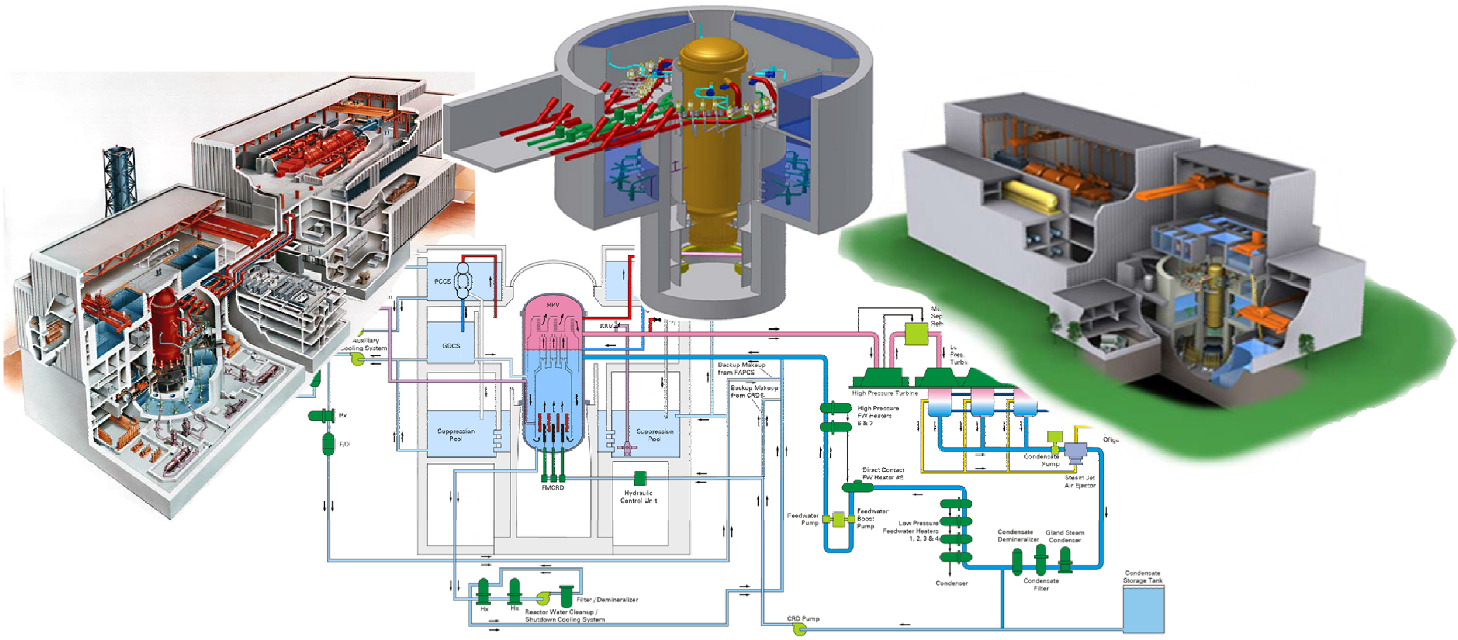
NUCLEAR REGULATORY COMMISSION

Reactor Technology Training Branch



# Part II
# Introduction to Reactor Technology - BWR

## Chapter 5.0, Recirculation and Flow Control Systems

UNITED STATES

NUCLEAR REGULATORY COMMISSION

HUMAN RESOURCES TRAINING & DEVELOPMENT

# Introduction to Reactor Technology

This manual is a text and reference document for the Introduction to Reactor Technology for the media briefing. It should be used by students as a study guide during attendance at this course. This manual was compiled by staff members from the Human Resources Training & Development in the Office of Human Resources.

The information in this manual was compiled for NRC personnel in support of internal training and qualification programs. No assumptions should be made as to its applicability for any other purpose. Information or statements contained in this manual should not be interpreted as setting official policy. The data provided are not necessarily specific to any particular nuclear power plant, but can be considered to be representative of the vendor design.
The Introduction to Reactor Technology – BWR briefing manual outlines the differences between the Boiling Water Reactors (BWR), Advanced Boiling Water Reactor (ABWR), and Economic Simplified Boiling Water Reactor (ESBWR). The course is broken down into discussions on design features, facility and plant layout, containment systems, nuclear steam supply systems, control and instrumentation, safety systems, balance of plant systems, normal, abnormal, and emergency operations.
The content of this course was based on the content provided in the following references:


- General Electric Systems Manual
- Introduction to ABWR Manual
- Introduction to ESBWR Course Manual
- Economic Simplified Boiling Water Reactor Plant General Description; June 2006, General Electric Company
- NUREG-1503, Final Safety Evaluation Report Related to the Certification of the Advanced Boiling Water Reactor Design and Appendices, U.S. Nuclear Regulatory Commission Office of Nuclear Reactor Regulation, July 1994
- ABWR, Advanced Boiling Water Reactor Plant General Description, “First of the Next Generation,” GE Nuclear Energy, June 2000
- Nuclear News, World List of Nuclear Power Plants, American Nuclear Society, March 2007
- J. Alan Beard & L.E. Fennern, General Electric presentation to DOE et.al, April 13th 2007, Germantown Md.



