, data from each case of the heat balance analysis are used to determine the ratio of required C_v for the FWH OOS case to that for the VWO baseline. Note that for the various FWH OOS alignments, the FWH immediately downstream (on the tubeside) of the isolated FWH must send drain flow to the condenser via the emergency drain path. Other FWHs drain by the normal path. Results are

Table 11 Emergency DCV required capacity vs. VWO.

	FWH OOS					
FWH No.	1	2	3	4	5	6
1	OOS	N[a]	N[a]	N[a]	N[a]	N[a]
2	106%	OOS	N[a]	N[a]	N[a]	N[a]
3	N[a]	109%	OOS	N[a]	N[a]	N[a]
4	N[a]	N[a]	113%	OOS	N[a]	N[a]
5	N[a]	N[a]	N[a]	95%	OOS	N[a]
6	N[a]	N[a]	N[a]	N[a]	109%	OOS

a: Flow is through normal DC for these heaters.

Table 12 Final feedwater temperature for FWH OOS.

Case[a]	FWH OOS	Final feedwater temperature	FFT reduction from 100%
1	N/A	236.1 °C	N/A
2a	No. 1	234.5 °C	0.5 °C
2b	No. 2	234.7 °C	0.3 °C
2c	No. 3	234.8 °C	0.2 °C
2d	No. 4	204.7 °C	30.3 °C
2e	No. 5	211.5 °C	23.5 °C
2f	No. 6	190.1 °C	44.1 °C

provided per Tables 10 (normal drain path) and 11 (emergency drain path).

For normal and emergency DCV sizing, FWH OOS conditions can result in a slightly higher duty than for VWO conditions (i.e., up to 133% for normal and 113% for emergency valves). Accepted engineering practice typically sizes control valves to operate at 70% capacity for limiting duty. For the AM600, the required duty under FWH OOS can be readily accommodated in the design and procurement for the DCVs.

7. Other Considerations

As described above, with an FWH OOS, the final feedwater temperature will be lower than for the normal alignment case. If operated in this way, this may impact the design and analysis of the NSSS. Feedwater temperatures are reported In Table 12 for follow-on analysis of NSSS considerations for FWH OOS (e.g., thermal stress, effect on core nucleonic, etc.).

From these results, the final feedwater temperature reduction is largest for isolation of FWH No. 4, 5, or 6. NSSS design typically allows for a sudden reduction in feedwater temperature due to plant transients of up to 55 °C. The values above all fall within that criterion but should be reviewed with the NSSS vendor for acceptability.

8. Conclusions

8.1 AM600 Design Considerations

The analysis reported here provides a basis for final design of the FWHs for the AM600 Turbine Island. Results are as follows:

- The installed diameter of the LP FWHs is expected to be on the order of 2,000 mm and the main condenser must be designed for this dimension.
- FWH OOS service conditions (for the configuration, power level, and bypass fraction modelled) result in high steam inlet nozzle velocities for several cases, particularly for FWH No. 1 and 2. There are certain design and/or operational measures which can be applied to address these conditions.
- FWH OOS service conditions result in acceptable

steam escape velocities for all cases and all FWHs.

- FWH OOS service conditions do not place excess requirements on drain cooler zone design (i.e., beyond the normal design duty). FWH OOS operating conditions should be specified as part of FWH procurement (normal practice).
- FWH OOS service conditions do not place excess capacity requirements on normal or emergency drain control valves. Accepted engineering practice would typically include margin to allow for OOS operations.
- The reduction in FFT under FWH OOS service conditions falls within typical industry limitations, but must be reviewed with the NSSS vendor for acceptability.

Final determination of limiting operating conditions for OOS operations (i.e., operating power level, and bypass fraction) must await detailed consultation with the LP and HP FWH vendors, but overall, based on the analysis here it is reasonable to expect that operation with an FWH OOS can be maintained at or near full power until the heater is restored to service.

8.2 Future Work

For the AM600, detailed design work on the T/G shaftline, the T/G support structure, the condenser design and configuration, Turbine Island layout, and other aspects is ongoing. Those interested in this project are encouraged to contact the authors for further information.

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Attachment 1: AM600 Heat Balance Diagram—FWH No. 3 OOS.