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Design of BOP Systems for the AM600

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1. Introduction

This paper describes the salient elements of BOP system design for the Advanced Modern 600 MWe (AM600) nuclear steam cycle. The AM600 Turbine-Generator (T/G) which converts thermodynamic energy to electrical energy is designed with a single-flow High Pressure Turbine (HPT) section and a single cylinder, two-flow Low Pressure Turbine (LPT) section (as described in detail elsewhere). Targeted for emergent nuclear countries with smaller grid capacity and/or large seasonal variation in grid frequency, the design is intended to be appropriate as an initial Nuclear Power Plant (NPP) installation. The AM600 shaftline is designed to have low capital and installation cost with robust resistance to torsional vibration and other operational insults.

This paper specifically examines the critical features of the Balance of Plant (BOP) design to support the AM600 T/G. The principal objectives for this BOP design are:

i. reduce BOP component count to reduce overall cost of the design, fabrication, and construction, and to simplify operation, maintenance, testing, and inspections,
ii. maximize use of modular fabrication and construction techniques, and
iii. reduce turbine building volume.

This paper will look at three areas of BOP design for the AM600 which differ from conventional design and employ special features or approaches:

i. Power Train Pump (PTP) design,
ii. Feedwater Heater (FWH) design, and
iii. Extraction Steam (ES) piping design.

2. System Description

2.1 Power Train Pumps (PTPs)

A reduction in the component count for power train pumps results in an associated reduction in supporting subcomponents such as pump drivers, switchgear, relays, and instrumentation. On the mechanical side, supporting component reductions include minimum flow control valves, isolation/block valves, lubricating oil systems, and others. Minimizing the number of PTPs also reduces operational complexity and the station burden of component maintenance, testing, and inspections. In addition the design for the AM600 PTP system eliminates the complex steam turbine drive units for the Steam Generator Feedwater Pumps (SGFPs). Rather, two, 100% capacity motor driven SGFPs are driven by electronic Variable Frequency Drive (VFD) units.

2.1.1 Condensate Pumps (CPs)

Each CP is coupled with a Condensate Booster Pump (CBP), sharing a common double shafted motor. Speed reduction for the CP is performed by a gearset. In the targeted market with a 50Hz grid frequency, the CP is designed to run at 1200 rpm via the gearset while the CBP operates at the operating speed of the motor, or 3000 rpm. Fig. 1 illustrates this arrangement.

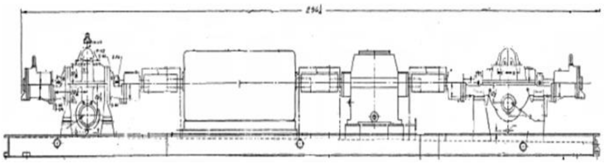

Fig. 1. Coupled condensate and condensate booster pump

The CPs and the CBPs are specified as standard design, single stage, double hung, and double suction horizontal pumps. This style of pump is the workhorse of the customer specified pump industry and is known for long-term, reliable performance. Fig. 2 shows a typical design for the single stage, double hung, double suction horizontal pump.

This CP/CBP configuration was adopted to address challenges associated with the vertical, multi-stage, high head CP pumps which include:

i. seasonal grid frequency drift in many emergent markets is not compatible with the long shaftline and associated natural frequencies of the vertical CP, potentially leading to damaging modes of resonant vibration,

ii. the vertical CP pump shaft is guided by bowl and shaftline bushings (which wear with time causing lateral shaft vibrations requiring frequent pump re-builds),
iii. the long vertical CP shaftline requires significant overhead pull- and lay-down space, while maintenance for the AM600 CP/CBP design specified here is simple and modular, and
iv. by separating the developed head across two pumps in series (CP/CBP), the condensate filter and demineralizer vessels can be served by the discharge of the CP and designed with a much lower design pressure, reducing cost.

Due to the low NPSHa available to the CP, the pump speed is selected to ensure adequate NPSH margin.