U.S. Nuclear Regulatory Commission
Technical Training Center • Osborne Office Center
5746 Marlin Road • Suite 200
Chattanooga, TN 37411-5677
Phone 423.855.6500 • Fax 423.855.6543

# Table of Contents

Table of Contents .......... 5-3
List of Figures .......... 5-3
5.0 RECIRCULATION AND FLOW CONTROL SYSTEMS .......... 5-4
5.1 Introduction .......... 5-4
5.2 BWR/2 .......... 5-4
5.2.1 Recirculation System .......... 5-4
5.2.1.1 Recirculation Pumps .......... 5-5
5.2.1.2 Recirculation Pump Seals .......... 5-5
5.3 BWR/3&4 .......... 5-6
5.3.1 Recirculation System .......... 5-6
5.3.1.1 Suction Valve .......... 5-6
5.3.1.2 Recirculation Pump .......... 5-6
5.3.1.3 Discharge Valve .......... 5-6
5.3.1.4 Jet Pumps .......... 5-6
5.3.2 Power/Flow Map .......... 5-7
5.0.3.2.1 28% Pump Speed Line .......... 5-7
5.0.3.2.2 Design Flow Control Line .......... 5-7
5.4 BWR/5-6 .......... 5-7
5.4.1 Recirculation System .......... 5-7
5.4.1.1 Suction Valve .......... 5-8
5.4.1.2 Recirculation Pump .......... 5-8
5.4.1.3 Flow Control Valve .......... 5-8
5.4.1.4 Discharge Isolation Valve .......... 5-8
5.4.2 Recirculation Pump Speed Control .......... 5-8

# List of Figures

Figure 5.0-1, Recirculation Flow Control System .......... 5-9
Figure 5.0-2, BWR/3&4 Recirculation System .......... 5-10
Figure 5.0-3, BWR/2 Recirculation System .......... 5-11
Figure 5.0-4, BWR/3&4 Power/Flow Map .......... 5-12
Figure 5.0-5, BWR/5&6 Recirculation System .......... 5-13

*The information contained in this chapter pertains to current operational reactor designs. Advanced reactor designs are provided in separate chapters.*

# 5.0 RECIRCULATION AND FLOW CONTROL SYSTEMS

## 5.1 Introduction

The Recirculation system provides variable forced circulation of water through the core, thereby allowing a higher power level to be achieved than with natural circulation alone. The Recirculation system, in conjunction with the Recirculation Flow Control system (Figure 5.0-1), provides a relatively rapid means of controlling reactor power over a limited range by adjusting the rate of coolant flow through the core.

Control rod movement and recirculation flow adjustment are the two means of controlling reactor power under normal operating conditions. Control rod motion produces local changes in reactivity and neutron flux, while recirculation flow adjustments produce changes in flux across the core without significantly affecting local to average flux values.

An increase in recirculation flow produces an increase in total core flow, or an increase in mass flow rate of subcooled fluid entering the core. This increase in flow suppresses boiling since additional heating is required to reach saturation. The boiling boundary moves upward and the void volume decreases. The resulting positive reactivity increases core power. Power continues to increase until the boiling boundary and void fraction are restored and core reactivity returns to zero. The reverse mechanism occurs on a recirculation flow decrease. In both cases, void fraction changes are transient and void fraction is eventually returned to near the beginning value. The doppler coefficient produces the slight difference in void fraction because of changes in fuel temperature.

## 5.2 BWR/2

The Recirculation system for BWR/2 product lines Figure 5.0-2 consists of five parallel piping loops, designated A through E. The pumping loops take suction from the reactor vessel downcomer annulus and discharge to the lower head area beneath the fuel region. The operator adjusts recirculation flow rate by varying the voltage and frequency output of motor generator sets which supply power to the recirculation pump motors.

### 5.2.1 Recirculation System

The five recirculation pumps, arranged in parallel, take suction from the reactor vessel downcomer annulus through individual outlet nozzles and motor operated suction valves. Pump discharge flow passes through individual motor operated discharge isolation valves and reenters the reactor vessel through five inlet nozzles. A 2-inch line containing a motor operated valve bypasses each pump discharge valve. This path allows a minimum flow during pump starting and provides a small backflow to keep an idle loop warm.

