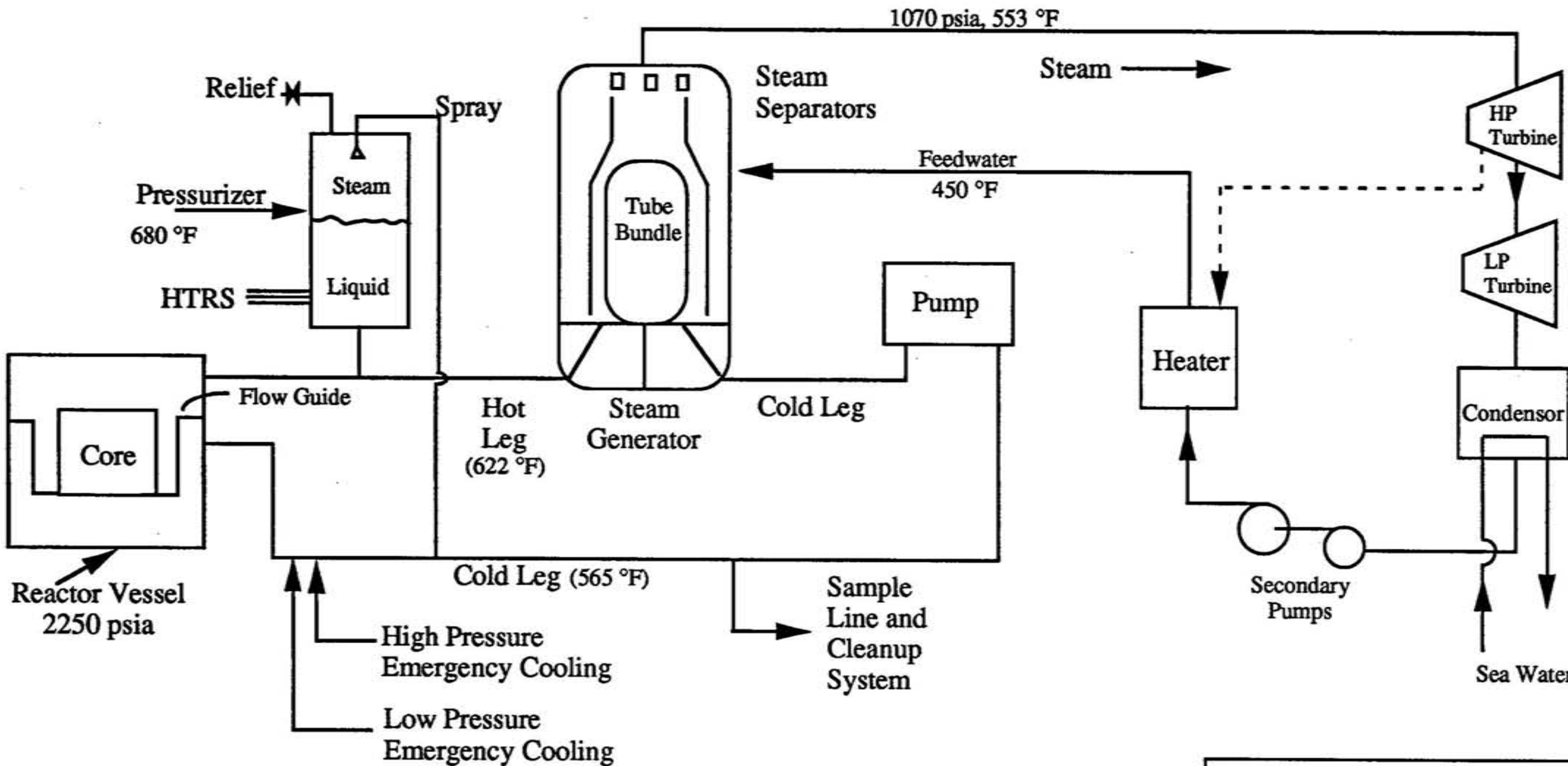
B. Nuclear Power Plant Layout

1. Pressurized Water Reactor (PWR) – The figure on the next page is a schematic diagram of a Pressurized Water Reactor (PWR). Shown are both the primary and secondary loops. The flowpaths of each loop are as follows:

