APR1400 Feedwater System Hydraulic Analysis using AFT Fathom™

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INTRODUCTION

Commercial scale Nuclear Power Plants (NPPs) employ several approaches to remove heat from the reactor core (e.g., circulation of light water, heavy water, sodium, helium, and CO_2). However, converting core heat to electricity is universally completed using the Rankine cycle.[1] The Rankine cycle is a 'closed' cycle which uses pressurized steam to drive a turbine-generator set. The cycle then converts exhaust steam from the turbine to liquid water in a condenser. This condensed steam, or 'condensate' must then be returned to the Steam Generator (S/G) to complete the cycle. This requires that condensate at condenser vacuum conditions be pressurized using a series of centrifugal pumps.

Pumping in the Rankine cycle must be both reliable and efficient. The hydraulic analysis reported here examines a part of the pumping cycle, namely for the Feedwater (FW) System, with proposed changes to the equipment which performs this duty. Results of the analysis can then be used as input to a 'Trade Study' to examine the potential costs and benefits of the proposed changes.

BACKGROUND

Historically, FW pump applications in the nuclear industry have been both motor driven and turbine driven. Motor driven FW pumps were typically specified on smaller nuclear units (e.g., 500 to 1000 MWe) while turbine driven pumps were specified for larger units (>1000 MWe). The basis for this selection is not well documented (i.e., with design decisions dating back to the 1960s and early 1970s). However, at that time new nuclear units were competing with coal units and capital cost was a significant consideration. For smaller units, the inefficiency associated with fixed speed motor driven pumps (i.e., due to flow control using throttling) could be justified by lower installed cost. For larger units, the efficiency afforded by using turbine driven pumps (i.e., speed control to replace throttling control) was used to justify higher capital costs (e.g., such as those associated with the installation of steam supply and exhaust piping systems, etc.).

Since the construction of the early nuclear fleet, alternative and efficient methods of pump speed control have become commercially available (e.g., electronic and mechanical variable speed control for large motors, >5000 hp). This paper examines the hydraulic considerations for use of these alternative drive technologies to address the FW System pumping duty.

DESCRIPTION OF THE APR1400 FW SYSTEM

The 'APR1400' or 1400 MWe Advanced Power Reactor is a light water reactor plant designed by the nuclear power industry in the Republic of Korea. The first APR1400 unit (Shinkori Unit 3) completed fuel load and synchronization to the grid in December 2015. Additional units are under construction in Korea and the United Arab Emirates. Licensing review of the Design Criteria Document (DCD)[2] for the APR1400 is currently underway in the United States.

The APR1400 Condensate and Feedwater (FW) Systems are illustrated per the simplified schematic in Fig. 1 below.

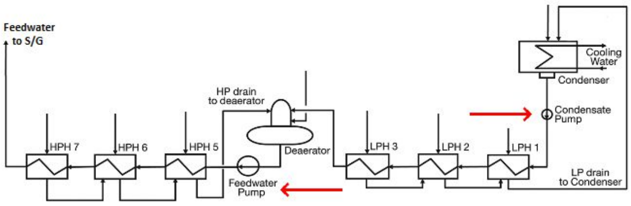

Fig. 1. APR1400 Condensate and Feedwater System Schematic

There are two pumping positions in the APR1400 design. The condensate is first pumped by three (3) vertical can turbine pumps termed 'Condensate Pumps' (CPs) operating in parallel. The CPs deliver pressurized condensate to the Deaerator which then drains to the Dearaetor Storate Tanks (DSTs). The DSTs then provide suction to three (3) Feedwater Booster Pumps (FWBPs) operatig in parallel. Each FWBP then supplies the suction of one of the Main Feedwater Pumps (MFWPs) in a close-coupled arragnement. The FW System pumping train is diagrammed in Fig. 2 below.

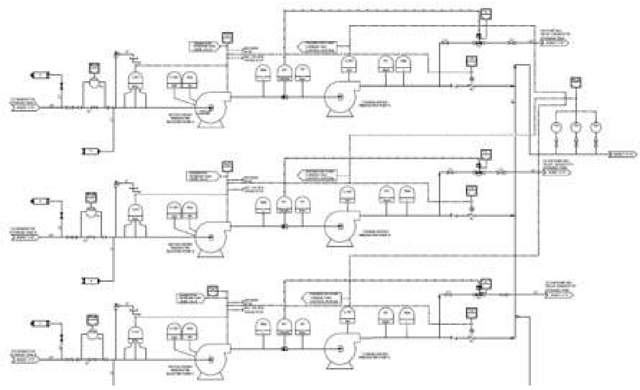

Fig. 2. APR1400 FW System Pumps (FWBP / MFWP)[2]

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The FWBPs are motor driven, medium (fixed) speed, medium head pumps with low NPSHr. These pumps then provide sufficient suction pressure for the steam turbine driven high (variable) speed, high head MFWPs.