All five recirculation loops are normally in operation, with the pumps at the same speed. Under certain conditions, plant operation is permitted with one loop idle, but not isolated.

Various other plant systems that connect to the recirculation system include:

- 10-inch line connects loop A upstream of the pump suction valve to provide a return flow path to the reactor vessel from isolation condenser A,
- 3/4-inch line taps off loop A upstream of the pump suction valve to provide a flow path to the sampling system,
- two 6-inch lines connect to loop B to provide supply and return flow for the Reactor Water Cleanup system,
- two 14-inch lines connect to loop E to provide supply and return flow for the Shutdown Cooling system and
- 10-inch line connects the 14-inch shutdown cooling supply line to provide a return flow path to the reactor vessel from isolation condenser B

The major components of the Recirculation system are discussed in the paragraphs that follow.

#### 5.2.1.1 Recirculation Pumps

The recirculation pumps provide the driving head for the recirculation system. Each pump is a vertical, single stage, centrifugal pump driven by a 1000 HP, variable speed induction motor. The pumps are powered from individual M/G sets which supply a variable frequency and voltage (11.5 - 57.5 Hz and 460-2300 volts) to change pump speed and flow rate. The flow rate per pump varies from a minimum of 6400 gpm to a maximum of 32,000 gpm.

#### 5.2.1.2 Recirculation Pump Seals

Each recirculation pump is equipped with a dual seal assembly which contains reactor water within the pump casing and associated controlled leakage lines and allows zero leakage to the primary containment. The assembly consists of two seals built into a cartridge that can be replaced without removing the motor from the pump. Each seal can withstand full pump design pressure so that either will adequately limit leakage if the other fails. A breakdown bushing in the pump casing limits leakage to approximately 60 gpm if both seals fail.

During normal operation, both seals share the sealing work load of the assembly, with an approximately 500 psid pressure drop across each seal. Thus, seal cavity #1 is at reactor pressure and seal cavity #2 is at one-half of reactor pressure. This arrangement is maintained by two internal restricting orifices which control the leakage between the seal cavities and from cavity #2 to the drywell equipment drain tank (DWEDT), at approximately 0.5 gpm. A flow switch in the controlled leakage line actuates an alarm on seal failure (high flow) or orifice plugging (low flow).

The seal cavities require forced cooling to remove heat generated by friction between the sealing surfaces. The Reactor Building Closed Cooling Water system supplies approximately

25 gpm of water to a heat exchanger surrounding the seal cartridge. Reactor water from the pump cavity passes through a hole in the main pump impeller, around the hydrostatic bearing, and through the shaft to casing clearance, to an auxiliary impeller located just below the seal cartridge. The auxiliary impeller forces the seal water through the tubes of the heat exchanger.

## 5.3 BWR/3&4

The recirculation system for BWRs 3&4 (Figure 5.0-3) consists of two piping loops external to the reactor vessel and 20 jet pumps which are internal to the reactor vessel. Each loop has a suction isolation valve, recirculation pump, a discharge isolation valve, instrumentation and piping connecting to the reactor vessel.

The variable speed recirculation pumps take suction from the reactor vessel annulus region and provide flow to the jet pump riser pipes through the reactor vessel shell. The jet pumps induce additional water from the reactor vessel annulus region into the flow path, increasing system efficiency.

### 5.3.1 Recirculation System

The major parts of the recirculation system are discussed in the paragraphs that follow.

#### 5.3.1.1 Suction Valve

There is a suction valve in each recirculation loop between the reactor vessel penetration and the recirculation pump. These motor operated suction valves are used for maintenance isolation of each recirculation pump.

#### 5.3.1.2 Recirculation Pump

The recirculation pumps are vertical, single stage, centrifugal pumps driven by a variable speed electrical motor. The pumps provide a rated flow of 45,200 gallons per minute each. The speed of the recirculation pumps, and hence the system flow rate, is controlled by the recirculation flow control system.

#### 5.3.1.3 Discharge Valve

Each recirculation loop contains a motor operated discharge valve located between the recirculation pump and the loop flow measurement device. The valve is remotely operated from the control room using a seal-in to close, throttle to open logic. The discharge valves are automatically jogged open on a pump startup by the recirculation flow control system. Additionally, the discharge valves close as part of the automatic initiation sequence for low pressure coolant injection mode logic of the Residual Heat Removal system to provide an emergency core cooling flow path to the reactor vessel.

#### 5.3.1.4 Jet Pumps

There is a bank of 10 jet pumps associated with each of the external recirculation loops. All jet pumps are located in the reactor vessel annulus region between the inner vessel wall and the

core shroud. The jet pumps are provided to increase the total core flow while minimizing the flow external to the reactor vessel.