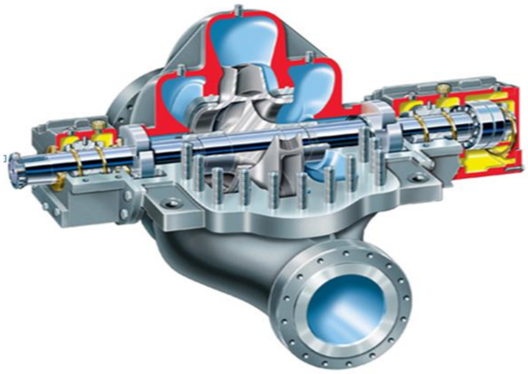

Fig. 2. CP/CBP - horizontal, single stage, double hung, double suction pump (Courtesy of Flowserve)

2.1.2 Condensate Booster Pumps (CBPs)

The CBP takes suction from the CP (after passing through the demineralizer vessels and other low pressure services) to add head in order to provide sufficient suction pressure for the SGFP. Since the CP and CBP are coupled they always operate together (i.e., there is no ‘clutch’).

2.1.3 Steam Generator Feedwater Pump (SGFP)

Feedwater system pumping is performed by 2x100% SGFPs. The SGFPs are specified as barrel type with single stage, double hung, double suction impellers. Each pump is driven by a gearset which in turn is driven by a variable frequency motor supplied fed a VFD. The initial AM600 design considers an SGFP operating speed of 5600 rpm when on single pump operations. For two pump operation the operating speed is projected as 5200 rpm. The suggested operating speeds are higher than typically found at operating NPPs. The targeted pump speeds here are adjusted higher based on suggestions by Karassik [1] (i.e., when the turbine drive unit speed limitation is removed, higher feedwater pump speeds are optimal). However, in the final selection, the optimal speed is subject to vendor consultation. Fig. 3 provides a cutaway view of the single stage, double hung, double suction barrel pump.

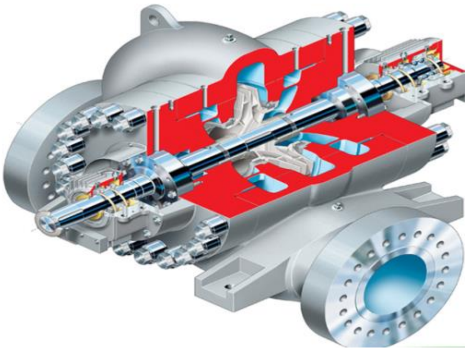

Fig. 3. SGFP - Single Stage, Double Hung, Double Suction Barrel Pump (Courtesy of Flowserve)

2.2 Feedwater Heaters (FWHs)

The optimal number of points for feedwater heating in a Rankine cycle is a balance between improved heat rate and life cycle cost (capital, operations, maintenance, testing, and inspections). For the nuclear steam cycle for light water reactor plants, the optimal number of points of feedwater heating has converged to a value of six (6) or seven (7). Since simplicity and low initial capital cost are the controlling factors for the design of the AM600, the number of points for feedwater heating is selected as six (6).

The number of ‘strings’ or ‘trains’ of FWHs is dictated by the number of LPT cylinders. For the AM600, there is only a single LPT cylinder, resulting in a single string of FWHs. Thus the AM600 design includes a total six (6) FWHs (four (4) Low Pressure (LP) FWHs and two (2) High Pressure (HP) FWHs).

The four (4) LP FWHs will be installed inside the condenser neck. For the tube side, condensate piping will have a minimal routing distance between the adjacent channel heads. To minimize line routing lengths, the two (2) HP FWHs will be located at a lower level in the turbine building between the SGFPs and the steam tunnel. It is intended for the condenser to be fabricated and assembled as a single module with LP FWHs and associated piping installed in the factory.

By modularizing the condenser and LP FWH construction, field work is minimized improving both the quality of the installation and the erection time.

2.3 LP Extraction Steam (ES) Pipe Routing

With four (4) FWHs located in the condenser neck, ‘real estate’ for routing ES lines between the LPT extraction nozzles and the FWH shell side inlet nozzles is very restricted. To examine a ‘proof of concept’ for this routing, the T/G and condenser geometry was modeled in detail. ES lines were sized based on volume flows and velocity limitations. Finally, the FWH shells and nozzle arrangements were added to the model. Fig. 4 illustrates the routing with included supports. Fig. 5 illustrates the operating temperatures for the ES lines in the condenser neck (orange – 76oC, yellow – 113oC, green – 142oC, blue – 210oC). This model is then used as input to a proof-of-concept analysis for pipe stress and support design.