(a) Primary - Primary coolant enters the core vessel and is directed downwards by a flow guide so that it goes under the core. The coolant then flows up through the core where it absorbs heat. Upon leaving the core it flows through the hot leg piping to the steam generator. It then flows through the tube bundle – a bundle of several thousand U-shaped tubes. Heat is transferred through the tube walls to the secondary system. Upon leaving the steam generator the coolant enters the cold leg. It flows through the pump and then back to the core. Other components to note are:

(i) Pressurizer – This is a tank that is situated above the core and primary piping. (It is also above the steam generator although the drawing doesn't show it as such.) The pressurizer has several purposes: It maintains system pressure, provides a surge volume, and provides over-pressure relief. The primary coolant is subcooled (593°F, 2250 psia). The pressurizer is at saturated conditions (680°F, 2250 psia). Thus, boiling occurs in the pressurizer and because of its location, the steam bubble in the pressurizer will not shift to the core. Heaters are used to heat the water in the pressurizer; a spray valve (connected to the cold leg) is used to condense the steam.

(ii) Sample and Cleanup – A portion of the primary is directed through a regenerative and a non-regenerative heat exchanger and then to an ion column for cleanup. Samples for radiochemical analysis are obtained here also.



Primary Flow	$1.6 \cdot 10^8$ lb_m / hr
Steam Flow	$9 \cdot 10^6$ lb_m / hr

Pressurized Water Reactor (PWR)

(iii) There are also connections for high and low pressure emergency cooling.

(b) Secondary – Secondary coolant enters the steam generator and is directed downwards by a flow guide so that it flows to the bottom of the tube bundle. It then flows up through the tube bundle from which it absorbs heat. The result is a steam/water mixture that then passes through separators. They remove the water. The steam then flows through a high pressure (HP) and a low pressure (LP) turbine from which work is extracted. Two turbines are used because the work obtained in going from high pressure (700 psia) to atmospheric is about the same as that obtained in going from atmospheric to vacuum. The exhaust steam then goes to the condenser where it is transformed to liquid. The liquid is then pumped and heated for return to the steam generator.

2. Control Loops – PWRs are characterized by a number of separate control loops. These are listed here in order of increasing complexity.

(a) Pressurizer Level – This is manually controlled. During steady-state operation, the level shouldn't change. During transients, it will vary as a result of changes in the density of the coolant. The most significant changes occur during plant startup and shutdown. During startup, the coolant is heated from 70 °F to 550 °F and it is necessary to drain water from the pressurizer to maintain level. The reverse is true during shutdown.

(b) Pressurize Pressure – This is a simple setpoint controller with manual override. If the pressure is too low, the heaters energize automatically. If it is too high, the spray valve opens. (The spray nozzle is like a shower head. It sprays out water droplets that are cool (565 °F) into the 680 °F steam. Hence, the steam condenses.) If the pressure gets too low or too high, the reactor operator can manually energize the heaters or the spray valve respectively. Also, pressurizers are equipped with relief valves. It was one of these valves that stuck open during the Three Mile Island accident.

(c) Primary Temperature – This is usually controlled manually. However, some plants are equipped with proportional-integral (PI) automatic controllers. The objective is to keep the average temperature of the primary coolant within ± 3 °C of its specified value. The allowed ± 3 °C band is called "the greenband." Changes is load (power demand) can cause the temperature to change. Upon detection of such a change, the operator (or the PI controller) causes the control rods to be moved so as to counteract the change in temperature. For example, if the temperature were dropping, the rods would be pulled out to increase power production. There have been reportable events as a result of malfunctions of the PI controllers. In one case, a temperature sensor failed. The controller interpreted this as a low temperature. So, it initiated rod withdrawal. This is one reason why the use of redundant sensors and signal validation is essential in automated control of safety-constrained systems. Computers don't recognize instruments as failed unless programmed to do so.

