CHAPTER 9

Nuclear Plant Operation

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Summary:

This chapter deals with the operating concepts of a CANDU nuclear power plant. It combines some theoretical aspects with basic operating procedures to explain how the plant operates. Key aspects related to plant control are addressed. Space allows only the primary energy generation, transport and conversion components to be covered, but there are many other components whose operation is vital for the efficient and safe operation of the plant. There is approximately an equal division of detail between the nuclear reactor, the heat transport and steam systems, and the steam turbine.

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Nomenclature for Equations

A	area	m^2
c_p	specific heat at constant pressure	kJ/kg°C
f	thermal utilization factor	
k	neutron multiplication factor	
M	mass flow rate	kg/s
U	overall heat transfer coefficient	$kJ/sm^2°C$
S_0	number of source neutrons	
S_∞	number of measured neutrons	
p	pressure	MPa
p	resonance escape probability	
v	specific volume	m^3/kg
V	velocity	m/s
Δk	change in neutron multiplication factor	
ΔT	rise in temperature (of fluid)	°C
ε	fast fission factor	

η	reproduction factor	
η	efficiency	
θ	temperature difference (between fluids)	°C
Λ_t	thermal neutron non-leakage probability	
Λ_f	fast neutron non-leakage probability	
ν	neutrons emitted per neutron absorbed	
ρ	density	kg/m^3
Σ_f	macroscopic fission cross section	m^{-1}
Σ_a	macroscopic absorption cross section	m^{-1}
Ω	rate of heat transfer	kJ/s

1 Power Production

1.1 Power Output Regulation

Consider a very simple system with a nuclear reactor, steam generator, and turbine generator supplying electrical power to an isolated electrical grid, as shown in Figure 1. The power must be generated at the moment it is required by the consumers connected to the grid. Power production must follow demand exactly, and any mismatch will cause the grid frequency to fall or rise as demand increases or decreases.

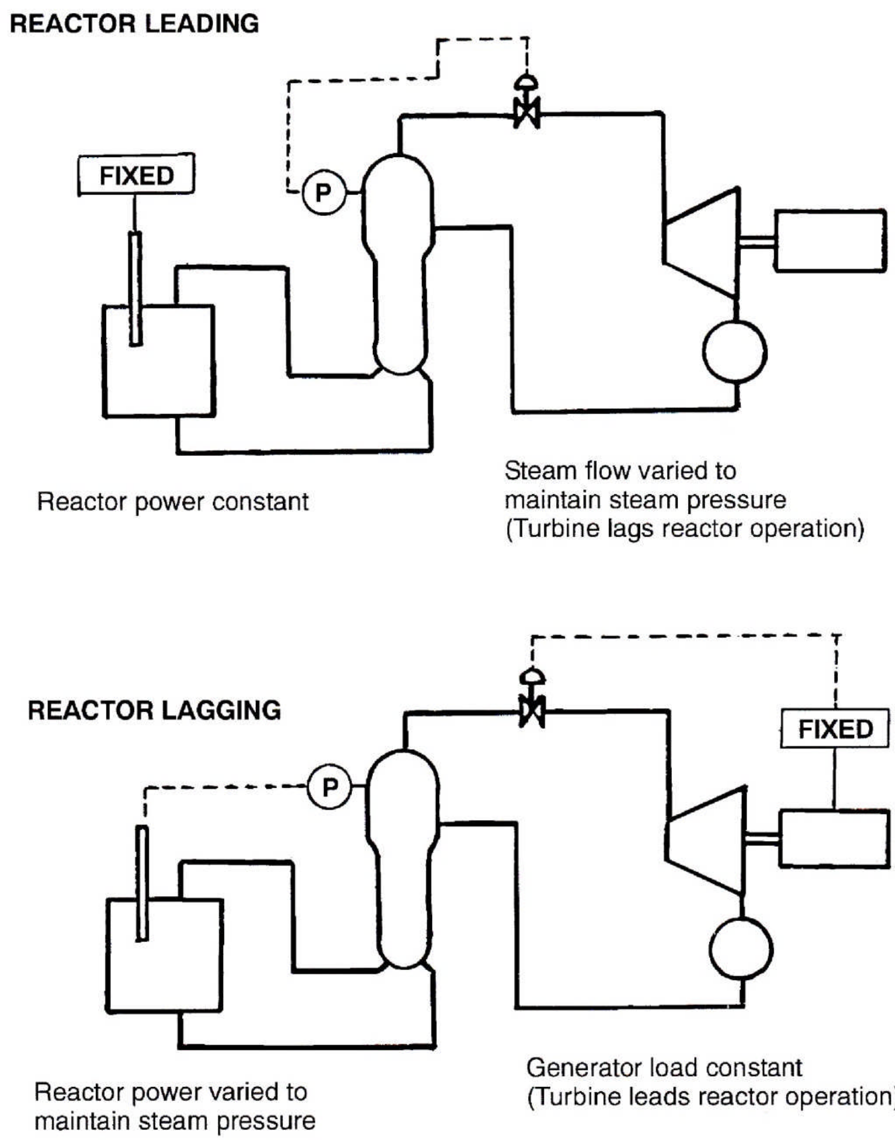


Figure 1 Lagging and leading plant operation

A basic control system works as follows to maintain appropriate power output from the plant. In the event of an increase in demand for electrical power, the mismatch will cause the grid frequency to fall. Because the turbine generator is synchronized to the grid, its speed will drop accordingly. This will be sensed by the turbine governor, which will open the governor valves to admit more steam to increase the power output of the turbine generator. The additional flow of steam to the turbine will cause a reduction in steam pressure in the steam generator. This in turn will be sensed by the reactor regulating system, which will lower the liquid zones or withdraw control rods from the reactor core until the increased fission rate generates sufficient additional heat to restore the steam generator pressure. In the event of a decrease in demand, the reverse occurs. This is known as the *reactor following* or *turbine leading* mode of operation (or normal mode in some plants because it is a natural way of maintaining stable conditions).

Such a system, however, cannot maintain the specified frequency (60 Hz in North America) exactly without large unstable oscillations, and therefore a certain speed droop is incorporated into the turbine governor. This enables a progressive increase in governor valve opening (steam flow) as the turbine speed (grid frequency) falls. A typical droop setting is 4%, which means that, if the turbine were initially at zero load and at full speed, its speed would have to drop to 96% before the governor valve would be fully open. Such a speed is not acceptable for the turbine due to possible blade vibration, nor to the grid due to loss in speed of connected motors. Therefore, the governor is adjusted to bring the speed back to 100% at full load. In the event of a turbine trip or load reduction to zero under these conditions, the reverse would occur, and the turbine speed would rise to 104% of full speed.

In the operating mode just described, the nuclear reactor output follows the electrical grid demand, and therefore its power level oscillates continuously. This can have certain adverse effects, depending upon the type and design of the reactor. Excessive oscillations impose temperature transients on the fuel, which could cause premature failures of the fuel cladding. Large oscillations near full power could cause power limits to be exceeded, thus tripping the reactor and losing power production as well as imposing restart transients on it and the turbine. Due to high capital cost and low fuel cost, it is desirable to run nuclear reactors at full power most of the time. An alternative mode of operation is therefore often used at nuclear plants, in which reactor power output is fixed. This is known as *reactor leading* or *turbine lagging* operation. To maintain stable operation, reactor power is controlled at a given value by measuring the neutron flux and adjusting the control rods or liquid zones accordingly. Pressure in the steam generator must be maintained at the proper value to ensure stable conditions in the reactor coolant circuit. This is done by opening or closing the turbine governor valves to control the steam flow from the generators. The turbine then delivers power according to the steam flow, and the generator sends this power into the grid system, regardless of the grid frequency. The grid frequency must then be controlled by other turbine generators which feed into the grid system and operate in the turbine leading mode.

By referring to Figure 1 showing the two modes of operation, it can be seen that steam generator pressure is a key controlling parameter in both modes. This highlights the importance of the steam generator, where a balance of heat input and heat output must be maintained to maintain its pressure. Furthermore, the difference in temperature between the primary coolant and the secondary working fluid determines the rate of heat transfer. Hence, the reactor coolant temperature is determined by the saturation temperature and thus by the pressure in the steam generator.

1.2 Operational Constraints

During operation, parts of the reactor, steam system, and turbine are subjected to high temperatures. If these parts have thick walls or a substantial solid mass, they will likely suffer thermal stress during the heating and cooling that arises during start-up and shutdown and also during load transients. If a thick component is heated on one side, this side will tend to expand. If constrained by the still cold base material so that it cannot expand, an internal stress will be set up. The reverse happens during cooling. This means that large rigid components which are subject to transient and uneven heating and cooling will suffer low cycle fatigue damage and may ultimately fail. This effect can be minimized by slow heating and cooling to reduce temperature differences in single components such as reactor pressure vessels, steam generators, steam pipes, turbine casings, and turbine rotors. This means that all these components must be preheated slowly before start-up and the unit loaded slowly. Similarly, load changes on the unit should be done slowly. This imposes operating restrictions on reactors and turbines. Generally, the larger the unit, the longer will be the time to start it up and load it. This makes large units less flexible in operation than smaller units.

In the reactor, temperature transients on the fuel cause structural changes within the fuel and stress on the cladding and therefore must be minimized to avoid premature fuel failures. In the turbine, uneven heating and cooling of the rotor can cause bending, which in turn causes excessive vibration and in the extreme case, contact with the casing. Therefore, heating and cooling must be monitored very carefully.

A nuclear reactor is also subject to xenon transients which may inhibit operation for a period. When the load on a reactor is suddenly reduced, xenon, a fission product that absorbs neutrons very strongly, builds up in the fuel and may force a reactor shutdown. The xenon eventually decays after about 40 hours, and the reactor can be restarted. During this time, there is a loss in electrical power production, and the larger the unit, the more serious will be this loss in revenue generating output.

2 Plant Control and Protection

2.1 CANDU Plant Control Systems

A CANDU nuclear plant can operate as a base load plant or as a load following plant. The latter is the conventional mode because the plant responds naturally to demand changes on the grid system, as explained above. Fossil fuel fired plants operate in this way. In nuclear plants, there are special considerations, the main one being the high capital cost and the low fuel cost compared with conventional plants. Nuclear plants should therefore operate continuously at maximum load to ensure the lowest generation cost. A steady load also avoids thermal transients, prolongs the life of all high temperature components, and minimizes the possibility of premature fuel failures. Hence, most nuclear plants operate as base load plants, and the control system in a CANDU unit provides for this, as shown in Figure 2.

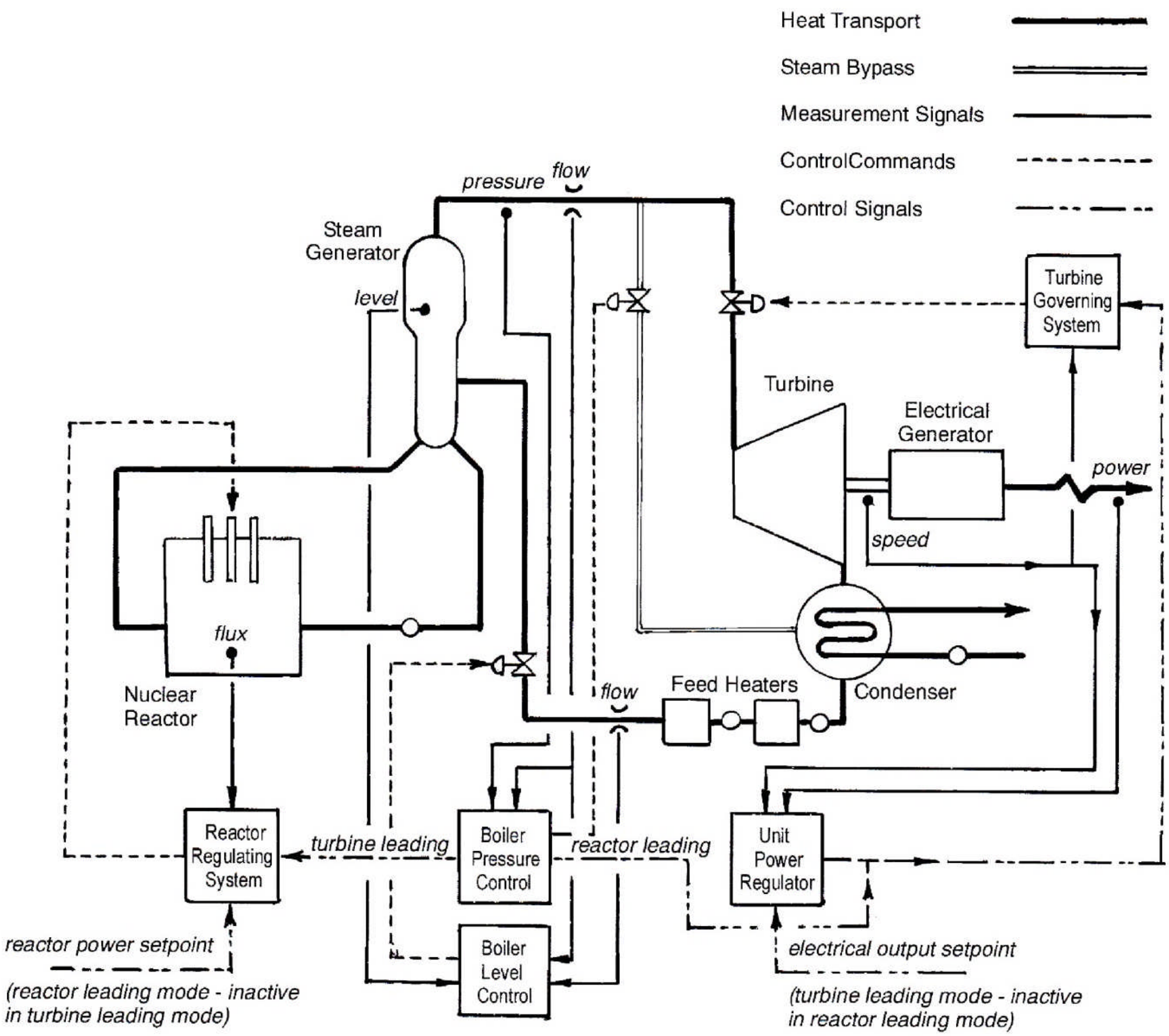


Figure 2 Basic plant control system

The plant can operate as a load following plant where the turbine responds to grid conditions and the reactor follows the turbine to produce the required output (turbine leading and reactor following). In the *alternate mode* the reactor power is fixed, and the turbine follows to produce the equivalent output (reactor leading and turbine following). This alternate mode with reactor power fixed enables the reactor to operate close to its power limits without risk of tripping due to control system oscillations from the turbine or other downstream component perturbations, thus maximizing plant output. In some plants, this *alternate mode* is called *normal mode* because the plant normally operates this way, and load following is the *alternate mode*.

The amount of steam produced in the steam generator depends upon the amount of heat received from the reactor. If the water level and pressure in the steam generator are to remain constant, the heat inflow and heat outflow must be perfectly balanced. Either one may be held constant (leading) and the other varied (lagging) to maintain conditions in the steam generator.

This determines the mode of operation of the plant (turbine leading and reactor lagging, or reactor leading and turbine lagging). Steam generator pressure controls both modes of operation. In turbine leading or reactor following, the steam pressure determines the required reactor output by signalling the reactor regulating system to increase or decrease fission heat release. In reactor leading or turbine following, the steam pressure determines the power output by signalling the turbine governing system to admit more or less steam to the turbine.

2.1.1 Steam generator pressure control

In the turbine leading mode, the steam generator or boiler pressure control (BPC) system measures steam pressure and manipulates reactor power by altering the reactor regulator setpoint. In the reactor leading mode, it measures steam pressure and manipulates steam flow by adjusting the turbine governor speeder gear.

2.1.2 Steam generator level control

The steam generator or boiler level control (BLC) system measures water level, compares steam and feedwater flows, and manipulates feedwater flow. In addition, reactor power or turbine power is measured and the level setpoint ramped up or down accordingly.

2.1.3 Unit power regulator

The unit power regulator (UPR) measures the electrical output and controls this output by manipulating steam flow, which is done by adjusting the turbine governor speeder gear. This is only applicable in turbine leading mode.

2.1.4 Reactor regulating system

The reactor regulating system (RRS) measures reactor neutron flux and thermal power and manipulates the liquid zone control absorbers and adjuster rod positions to control neutron flux.

2.1.5 Heat transport system (not shown in Figure 2)

The heat transport system pressure and level (HTSP&L) control system measures the reactor coolant pressure and pressurizer water level and manipulates the feed and bleed system as well as the pressurizer heaters and water sprays and also the steam release if pressure rise is excessive.

2.1.6 Turbine governing system

The turbine governor senses the turbine speed and adjusts the steam flow to maintain the required speed. This action is applicable only when the turbine generator is not connected to the grid system. Before synchronization, the speed is adjusted by the speeder gear to match the frequency of the grid system exactly. Once synchronized, the turbine generator speed is fixed by the grid frequency. If the speeder gear is then manipulated, it will open or close the governor valves to admit more or less steam and hence increase or decrease the turbine load. Once the load has been set on the turbine, any change in frequency on the grid system will alter the turbine speed, and the turbine governor will respond accordingly and change the governor valve position to adapt to the change in grid demand. This will alter the turbine generator output according to the speed droop setting. Further manipulation of the speeder gear by the unit power regulator (turbine leading) or the boiler pressure control (reactor leading) will restore the desired power output.

2.2 Reactor Protection Systems

The reactor has protection systems that prevent excessive operating conditions which could cause a reactor trip and that trip the reactor if certain operating conditions are exceeded. A reactor trip is to be avoided if unnecessary because it causes a loss in electric power production and imposes thermal transients on components. Therefore, provision is made for the reactor power to be reduced by a setback or stepback to avoid potential trip conditions. Certain conditions, however, require an immediate reactor trip because continued operation could put the reactor into a dangerous condition. Such conditions require assurance that the reactor will trip, and therefore dual shutdown systems are provided, where each system is completely independent of the other, operates on different principles, and is activated by different inputs.

2.2.1 Reactor setback

A reactor setback reduces reactor power in a ramped manner to a predetermined level. The rate of power reduction and the end point of the power level depend upon the initiating conditions. For example, a high local neutron flux or flux tilts beyond a certain level will trigger a setback to 60% or 20% of full load, depending upon severity, to avoid overrating the fuel locally. A turbine trip or load rejection initiates a setback to 60% of full power because the condenser can absorb this level of heat load. A high steam generator pressure requires a setback to 10% because it indicates an inability of the turbine and condenser to absorb the steam flow adequately. Failure to meet other conditions which are essential for safe reactor operation, but which could be rectified with the reactor on load, requires a setback to 2%.

2.2.2 Reactor stepback

A reactor stepback reduces reactor power immediately to approximately 60% of full power by initiating a drop of the mechanical control absorbers. It is therefore similar to a reactor trip, but does not invoke the reactor shutdown systems, although it is a backup to the shutdown systems. For example, a trip of the heat transport pumps or low steam generator water level will trigger a stepback because these indicate a loss of heat removal capability. A high rate of neutron power increase will also initiate a stepback because it indicates a lack of safe reactor control.

2.3 Reactor Shutdown Systems

The reactor must be protected from the worst type of failure or combinations of failures. A loss of coolant accident is one such scenario. In the event of loss of coolant from one or more fuel channels, the voidage will initially cause an increase in reactivity. This must be counteracted by immediate insertion of a greater amount of negative reactivity to ensure subcritical conditions. There are two independent shutdown systems, SDS1 and SDS2, which are capable of doing this.

2.3.1 Shut-off rod insertion

Shut-off rods controlled by the SDS1 system drop by gravity into the reactor core to absorb neutrons. They are made of hollow cadmium rods encased in stainless steel and are guided into the reactor by vertical guide tubes. Cadmium is a strong neutron absorber and quickly takes the reactor power to a very low level. Activation occurs by release of electrically energized clutches, and the initial fall is accelerated by springs.

2.3.2 Liquid poison injection

Liquid poison controlled by the SDS2 system is injected by pressurized helium into the moderator to absorb neutrons. The gadolinium nitrate solution absorbs neutrons strongly, thus effecting a rapid drop in reactor power to a very low level. To ensure adequate distribution of the liquid poison, it is injected through a pattern of horizontal tubes within the reactor core. Activation occurs by the release of air pressure which holds the helium release valves in the closed position.