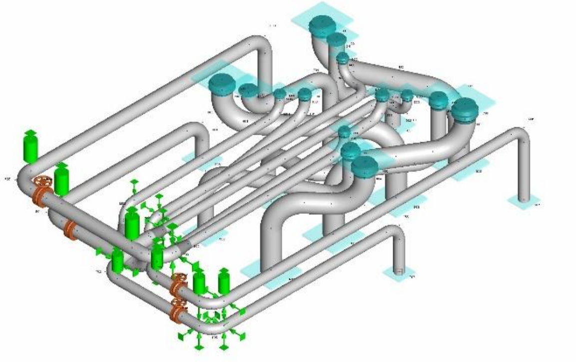

Fig. 4. AM600 LP-FWH ES piping model with supports

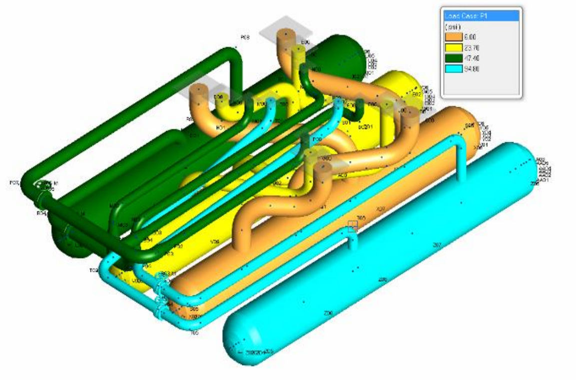

Fig. 5. AM600 LP-FWH ES operating temperatures

3. Methodology

3.1 Power Train Pumps (PTPs)

A hydraulic model of the condensate and feedwater systems was developed using Microsoft Excel. Case analysis was performed for different power levels. With these models, the PTP were sized and using pump affinity laws [1], cases for the various options (PTPs configurations) were analyzed (e.g., normal full power operations and operational transients).

The PTP alignments considered for CP/CBP/FWP operations included: 3/3/2, 3/3/1, 2/2/2, and 2/2/1. The performance comparison criteria were based on:

i. NPSH ratio / NPSH margin,

ii. operation within the Preferred Operating Region (POR), and

iii. operation within the duty ratings of the pump drivers.

The hydraulic model is illustrated in Fig. 6 below.

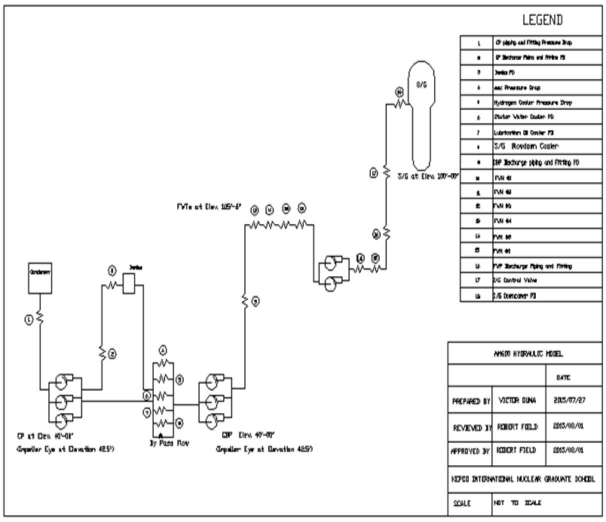

Fig. 6. AM600 Hydraulic Model

3.2 Feedwater Heaters (FWHs)

For feedwater heaters, the first design step involves a determination of the number of tubes. Since the AM600 design has only one string of six (6) FWHs, the FWH sizes in terms of shell diameter and tube surface area are expected to largest designs in the industry. To calculate the required number of tubes, it is necessary to first select the tube outside diameter (OD).

For LP FWHs (AM600 Nos. 1 through 4), tubing is typically specified with an OD of 3/4-in. This represents a balance between good heat transfer, fabrication cost, and thin tube wall as dictated by design pressure [2].

For HP FWHs (AM600 Nos. 5 and 6), a smaller tube diameter is often specified. This permits a thin wall while still meeting the design pressure rating. The standard industry OD of 5/8-in is thus selected. For tube wall thickness, the industry standard wall of 18 BWG (Birmingham Wire Gauge) was selected for all tubes.