OPERATING HISTORY

The operating history of FW pumps in light water reactor plants indicates that turbine driven units have lower reliability than motor driven units.[3] Much of the unreliability has been due to control system failures. Through digital upgrades to analog control systems with improved redundancy and self-diagnostics, many of the reliability issues for turbine driven pumps have been addressed. In addition, it is noted here that for the modern OPR1000 nuclear units in Korea (with similar feedwater pump drive technology to the APR1400) reliability is considered to be very good.

However, alternative drive technologies may yet offer advantages in terms of reliability, installed cost, and operations and maintenance. These technologies are discussed below.

TECHNOLOGY DEVELOPMENTS

Turbine drive units provide several advantages in the design of FW systems including:

- Suitable operating speed without the need for gearsets
- Very large range for efficient supply of shaft power
- Very fast transient response
- Proven technology
- Proven maintenance / inspection methods
- Familiarity for operators

Disadvantages include long term degradation issues (e.g., cyclic fatigue, casing erosion) and installed cost. In addition, the use of turbine driven feedwater pumps requires a motor driven startup pump for conditions prior to steaming in the S/Gs.

Subsequent to design of the first generation of large commercial NPPs, two alternative technologies for feedwater pump drive units have been introduced to the market. These are:

- Electronic Variable Speed Drive (EVSD)
- Mechanical Variable Speed Drive (MVSD)

EVSD - Here, EVSD refers to Adjustable Speed Drive (ASD) units which employ Variable Frequency Drive (VFD) technology. EVSD units are designed to supply electrical power over a range of frequencies to an Alternating Current (AC) induction motor to automatically change and control operating speed. The output frequency supplied to the motor is produced by solid-state power electronics which 'clip' and convert line power to Direct Current (DC) and then back to AC power at a frequency established by the controller unit. The capacity, reliability, and fault tolerance of EVSD units have advanced over the past forty (40) years through improved semiconductor switching devices, drive topologies, and control system design (hardware, software). Current technology from any of several vendors offers high efficiency, high reliability, and competitive cost. An EVSF unit with exposed internal components is shown in Fig. 3 below.

Fig. 3. EVSD Cabinet (Courtesy Siemens-Robicon)

Today, EVSD units are used in the following mission critical applications in the nuclear power industry:

- Reactor Recirculation (RR) pump speed control in Boiling Water Reactor (BWR) units
- Circulating Water (CW) pump speed control in Pressurized Water Reactor (PWR) units
- Cooling Lake Blowdown pump speed control in PWR units

MVSD - Here, MVSD refers to ASD units which provide a variable output speed through use of torque converters. Through not common in NPP applications, MVSD units using similar technology (i.e., magnetic coupling) have been in service in certain NPPs units for more than forty (40) years in Heater Drain (HD) pump applications. In addition, more recently it has been reported that MVSD units based on torque converter technology have been used in more than 500 new build combined cycle units. However, the efficiency of such units at off design conditions is low and not adequate for consideration here.

Rather, a specific vendor offering, the 'Vorecon' (Voith), which employs a combination of torque converters with a planetary gearset is considered. Since the planetary gearset transmits most of the power and torque (up to 80%), only a fraction of total power is transmitted through the torque converters improving the overall efficiency. Thus mechanical efficiency can be maintained at a high level over a broad range of output speeds making the component competitive with EVSD units.

These unit units have wide application in powering rotating equipment such as FW pump (for fossil units) and gas compressors in sizes ranging from 5,000 to more than 60,000 hp. The vendor report Mean Time Between Failure (MTBF) is 48 years making the component appropriate for the reliability critical application considered here.

Fig. 4 depicts a large Vorecon unit from Voith.

Fig. 4. MVSD Unit **(Courtesy Voith)**

CONFIGURATIONS

The APR1400 FW pumping system is arranged with the FWBPs located on plant elevation 73'-0". This is to afford the pumps with sufficient NPSHa. The FWBP and motor drive unit is illustrated in Fig. 5a below.

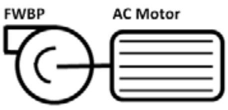

Fig. 5a. APR1400 FWBP – Pump-Driver Arrangement

The MFWPs are located on the next higher floor elevation, El. 100'-0". This permits the routing of the downward exhaust steam piping from the turbine drive unit. The MFWP and steam turbine drive unit is illustrated in Fig. 5b below.

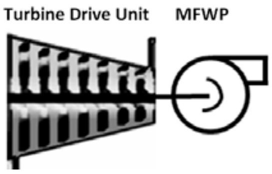

Fig. 5b. APR1400 MFWP - Pump-Driver Arrangement

For Option 1 using the EVSD, each FWBP and MFWP would be aligned on a single drive train. Flow control is then achieved by variation of the operating speed of the AC motor (by changes to the input frequency). This arrangement is depicted in Fig. 6a below.