Both systems are activated within one second of failure detection, and sufficient negative reactivity is inserted within two seconds. The two systems are entirely independent of one another, and their operation depends on different principles and mechanisms. Although a loss of coolant accident is obviously very serious, there are several other scenarios which could put the reactor at risk, some of which may be transient due to operating disturbances. Several control parameters therefore feed into the SDS1 and SDS2 systems to shut down the reactor if these parameters deviate too far from what is deemed to be a safe operating condition. A dropping steam generator level, for example, will initiate first a stepback, then the SDS1 system, and finally the SDS2 system, so that if the stepback does not arrest the loss in inventory, the first shutdown system should, but if it fails, the second shutdown system will respond accordingly.

Quick recovery after an SDS1 trip is possible because the shut-off rod control mechanism can be reset and the rods withdrawn without residual reactivity effects. However, this is not possible after an SDS2 shutdown because the liquid poison will have thoroughly mixed with the moderator, and it will take several hours for the moderator purification system to remove the gadolinium. The SDS1 system is therefore the first to be actuated, and if this fails to arrest the fault condition, the SDS2 system will follow. Therefore, transient conditions or minor problems which initiate only an SDS1 trip and which can be corrected quickly can be recovered from before the xenon transient causes the reactor to poison out. Major faults or excessive deviations from required parameters would result in both systems tripping in quick succession.

2.4 Emergency Coolant Injection

In the event of a loss of coolant accident, an assured supply of coolant must be supplied to the fuel channels to maintain cooling immediately after the resulting reactor shutdown. This is effected by the emergency coolant injection system, which injects high pressure water into the heat transport system. This water is maintained under pressure in tanks by pressurized nitrogen. After this has been exhausted and the heat transport system pressure has fallen to a lower level, a pump-driven low pressure injection system takes over. Ultimately, lost coolant is recovered, circulated through heat removal exchangers, and returned to the heat transport system to stabilize the situation. Typically, the high pressure system is actuated at a heat transport system pressure of about 5 MPa to give sufficient margin from normal operating pressure to minimize spurious injections during normal reactor cooldown.

2.5 Turbine Protection System

Like the reactor, the turbine has protection systems to prevent damage to components or catastrophic failure. As with the reactor, avoidance of unnecessary tripping is achieved by a runback to reduce turbine power sufficiently to regain safe operating conditions. In this way, speed and temperature transients on the turbine can be avoided, as well as the risk of faulty synchronization. Serious faults, however, require an immediate turbine trip.

2.5.1 Turbine runback

A turbine runback is the reduction of turbine load at a preset rate to zero load or until the initiating condition has been cleared. The rate is typically in the range of 1% to 10% of full load per second. The rate may be *fast* or *slow* depending upon the condition. A *latched* runback is one in which the governor speeder gear returns the turbine to the no-load speed setpoint. An *unlatched* runback terminates when the initiating condition has been cleared. As an example, a turbine trip would cause a fast latched runback to ensure that the governor speeder gear was reset to its no-load speed condition to avoid rapid reopening of the governor valves when clearing and resetting the trip (after rectifying the fault). A fast unlatched runback would be initiated by high condenser pressure (poor vacuum) because the condenser was unable to handle the exhaust steam flow adequately. This runback would terminate when the pressure had been restored to an acceptable value, and the turbine load would be maintained at this level.

2.5.2 Turbine trip system

In the event of a serious problem on the turbine generator, the turbine is tripped. This action causes a fast runback to the no-load set point on the governor and releases hydraulic pressure from the governor and stop valve actuators. This enables the valves to close rapidly and shut off steam flow to the turbine. Signals causing a trip come from various sources such as excessive rotor vibration, high bearing temperature, a generator electrical fault, and other parameters which have the potential to damage the turbine.

2.5.3 Overspeed governor

A major concern with regard to the turbine generator is the risk of overspeeding. This can happen only when the turbine is disconnected from the electrical grid, which means that critical times are before synchronization and after a turbine generator trip or load rejection. Some degree of overspeeding occurs with a generator trip or a load rejection when the steam valves are still closing after electrical output has been terminated. To provide protection against excessive overspeed, an overspeed governor is mounted on the turbine shaft. This is activated by increasing centrifugal force on overspeed bolts which independently trigger hydraulic pressure release from the steam valve actuators to shut off the steam flow.

3 Nuclear Reactor Operation

3.1 Reactivity Characteristics

To maintain the neutron multiplication factor k equal to unity in an operating reactor, small adjustments must be made continually to one of the factors in the six-factor formula given as follows:

$$k = \varepsilon\, p\, \eta\, f\, \Lambda_f \Lambda_t, \tag{1}$$

where ε is the fast fission factor, p the resonance escape probability, η the reproduction factor, f the thermal utilization factor, Λ_f the fast neutron non-leakage probability, and Λ_t the thermal neutron non-leakage probability. The manipulated factor is usually the factor f, the thermal utilization factor, which includes the neutron absorption in the reactor, Σ_a. This affects the number of neutrons and hence the neutron flux and reactor power.

Control systems must be designed to maintain the desired neutron power following short term changes initiated by natural perturbations or imposed transients. In the longer term, changes occur due to buildup of neutron absorbers and burnup of neutron producers in the reactor core. Because these changes are slow, they do not affect the control system as such, but the overall reactor configuration must be adjusted to maintain the desired balanced condition for a steady neutron chain reaction. The control system then maintains an equilibrium about this balanced condition.

An important consideration is the extremely high velocity of neutrons (2200 m/s when thermalized at 20°C). With the close spacing of fuel elements in the reactor, neutrons do not travel very far. The overall neutron lifetime from production due to fission until absorption to produce fission is therefore extremely short. The average neutron lifetime in a heavy water moderated CANDU reactor is about 1 millisecond, and in a light water moderated reactor such as a PWR or a BWR, it is much less. The complete neutron cycle from one generation to the next takes only this amount of time. It is evident, therefore, that any small deviation from the equilibrium situation, in which the number of neutrons in one generation is equal to that of the previous generation, will very rapidly grow in magnitude.

If all neutrons had a lifetime of about 1 millisecond, it would be almost impossible to design a control system that would be able to sense changes and effect control before the neutron population grew or shrank out of the control range. Fortuitously, some neutrons are produced a short time after the actual fission process. The kinetic behaviour of a reactor is critically dependent upon the existence of these delayed neutrons because they have the effect of increasing the average lifetime of the neutrons arising from fission. This increase in average lifetime to about 1 second because fewer than 1% of the neutrons have much longer effective lifetimes enables control systems to maintain stable operation provided that certain limits are not exceeded.

3.2 Source Multiplication

The delayed neutrons also influence the reactor under shutdown conditions because they are produced by the decay of certain precursors. While the reactor is shut down, this decay process continues, and some neutrons are always present because the decay curve is asymptotic. Both uranium-235 and uranium-238 are naturally unstable and decay mainly by α-particle emission. Both also fission spontaneously, giving off neutrons in the process. Any fuel, even unused fuel, therefore produces small numbers of neutrons. Furthermore, in heavy water moderated reactors such as the CANDU, neutrons can be created by interaction of high energy γ-rays from certain fission products with deuterium atoms. These are known as photoneutrons. If, after a very long shutdown, these natural sources of neutrons do not produce sufficient neutrons to be detected by the reactor instrumentation, then artificial neutron sources are inserted into the reactor.

These source neutrons can cause fission in fissile fuel, producing more neutrons and establishing a chain reaction. When the reactor is shut down, the neutron multiplication factor k is, however, less than unity. This means that the chain reaction will decay, but in the meantime, other source neutrons will start new chain reactions. The result is that, along with these neutrons, there will be some fission neutrons, so that the total number of neutrons will be greater than would have arisen from the neutron sources only. The factor by which the total number of neutrons S_∞ is greater than the number of source neutrons S_0 is known as the *subcritical multiplication factor.* The relationship between these and the value of k is given by the following formula:

$$S_\infty = S_0 / (1- k) \qquad (2)$$

From the above equation, it can be seen that, as k approaches unity, the measured number of neutrons S_∞ becomes many times greater than the source number of neutrons S_0. Furthermore, it takes longer for an equilibrium condition to be reached. A very simple numerical example for $k = 0.5$ and $S_0 =100$ is given in Figure 3 for illustrative purposes.

As long as S_∞ stabilizes at a fixed value after an increase in k, the reactor remains in a *subcritical* condition, with k less than unity. When k is exactly unity, however, the fraction of source neutrons is negligible compared with the total number of neutrons, and the number of neutrons in each generation will be the same. The system is then said to be *critical*.

Source Multiplication

Source strength S_0 = 100
Neutron multiplication factor k = 0.5
Measured strength S_∞ = 199 [actually 200 since $S_\infty = S_0 / (1 - k)$]
Subcritical multiplication factor = 1 / (k - 1)

Generation	1	2	3	4	5	6	7	8	9	10	11	12
	100	50	25	12	6	3	2	1	..	..	..	..
		100	50	25	12	6	3	2	1	..	..	..
			100	50	25	12	6	3	2	1	..	..
				100	50	25	12	6	3	2	1	..
					100	50	25	12	6	3	2	1
						100	50	25	12	6	3	2
							100	50	25	12	6	3
								100	50	25	12	6
									100	50	25	12
										100	50	25
											100	50
												100
Total	100	150	175	187	193	196	198	199	199	199	199	199

Figure 3 Source multiplication by subcritical multiplication factor

3.3 Approach to Criticality

When a nuclear reactor is started up from the shutdown condition, the neutron flux must be increased by several orders of magnitude. In the shutdown condition, the neutron flux is determined by the intensity of the neutron sources and the subcritical multiplication factor. The value of the neutron multiplication factor k is substantially less than unity, and the reactor is subcritical. When starting up the reactor, the value of k is adjusted to bring it to unity, making the reactor critical and capable of sustaining a continuous fission chain reaction. In so doing, the subcritical multiplication factor increases the neutron flux level because the difference between k and unity, Δk, becomes smaller and smaller:

$$S_\infty = S_0 / (1 - k), \tag{3}$$

$$S_\infty = - S_0 / \Delta k. \tag{4}$$

As Δk approaches zero, the measured neutron flux S_∞ theoretically goes to infinity. This is obviously not practical because critical conditions must be established at a measurable neutron flux level. The real situation is that Δk can only be determined and controlled to a certain degree of accuracy. Once this limit has been reached, slight perturbations cause control system responses that mask the actual value of Δk, and the reactor can be considered to be oscillating very slightly above and below criticality. Under these conditions, the reactor is considered to be critical, with the average value of k equal to unity.

Even though a nuclear reactor may be shut down, the reactivity within the reactor may change with time due to buildup or decay of fission products. This means that one cannot simply restart a reactor by inserting an amount of positive reactivity equal to the amount of negative reactivity inserted to shut it down. Approach to critical is therefore a delicate manoeuvre, like an approach to a moving and invisible target. At every step, therefore, an assessment must be made of how far from critical the reactor actually is. Each step must also be small enough so as not to overshoot the point of criticality.

While Δk has a large negative value, a change in reactivity will be reflected quickly on the instruments because the fission chain reactions initiated by the source neutrons die away rapidly since the value of k is far below unity. Following insertion of some positive reactivity, the reactor power will rise quickly to a new equilibrium value. When, however, Δk has a small negative value and k is very close to unity, the reactor will respond very much more slowly. Under these circumstances, the fission chain reactions initiated by the source neutrons persist for many generations. Following insertion of some positive reactivity, the reactor power will rise slowly, but more significantly, and take much longer to settle at its new equilibrium value. When the reactor becomes critical due to insertion of additional positive reactivity, the reactor power will rise steadily and continuously without levelling off at an equilibrium value. Because the reactor will be very slightly supercritical, the power will in fact rise exponentially. If power versus time is plotted as shown in Figure 4, criticality will have been achieved when the measured power does not level off, but increases exponentially. Generally, such a crude mechanism of monitoring the approach to criticality is not suitable for commercial reactors.

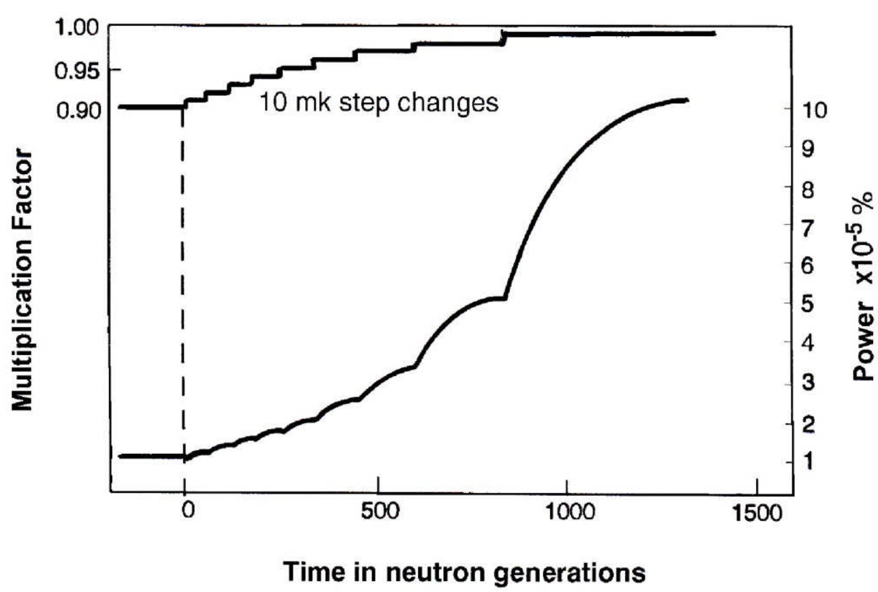


Figure 4 Stabilization time for different subcritical multiplication factors

If it is assumed that the measured reactor power P_∞ (equivalent to S_∞) doubles at each step, then various parameters such as k and Δk can be calculated to show their changes. Figure 5 shows how k and Δk change with each doubling of power from P_∞ = 0.0001 at k = 0.9.

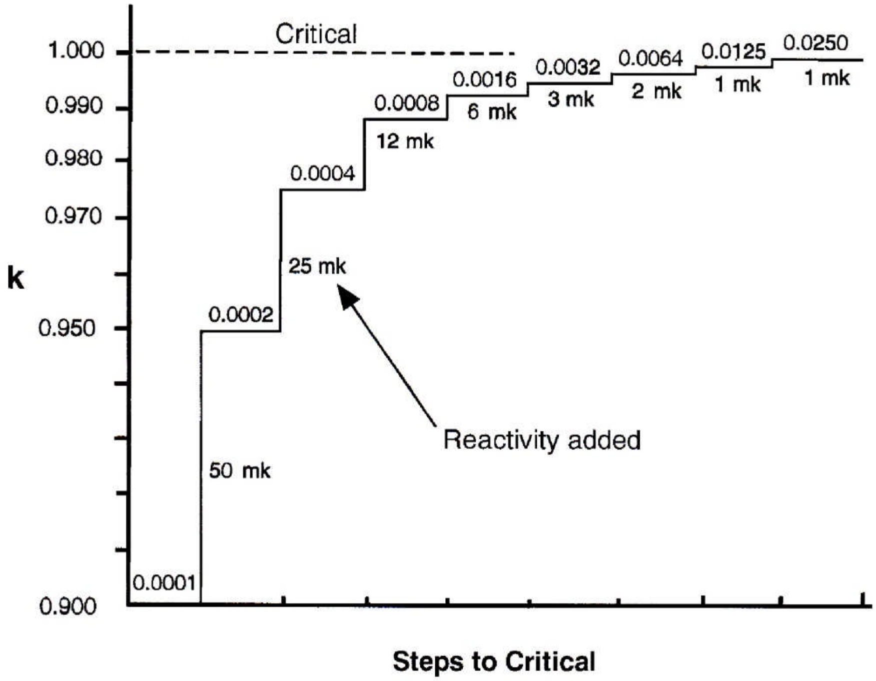


Figure 5 Approach to critical - subcritical multiplication factor change

The neutron count rate on the instruments can be assumed to be proportional to the measured neutron flux S_∞ and the inverse count rate then determined. These changes may be plotted graphically. The most useful plot is the inverse of count rate versus reactivity added, as shown in Figure 6. This shows that criticality is achieved when the inverse of count rate becomes zero. The plot is nearly linear, enabling the amount of reactivity to be added to achieve criticality to be easily determined by extrapolation.

Once the reactor is confirmed to be critical and under control of the reactor regulating system, a specific power level can be set, and the reactor regulating system will reduce the liquid zone levels slightly to insert a little more reactivity and maintain a stable rise in power to the desired level. Typically, the reactor regulating system never needs more than about 0.1 mk of reactivity change to maintain stable conditions or to change the power level.

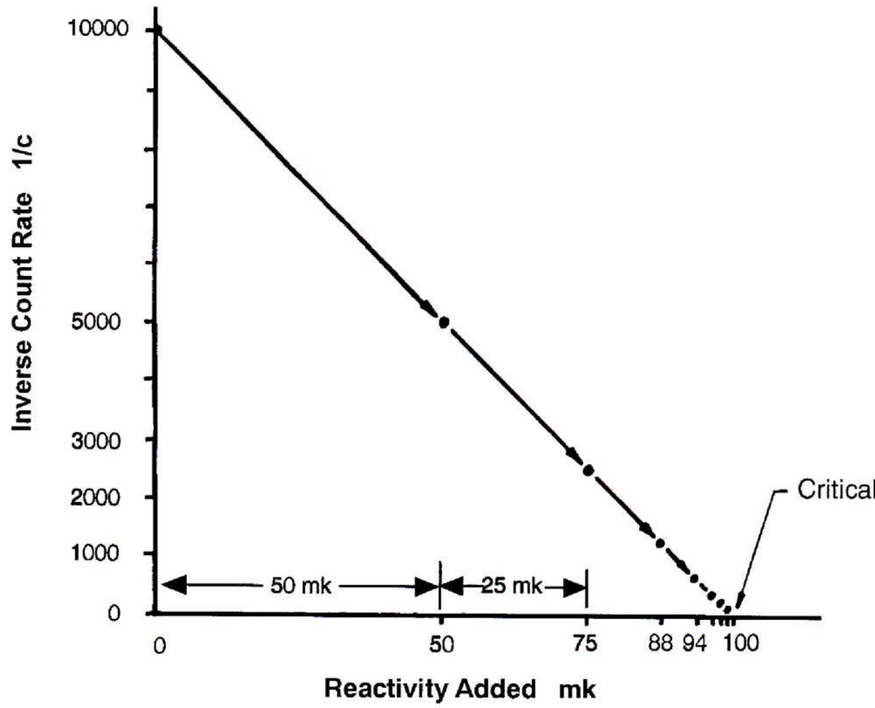


Figure 6 Approach to critical - inverse count rate change

3.4 Approach Technique

The actual process of approach to criticality depends upon how long the reactor has been shut down. After a period of several weeks, the source of neutrons from delayed neutrons and photoneutrons will have fallen to a sufficiently low level so that, even with the subcritical multiplication factor, the reactor regulating system instruments will have drifted off scale and will not be able to measure the neutron flux. Supplementary start-up instrumentation is therefore used as a temporary measure until the regular instrumentation can read the neutron flux. During power raising under these conditions, manual manipulation of reactivity and hence power is required. This requires careful monitoring and plotting of inverse count rate versus reactivity. Once the power is within the range of the regular instruments, they can be relied upon to hold the power at a particular level. The time for power to stabilize becomes longer as the reactor moves closer to criticality, and therefore using the reactor regulating system to maintain a particular power level minimizes the risk of adding more reactivity before the power has stabilized. If the reactor is started up after a short shutdown period, the reactor regulating system will be able to sense the neutron flux and react accordingly.

Assuming that the regular instruments can be used for reactor control, the general procedure is as described below. If not, the same procedure applies, but must be done manually. The reactor regulating system can be used with the reactor in reactor leading mode of operation. With poison removal stopped, the operator requests a doubling of power and monitors the liquid zone control absorber levels. When these have reached about the 20% level, power raising is stopped and the power held at this level by the reactor regulating system. The poison removal process is then started or restarted with the RRS holding the power level. As the reactivity tends to increase, the liquid zone levels rise to compensate, keeping reactivity and hence power level constant. When the liquid level is high, the poison removal process is stopped. Again the operator requests a doubling of power, and the process is repeated. Because smaller and smaller amounts of reactivity addition are required as criticality is approached, the drop in liquid level becomes smaller and smaller, and after a few iterations, the liquid zone absorber levels can accommodate a full doubling of power. In a typical CANDU reactor, a drop in liquid level from 65% to 20% represents a reactivity change of about 3 mk. If the power were doubled with this change, the reactor would be about 6 mk below criticality. Further iterations of the process can bring the reactor to within 1 mk of criticality. The final step in the process is verification that the reactor is sufficiently close to criticality for the RRS to maintain control of power. Power raising can then follow by the operator adjusting the power setpoint to the required value.

The advantage of this method of approach to criticality is that the reactor does not actually go critical and, when it is nearly critical, power is increased by adjusting power level and not by direct manipulation of reactivity devices.