The required number of tubes 'n' can then be calculated using:

$$\mathrm{n} = \frac{Flow\ Rate\ \times v}{A_i \times v_t}$$

with

v = specific volume at 60°F

$$A_i = Area\ of\ tubes\ = \ \pi \times \left(\frac{D_i}{2}\right)^2$$

$$v_t = Tube\ Velocity = 10ft/\sec\ (assumed)$$

3.3 Extraction Piping

AM600 LP-FWH ES layout and analysis were performed using AutoPIPETM software [3].

4. Results

4.1 Power Train Pumps (PTPs)

Tables I, II and III below provide results for hydraulic modeling of CPs, CBPs, and SGFPs. Evaluation criteria include calculations of NPSH ratio, motor power, flow, and pressure [4]. Since the pumps are designed as 3x50% (CP, CBP), and 2x100% (SGFP), the best efficiency is achieved with 2/2/1 operations.

Table I: CP Design Analysis

Parameter	Unit	101.5%		A.C.[1]
Pumps in Operation		3	2	
Speed	rpm	1200	1200	
Flow per Pump	gpm	5576	8364	
Head	ft	420	380	
NPSHa	ft	27.5	27.5	1.2~1.5
NPSH ratio	ft	1.45	1.38	
Motor Power	hp	780	995	
Flow vs. BEP	%	66	98	70~120

1) A.C. – Acceptance Criterion

Table II: CBP Design Analysis

Power Level	Unit	101.50%		A.C.
Pumps in Operation		3	2	
Speed	rpm	3000	3000	
Flow per Pump	gpm	5579	8368	
Head	ft	1450	1200	
NPSHa	ft	253	213	
NPSH ratio	ft	4.08	2.10	2.0~4.0
Motor Power	hp	2660	3144	
Total Motor Power	hp	3439	4140	
Total Power Demand	hp	10318	8280	
Flow vs. BEP	%	66	99	70~120

Table III: Feed Water Pumps Design Result

Power Level	Unit	101.50%				A.C.
Pumps Operation		3/3/2	2/2/2	3/3/1	2/2/1	
Speed	rpm	5200	5200	5600	5600	
Flow per Pump	gpm	9098	9078	18156	18156	
Head H	ft	2800	2800	2650	2650	
NPSHm	ft	6.6	5.65	6.24	5.37	5.0~7.0
NPSHa	ft	1254	1080	1254	1080	
Motor Power	hp	8103	8103	14044	14044	
Total Power Demand	hp	16206	16206	14044	14044	
BEP	%	73	73	113.50	113.50	80~120

Design Option Selection Criteria

i. NPSH ratio at 101.5% Power level - All the design options satisfy the NPSH margin requirement [5]
ii. Design Flow vs. BEP - 2/2/1 option offers acceptable flow within the POR for all the pump operation options
iii. Motor Power Consumption - The result from the graph show that 2/2 CP/CBP and 1 FWP pump train operation indicates limiting driver duty, but overall has less total motor power consumption

4.2 Feedwater Heaters (FWHs)

The calculated minimum number of tubes for the LP FWHs is 1,610 and for the HP FWHs is 2,464. Industry standard plugging margins are 10% for these heaters. However, since the AM600 design only employs a single string of FWHs, special design considerations for FWH Out-Of-Service (OOS) operations are required. In the event of FWH OOS, the typical design isolates the entire string. The remaining strings plus bypass flow are then used for continued operations.

For the AM600, string isolation is not an option. Rather, an individual FWH will be isolated in the event of tube rupture (or failed drain control valve), and all of the remaining FWHs will be operated within their capability (with necessary bypass). Thus to maximize operating capacity with a FWH OOS, all FWHs were oversized. In the case of LP FWHs, the shell diameter was maximized to the available space in the condenser neck.

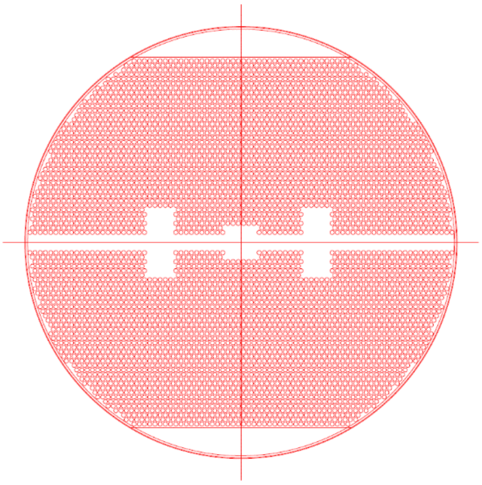

Fig. 7. Drilling pattern for FWHs 1 to 4

For the conceptual AM600 tube sheet arrangements, 2,603 tubes are used for LP FWHs and 3,478 tubes for