Each jet pump has a converging nozzle through which the driving flow passes. This creates a high velocity and relatively low pressure condition at the jet pump suction. This low pressure condition creates additional flow from the vessel annulus, called induced flow, through the jet pumps. The combined flows mix in the mixer section of the jet pumps and then pass through the diffuser section. The diffuser section increases the pressure and decreases the fluid velocity. During full power operation approximately one-third of the total core flow comes from the discharge of the recirculation pumps while the remaining two-thirds is induced by the jet pumps. An error signal is sent to the speed controller. The error signal is limited to about 8% of the control band.

### 5.3.2 Power/Flow Map

The power/flow map (Figure 5.0-4) is a plot of percent core thermal power versus percent of total core flow for various operating conditions. The power/flow map contains information on expected system performance.

#### 5.0.3.2.1 28% Pump Speed Line

Startup operations of the plant are normally carried out with both recirculation pumps at minimum speed. Reactor power and core flow follow this line for the normal control rod withdraw sequence with the recirculation pumps operating at approximately 28% speed.

#### 5.0.3.2.2 Design Flow Control Line

This line is defined by the control rod withdraw pattern which results in being at 100% core thermal power and 100% core flow, assuming equilibrium xenon conditions. Reactor power should follow this line for recirculation flow changes with a fixed control rod pattern.

## 5.4 BWR/5-6

The recirculation system for BWRs 5&6 (Figure 5.0-5) consists of two piping loops external to the reactor vessel and 20 jet pumps which are internal to the reactor vessel. Each loop has a suction isolation valve, recirculation pump, flow control valve, a discharge isolation valve, instrumentation, and piping connecting to the reactor vessel. The two speed recirculation pumps take suction from the reactor vessel annulus region and provide flow to the jet pump riser pipes through the reactor vessel shell. The jet pumps induce additional water from the reactor vessel annulus region into the flow path.

### 5.4.1 Recirculation System

The major parts of the recirculation system are discussed in the paragraphs that follow.

#### 5.4.1.1 Suction Valve

There is a suction isolation valve in each recirculation loop between the reactor vessel penetration and the recirculation pump. These motor operated suction valves are used for maintenance isolation of each recirculation pump.

#### 5.4.1.2 Recirculation Pump

The recirculation pumps are vertical, single stage, two speed, centrifugal pumps. Each is designed to deliver a rated flow of 35,400 gpm at a discharge pressure head of 865 feet. The pumps motors can receive 60 Hz power from 6.9kV buses or 15 Hz power from the associated low frequency motor generator set (LFMG).

In slow speed, the net positive suction head is supplied by the height of water in the reactor vessel. In fast speed, most of the net positive suction head is provided by the subcooling effect of the cooler feedwater flow entering the annulus region where it mixes with the moisture returning from the steam separation stages.

#### 5.4.1.3 Flow Control Valve

The flow control valve is a 24 inch, stainless steel, hydraulic operated ball valve. The valve is designed to provide a linear flow response throughout its entire stroke (22 to 100% open). The valve is positioned by a hydraulically actuated ram that receives motive power from an independent hydraulic power unit. The actuator is positioned by the Recirculation Flow Control system.

#### 5.4.1.4 Discharge Isolation Valve

The discharge isolation valve is a 24 inch, motor operated, stainless steel, gate valve. Valve operation is similar to the suction valve.

### 5.4.2 Recirculation Pump Speed Control

The switchgear includes five separate circuit breakers and a low frequency motor generator (LFMG) set. The breakers are interlocked through the pump control logic to prevent supplying the pump motor from both power supplies.

The interlocks provide the proper sequencing of circuit breaker closure during pump startup, speed changes, and shutdown.

The recirculation pump is always started in fast speed because the LFMG does not have the required capacity to supply the necessary breakaway torque.