(d) Turbine Runback – This is an automated controller that closes (runs back) the steam admission valve to the turbine if there is either an incipient over-power or over-temperature condition. The objective of this circuit is to prevent the need for action by the reactor safety system. In addition, the turbine is automatically run-back in the event of a dropped rod. This is because dropping a rod would temporarily make the reactor subcritical and, were the turbine still at full load, the reactor would rapidly cool off. As discussed earlier, as a result of the negative temperature coefficient, enough positive reactivity would be added to not only make the reactor critical but also to cause its power level to overshoot, both on the average and locally, in fuel assemblies not affected by the dropped rod.

(e) Steam Dump Control – The steam dump control system is designed so that the plant can experience a sudden loss of load without it being necessary either to incur a reactor trip or to actuate the steam generator reliefs. This automated system is necessary because, in the event of a sudden, large reduction in load, the energy being generated by the reactor will greatly exceed that being removed by the turbine. Hence, both primary and steam generator temperatures and pressures will rise to unacceptable levels. This type of transient is averted by opening specially designed valves that allow steam to be dumped directly to the condenser. The actuating signal for these valves is the difference between the primary system's average coolant temperature and the preprogrammed reference temperature. Should there be a sudden decrease in load, the former temperature will rise while the latter will decrease. Once the deviation between the actual and the reference temperature exceeds the value corresponding to a 10% step load reduction, the dump valves will be opened and steam sent directly to the condenser. The error in the system temperature will also cause the full-length control rods to be driven into the core thereby lowering both the power and the temperature. The amount of steam being dumped will be gradually reduced to zero as a result of the control rods returning the temperature to the specified value.

(f) Steam Generator Level Control – Steam generator levels fluctuate significantly with load changes. When power is being raised, the shell side volume, which occupied by vapor, will increase thereby causing the water in the downcomer region to rise. Conversely, if the power level is being lowered, the vapor volume decreases and the water level in the downcomer region drops. These phenomena are referred to as "swell" and "shrink" respectively.

The desired steam generator level may be either a preprogrammed function of the demand power or a constant. A three-element controller is used to maintain the actual level at the reference value. The controller generates an error signal based on the difference between the steam and feed flows and on the deviation in the actual and reference levels. The error signal controls the motorized steam generator feedwater regulating valve which admits water to the downcomer region. It should be noted that the swell and shrink phenomena may initially cause a conflict within the controller. For example, if the demanded power is being raised, both the water level and the steam flow will initially rise. The rise in level will tend to close the regulating valve while the rise in steam flow will cause it to open. Once the initial swell is over, the water level will drop and both signals will act in unison. Most steam generator level controllers are adjusted so that the steam/feed flow mismatch is the dominant signal.

(g) Feed Flow Control – The speed of the main feed pumps is regulated by an air-operated pneumatic system so that the pressure drop across the steam generator feedwater regulating valves will be kept at a specified, preset value. In the event that the automatic system fails, the controller can be shifted to either manual or to a preset automatic mode.

(h) Hot Well Control – Any closed system must have some storage capacity in order to accommodate the volume changes that occur due to variations in the temperature of the working fluid. The secondary system has two such reservoirs. These are the condenser hot well and the heater drain tanks. The water level in the hot well is controlled by a pneumatically operated valve. The condensate is usually subcooled by several degrees in order to permit it to be pumped without too much cavitation. (Water at the saturation temperature would flash when entering the low-pressure, suction-side of a pump.) As such, the condensate is relatively cold compared to the feedwater. This is because the feedwater is preheated with auxiliary steam. The steam pressure is automatically regulated to be maintained within prescribed limits. These control systems appear quite simple. However, every fresh water drain eventually goes to the condenser and every auxiliary steam load exhausts to a heater. The condenser level and the auxiliary exhaust steam pressure are therefore both sensitive functions of the plant power. Any malfunction in either of these controllers can lead to a loss of net positive suction head to the main feed pumps.