3.5 Reactor Start-up

A simplified procedure for a reactor start-up is shown in Figure 7. Besides the important process of achieving criticality, all auxiliary systems must be available and in operation as required, and the heat transport system must be pressurized and heated. Auxiliary systems such as the feed and bleed system, moderator cooling system, shutdown cooling system, and emergency core cooling system must be available as required. The emergency core cooling system is disabled during a cold depressurized state to prevent inadvertent initiation in this plant state. The cooling systems, however, will be in operation to remove decay heat under cold shutdown conditions. There is naturally some overlap in these activities, as well as with those of the steam turbine and the steam and feedwater heating systems (which are described later).

Warming up of the pressurizer and degasser can begin before the approach to criticality. Initially, the pressurizer is isolated from the heat transport system and warmed until it reaches a pressure of 4 Mpa while the degasser is warmed to a pressure of 1.1 MPa. At this point, approval is required to proceed with connecting the pressurizer to the heat transport system because plant conditions will be changed during pressurization of the heat transport system. The pressurizer and heat transport system are then pressurized separately to 6.7 MPa by the pressurizer heaters and the feed and bleed system respectively. They are then connected together by opening two motorized isolation valves. Once connected, the main heat transport pumps can be started, and the heat transport system and pressurizer can be warmed together as one system by controlling the shutdown cooling system to remove excess heat as required. Warming of the heat transport system is done using pump heat from the main pumps because their energy is dissipated in the system. Initially, a significant challenge exists for the operator to maintain the heat transport system temperature below 100°C until the emergency core cooling system has been enabled. Normal procedure is to maintain the heat transport system temperature at less than 80°C. Regulations require that the emergency core cooling system be enabled anytime that the heat transport system temperature rises above 100°C. With the heat transport system temperature at 80°C, the approach to critical would typically commence, along with further warming of the heat transport system.

During the approach to criticality, initiation of reactor power increase by removing moderator poison and continued warming of the heat transport system proceed as parallel activities. The concern about warming the heat transport system during approach to criticality is the effect that it has on core reactivity when reactor power is being increased and criticality has not been achieved. During the approach to criticality, only one reactivity addition mechanism should be in use at any one time. The primary method is moderator purification by removing poison. However, by adding pump heat from the heat transport system pumps, the reactivity is being adjusted due to the temperature coefficients, including those of the fuel, at play during warm-up. This reactivity effect must be considered regardless of whether an equilibrium core or a fresh core is in place. As the heat transport system is warmed, the temperature coefficients add overall positive reactivity to an equilibrium core due to the buildup of Pu-239 which fissions more readily as temperature rises within this range, whereas in a fresh core, this reactivity effect is negative due to the lack of Pu-239. Therefore, warm-up of the heat transport system is stopped when the core is 30 mk subcritical, which is approximately equivalent to the presence of 1 ppm of moderator poison (gadolinium nitrate). This concentration can be confirmed by monitoring the online moderator conductivity, which is proportional to the concentration. A subcritical reactivity balance is conducted at 30 mk to verify the prediction for criticality and to ensure that all reactivity factors have been accounted for. For the remaining approach to criticality, no other actions which adjust reactivity other than that of the operator removing moderator poison by moderator purification are permitted. This guarantees that the core achieves criticality as predicted. In practice, criticality is defined as the point where the reactor regulating system has sufficient positive and negative reactive addition available by means of the liquid zone control absorbers to maintain reactor power at its setpoint. This occurs in an equilibrium core when the reactor regulating system can double reactor power within a 10% change in liquid zone level.

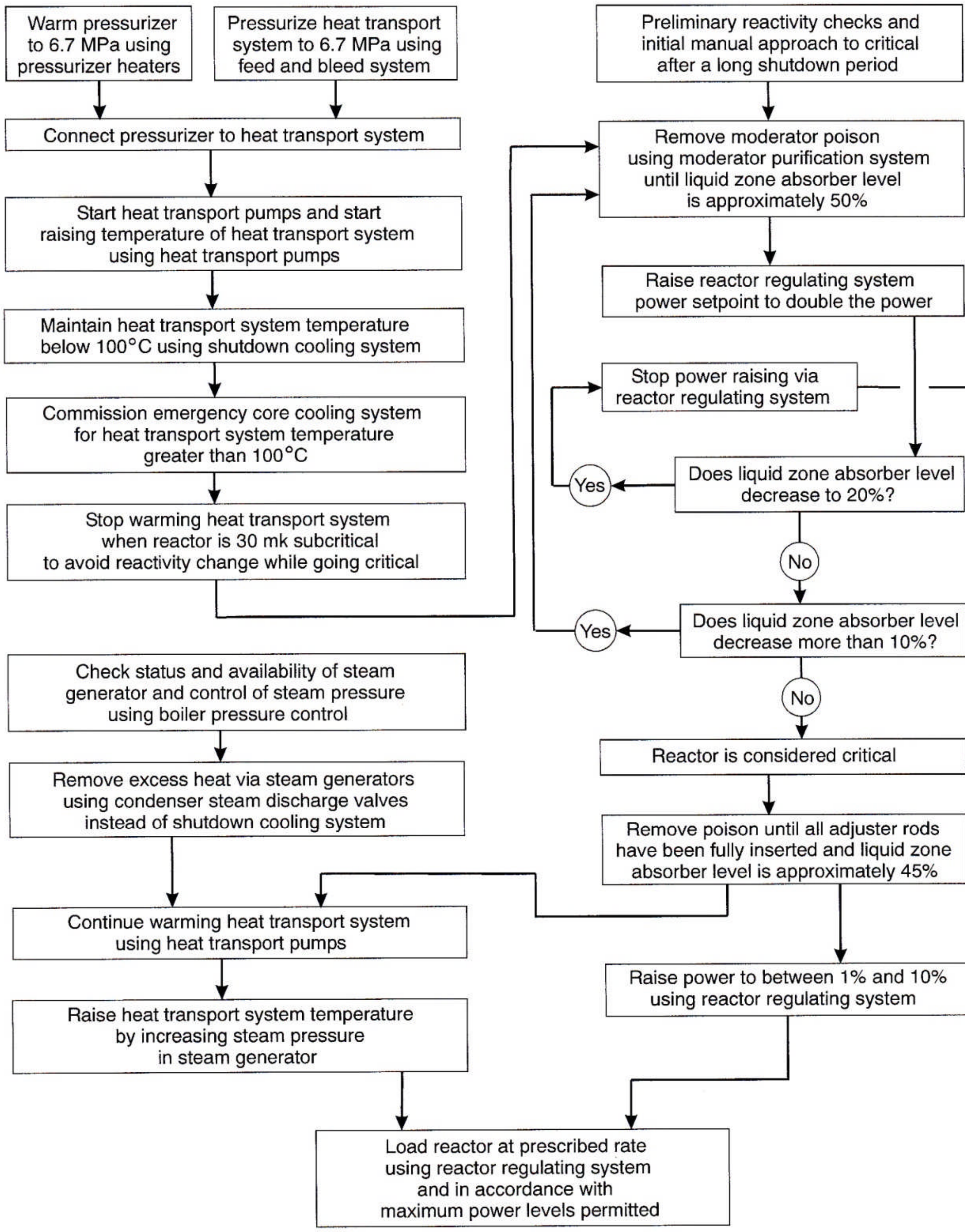


Figure 7 Major activities during start-up and loading

3.6 Reactivity Changes

The previous section considered short term reactivity changes due to operational manoeuvring, including start-up. This requires relatively small changes in reactivity to effect the desired result. In fact, it is important that, except in the case of a reactor trip, such changes be small to ensure proper control of the reactor.

Of further concern, however, are certain other effects which, during normal operation, result in reactivity changes much greater in magnitude than are required for operational control purposes. These occur over a much longer time frame and as such do not upset normal control. They do, however, require significant reactivity adjustment to maintain criticality in the reactor. These effects change one or more factors in the six-factor formula, given again as follows:

$$k = \varepsilon \, p \, \eta \, f \, \Lambda_f \Lambda_t. \tag{5}$$

The result is a drift of k from unity in a critical reactor. To restore criticality, that factor must be returned to its original value or another adjusted to compensate for the change so as to bring *k* back to unity.

The effects causing these changes fall into three main categories:

Fuel burnup
Xenon transients
Temperature effects.

The fuel effects are due to fuel depletion, buildup of transuranic nuclides, and production of fission products. Eventually, the combination of these factors prevents criticality from being maintained, and refuelling with new fuel is required.

Xenon-135 in particular is troublesome because its equilibrium level in the reactor is maintained by its being destroyed by neutron absorption as fast as it is created. A reduction in reactor power decreases the neutron flux and hence its rate of destruction. This results in a surge of xenon production and an increase in neutron absorption. The consequent reactivity changes may be difficult for the control system to overcome, especially after a significant power reduction.

The temperature effects are related to the neutron absorption characteristics of the fuel and moderator. The temperature of the whole reactor increases from the cold shutdown condition to the hot zero load condition. The temperature of the fuel then increases further as power is raised from the zero load condition to the full load condition. It is desirable that the overall effect on reactivity due to temperature be negative so that the natural tendency of the reactor is to go subcritical (*k* less than unity) during a temperature excursion. This enhances the stability of the reactor, giving it a degree of self-regulation and hence increased safety.

3.7 Fuel Burnup

During operation, fissile fuel such as uranium-235 burns up continuously and eventually reaches a point where it is so depleted that it cannot sustain a nuclear chain reaction. At this time, the fuel is replaced with new fuel and the process continued. As the uranium-235 is burned up, fission products build up in the fuel, and some of these are neutron absorbers. On the other hand, some uranium-238 is converted into plutonium-239 by neutron absorption and two successive β-particle emissions:

Plutonium-239 builds up quite rapidly at first. Some of it absorbs neutrons in two stages to become plutonium-241, another fissile fuel, but the concentration of this never reaches significant proportions within the normal fuel lifetime. Initially, the buildup of plutonium-239 actually causes an increase in core reactivity. This is due to its higher fission cross section as well as the greater number of neutrons produced per fission compared with uranium-235. Ultimately, depletion of uranium-235 and buildup of fission products in the reactor result in a decrease in core reactivity.

The effect of fuel burnup on reactor reactivity is felt primarily through the factor η, which combines the number of neutrons emitted per neutron absorbed ν, the macroscopic fission cross section of the fuel, $\Sigma_{f\ fuel}$, and the macroscopic absorption cross section of the fuel, $\Sigma_{a\ fuel}$:

$$\eta = \nu \, \Sigma_{f\ fuel} / \Sigma_{a\ fuel}. \tag{6}$$

As the fuel is burned up, $\Sigma_{f\ fuel}$ decreases, and as fission products accumulate, $\Sigma_{a\ fuel}$ increases. The overall effect is that η decreases with time. The effects of samarium-149 and plutonium-239 as mentioned above, together with uranium-235 depletion and fission product buildup, can be shown graphically as in Figure 8 by plotting the value of η with respect to time and noting that the neutron multiplication factor k varies accordingly. At the very beginning, there is a drop in η (and hence k) due to buildup of samarium-149, a neutron absorber. Somewhat later, but still early in the fuel cycle, the value of η (and k) increases and reaches a peak due to formation of plutonium-239. Then the effects of uranium-235 depletion and fission product buildup become significant, and η (and k) falls progressively.

The effects of xenon-135 are not shown on this graph because the associated degree of reactivity change is due mainly to reactor load (neutron flux) and is greater in magnitude than the effects shown here, being as much as -30 mk under full load conditions.

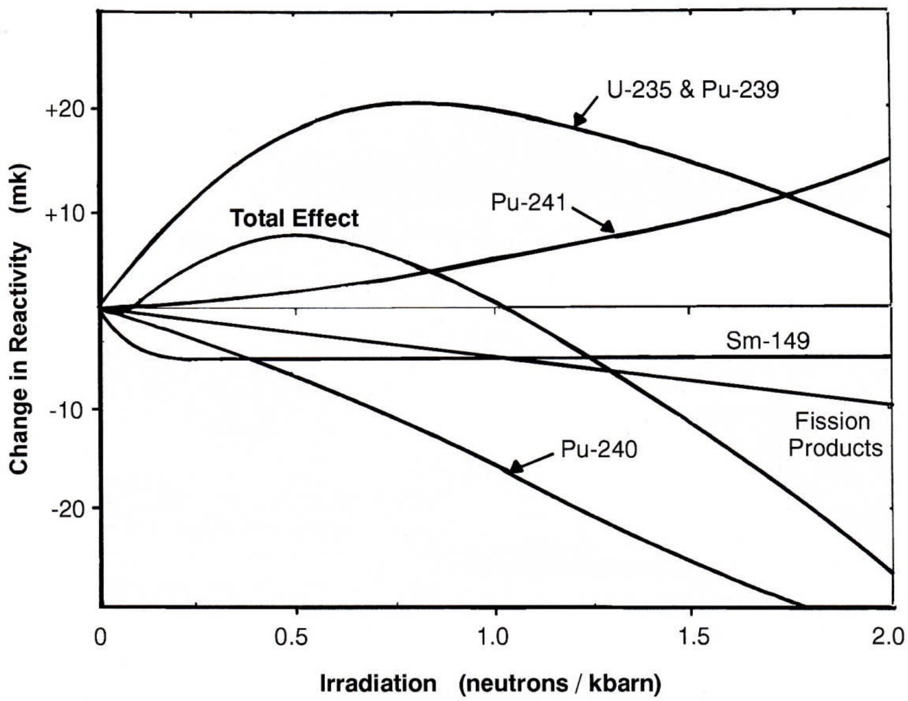


Figure 8 Effects of fuel burnup on reactivity

3.8 Refuelling Considerations

Except when a reactor is loaded with fresh fuel, reactor refuelling is a continuous process, with about a dozen channels being refuelled each week. In selecting the channels to be refuelled, a number of factors should be considered. Channels with the highest burnup should be refuelled first, the reactor power distribution should be kept symmetrical, and the channels with the largest reactivity gain should be selected if the overall core reactivity is low. However, channels close to recently refuelled channels should be avoided, as well as those with known abnormal conditions which could force an unplanned reactor shutdown if a refuelling failure should occur. Any channels containing defective fuel should be refuelled as soon as possible.

The preferred state during refuelling is with the reactor critical, on load, and under control of the reactor regulating system. Control absorbers must not be in the core because this is an abnormal and transient operating condition. There should be no reactivity changes during refuelling, meaning that adjuster positions should not be altered nor poison addition or removal be in progress. This ensures that reactivity changes during refuelling are readily observable.

4 Heat Transport System

4.1 Operational Considerations

When at full power, the reactor derives approximately 92% of its heat from the fission process, 7% from decay of fission products, and 1% from the heat transport system pumps. Immediately after a reactor trip, the heat generated by fission products, even though it decreases rapidly initially, and that generated by the pumps continues. The heat transport system must remove heat at all times through the steam generators. This requires that a temperature difference between the reactor coolant and the steam circuit be maintained. At full load, this temperature difference is large, but at low load and under shutdown conditions, it must be small enough to control the rate of heat discharge, because too high a rate would impose excessive cooling and large thermal transients. Steam generator pressure is the main temperature control parameter.

During warm-up from the cold condition, pump heat input and residual decay heat, even after a long cooldown, are sufficient to bring the system up to the hot standby condition. During shutdown, with a higher decay heat load, steam is discharged from the steam generators under controlled conditions to bring down the pressure and temperature slowly enough to avoid excessive thermal stress on large components. This steam is usually discharged to the condenser through the condenser steam discharge valves. These valves open progressively, but because the steam specific volume increases with decreasing pressure, they eventually reach their fully open condition, and the rate of cooling decreases. Beyond this point, the shutdown cooling system can control the cooling rate. During this cooldown period, one concern is delayed hydride cracking of the zirconium alloy pressure tubes at an intermediate temperature in the range of about 100°C to 200°C, and therefore the system must not be allowed to remain within this temperature range for longer than necessary.

In the event that the condensers are unavailable, steam can be discharged to the atmosphere through the steam reject valves, although this results in loss of treated water. If the steam generators are unavailable or the pressure control system faulty, the heat transport system can be cooled directly by the shutdown cooling system, which has sufficient capacity to handle the decay heat. It can also maintain sufficient flow in the fuel channels under shutdown conditions to remove the heat generated should the heat transport pumps not be available.

The inventory and flow of the heat transport system must naturally be maintained for effective removal of heat from the fuel. Possible failures of various valves which admit or release fluid to and from the system must be considered and allowance made for the system to accommodate such failures without jeopardizing safety. One situation which initially gives a wrong indication is a failed-open pressurizer steam vent valve. This represents a loss of inventory, but the decreased pressure causes boiling in the pressurizer and a consequent increase in level, which indicates excessive inventory. All losses of inventory through valves and fittings can be accommodated by the normal control systems, which either compensate for the problem or reduce reactor power.

An accidental loss of inventory or loss of coolant accident due to a system rupture requires different actions depending upon its severity. A major rupture could result in loss of coolant flow to one or more fuel channels. An emergency coolant injection system is provided to supply water to the reactor under these circumstances. This system, however, operates at a lower pressure than that of the heat transport system, and therefore rapid depressurization is necessary. This implies reducing temperature and pressure rapidly by discharging steam from the steam generator through the steam reject valves. This procedure, known as crash cooling or crash cooldown, imposes severe thermal stress on the components, which would subsequently require intensive inspection.

The configuration of a CANDU reactor is such that all feeder pipes from the fuel channels are directed upwards to headers, which in turn are connected to the steam generators at an even higher level. Hence, any buoyancy effect due to heating or vapour generation will tend to draw coolant upwards from the reactor to the steam generators, promoting circulation by natural convection. In the event that the heat transport pumps fail, this provision for *thermosyphoning* between the reactor and steam generator is a safety feature of the reactor. The difference in elevation between the reactor and the steam generators promotes natural circulation, and the built-in inertia of the pumps, giving a rundown time of between 2 and 3 minutes, enables this circulation to be established during the initial disturbing transients. This natural circulation is much slower than the normal forced circulation provided by the heat transport system pumps and therefore can be used only under low power conditions.

A typical scenario under which thermosyphoning would be required is in the event of electrical power loss to the heat transport pumps. This would result in an immediate reactor trip. As reactor power drops to about 5% of full power within about 10 seconds (as a result of decay heat), the circulating pumps run down slowly due to built-in rotational inertia, and flow decreases progressively to the point where thermosyphoning takes over naturally and maintains flow in the same direction, but at a much reduced flow rate.

5 Steam Generators

5.1 Plant Control

As is evident from the introduction which deals with power output regulation and from Figure 1, the steam generator is a key component in satisfactory plant control. In both modes of operation, the steam generator pressure is the measured parameter, and the control system acts accordingly.

The rate of heat transfer Ω is governed by the following equation:

$$\Omega = U A \theta, \tag{7}$$

where U is the overall heat transfer coefficient, A is the surface area through which heat is transferred, and θ is the temperature difference between the fluids on each side of the heat exchange surface that exists between the primary side reactor coolant and the secondary side steam-water circuit. Because U and A do not vary much, it is evident that any change in θ will affect Ω, and vice versa. Figure 9 shows typical conditions of the reactor coolant and steam-water mixture in the steam generator under full load.

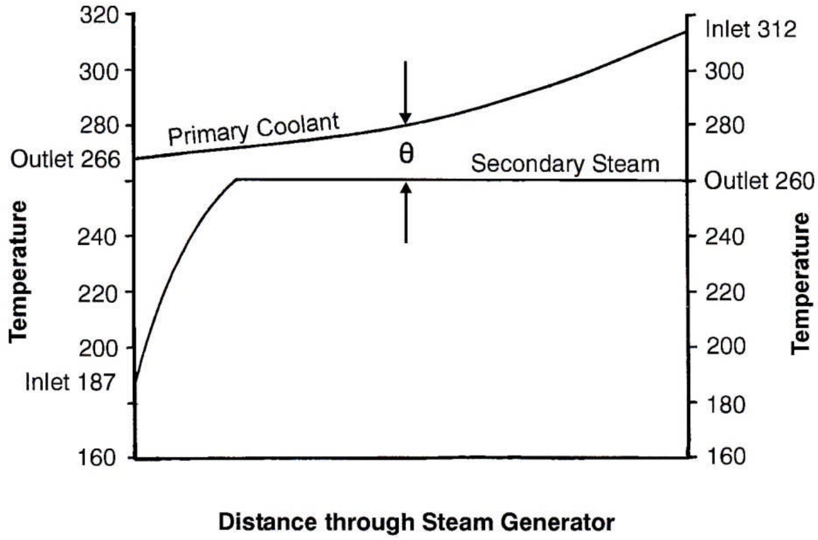


Figure 9 Steam generator temperature profile

The steam pressure affects the saturation temperature of the secondary side steam-water mixture, so the latter can be manipulated by adjusting the steam generator pressure. This in turn will affect the primary side reactor coolant temperature and is an important control parameter in reactor warm-up and cooldown procedures. Under these conditions, the heat transfer rate Ω is very low, although it may be somewhat higher following a trip from a high load condition due to a larger decay heat load.