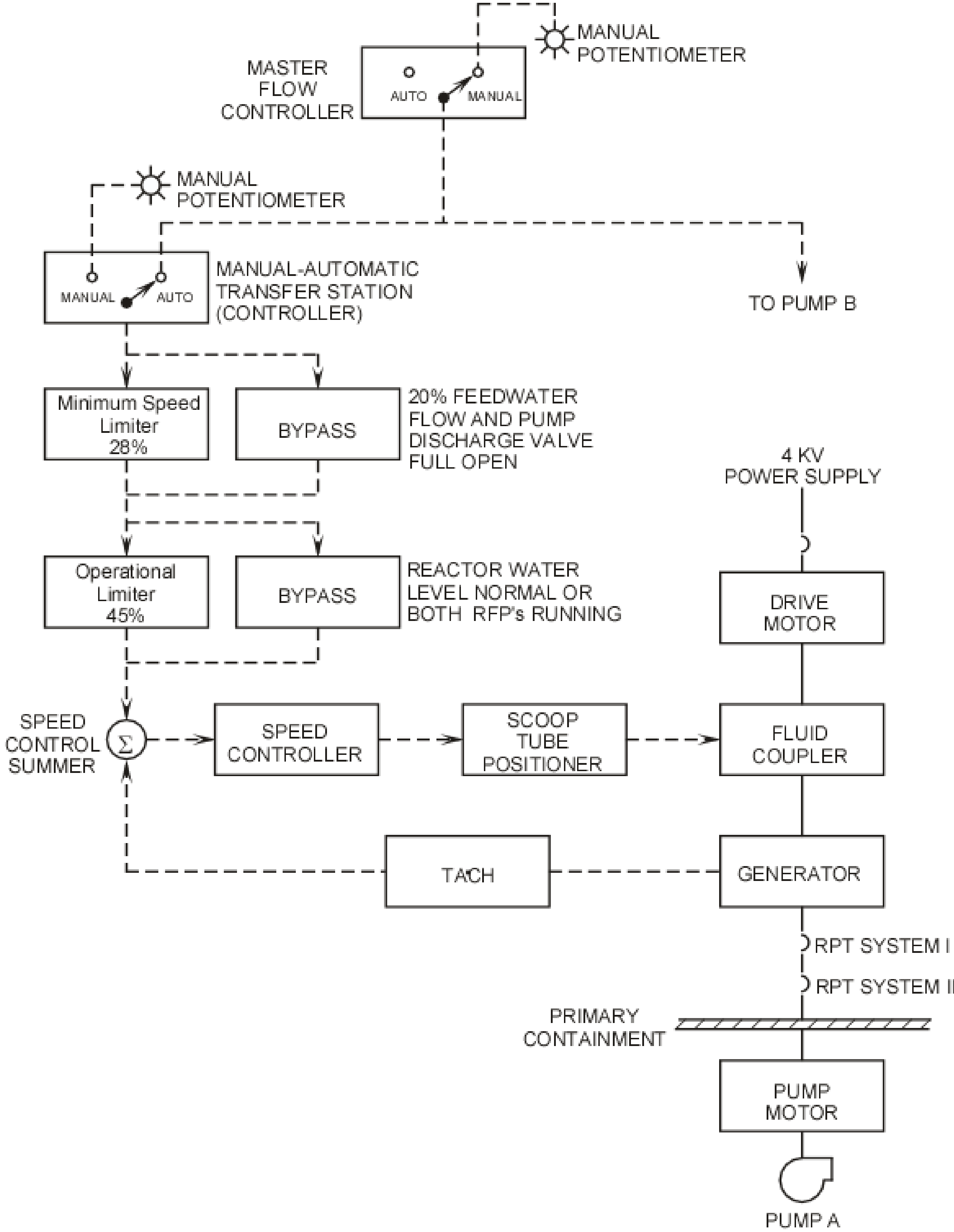



Figure 5.0-1, Recirculation Flow Control System