HP FWHs. The margin above the minimum number of tubes is ~60% for LP FWHs and ~70% for HP FWHs

With this design, a very large overload flow for operations with FWH OOS can be specified. This design also results in good capacity to handle the very large drain cooler flows for the fully cascading AM600 design (i.e., drain flows in the LP FWH No. 1 approach 3,600 m3/hr, or 16,000 gpm). The ‘oversized’ tube bundles will reduce steam velocities for FWH OOS operations, reducing the potential for condensing zone vibration damage. Similarly, the ‘oversized’ bundles will reduce the limiting velocities in the drain cooler (which occur at full power) minimizing the potential for damaging drain cooler vibration. Fig.’s 7 and 8 illustrate the tube sheet layout for LP FWHs and HP FWHs, respectively.

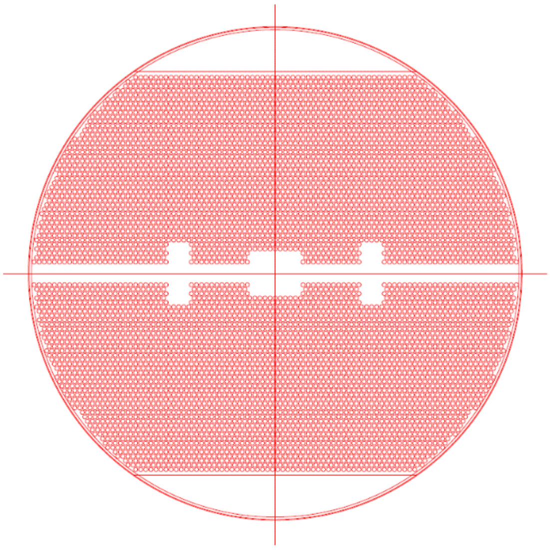

Fig. 8. Drilling pattern for FWHs 5 and 6

The AM600 FWHs are standard design two-zone heaters with horizontal U-tube bundles [6]. The current design assumes all FWHs include an integral drain cooling zone. This approach requires consultation with FWH vendors for the lowest pressure heaters to determine if an external drain cooler is required.

Fig. 9 shows the typical design for the LP FWHs. FWH No. 1 will be located in condenser neck. The shell design includes four (4) 30-in ES nozzles, one 30-in drain inlet nozzle above the flash chamber, and one bottom mounted 30-in drain outlet nozzle. Channel head nozzles are each 30-in. The channel heads for the LP FWHs are designed as full access with an internally sealed pass partition box.

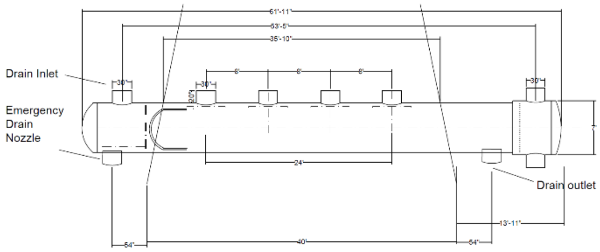

Fig. 9. Schematic drawing of FWH 1

Table IV outlines the nozzle design for FWH Nos. 1 to 4.

Table IV: FWH nozzles

		FWH 1	FWH 2	FWH 3	FWH 4
ES Inlet	Diameter	30"	22"	20"	16"
	Number	4	4	2	2
Drain Inlet	Diameter	30"	30"	22"	22"
	Number	1	1	1	1
Drain Outlet	Diameter	30"	22"	22"	22"
	Number	1	1	1	1
Channel Head	Inlet	30"	30"	30"	30"
	Outlet	30"	30"	30"	30"

4.3 LP Extraction Piping

Fig.’s 10 and 11 illustrate the design process for support ES lines in the condenser neck. Fig. 10 indicates bending stress for unsupported lines (red is high stress, blue – low). By adding vertical supports and guides and expansion joints, significant stress reduction is possible.