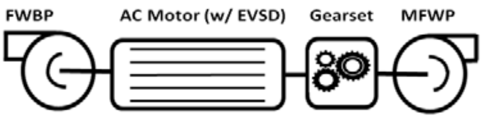

Fig. 6a. FW Pumps-Driver Arrangement using EVSD

For Option 2 using the MVSD, each FWBP and MFWP is again aligned on a single drive train. Flow control is then achieved by variation of the operating speed of the MVSD through changes to the 'scoop tube' position (and hence to the power transmission through the torque converters). This arrangement is depicted in Fig. 6b below.

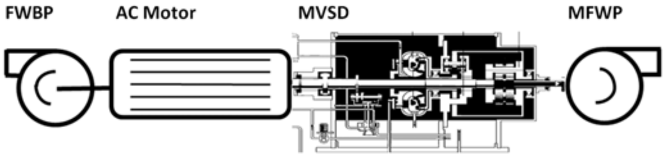

Fig. 6b. FW Pumps-Driver Arrangement using MVSD

Table 1 provides a comparison of the major components required for each of the arrangements.

Table 1. Comparison for FW System Pump Arrangements

	APR1400 Standard	APR1400 Option 1	APR1400 Option 2
Drive Arrangement	MD[1] / TD[1]	EVSD	MVSD
FWBP Speed	Fixed	Variable	Fixed
MFWP Speed	Variable	Variable	Variable
FWBP/MFWP Speed Ratio	Variable	Fixed	Variable
No. of FWBPs	3	3	3
No. of MFWPs	3	3	3
No. of SUFWPs[3]	1	-	-
No. of Motor Drive Units	3	3	3
No. of ST[4] Drive Units	3	-	-
SUFWP Motor Drive Units	1	-	-
No. of EVSD Units	-	3	-
No. of Gearsets	-	3	-
No. of MVSD Units	-	-	3

1) MD – Motor Driven
2) TD – Turbine Driven
3) SUFWP – Startup Feedwater Pump
4) ST – Steam Turbine

For Option 1, the three (3) steam turbine drive units (and associated support systems) and the SUFWP set (pump plus motor) included in the standard APR1400 design are replaced by three (3) EVSD units and three (3) gearsets. The three (3) FWBP motors are replaced by three (3) larger motors (along with associated cables, breakers, etc.).

For Option 2, the three (3) steam turbine drive units (and associated support systems) and the SUFWP set (pump plus motor) included in the standard APR1400 design are replaced by three (3) MVSD units. The three (3) FWBP motors are replaced by three (3) larger motors (along with associated cables, breakers, etc.).

SYSTEM REQUIREMENTS

Reliable delivery of water to the S/Gs by the FW System is critical to NPP safety and operations. To ensure reliable operation, design criteria are carefully considered and established. These criteria relate to steady operations, equipment Out-Of-Service (OOS), transient system response, and safety analyses. These criteria are discussed below.

<u>Steady-state Operations</u> – A NPP operates full rated power for more than 99% of the time the unit operates. As

such, design for this condition is critical in the specification of equipment. Table 2 provides a listing of the basic pump and driver parameters for steady-state full power operation.

Table 2. APR1400 Pumping Duty[2]

Parameter	Units	2 of 3[1]	3 of 3[2]
FWBP			
Quantity	(-)	3	
Type	(-)	Horizontal, centrifugal, single stage	
Mass Flow Rate per Pump	(lb_m/hr)	9.00x10^6	6.00x10^6
Fluid Temperature	(^{o}F)	286	286
Volumetric Flow per Pump	(gpm)	21,450	14,300
Rated Head	(ft)	N/A	963
Motor Drive Unit	(-)	5,000 hp @ 13.2 kV / 3ϕ / 60 Hz	
MFWP			
Quantity	(-)	3	
Type	(-)	Horizontal, centrifugal, single stage	
Fluid Temperature	(^{o}F)	287	287
Mass Flow Rate per Pump	(lb_m/hr)	9.00x10^6	6.00x10^6
Volumetric Flow per Pump	(gpm)	21,450	14,300
Rated Head	(ft)	N/A	2000
Steam Turbine Drive Unit	(-)	7,000 hp @ 4400 rpm	

1) Operation with two of three pump sets (FWBP / MFWP).
2) Operation with three of three pump sets (FWBP / MFWP)

The FW pumping system is designed to operate with three of three pump sets.