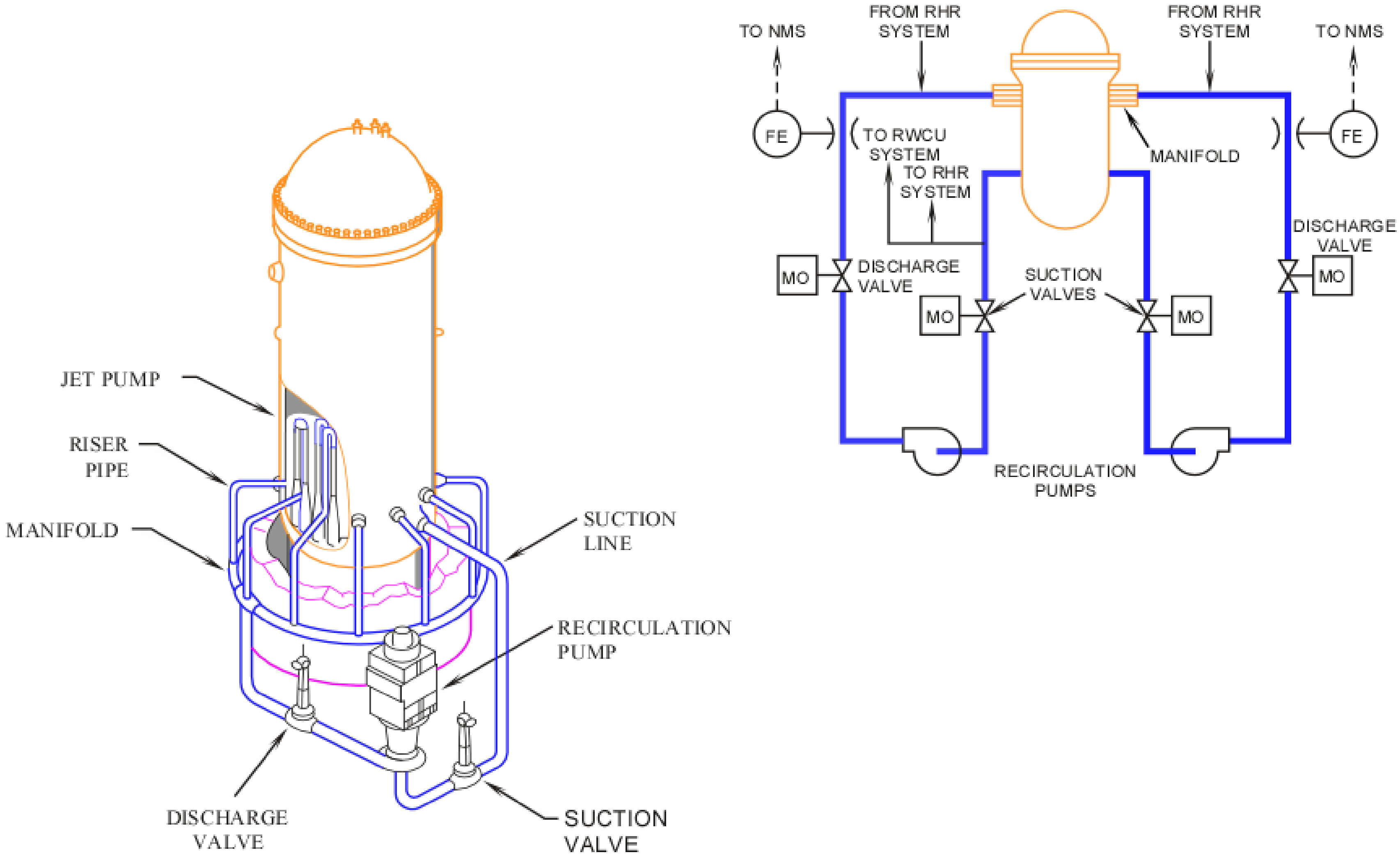



Figure 5.0-2, BWR/3&4 Recirculation System

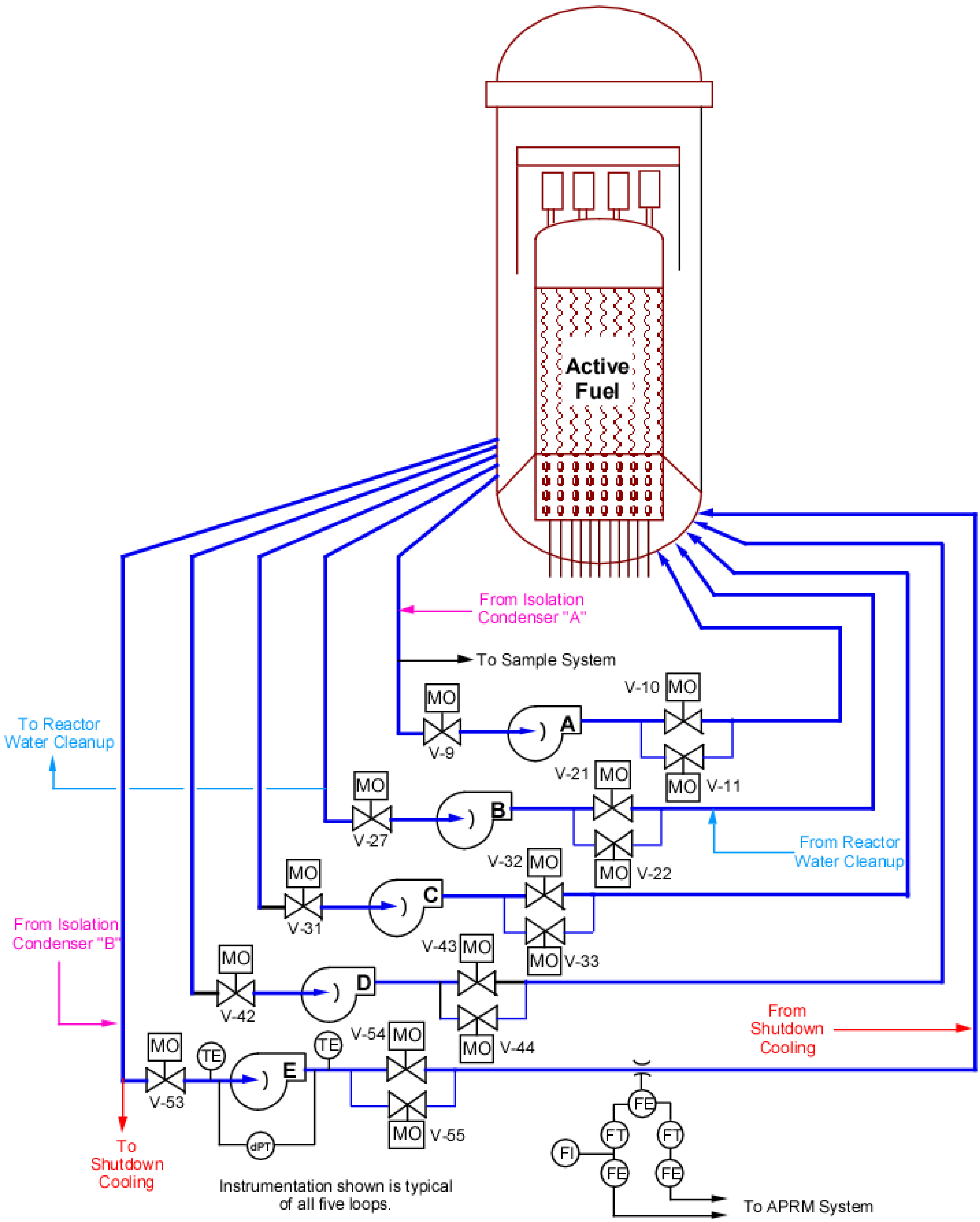