When supplying power to the grid system under a set steam generator pressure, as load and hence Ω is increased or decreased, the primary side reactor coolant temperature will rise or fall as θ changes.

Steam generator pressure is therefore a key parameter under all operational conditions.

5.2 Steam Generator Pressure Control

Figure 2 shows the basic plant control system. It may be seen that the steam generator pressure is controlled by the boiler pressure control (BPC) system, which senses the steam generator pressure. In the reactor leading mode of operation, the BPC signals the turbine governing system to adjust the governor valves (steam flow) to the turbine to maintain the set pressure. In the turbine leading mode of operation, the BPC signals the reactor regulating system to adjust the neutron flux (heat output) of the reactor to maintain the set pressure.

Under abnormal conditions when there is a mismatch between reactor heat production and turbine power output, such as would occur immediately after an electrical load rejection or turbine trip, boiler pressure is controlled by the condenser steam discharge valves (CSDVs in Figure 16) to be described later in the text. There is also provision for steam discharge directly to the atmosphere through the main steam safety valves and the atmospheric steam discharge valves (MSSVs and ASDVs in Figure 16) to avoid excessive pressure in the steam generator.

These valves are a backup in the event that the CSDVs malfunction or are not available due to condenser restrictions.

5.3 Swelling and Shrinking

It is important to maintain an adequate water level in the steam generators to ensure proper heat transfer and heat removal capability. A further reason to maintain the water level within certain limits is to maintain efficient separation of steam from water in the cyclonic separators. Too high a level can cause flooding of the separation region, and too low a level can result in surging within that region. The water level, however, is affected by the operational conditions within the steam generator and can change markedly without any change in the total water inventory due to the phenomena of swelling and shrinking.

When steam is generated in the steam generator, vapour bubbles are formed on the surfaces of the tubes and rise with the circulating water. These vapour bubbles occupy more space than the water from which they were formed, resulting in an apparent swelling of the total water inventory in the steam generator. The effect of water displaced by the vapour bubbles is seen as an increase in level in the system. This is commonly known as *swelling*, and the converse as *shrinking*. There are steady state and transient effects with regard to swelling and shrinking.

5.3.1 Steady state swelling and shrinking

During steady state operation, the system is in a state of thermal equilibrium, that is, the rate of heat removal from the system by the turbine is equal to the rate of heat input to the system by the reactor. At zero load, no vapour bubbles are formed, and the water level is at a certain point. As load increases, vapour bubbles are formed. These displace water and cause a rise in level, as shown in Figure 10. For each load, there is an appropriate water level in the steam generator corresponding to the number of vapour bubbles in the water. At full load, the water has the highest concentration of vapour bubbles, and the water level is at its highest. This analysis assumes that there has been no attempt to control the water level and that the feed-water flow has matched the steam flow throughout the load change. On a reduction in load, the water level would return to its original value. This increase and decrease in level are respectively known as *steady state swelling* and *steady state shrinking*.

Up to this point in the analysis, it has been assumed that steam generator pressure remains constant under all conditions. This is not necessarily the case. Certain load manoeuvres on the turbine and operation of certain steam valves will cause pressure changes in the steam lines and hence in the steam generator itself. Thus, transient conditions known as *transient swelling* and *transient shrinking* arise.

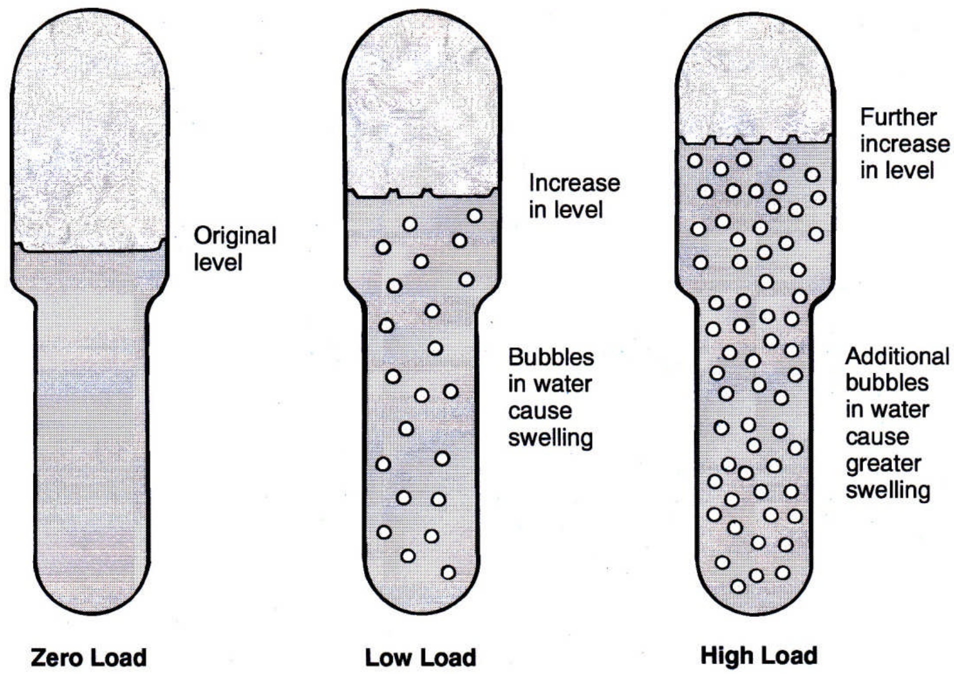


Figure 10 Steady state swelling due to different load conditions

5.3.2 Transient swelling and shrinking

At a particular turbine load there is to a certain rate of steam generation and a certain number of vapour bubbles in suspension in the water. In the event of an increase in power demand, the turbine will require more steam. The increased opening of the governor valves draws additional steam from the steam line and steam generator, causing a temporary pressure drop in the system. The drop in pressure in the steam generator allows the vapour bubbles to expand and increase their volume. In addition, because the new saturation temperature is below that of the water in the steam generator, some water flashes to steam, creating even more vapour volume. The combined effect is reflected as a swelling of the steam generator contents and a rise in water level, as shown in Figure 11. Once the reactor responds to this increased demand for power and thermal equilibrium has been restored, the pressure in the steam generator will return to its set value, and the transient swelling will subside.

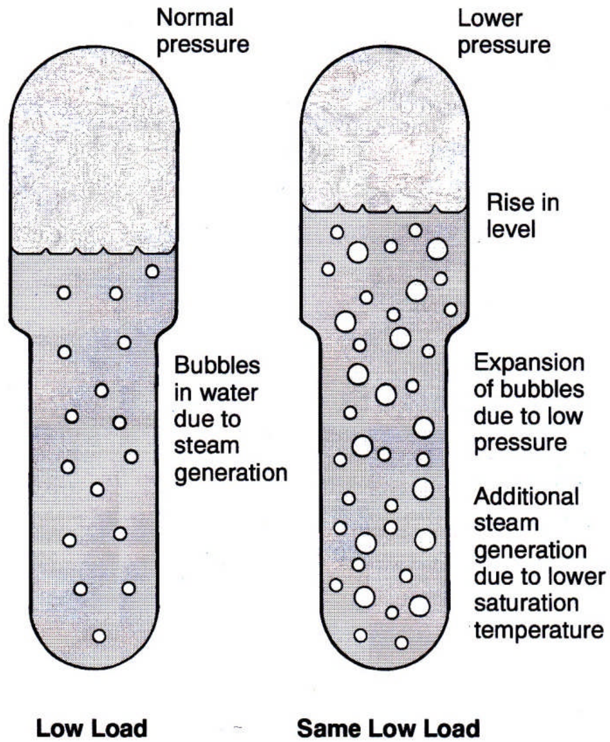


Figure 11 Transient swelling due to changing load conditions

In the event of a decrease in turbine power demand, the effect will be a temporary rise in steam generator pressure. This will be followed by compression of the vapour bubbles and shrinking of the steam generator contents until thermal equilibrium is restored.

A rapid increase in reactor power due to certain manoeuvres, such as recovering from a reactor trip to prevent poisoning out, can also produce transient swelling. The increased power increases the rate of steam generation and vapour production in the steam generator. This causes a temporary swelling effect until the turbine load is matched and thermal equilibrium restored.

A rapid decrease in reactor power, for example following a reactor trip, will reduce vapour production, causing a temporary shrinking effect until thermal equilibrium is restored.

Note that transient swelling and shrinking occur only during rapid load changes. During normal load changes, only steady state effects will be evident, and these will be related to the particular power level. Transient swelling and shrinking effects, when they occur, are superimposed on the steady state swelling and shrinking.

5.4 Steam Generator Level Control

Whenever there is a free liquid surface in a system, the system inventory must be controlled to ensure that the level remains within limits. In the steam generator, this is done by measuring the level and controlling the feedwater flow rate. Any deviation of the actual level from the desired or set level results in a correction to the flow rate.

Swelling and shrinking have an influence on level control in that, for a given water inventory in the steam generator, the level will rise and fall as the load increases or decreases. Alternatively, for a given water level, the inventory will go down or go up as the load increases or decreases. Both situations can lead to difficulties in maintaining desired conditions in the steam generator, particularly during rapid changes in load when transient swelling and shrinking effects are superimposed on the steady state effects.

Consider first the situation in which the water level is to be kept constant, as shown in Figure 12. For fixed level control, a certain margin is required to allow for transient swelling and shrinking because, during rapid load changes, the level control system cannot respond quickly enough to maintain the level. At low load, swelling will occur as load increases, and at high load, shrinking will occur as load decreases. The steam generator must therefore be large enough to accommodate these fluctuations in volume and hence in level. This is done by increasing the diameter of the upper portion and making it tall enough so that there is a margin above and below the desired water level.

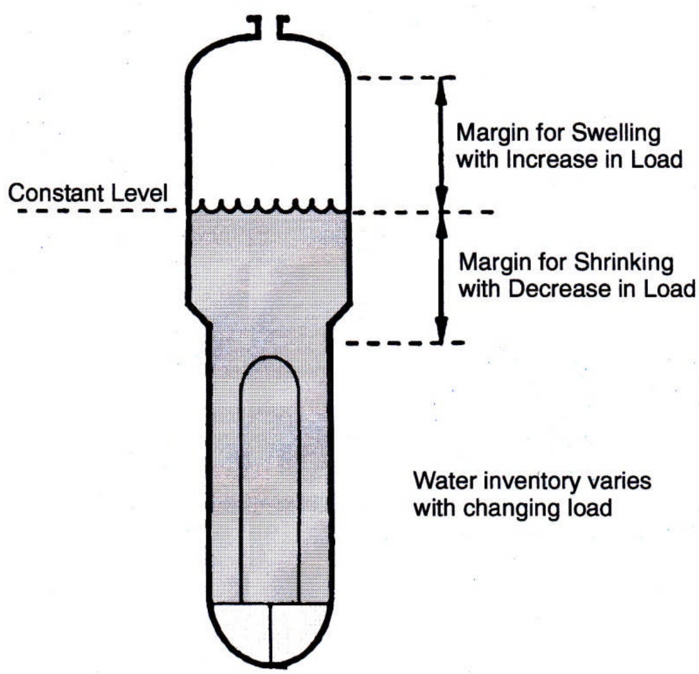


Figure 12 Constant steam generator water level

If, however, the water inventory is maintained at a fixed value and the set level is allowed to rise and fall with load, then this range of level can be used to accommodate transient swelling and shrinking partially, as shown in Figure 13. Transient swelling will occur only from a low load, and hence the required margin must be above this level. Transient shrinking likewise will occur only from a high load and requires a margin below the level at high load. If the set level at high load is already above the set level at zero load, the margins will overlap, as shown in Figure 13. This enables the vessel to be made smaller while still providing appropriate margins for transient conditions. To achieve this, the desired or set level must be increased with load, resulting in so-called *ramped level control*. This is a more natural method of control because the total inventory remains nearly constant and the control system does not have to drive towards a new inventory every time the load changes.

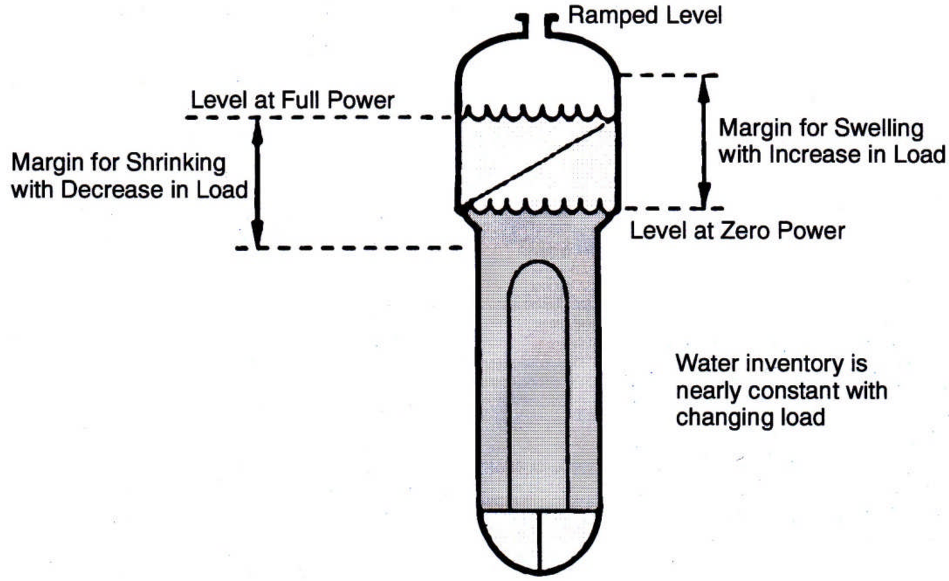


Figure 13 Ramped steam generator water level

Transient swelling and shrinking have influenced the design of level control systems in all types of steam generators and boiler drums. A sudden increase in turbine load will increase steam flow and reduce pressure in the vessel. This will result in transient swelling and a high water level. A controller that responds to water level only will reduce feedwater flow to bring down the water level just at a time when in fact more water is required. After the transient, the steam generator can be left with a severe shortage in inventory. Such a single element controller tends to respond the wrong way during transients. The problem may be overcome by using a *three element controller* which measures steam flow and feedwater flow as well as water level, as shown in Figure 14. This figure is an expansion of the boiler level control (BLC) system shown as part of the overall plant control system in Figure 14, which shows just the inputs and outputs of the boiler level control system. For the case given above, it would sense high steam flow, compare this with feedwater flow, and send a flow error signal to indicate a required increase in feedwater flow. At the same time, the transient swelling would send a level error signal to indicate that a decrease in feedwater flow was required. Initially, the two signals would cancel one another until the transient swelling had subsided, and then the feedwater regulating valve would open to balance the steam and feedwater flows to restore the water level to the setpoint. The level setpoint would in the meantime have been raised by the level control program to correspond to the new turbine load. The use of a three element level control system in conjunction with a ramped level setpoint results in relatively smooth control of water level during all types of transients.

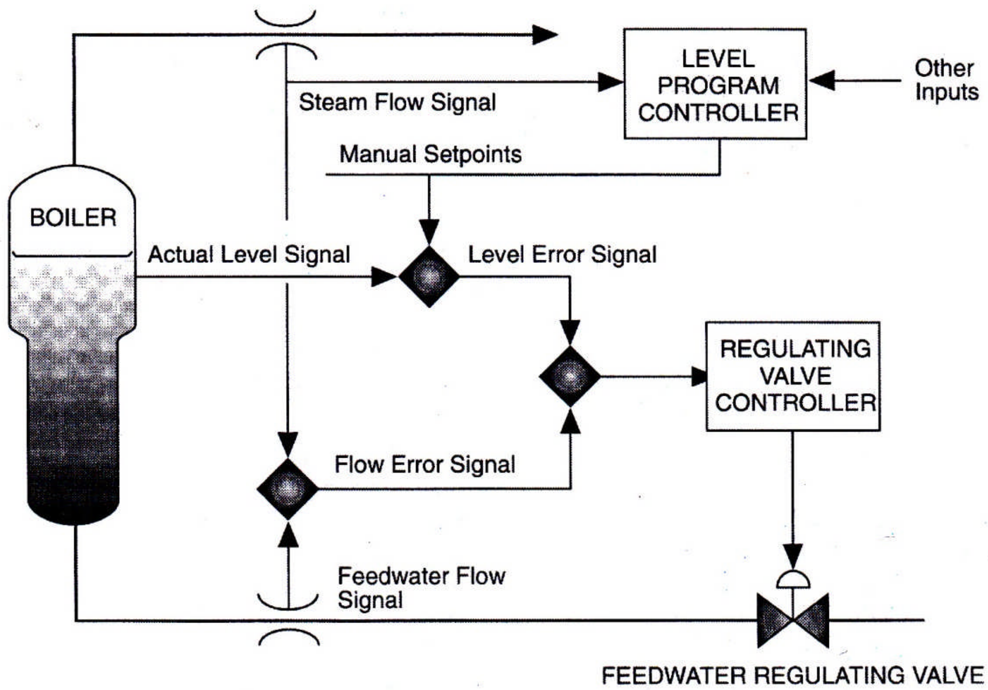


Figure 14 Three element steam generator level control system
(courtesy of NB Power)

Figure 15 shows how the level setpoint is ramped up with load. The initial steep slope roughly matches the degree of steady state swelling. This is desirable because the low ratio of through-put to inventory makes the control system take longer to adjust the inventory to correct level errors. Inventory adjustment is faster at higher throughputs, and therefore the level ramp slope can be less steep, as shown in Figure 15. This lesser slope indicates that in fact the steam generator inventory is decreased as load increases in the higher load range. This is desirable with regard to the efficiency of the cyclonic steam separators, which do not operate at optimum efficiency at very high or very low water levels.

Figure 15 also shows how the low level alarm and reactor stepback as well as the SDS1 and SDS2 trips are also ramped with reactor power. The latter slopes are steep to match the degree of swelling or shrinking closely to ensure adequate inventory after a reactor trip from any power level.

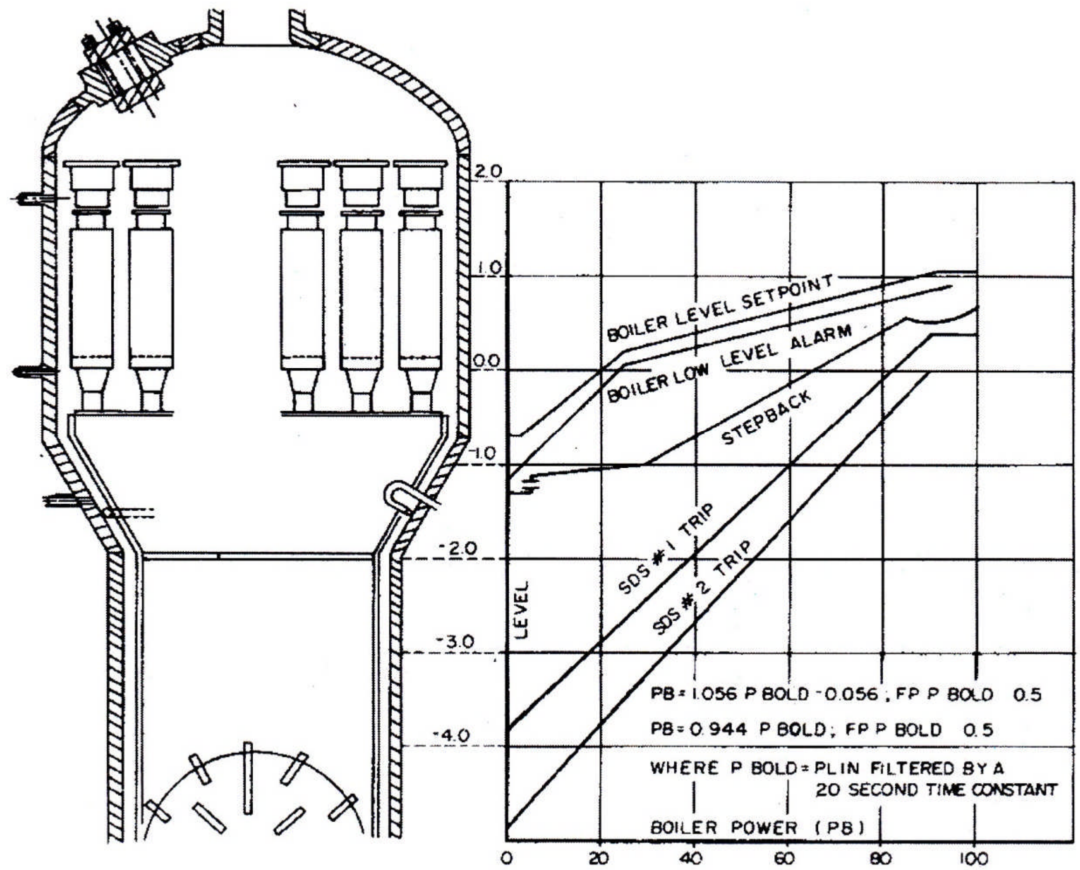


Figure 15 Steam generator level alarms and set points (courtesy of NB Power)

6 Steam System

6.1 Characteristics and Function

The main purpose of the steam system is to convey steam from the steam generators to the steam turbine. In a nuclear plant, the steam generators also serve as a heat sink for the reactor under all operating conditions, and because steam is produced, the steam system becomes the major part of the reactor heat rejection system. Provision must therefore be made to handle steam in large quantities even when not required by the steam turbine.