Equipment OOS – Two conditions are considered for power ascension and equipment OOS as follows:

- Each FW pump set shall be individually capable of supplying 55% of the rated steam flow against a S/G outlet nozzle pressure of 1120 psia
- For operations with two-of-three FW pump sets in operation, these pumps shall be capable of delivering 110% of system rated flow against a S/G outlet nozzle pressure of 1040 psia

Transient Response – In order to respond to level transients in the S/Gs, the FW pumping system is designed for rapid transient response. This is assured through the following design requirement.

- In response to a step change in the FW control system setpoint, the MFWPs shall achieve the signaled pump speed within 5 seconds of receipt of signal.

Safety Criteria – The following design criteria is included in the FW System design to assure: (i) overcooling of the Reactor Coolant system is avoided, and (ii) overpressurization of the primary containment is avoided.

- At 'runout' flow conditions with S/G level control valves in the wide opened position, and with a S/G outlet nozzle pressure of 700 psia, total system flow shall not exceed 190% of system design flow
- Following a steam line break accident, the maximum FW flow delivered to the S?G with the broken steam line shall not exceed 330% of normal full power flow to that S/G

The above design criteria are evaluated using hydraulic modeling of the FW System using the Fathom^{TM} model described below.

HYDRAULIC MODEL

As shown in Fig. 1, the APR1400 FW System begins at the outlet nozzles on the DST, passing in parallel through the FWBP / MFWP sets, through three (3) sets of feedwater heaters and on to the S/Gs. A hydraulic model of this system was prepared using the AFT Fathom^{TM} software as shown below:

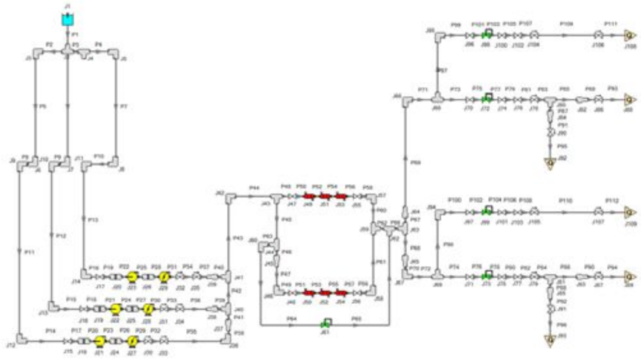

Fig. 7. Fathom^{TM} Model of APR1400 FW System

The model employs several component types offered by Fathom^{TM} including:

- tank model
- elbow
- tee
- reducer / expander
- flow straightener
- fixed speed pumps in parallel
- variable speed pumps in parallel
- pump sets in series
- gate valve
- check valve
- throttle valve
- heat exchanger

The model also includes several modeling options and control features including:

- steam table property data
- variable temperature fluid
- pump speed control
- throttle valve – pressure drop control
- throttle valve - flow control
- heat exchanger – heat transfer versus flow
- terminal node – backpressure
- terminal node – flow control

Case analysis was then performed by variation of the following:

- system flow

- number of operating pump sets
- FWBP speed (EVSD case only)
- MFWP speed
- backpressure
- flow split
- etc.

RESULTS

(later)

CONCLUSIONS AND FUTURE WORK

(later)

ACKNOWLEDGEMENTS

This work was performed under an academic license for Fathom™ provided by AFT. The Kepco International Nuclear Graduate School (KNGS) would like to wholeheartedly recognize this generous support. The process for requesting and activating the licensing was smooth and the e-license worked well for all students involved in the research. International students from three continents were very impressed with Fathom. It is easy to learn and use and yet is a very powerful modeling tool. Based on many decades of experience in this field, I can enthusiastically recommend Fathom™ as the first choice in steady-state hydraulic network software.

REFERENCES

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Acronyms and Abbreviations

AC	Alternating Current
AFT	Applied Flow Technology
APR1400	Advanced Power Reactor 1400
ASD	Adjustable Speed Drive
BWR	Boiling Water Reactor
CP	Condensate Pump
CW	Circulating Water (System)
DC	Direct Current
DCD	Design Criteria Document
DST	Deaerator Storage Tank
EVSD	Electronic Variable Speed Drive
oF	(degrees) Fahrenheit
ft	feet
FW	FeedWater
FWBP	FeedWater Booster Pump
gpm	gallons per minute
HD	Heater Drain
hp	horsepower
Hz	Hertz
kV	kiloVolts
lb_m	pound mass
MD	Motor Drive (unit)
MFWP	Main FeedWater Pump
MVSD	Mechanical Variable Speed Drive
MWe	MegaWatts (electric)
NPP	Nuclear Power Plant
NHSHa	Net Positive Suction Head available
NHSHr	Net Positive Suction Head required
OPR1000	Optimized Pressurized Reactor 1000
PWR	Pressurized Water Reactor
RR	Reactor Recirculation (System)
S/G	Steam Generator
ST	Steam Turbine
SUFWP	StartUp FeedWater Pump
TD	Turbine Drive (unit)
VFD	Variable Frequency Drive