Figure 5.0-3, BWR/2 Recirculation System

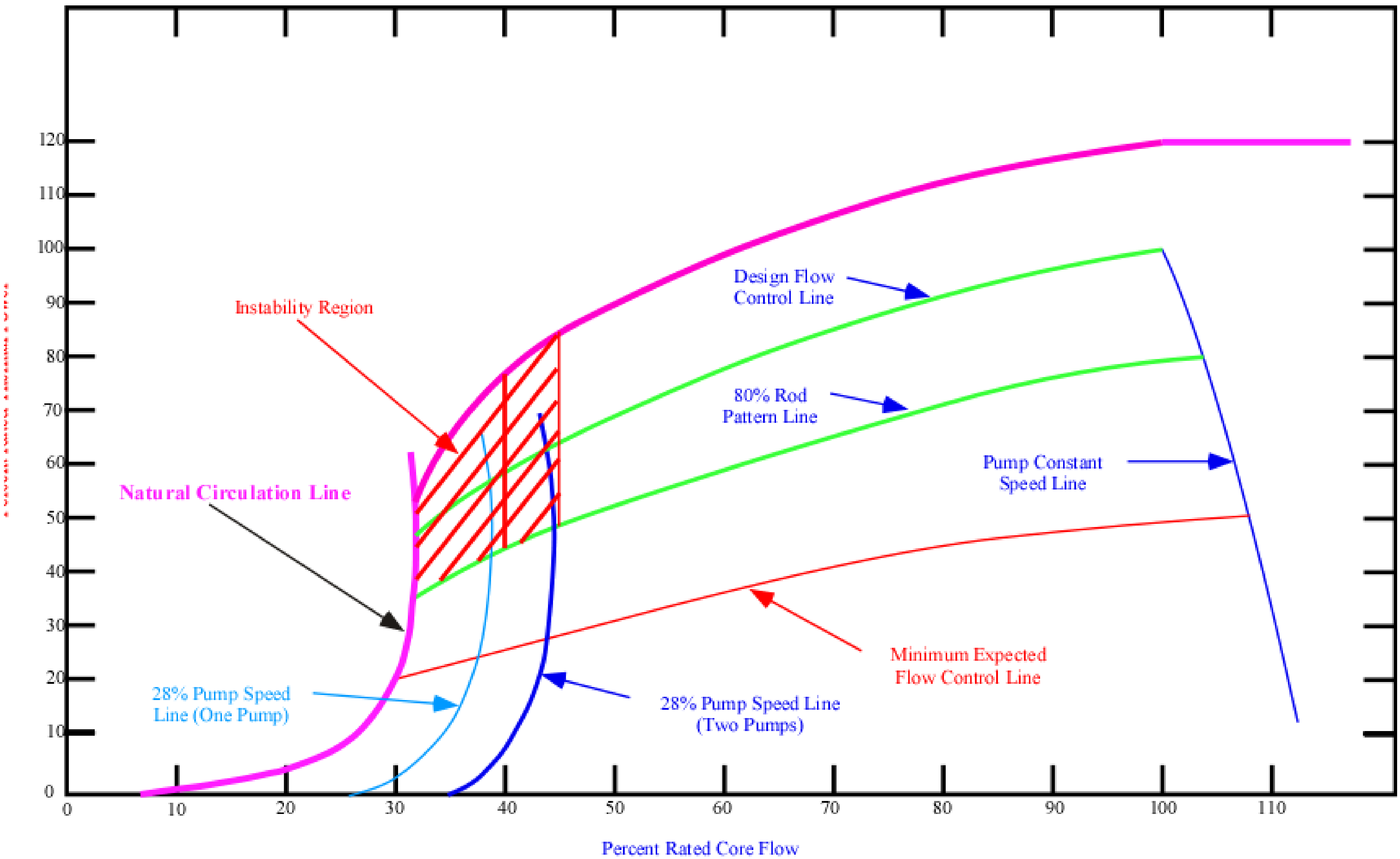