Steam pressure control in the steam generators is important with regard to their function as a heat sink. As steam pressure varies, so does the prevailing saturation temperature. Because the rate of heat transfer depends upon the difference in temperature between the primary coolant and secondary steam systems, a variation in steam temperature will affect the overall capacity for heat removal. Assuming that the primary coolant pressure is fixed and controlled by the pressurizer, thus limiting the maximum primary coolant temperature, an excessive steam pressure will limit the heat rejection capabilities of the steam generator. However, excessive steam pressures, which would likely arise from insufficient steam discharge, would be prevented by steam discharge through the main steam safety valves. Conversely, an excessively low steam pressure and corresponding temperature will produce excessive heat flow across the steam generator and pull down the temperature of the reactor coolant. This is done in a controlled manner during a reactor cooldown.

For proper control of the reactor state, the steam system must therefore be able to handle the amount of steam produced under all operating conditions and to control and maintain steam generator pressure within prescribed limits. The steam system must be designed to handle decay heat generation following a reactor shutdown, and it is also desirable that it be able to maintain a high heat discharge rate to prevent xenon poisoning during a short-duration unplanned turbine shutdown.

In the turbine steam cycle, approximately one third of reactor heat is converted into electricity, with the remaining two thirds rejected to the environment through the turbine condenser. The rejection path is a convenient way of disposing of heat when the turbine is unavailable. Thus, if a turbine trip forces a short term shutdown of the turbine generator system, the reactor can be maintained at approximately two thirds power, with the excess steam production dumped to the condenser. Two thirds of full power on the reactor is sufficient to maintain the neutron flux at a high enough level to prevent poisoning out of the reactor and thus permit a restart at any time.

In the event that the turbine condenser is unavailable, an alternative steam discharge path is required. This is directly to the atmosphere, but naturally results in an enormous loss of fluid inventory from the system. For this reason, it is an undesirable mode of operation, but an essential safety feature.

Figure 16 shows a typical steam system with various control, isolation, and relief valves.

6.2 Atmospheric and Condenser Steam Discharge Valves

The atmospheric steam discharge valves (ASDVs) and condenser steam discharge valves (CSDVs) are used to control steam generator pressure rather than to protect against overpressure. For this reason, under certain conditions, the setpoint at which they operate may be lowered to avoid an excessive pressure transient when their operation is known to be inevitable. This lowering of the pressure setpoint occurs upon a turbine trip or load rejection and possible subsequent poison prevention operation. As stated earlier, the atmospheric steam discharge valves and condenser steam discharge valves divert steam from the turbine and respectively discharge excess steam to the atmosphere or dump it to the condenser to balance the heat flow from the steam generators against the heat flow into the steam generators.

Operation of the atmospheric steam discharge valves and condenser steam discharge valves may occur under operational conditions such as a controlled cooldown of the heat transport system, a turbine trip or load rejection followed by poison prevent operation, during start-up conditions when more steam is produced than is required by the turbine, or during any operation when an excess of steam is produced.

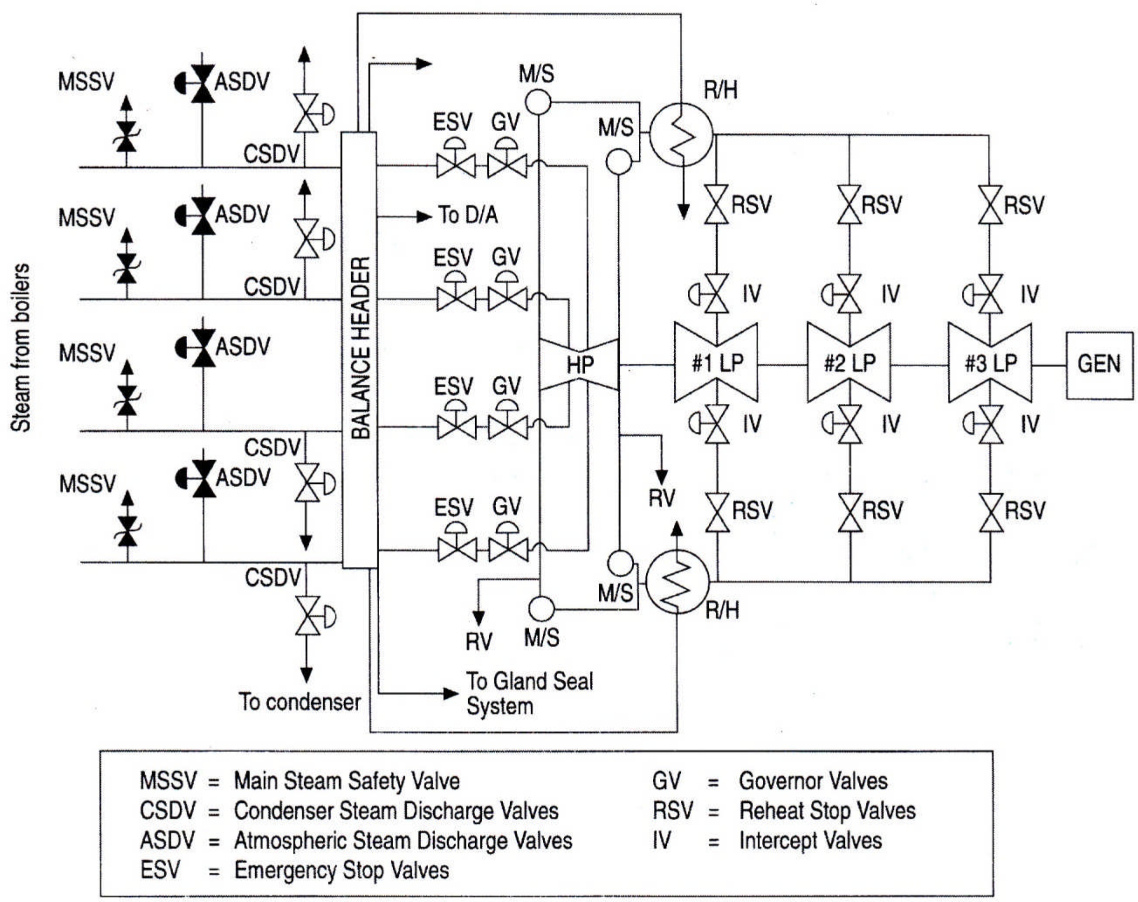


Figure 16 Main steam system (Point Lepreau) (courtesy of NB Power)

Discharge of steam to the atmosphere is of course wasteful because the loss must be made up with appropriately treated water. In any case, the total quantity of steam discharged is limited by the available make-up water capacity. If the condenser is unavailable, this becomes the major path for heat rejection on the steam side. Discharge of steam in this way should be limited to emergency or unusual circumstances.

6.3 Steam System Operation

One important aspect of the steam pipework is valve operation. In the event of a fault on the turbine, generator, or electrical system, the steam supply must be isolated very quickly, usually in a fraction of a second, and therefore the stop valves must operate quickly and reliably.

Another aspect of steam system operation is the possibility of pipe vibration due to sudden changes in steam flow or flow disturbances due to bends and fittings. Steam pipes must be suspended on flexible supports to allow for small changes in length due to thermal expansion. These would permit vibration in the absence of proper restraints and dampers, and therefore their design is an important aspect of steam pipework. Thermal effects are not confined to thermal expansion. To withstand high steam pressures, pipe walls must be thick enough to ensure a safe working stress. When a pipe is heated from a cold condition with hot steam, the inside wall temperature rises faster than the outside wall temperature. This causes the inside of the pipe to try to expand while restrained by the outside. The inside is therefore subject to a compressive stress and the outside to a tensile stress (in the absence of stress due to internal pressure). If subjected to internal pressure at the same time, parts of the pipe may be subjected to stresses greater than their permissible working stress. The result may be deformation of or damage to the pipe. This can be avoided by limiting the heating rate of the pipe, and all systems therefore have provision for slow heating by admitting a small quantity of steam before subjecting the pipe to full steam temperature and pressure.

During steam line heating, considerable quantities of steam condense on the inside surfaces of the pipes and must be removed through drains at the low points of the system. The drains are open during pipe warming to ensure that collected water is properly drained away and are then closed during normal operation. If not properly drained, water could be entrained with the flowing steam and carried into the turbine, where it could cause severe thermal shock or impact damage to the turbine blading.

7 Main Condenser

7.1 Thermodynamics and Heat Transfer

From a thermodynamic point of view, the steam-water circuit receives heat at a high temperature in the boiler and rejects heat at a low temperature in the condenser. The greater the difference in temperature, the greater will be the drop in enthalpy and the more work produced per kilogram of steam. If the initial steam conditions remain unchanged, it is evident that a reduction in the exhaust temperature will increase the work done in the turbine. This will ultimately improve overall station efficiency. Exhaust conditions are therefore important and have a direct impact on plant performance.

Exhaust steam temperature is determined largely by cooling water temperature. The heat flow per unit time Ω from the exhaust steam to the cooling water is governed by the following equation:

$$\Omega = U A \theta, \tag{8}$$

where U is the overall heat transfer coefficient, A the surface area through which the heat is transferred, and θ the difference in temperature between the water and the steam. Once the condenser has been designed, A is fixed, and, for given flow rates on both steam and water sides, the value of U is unchanged if the condenser tubes remain clean. The amount of heat transferred is therefore proportional to θ, the difference in temperature between the steam and the water.

The cooling water, in passing through the condenser tubes, picks up heat Ω at a certain rate and increases in temperature ΔT according to the following formula:

$$\Omega = M c_p \Delta T, \tag{9}$$

where M is the mass flow rate and c_p the specific heat of water. The outlet temperature of the cooling water is generally some 10°C higher than the inlet temperature for the design mass flow rate. Note that Ω in this formula is the same as Ω in the previous formula because all the heat transferred across the tubes is absorbed by the cooling water. The result is a temperature gradient in the water along the tubes from one end of the condenser to the other.

On the steam side, there is no temperature gradient because the saturation temperature and pressure are interdependent and the pressure everywhere in the condenser is practically the same. A temperature profile through the condenser illustrating the meaning of θ and ΔT may therefore be drawn, as shown in Figure 17. Note that θ is the average difference in temperature between the steam and the water. More correctly, it should be the log mean temperature difference, but using the average simplifies the analysis.

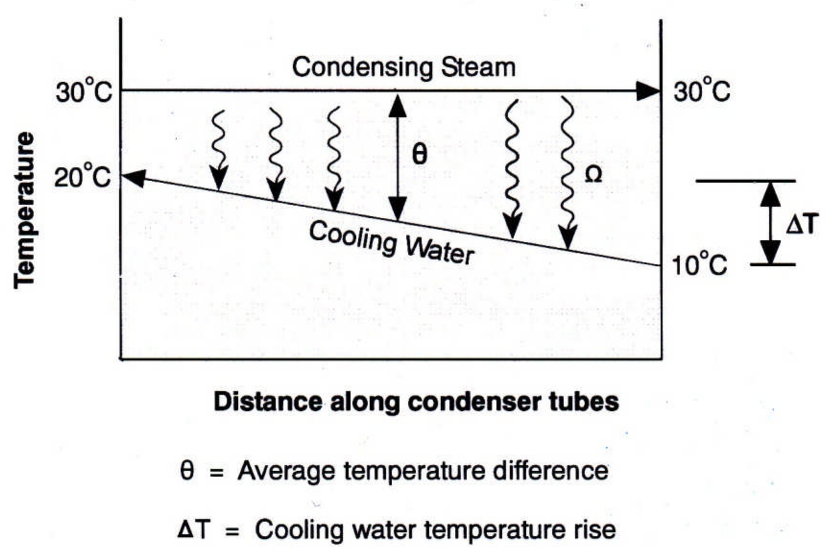
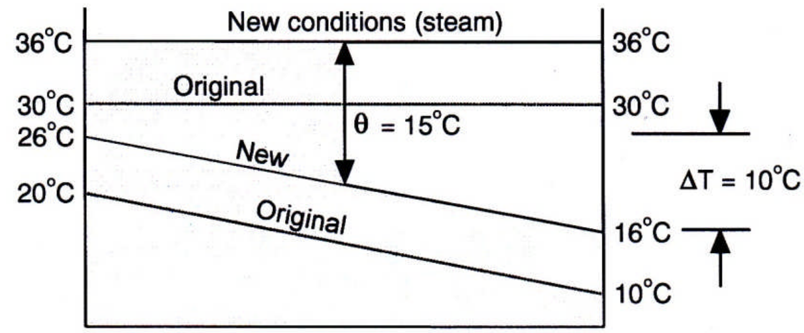
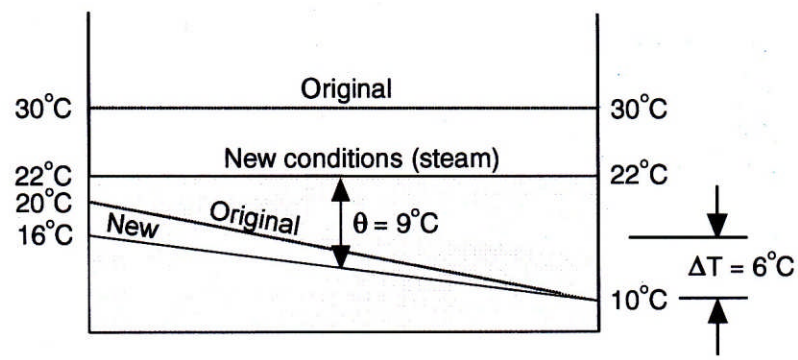


Figure 17 Condenser temperature profile

Figure 18 helps to visualize the effect of various changes. One effect is a change in inlet cooling water temperature. This has a direct and proportional effect on steam temperature. Another effect is a change in turbine load. This in turn changes the rate of heat transferred, Ω, and hence both θ and ΔT. Some simple numerical examples make it possible to verify these effects. Generally, the variation in steam temperature is proportional to load.



Change in cooling water inlet temperature (increase to 16°C)



Change in load on turbine (decrease to 60%)

Figure 18 Changes in condenser temperature profile

The steam pressure in the condenser is governed by the temperature of condensation. The steam pressure, however, is not proportional to load because the relationship between saturation temperature and pressure is not linear, as indicated in Figure 19. By combining this variation in steam properties with the temperature variation with load, a condenser performance curve may be obtained, as shown in Figure 20. Using this figure, the pressure in the condenser can be predicted for various cooling water conditions. Superimposed on this figure are the turbine operating limits for a 900 MW nuclear unit.

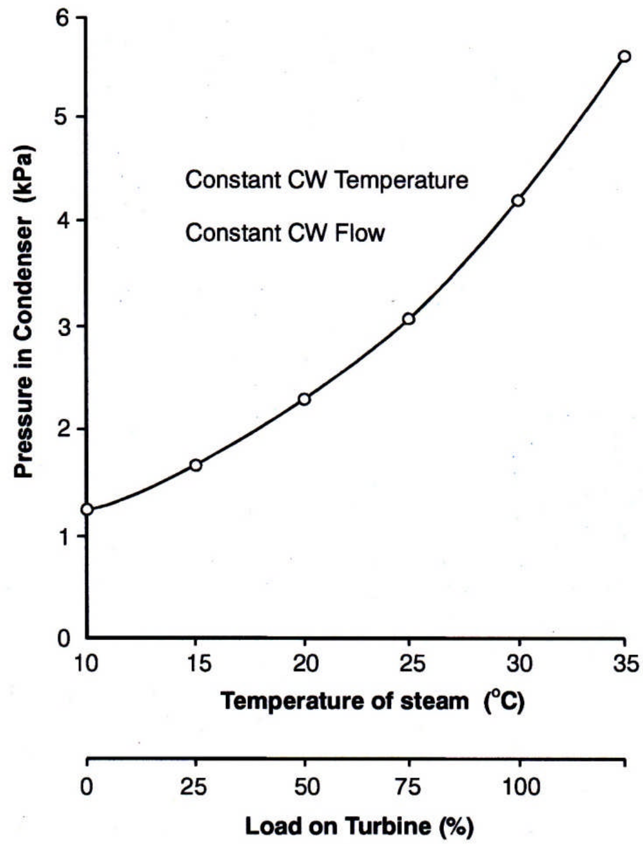


Figure 19 Variation in condenser pressure

7.2 Turbine Limitations

In most power plants, the condenser pressure is governed by the prevailing ambient temperatures. These pressures range from about 0.004 MPa to about 0.005 MPa, corresponding to a range of exhaust steam temperatures from 29°C to 33°C respectively. Steam turbines are designed for this range of backpressures and operate well within this range. If, however, operation is extended outside this range, operating problems may arise. These are primarily due to the change in the specific volume of steam as the pressure deviates from the design value. At high backpressures (high temperatures), steam specific volume decreases, so that the steam passes through the last stage blading at lower velocities. Conversely, at low backpressures (low temperatures), steam specific volume increases, so that the steam passes through the last stage blading at higher velocities. This may be confirmed by reference to the mass flow rate equation:

$$M = \rho\ V\ A = V\ A\ /\ v, \qquad (10)$$

where the density ρ is the inverse of the specific volume v. For a given mass flow rate M passing through a fixed area A, the velocity V increases as the specific volume v increases, and vice-versa.

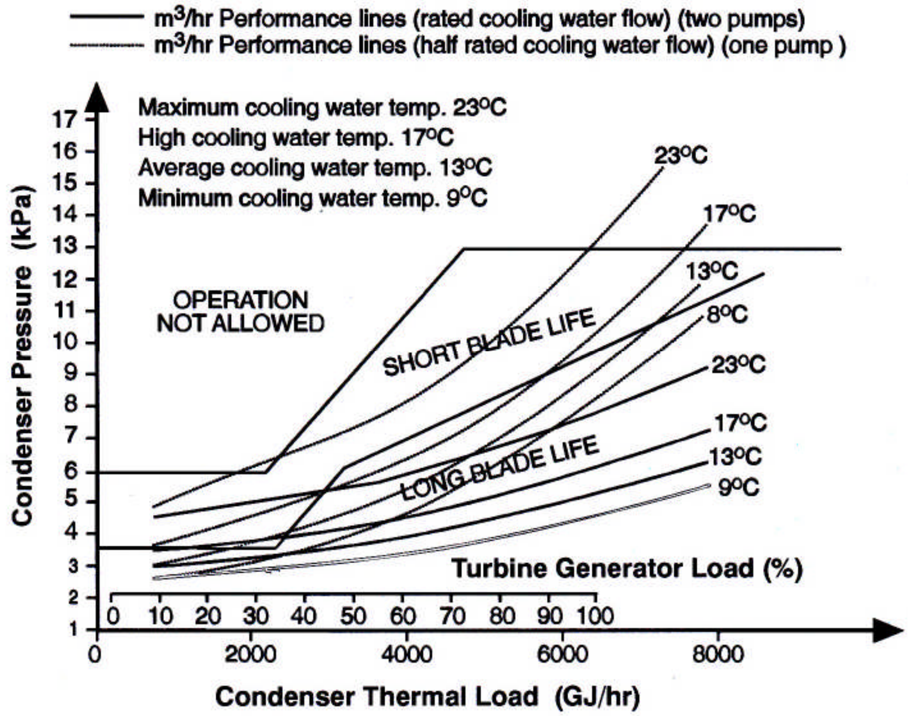


Figure 20 Condenser performance curves (adapted courtesy of Eskom)

The turbine blades are designed only for a certain velocity range. Low velocities (due to high backpressure) result in incorrect blade entry angles and buffeting of the steam on the blades. This causes vibration and high stress (due to increased density) on the turbine blades and shortens turbine life. High velocities (due to low backpressure) result in larger kinetic energy losses in the steam leaving the turbine. This ultimately limits the advantage gained in reducing the backpressure because the increased leaving losses eventually become greater than the increased work done in the blades. High velocities (due to low backpressure) may also result in choking of steam flow due to sonic conditions in the turbine blades. In any case, no additional work is obtained from the turbine once the flow has choked. Figure 20 shows the upper back-pressure limits for a typical large turbine.