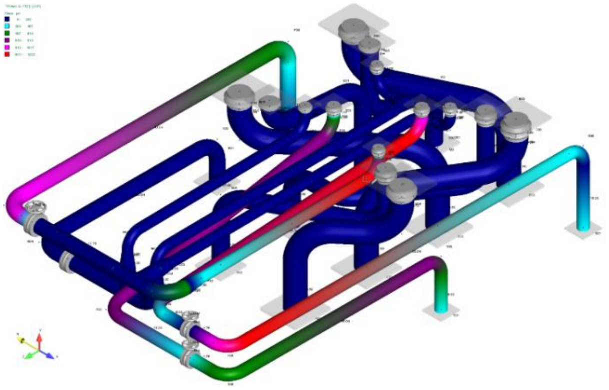

Fig. 10. The stress distribution for AM600 LP-FWH ES Piping Model without supports

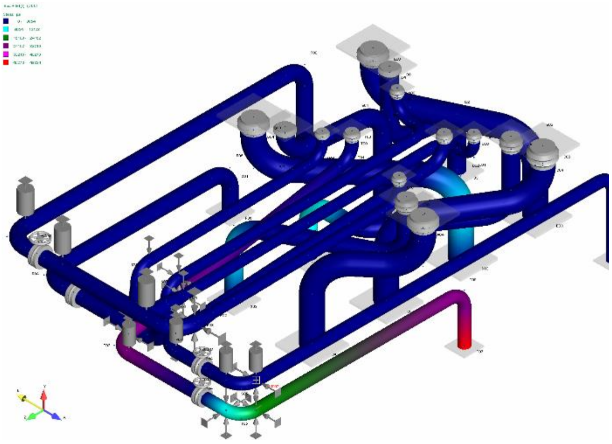

Fig. 11. Stress distribution for AM600 LP-FWH ES Piping Model with supports and expansion joints

Fig. 10 illustrates stress without supports. Fig. 11 illustrates reduced stress for the 'top' line in the front of the diagram while the 'unsupported' bottom line still indicates high stress.

5. Conclusions

The proposed AM600 design for pumping condensate from the hotwell to the SGFP suction is a horizontal CP/CBP combination. This design avoids many of the problems associated with vertical condensate pumps as outlined above. Further, this design represents a robust, reliable, approach with simplified maintenance and overhauls. Finally, this design has been specified and used by a major U.S. NPP operator at twelve nuclear units with more than 10 million cumulative 'pump set' operating hours with very reliable performance.

The specification of a single stage, double hung, double suction barrel pump for the SGFPs avoids design issues associated with horizontal split case pumps and with multiple impeller designs. The use of electronic VFD to drive a variable speed motor simplifies the design, fabrication, and installation of the SGFP driver. Further, it eliminates the need for a 'startup' SGFP and permits use of the SGFPs independent of having a vacuum in the main condenser.

The main characteristics of the design specification for the AM600 FWHs is that they consist of a single string. Moreover, four (4) LP FWHs are located in the condenser neck. Modularizing the installation of FWHs can bring significant economies by a reduction in installation work in the field with an associated reduction in erection schedules. However, the design with a single string limits operational flexibility to take a FWH out-of-service to address tube rupture. This issue will be addressed in a future paper.

Based on the layout work documented here, an arrangement for the AM600 LP ES piping is feasible using accepted engineering practice. Further, sample stress analysis using the AutoPIPETM model shows relatively low stresses when the lines are properly supported. However, detailed design will require additional inputs such as thermal anchor movements and T/G nozzle allowable loadings which were not available for this study.

The AM600 design for PTPs with a single train of FWHs (i.e., intended to maximize factory assembly and modularization) can bring significant cost and operational benefits. However, this design will present significant challenges. Three specific areas are identified here:

- Operation of PTPs in the 2/2/1 configuration will ensure maximum pump efficiency and optimal operating points. However, pump trip will require fast, auto-start of the standby pump. Adequate response time will require specialized transient hydraulic analysis, proper time delay settings for pump trips on low suction pressure, and startup testing,
- For FWH OOS conditions, isolation of an individual FWH will require special valving along with design of FWH bundles for very large overload flow conditions. This will require the FWHs to be 'oversized',
- Routing of ES and FWH drain piping in the condenser neck will require expert design to ensure constructability.

Studies in these areas are an ongoing part of the development of the AM600 design.

Acknowledgement

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Reference

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