Figure 5.0-4, BWR/3&4 Power/Flow Map

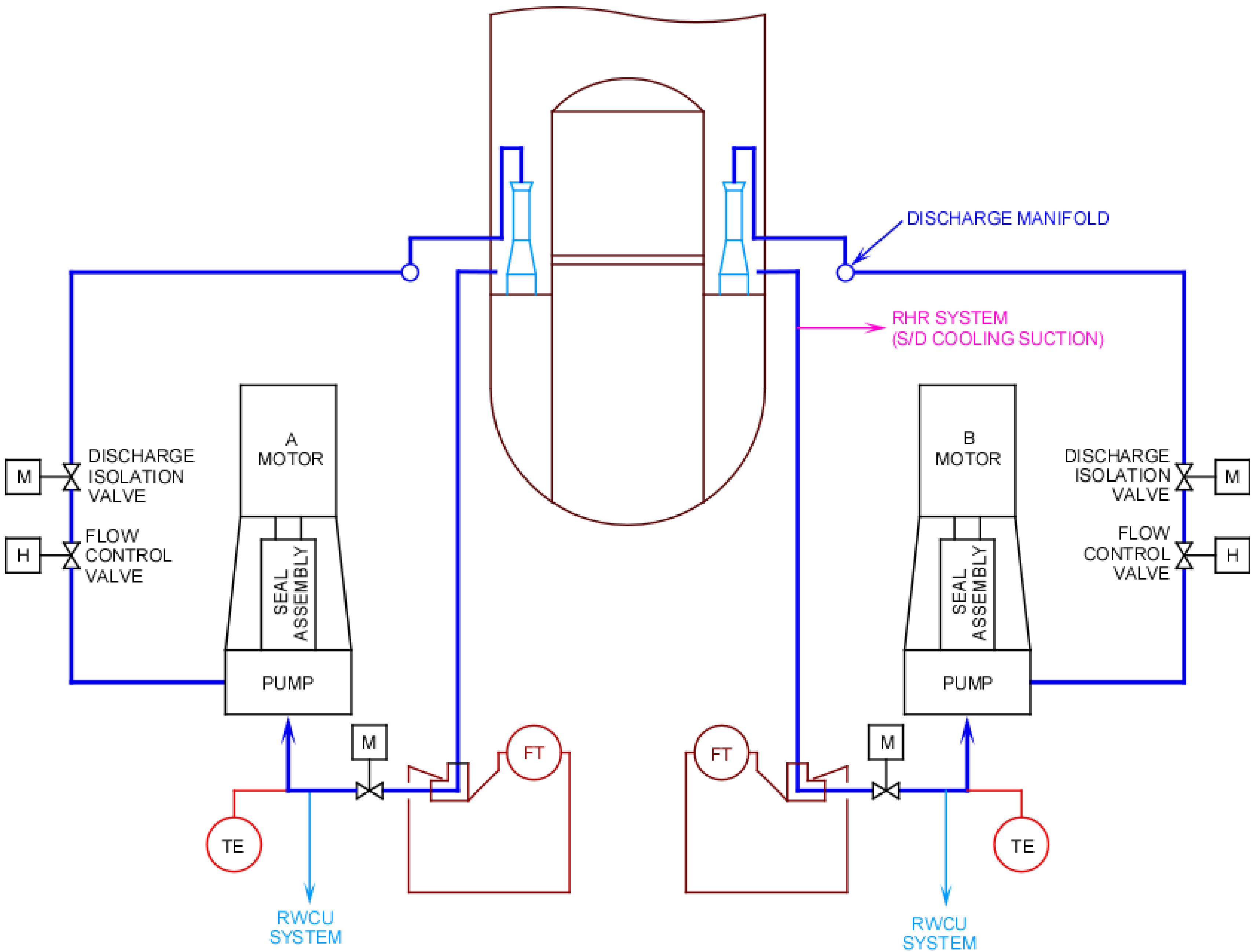



Figure 5.0-5, BWR/5&6 Recirculation System