7.3 Environmental Limitations

Cooling water leaving the plant carries with it some 2/3 of the heat produced by a nuclear reactor or fossil fired boiler. Most of this is rejected through the condenser and is reflected as a rise in the temperature of the condenser cooling water. The discharged warm cooling water subsequently mixes with that in the environment and may affect aquatic life. For this reason, limits may be imposed on the cooling water temperature rise ΔT and on the effluent temperature T_E.

7.4 Condenser Tube Fouling

Fouling of condenser tubes by material deposition, biological growth, or physical blockage will reduce condenser performance by reducing either the overall heat transfer coefficient U or the effective surface area A if some tubes are completely blocked. The following equation illustrates these phenomena:

$$\Omega = U A \theta. \tag{11}$$

If either U or A is reduced, then the temperature difference θ between the steam and the cooling water will have to increase to maintain the same total heat transfer rate Ω. The net result is an increase in steam temperature and exhaust pressure and a consequent drop in the work done by the turbine and a loss in plant efficiency.

To avoid fouling, provision is made in most plants to filter the incoming water through screens and in some plants to dose the water with a biological growth inhibitor. Some fouling is inevitable, and condenser tubes must be cleaned periodically either online or offline.

7.5 Cooling Water Circuit

A typical condenser cooling water system consists of an intake structure with suitable rotating or travelling screens, two or three pumps in parallel, ducts to and from the condenser, and an outfall to discharge the water far enough from the intake to prevent external recirculation. Figure 21 shows diagrammatically a system with three pumps and screens, control valves to allow any pair of pumps to be in operation, and isolating gates at the intake and outfall to allow drainage of the system for maintenance. This system supplies three pairs of condensers which are associated with a turbine having three low pressure cylinders. Each pump can normally supply 50% of the design water flow. If only a small derating of the unit is necessary when operating on one pump, then two pumps will suffice, but if a large derating is required, a third pump is usually installed. The former case applies to plants where cooling water temperatures during the year are particularly low, whereas the latter case usually applies to plants using warmer water. The third pump also enables the plant to operate at full power when one pump or screen is out of commission for maintenance.

Generally, some control of condenser conditions is possible by operating one or two condenser cooling water pumps. A change in flow will affect exhaust steam temperature and condenser pressure, as explained in the previous section. At plants operating in areas with particularly cold cooling water, for example, if condenser pressure becomes too low and choking occurs in the turbine blades, one pump can be shut down to raise condenser pressure. This in fact is desirable because it saves auxiliary power and improves overall plant efficiency. At plants operating in areas with high cooling water temperatures, operating limitations are usually at the other end of the scale, and the maximum flow of cooling water is required to avoid excessive condenser pressures.

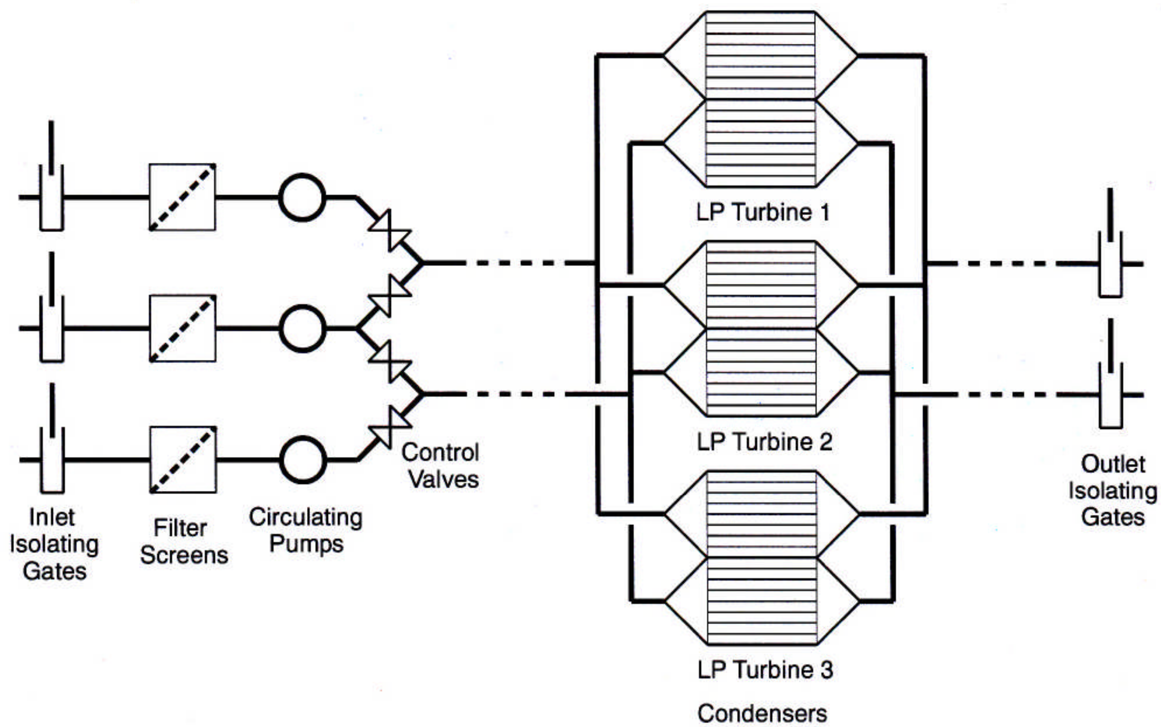


Figure 21 Typical condenser cooling water system

7.6 Flow Transients

The condenser cooling water system has very long and large pipes carrying water at high velocities. Such a large mass of moving water has an enormous amount of kinetic energy. Precautions must therefore be taken when starting and stopping this flow of water. It is important that sufficient time be allowed for the water to accelerate or decelerate before initiating another operation.

The condenser is usually the highest point in the system and operates like a syphon, as shown in Figure 22. In the event of a pump trip, the water upstream of the condenser is retarded by gravity, whereas that downstream of the condenser tends to continue flowing under the influence of gravity. This causes separation of the water column at the condenser due to elevation and pressure drop in the condenser tubes. The resulting vacuum in this part of the system will decelerate the flow downstream of the condenser and eventually suck it back towards the condenser. This reverse flow, on striking the upstream water column near the condenser, will cause severe shock and damage to the condenser or even destroy its tubes and tube plates. Such disastrous consequences can be prevented by incorporating vacuum breakers at the condenser outlet water boxes. These open under the vacuum conditions caused by water column separation and allow air to enter the system and provide an air cushion to prevent or minimize reverse flow of the downstream water column.

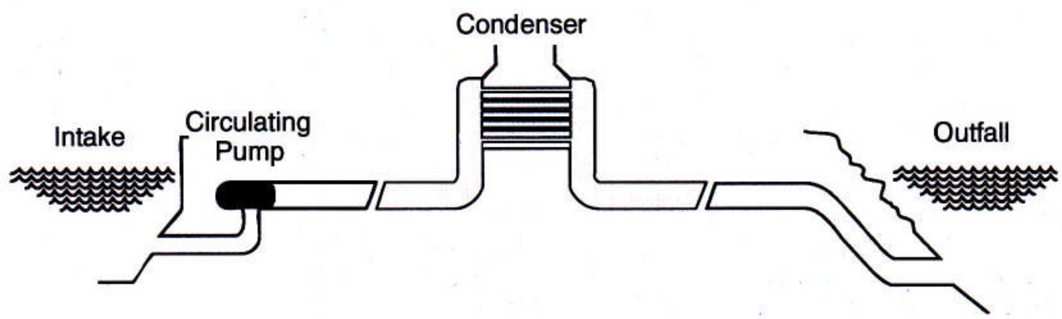


Figure 22 Simplified condenser cooling water system

During a complete system trip, priming may be lost due to admittance of air into sub-atmospheric regions. To restore priming, a vacuum priming system is connected to the condenser water boxes. This draws air out of the system before start-up and ensures that all condenser tubes are filled with water and that there are no air pockets in the water boxes which could persist during normal operation.

7.7 Variation in Condenser Vacuum

An increase in condenser pressure has obvious effects. The enthalpy drop across the turbine is reduced, and the steam flow through the last stage blades departs from the optimum, thus reducing their efficiency. Both these phenomena cause a drop in turbine output and a loss in plant efficiency.

A decrease in condenser pressure has opposite effects on turbine output. A lower pressure causes an increase in the enthalpy drop across the turbine, thus increasing the turbine output. It also causes the steam flow pattern to depart from design conditions, thus decreasing the work done by the turbine. This latter effect is smaller, so that overall there is an increase in turbine output. Other effects, however, become significant at very low pressures. Choking may occur in the last stage turbine blades, thus limiting the increase in turbine output. Even if this does not occur, the increased steam specific volume creates high steam velocities, which increase the kinetic energy loss in the exhaust steam and increase the friction loss in the steam passing through the blades. Both losses increase with the square of the velocity and rapidly overtake the gain due to increased enthalpy drop across the turbine. Beyond a certain point, therefore, the turbine suffers a net loss in output.

Increased steam moisture content at very low condenser pressures can damage the turbine, and certain limits may be imposed on operation under such conditions to avoid excessive blade erosion. Moisture in the steam also affects turbine output because the impact of the moisture drops retards the blades and slightly reduces turbine output.

The net result of these effects is shown in Figure 23. With rising pressure, turbine output decreases almost linearly, but with falling pressure, the increase in turbine output is less, and a maximum is reached. Beyond the maximum, the turbine suffers a decrease in output with falling pressure.

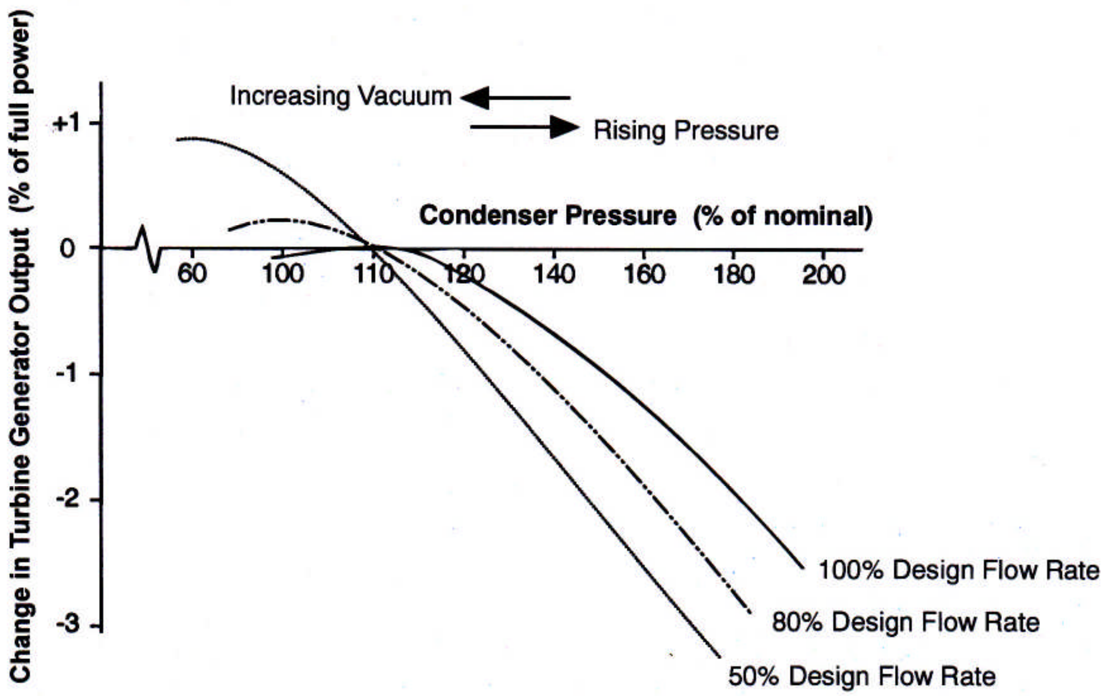


Figure 23 Effect of change in condenser pressure (courtesy of NB Power)

The effects of increased or decreased condenser pressure on the turbine have been discussed. Reference to a Mollier diagram will clarify these effects and enable them to be visualized in conjunction with load changes on the turbine. A change in condenser pressure moves the exhaust point along the turbine expansion line, whereas a change in turbine load moves the exhaust point along a constant pressure line, as shown in Figure 24. Such changes affect the temperature, density, wetness, and enthalpy of the exhaust steam and hence the turbine output.

7.8 Causes of Poor Condenser Vacuum

Cooling water temperature and turbine load variations will drive the condenser pressure one way or the other. Such changes are normal, but may cause the condenser pressure to deviate beyond normal limits. Other causes of rising pressure usually require operator intervention to restore the condition of the system. Condenser tube fouling, for example, will ultimately require that the tubes be cleaned to restore conditions. Tube flooding on the steam side, tube draining on the water side due to air accumulation at high points in the cooling water system, and accumulation of incondensable gases blanketing the tubes in the steam space are further causes of poor vacuum which require an analysis of conditions to determine the reason.

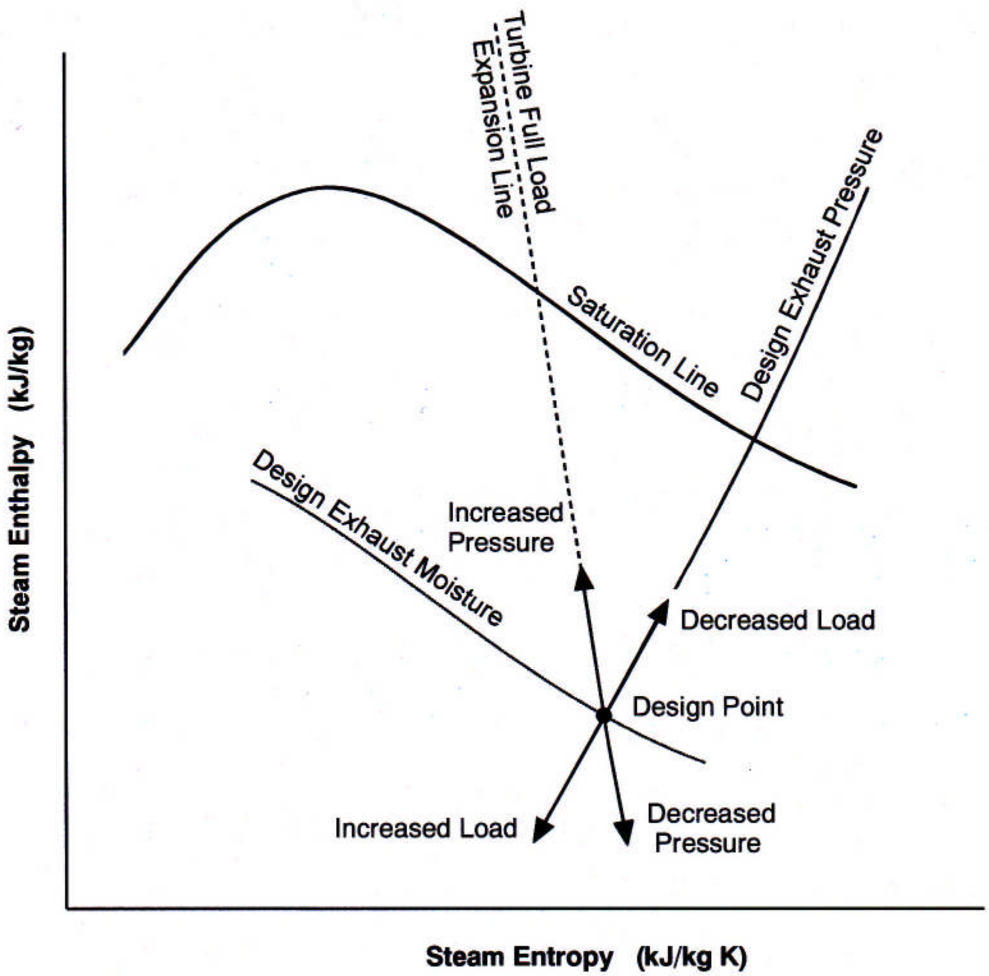


Figure 24 Effect of change in turbine load and condenser pressure

7.9 Condenser Vacuum Raising

On start-up, the entire steam space of the condenser as well as those of the turbine and the separator-reheaters must be evacuated. Initially, the extracted air is of near-atmospheric density, but eventually it is of exceedingly low density as high vacuum conditions are approached. As vacuum raising progresses, the mass flow rate drops as the density decreases. During vacuum raising, therefore, a high flow, low vacuum system is desirable, whereas under normal operating conditions, a low flow, high vacuum system is required. Note that some air leakage into the system always occurs during operation.

Air entering the condenser is carried by the steam until the steam condenses on the tubes. The air cannot flow back against other steam coming in and remains near the tubes at the end of the steam flow path. Obviously, air must be removed from these parts of the condenser. An air removal system is therefore required to pick up air from the appropriate places in the condenser tube bundle. Air extraction efficiency depends upon the partial pressures of air, p_{air}, and steam, p_{steam}, in the condenser. The total pressure, p_{total}, is the sum of these partial pressures:

$$p_{total} = p_{steam} + p_{air}. \tag{12}$$

The total pressure is the prevailing pressure in the condenser as dictated by the saturation conditions. Under these conditions, the partial pressure of air is negligible, and an air extraction system would extract mainly steam, which is not very effective. If, however, the partial pressure of air is increased such that the ratio p_{air}/p_{steam} is increased from near zero to a reasonable value, air removal effectiveness is much increased. This can be done by local cooling within the condenser. Local cooling to a lower temperature will reduce p_{steam} to a pressure corresponding to the saturation pressure at the lower temperature. Because p_{total} is dictated by the overall conditions in the condenser, the value of p_{air} must rise to make up the difference. Thus, the ratio of p_{air}/p_{steam} is increased, and the ratio of air to steam by mass in that area is also increased. The greater the mass of air in the steam, the greater will be the efficiency of air extraction.

Local cooling in the condenser is effected by shielding sections of tubes in the tube bundle from the incoming steam flow. The air extraction points are located in these zones where the partial pressure of air has been increased, as can be seen in Figure 25.

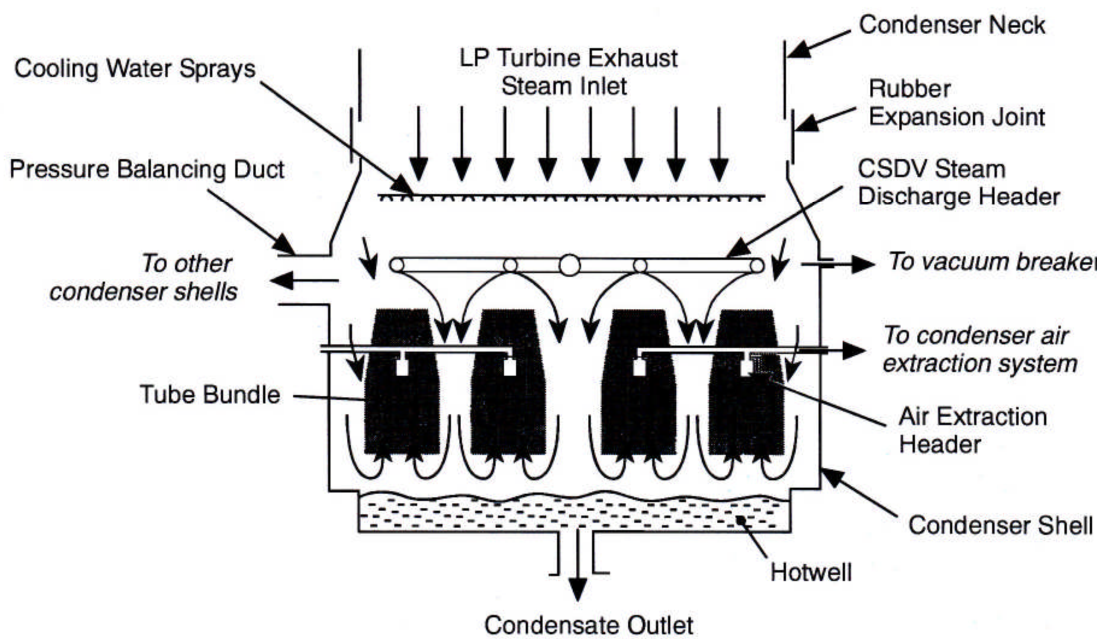


Figure 25 Condenser cross section (courtesy of NB Power)

7.10 Condenser Vacuum Breaking

Condenser vacuum can be relieved on shutdown by condenser vacuum breaking valves which allow atmospheric air to enter the condenser shell and the steam turbine. Vacuum may be broken during or after turbine rundown depending upon operating recommendations and circumstances. When the vacuum breakers are opened, condenser pressure increases rapidly. If the turbine is still rotating, the denser atmosphere around the rotor resists the turbine blade motion, causing the rotor to decelerate quickly. These retarding forces are very high and may stress the blades severely. On the other hand, the rundown time is shortened dramatically, which may be desirable in the event of a turbine fault such as a bearing failure.

8 Steam Turbine

8.1 General Operational Considerations

Steam turbines generally operate very reliably and for lengthy periods between shutdowns for major maintenance. During these periods, however, slow performance degradation may occur due to wear, erosion, or fouling of critical components. This has a slight detrimental effect on overall plant efficiency, but this translates into a loss in electrical power output and loss in revenue, which is significant in the long term, especially in a nuclear plant which normally operates at full load. To optimize plant efficiency, these performance losses must be categorized and monitored with a view to correcting deviations where possible.

Moisture in the steam in the turbine has a detrimental effect, but it tends to decrease as load is decreased. At very low loads, the exhaust steam may actually become superheated, which is even worse. Therefore, slightly wet exhaust steam provides some operating flexibility without changes in exhaust steam temperature.

Turbine back-pressure as determined by condenser conditions is also critical to turbine operation. Deviations in back-pressure affect steam flow through the last stage turbine blades, resulting in various undesirable effects. The turbine must therefore operate within prescribed back-pressure limits, and the condenser must be capable of maintaining these limits.

Steam turbines are also subject to thermal transients, which result in thermal stress and differential expansion. These require monitoring to ensure that they do not exceed prescribed limits and endanger turbine integrity.

The heavy turbine and generator rotors run at high speed, and therefore any slight mass imbalance or shaft bending will cause serious and potentially damaging vibration. When a turbine has been shut down and stationary for a long period, the shafts begin to sag. This *sagging* is in addition to the natural deflection under gravity and is the beginning of creep, but is reversible by slowly rotating the shaft and reversing the sag. This takes time, and, until reversed, the sag bows the shaft, creating an imbalance. When a hot turbine is shut down after a period of operation and comes to rest, the natural cooling process results in a temperature difference between the top and bottom of the casing and rotor. The cooler bottom part of the rotor shrinks slightly relative to the top, bowing the shaft upwards. This *hogging* also creates an imbalance should the turbine be restarted and may in an extreme case jam the rotor against the casing. This can be avoided by putting the turbine onto turning gear and turning the rotor until uniformly cool.

Another critical aspect of turbine operation is governing to maintain speed and load. The turbine is the link between the energy input as steam and the energy output as electricity. Any mismatch between these will cause the turbine to accelerate or decelerate. Uncontrolled acceleration is very dangerous, and precautions must be taken to ensure rapid closure of the steam valves in the event of disconnection from the electrical grid system.

8.2 Turbine Start-up

A simplified turbine start-up procedure is shown in Figure 26. Before turbine runup, several lengthy processes are required, but these can be done concurrently to some degree. The first key operation is to start the lubrication system and to put the turbine onto turning gear to roll out any sag and to ensure uniform heating once steam is admitted. Before any heat can be received, the condensate system and feedwater system must be put into service, followed by the condenser cooling water system to remove reject heat. When steam is available, warming of the steam lines can commence, and the turbine gland sealing system can be put into service. With sealing steam in place, vacuum raising can commence. When sufficient vacuum is available, steam can be admitted to the turbine to commence the runup. The turbine is normally held at a low speed while shaft eccentricity, bearing vibration, etc. are checked and then accelerated to pass quickly through the critical rotor speeds so as not to excite excessive rotor vibration. Full speed must, however, not be reached until full vacuum is available to avoid putting excessive stress on the long low pressure turbine blades due to windage. When at full speed, connection to the grid system can be requested. For satisfactory synchronization, the generator voltage must be the same as that of the grid, the generator frequency, determined by the turbine speed, must be equal to the grid frequency, and the generator phase angle must match the grid phase angle. If synchronization is done manually, it is better to err on the side of the turbine being slightly fast so that it picks up some load immediately as the turbine speed drops to match that of the grid. This avoids an unnecessary reverse torque on the turbine generator shafts, and a small load should immediately be applied to prevent fluctuating torque. Once synchronized, the turbine can be loaded at a rate dependent upon the cylinder temperatures. The initial rate is usually slow to allow metal temperatures to rise slowly to minimize thermal stress due to steep temperature gradients in the cylinders and rotors. The reheaters are valved in above about 25% load, and the loading rate can usually be increased after that, provided that various checks verify that key parameters such as differential expansions are within limits.

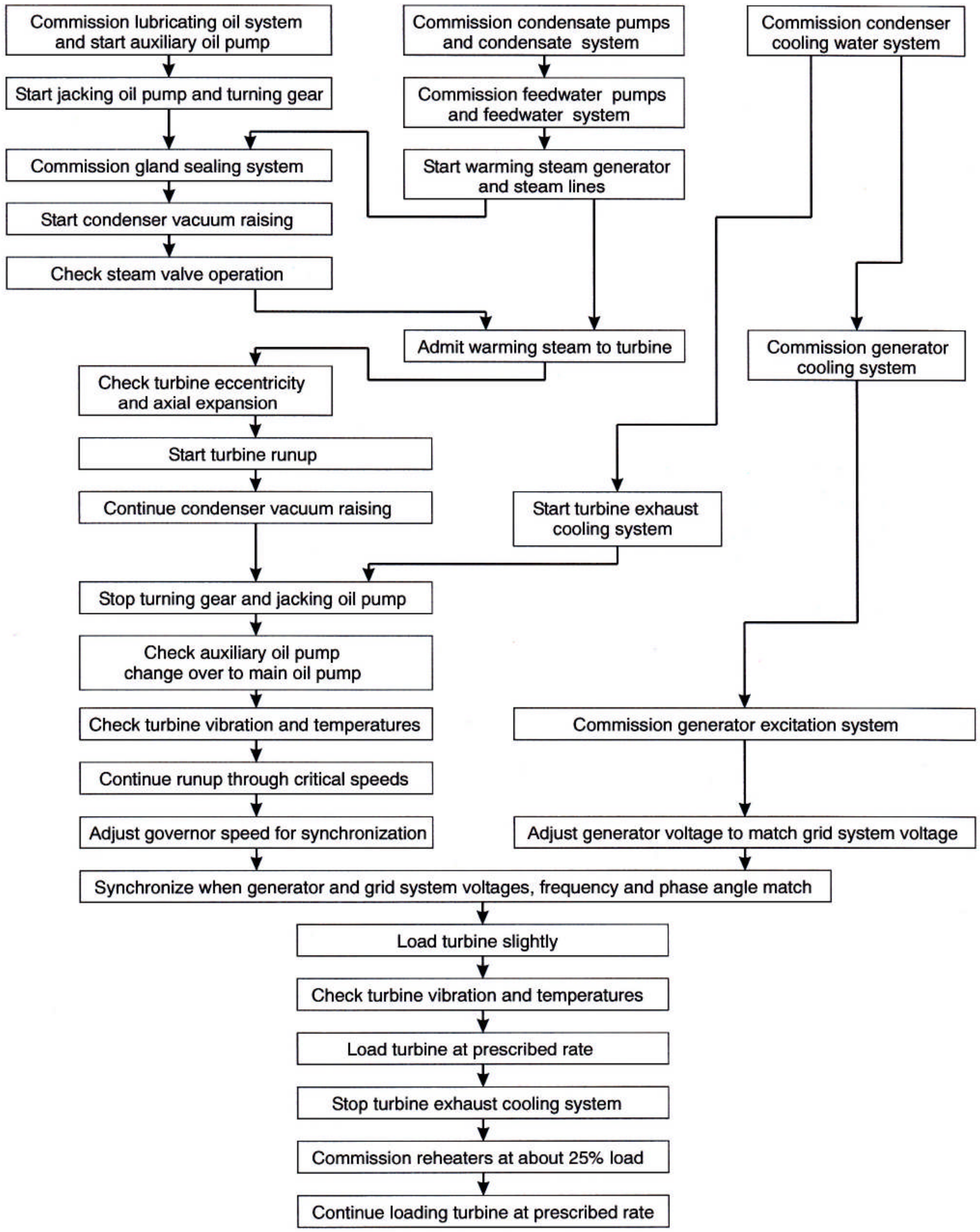


Figure 26 Major activities during start-up and loading

8.3 Turbine Losses

Fluid friction is the most significant of all turbine losses. High velocity steam encounters surface friction and turbulence in passing through the turbine blading. Fluid friction losses amount to about 10% of the total energy input to the turbine. This is a major loss factor which is ultimately reflected in turbine internal efficiency.

Moisture loss occurs when condensed moisture passes through the turbine blades and the moisture drops impinge upon the moving blades. This retards the moving blades, reducing turbine output and efficiency. There is a loss in stage efficiency of about 1% for each 1% moisture content of steam at that point in the machine.

The residual kinetic energy in the steam leaving each stage is usually recovered in the following stage. At the last stage, however, the specific volume of the steam is very large, and to obtain manageable flow areas at the turbine exit, high velocities must be tolerated. This results in a high residual kinetic energy and a significant leaving loss in the order of 2% to 3% of total energy input.

Heat losses occur directly from the turbine. This results in a small overall loss due to convection and radiation to the surrounding atmosphere.

Bearing losses arise due to oil friction in the bearings. Some auxiliaries such as the main oil pump are usually directly driven from the turbine shaft and add to these losses.

Windage loss occurs in the generator where fans mounted directly on the generator rotor circulate the hydrogen coolant within the generator housing.

Some electrical losses occur within the generator windings, but are quite small.

8.4 Turbine Load Variation

As the load on a turbine varies, the pressure profile throughout the turbine changes, as shown in Figure 27. At any one point along the steam flow path, the pressure varies according to steam flow in a linear manner, as shown in Figure 28. This has been demonstrated in practice on a number of machines and is an accepted result. At different points in the turbine, a similar relationship is found. At zero load, however, some steam flow is required to drive the turbine against bearing friction and generator windage. Turbine load (generator output) is therefore not quite proportional to steam flow. The overall result can be summarized as in Figure 29, which shows steam pressure, steam flow, and turbine load or output all on the same plot. Note that in many problems, the zero load steam flow is not known. In such cases, this zero load steam flow may be assumed to be small and the overall steam flow taken to be proportional to turbine load. Note that the value for zero load steam flow is much exaggerated in the diagram.

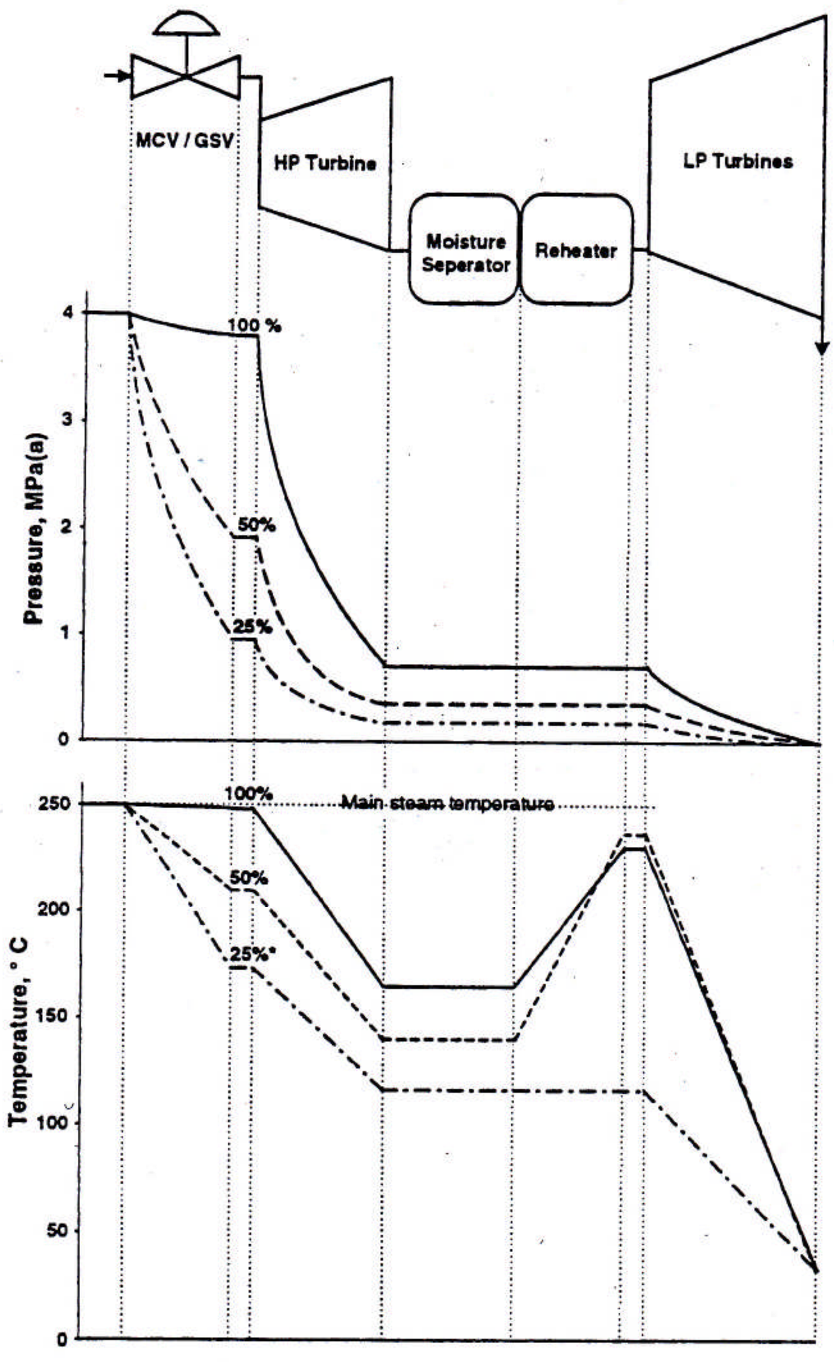


Figure 27 Steam pressure variation through the turbine (courtesy of NB Power)

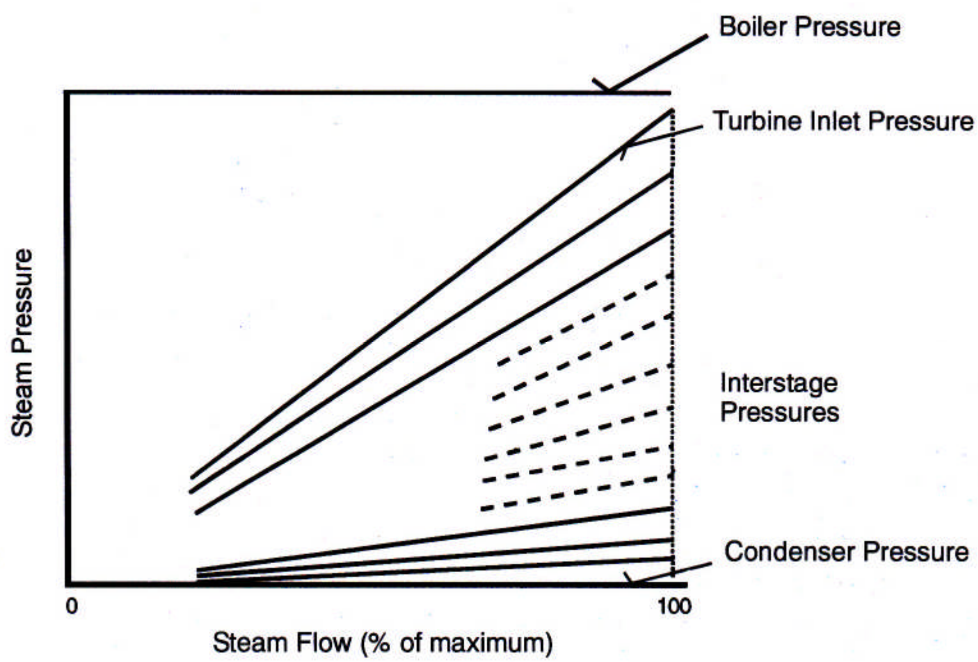
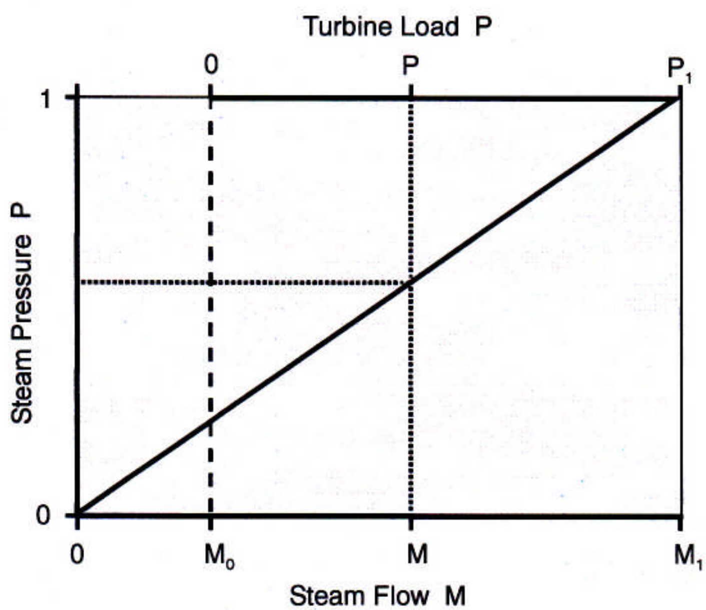


Figure 28 Steam pressure variation with load change

Figure 29 Steam pressure versus steam flow and turbine load



The Mollier diagram is an ideal way to represent varying load conditions. Figure 30 shows the changes in the turbine expansion line for different loads on a large nuclear unit. Some interesting characteristics are apparent in this figure. Because reheating is effected by live steam, the temperature of the reheated steam remains essentially the same with decreasing load. In practice, the reheat temperature actually rises with decreasing flow because the temperature difference for heat transfer becomes less with reduced heat flow. At the low pressure turbine exhaust, the moisture becomes less with reducing load, and eventually the exhaust steam actually becomes superheated. To avoid this situation, the reheating steam flow is throttled at very low loads to reduce steam temperatures in the low pressure turbine. Even with no reheat, at very low loads, the decrease in internal efficiency due to incorrect steam flow in the blades causes the exhaust temperature to rise to excessive values. This is aggravated by possible recirculation of exhaust steam within the turbine blading.

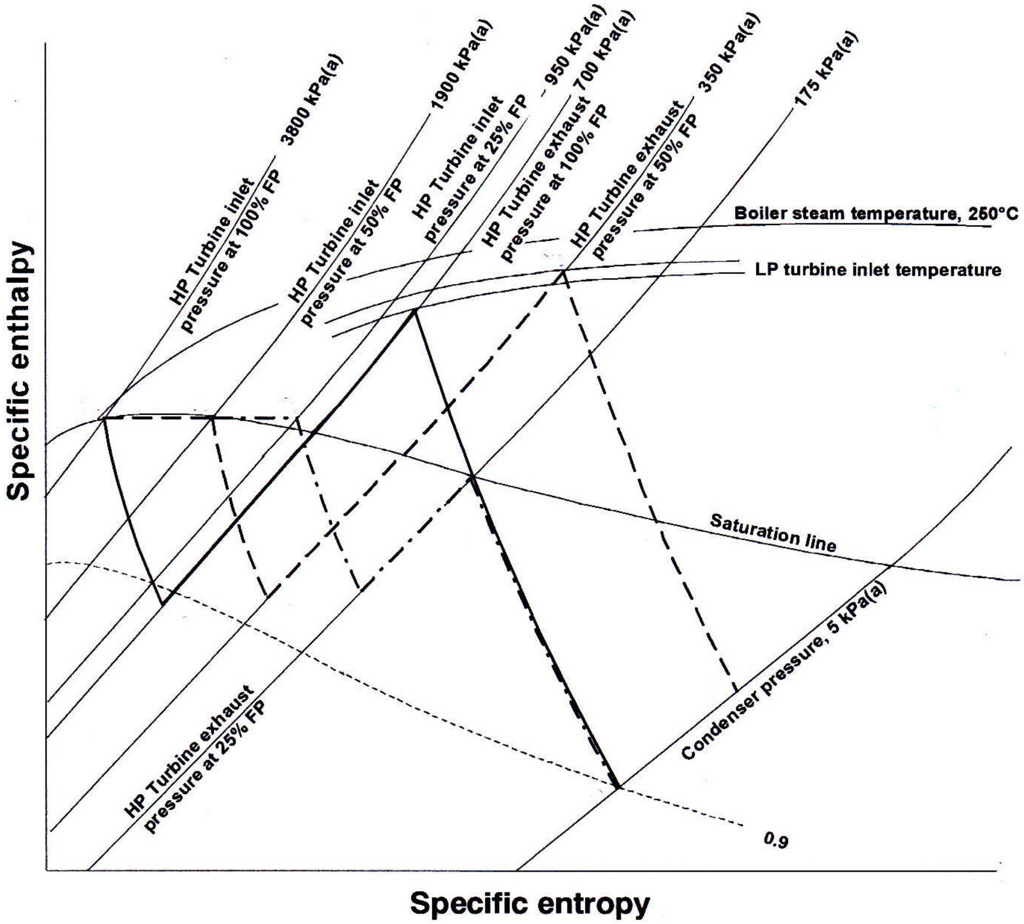


Figure 30 Partial load turbine expansion lines (courtesy of NB Power)

During partial load operation, the incoming steam is throttled to reduce its pressure. As a consequence, the specific volume of the steam increases. Except in the high pressure areas of the Mollier diagram, the constant temperature lines in the superheated regions are nearly horizontal. This means that the throttling process, which is at constant enthalpy, is also almost at constant temperature. Therefore, the expansion index n in pv^n equals a constant is approximately unity. The change in specific steam volume therefore almost exactly offsets the change in pressure. Flow velocities in the superheated region of the turbine are therefore practically constant over a wide range of loads. This means that the velocity triangles are largely unaffected and that the steam continues to pass through the blades at the correct angle. This is fortuitous and promotes high efficiency. In contrast, hydro turbines operating with incompressible water suffer marked losses in efficiency at low loads due to off-design flow directions.

As the steam pressure becomes less in the low pressure parts of the turbine, this no longer applies because the turbine exhausts against a positive (even though very low) absolute pressure. The absolute pressures around the last stages are therefore not quite proportional to steam flow, and the pressure ratio across the last stages (especially the last) drops. This results in reduced steam velocity entering the moving blades.

In large modern turbines, the changes in the velocity diagram at the last stage can be quite significant, as illustrated in Figure 31. Here, the velocity diagram has been redrawn to show the whirl velocity V_W. As long as the whirl velocity is positive, that is, Y is on the right hand side, the steam does work on the blade. At very low loads, the steam incoming velocity V_{S1} is reduced, and at the blade tip, the whirl velocity becomes negative, that is, Y is on the left hand side, indicating that the blade now does work on the steam. Observation of the blade profile at the tip indicates that, once V_{S1} becomes substantially less than V_B, the blades will act as a fan and will drive the steam onwards. This fanning action at low steam flows occurs towards the tips of the blades, that is, around the outer periphery of the turbine rotor. When the fanning action exceeds the normal steam flow, a recirculation in the last stage will be set up, with steam returning through the blades near their roots where the impulse type profile simply plows through the steam at low loads. Such a recirculation is shown in Figure 32. Once set up, this recirculation results in excessive steam heating by friction and turbulence. If no corrective action is taken, steam temperatures can become so high as to cause thermal damage to the turbine.

Two types of corrective action are possible, assuming that the turbine is obliged to continue operation at this abnormally low load. One is simply to displace the recirculating hot steam with a small flow of "cooling" steam through the turbine. The other is to spray cooling water into the recirculating steam at the turbine exhaust so as to reduce its degree of superheat before it circulates back into the turbine blades. Large nuclear units may have to operate at very low loads for extended periods during operating manoeuvres on the reactor. These turbines are usually fitted with exhaust hood sprays or a cooling steam system. Furthermore, a nuclear reactor such as a CANDU may trip inadvertently or be shut down for a quick repair. In this case, it would have to be brought back on load within about 40 minutes to avoid suffering long term (40 hour) unavailability due to buildup of neutron absorbing xenon in the reactor core while off load. During such events, it is desirable to maintain the turbine at full speed and ready to be loaded up once reactor power has been restored. This may be accomplished by keeping the generator connected to the grid system and allowing it to drive the turbine. Such operation is known as *motoring*. When motoring, recirculation of steam in the turbine blades is most severe, and cooling steam and water sprays are required to maintain the temperature of the low pressure turbine blades within limits.

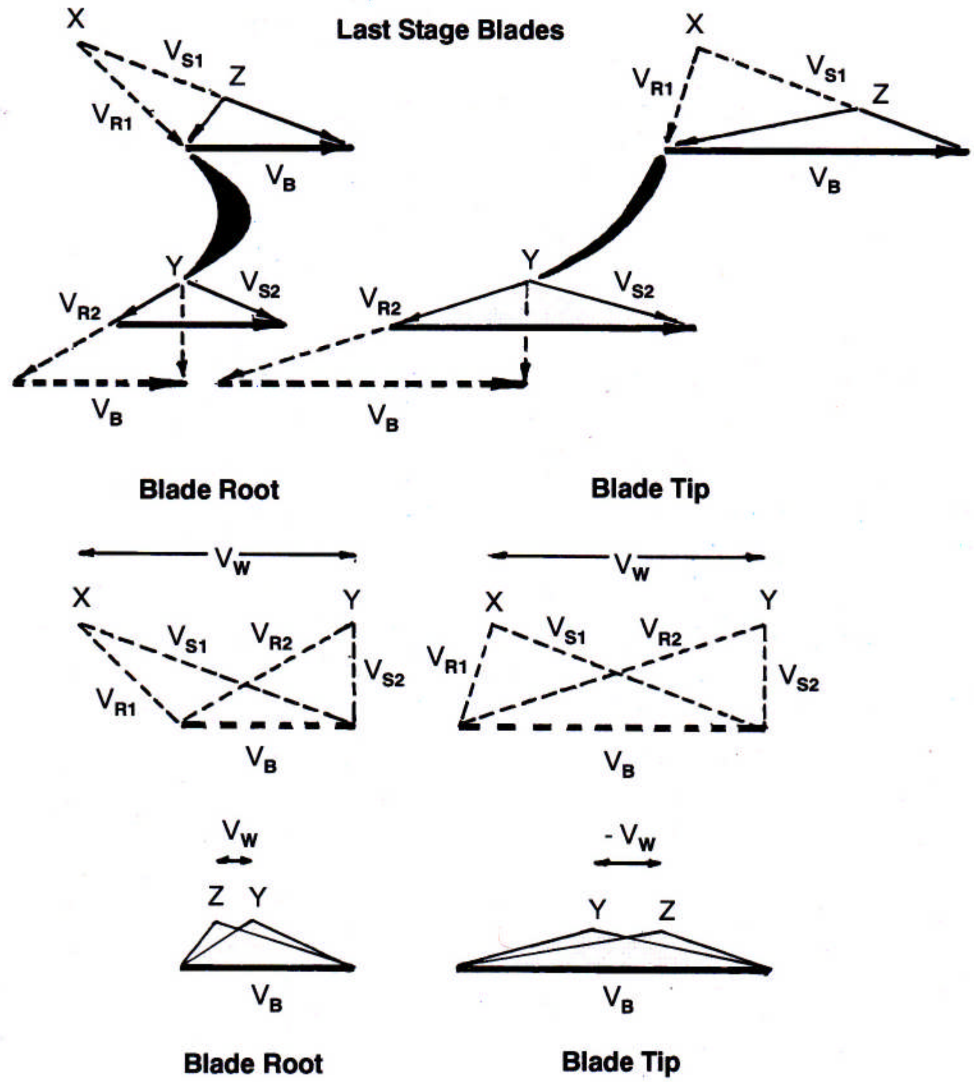


Figure 31 Change in whirl velocity at low loads

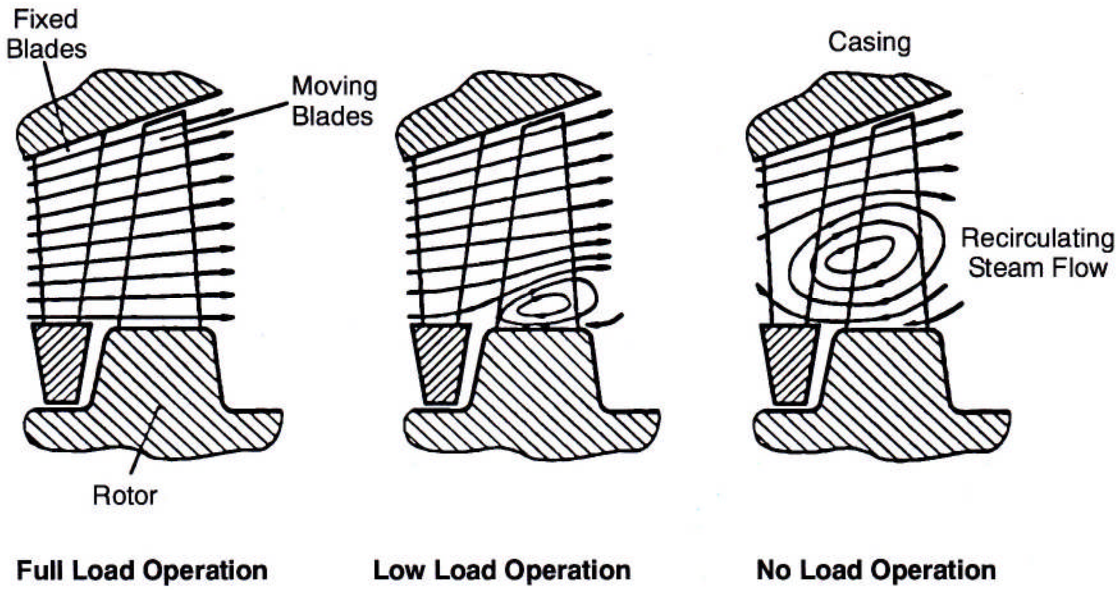


Figure 32 Recirculation of steam at low loads (courtesy of NB Power)

During turbine operation, it is important to minimize thermal transients and to avoid damaging combinations of thermal stress and mechanical stress. For this reason, turbines are warmed thoroughly before being run up to full speed, and, during operation, major load changes are made progressively and slowly so that the turbine casing and rotor can adapt to the changes in internal steam temperatures. Small load changes within certain limits can naturally be made quickly to enable the turbine to follow system load requirements or to control frequency. The turbine may, of course, suffer a trip and immediate initiation of the automatic shutdown sequence. This does not necessarily impose a severe thermal transient because steam flow through the turbine is stopped and it remains hot for an extended period. A restart during this period must, however, be accompanied by rapid loading so as to minimize the period of admission of cooler throttled steam to the turbine casings under low load conditions.

All start-ups, shutdowns, and major load changes subject the turbine to some thermal stress. Such operations reduce the ultimate life of various turbine components and, depending upon their severity, may be considered as equivalent to a certain number of normal steady state running hours on the turbine.

8.5 Differential Expansion

When turbine casings and rotors are heated, they expand generally in all directions. During this expansion, the centre lines of both must remain coincident while the casings and rotors expand in an axial direction, as shown in Figure 33.

The rotor, having less mass than the casing and being surrounded by steam, tends to expand more rapidly than the casing, leading to so-called *differential expansion* between them. This is apparent mainly in the axial direction and blading, and seals must be designed to accommodate this relative axial movement as the temperature changes. Furthermore, each cylinder casing is separately supported on its foundations, but the rotors of all the cylinders are linked together to form a continuous shaft. There is one thrust bearing to locate the shaft in an axial direction, usually near the high pressure cylinder. From this point, the expansion of each rotor contributes to the total expansion, so that there is an additional differential expansion which is cumulative and greatest at the cylinder furthest from the thrust bearings. Such differential expansion must be monitored during warm-up and loading to ensure that there is no risk of contact between the fixed and moving parts.

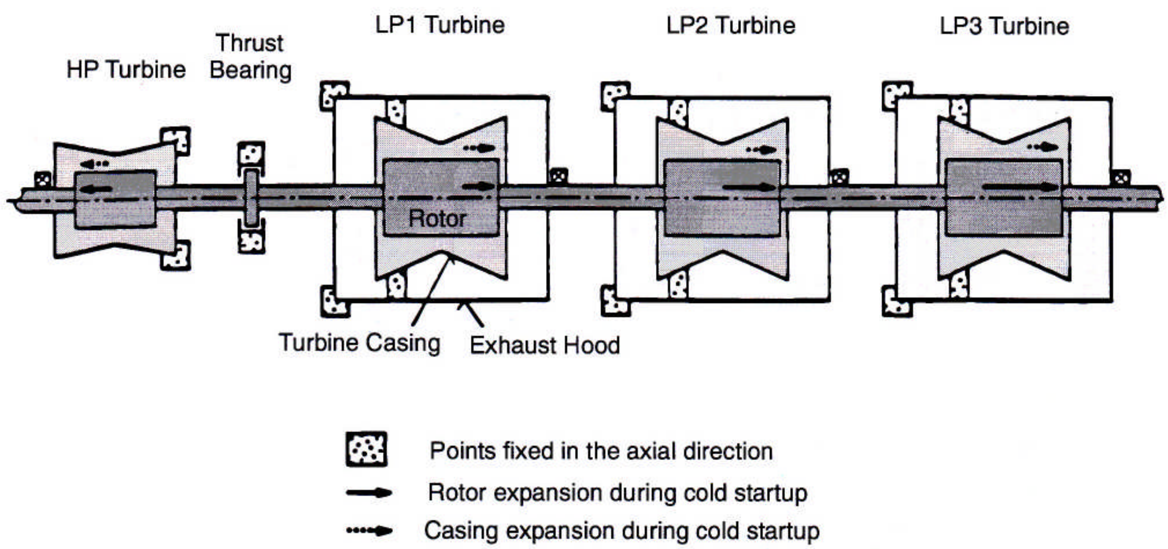


Figure 33 Differential axial expansion of turbine rotors and casings

(courtesy of NB Power)

8.6 Turbine Governing

The turbine governor valves control the flow of steam to the turbine and, as such, are part of the main steam system. As the governor valves are opened from the closed position during start-up, the energy input to the turbine increases. The turbine then accelerates until the energy losses due to windage and friction balance the energy input. Further admission of steam increases the speed of the turbine. Turbine speed is therefore dependent upon governor valve position, and the governor acts to control turbine speed. In this way, the full speed zero load condition can be maintained.

Once the turbine generator has been synchronized to the electrical grid system, the turbine speed is locked to the grid frequency. Additional opening of the governor valves increases the energy input to the turbine, but the speed can no longer increase. At a constant speed, the windage and friction losses remain constant, and therefore the excess energy appears as generator output. Further admission of steam increases the load on the generator. Turbine load is therefore dependent upon governor valve position, and the governor acts to control turbine generator load.

The main characteristic of the governor is the *speed droop*. This indicates the amount that the speed will change as the load is varied. A speed droop of 5% indicates that, if the speed is 100% at zero load, it will be 95% at full load. Such a change would not normally be permitted, and the speed would be progressively reset as the load increased. The speed droop, however, determines how turbines operating in parallel will maintain stability and share load. With turbines operating in parallel, the speeds must all be the same and match the system frequency. Then, for a given change in frequency, a turbine with a smaller speed droop will change its load by a greater amount.

8.7 Turbine Responses

In the event of various transients and plant upsets, the turbine will respond in different ways to minimize risk to the plant and to facilitate return to normal operating conditions. The following plant upsets are considered:

Reactor trip
Turbine trip
Electrical load rejection.

For each of these, the main steam system valves must operate in an appropriate way to protect the turbine.

Once the generator has been disconnected from the grid system, any mismatch between power input to the turbine and electrical output from the generator will result in a change in speed. In a modern steam turbine, the mechanical inertia of the rotors is relatively small compared with its rated power output. This means that it can accelerate very quickly under an excessive mismatch between power input and power output. Overspeeding is potentially the most dangerous condition that can occur on a turbine because it can have the most disastrous consequences. Past experience has shown that a turbine will literally explode under very high overspeed conditions. The overspeed accident of the 600 MW Unit 4 at Duvha Power Station in South Africa in February 2011 is a stark reminder of this.

8.8 Reactor Trip

In the event of a reactor trip in a nuclear unit, the mismatch in power input to and power output from the steam generators will result in a rapid drop in steam generator pressure and fast cooling of the primary heat transport system. This fast cooling will cause shrinking and reduce pressure in the secondary steam system.

To avoid these adverse consequences, turbine steam flow must be quickly reduced by closing the governor valves. Ideally, steam flow to the turbine should be reduced at the same rate as the reduction in steam generator steam production. The drop in steam generator output slightly lags the drop in reactor fission power because of the heat stored in the primary heat transport fluid and because of decay heat generated in the nuclear reactor.

To ensure a proper response, the boiler pressure control system ensures that the governor valve will be closed progressively and power input from the steam generators to the turbine reduced to zero while excess steam is diverted to the condenser through the condenser steam discharge valves. When the turbine power falls below that required to overcome windage and friction, the generator will draw the necessary power from the grid system. Under these conditions, the turbine generator is driven at synchronous speed by the electrical grid and is said to be in *motoring* mode. A quick recovery from motoring mode is possible so that, once the reactor trip has been cleared, the unit can be brought up to full power quickly to minimize the effect of the xenon transient. For this reason, other valves in the system, such as the intercept valves, may be automatically positioned in readiness for a turbine restart. The advantage of the motoring mode is to avoid disconnecting the turbine from the grid system, thereby eliminating partial turbine rundown and runup as well as resynchronization, all of which require careful manoeuvring.

Once tripped, however, a reactor requires checking to verify the cause of tripping and careful restart procedures, all of which take time. Therefore, motoring may not be a practical option, and the turbine may need to be tripped automatically in response to a reactor trip.

8.9 Turbine Trip

The purpose of a turbine trip is to protect the turbine in the event of adverse operating circumstances or component malfunction or failure. A turbine trip should be initiated whenever continued operation poses a risk of damage to the turbine.

When a turbine trip occurs, power input and power output must be stopped. On the generator side, power output is stopped virtually instantaneously as the generator circuit breaker opens. On the turbine side, however, the steam valves take a finite time to close. During this brief period, some steam passes through the valves, carrying with it substantial energy. This steam, along with the steam already trapped within the turbine, expands and produces a transient power input to the turbine. The mismatch between power input and power output results in a temporary rise in speed until the effects of windage and friction cause the speed to fall.

This is known as a *non-sequential trip*. The temporary speed rise can be avoided if the trip on the generator side is slightly delayed to balance the power output against the power input. The excess energy in the steam entering the turbine is then passed into the grid system during the tripping process. Once this energy flow ceases, the generator circuit breakers are opened. The turbine then coasts down from its normal running speed under the influence of windage and friction. This is known as a *sequential trip*.

8.9.1 Non-sequential trip

As indicated above, in a non-sequential turbine trip, the generator circuit breakers open at the same time as turbine steam valve closure is initiated. The valves take a finite time (perhaps half a second) to close, and the incoming steam along with the trapped steam in the turbine accelerates the turbine into an overspeed condition (about 10% above normal speed), as shown in Figure 34. Note that the horizontal time scale is not linear. The speed rise is in seconds, and the speed drop is in minutes.

A non-sequential trip must be initiated whenever there is an electrical fault on the generator or generator transformer because the heavy currents arising from faults can cause severe damage very quickly.

8.9.2 Sequential trip

In a sequential trip, the generator circuit breakers remain closed while the turbine steam valves are closing, so that the surplus power from the steam can be passed into the electrical grid. As soon as the electrical power flow from the generator falls to zero or reverses, the generator circuit breakers open. In this way, overspeeding of the turbine is prevented, as shown in Figure 34. This is inherently safer for the turbine generator than a non-sequential trip.

A sequential trip is initiated whenever there is a mechanical fault on the turbine or associated equipment. A sequential trip actually promotes a slightly faster shutdown in an emergency because the overspeed transient is avoided. Moreover, if the mechanical fault is due to bearing problems or excessive vibration, it is highly desirable not to subject the turbine to overspeed conditions.

8.10 Steam Flow Control

Mention has been made of the steam trapped inside the turbine after the steam inlet valves have closed. This steam, on expansion to vacuum conditions in the condenser, will continue to accelerate the turbine. Modern steam turbines contain a large volume of steam in their casings and associated pipework and components such as moisture separator reheaters and feedwater heaters. To minimize the effects of this trapped steam, certain other valves such as the intercept valves and the extraction steam line check valves also close to restrict steam flow into the turbine.

8.11 Load Rejection

A load rejection is, in effect, an electrical trip. In the event of certain external faults on the electrical grid system or transmission line leaving the plant, the generator transformer circuit breaker will open, leaving the unit isolated from the system, but still supplying its own unit service load. Under these circumstances, the unit suffers an instantaneous rejection of virtually its entire load, but it must be kept running and ready for resynchronization with the grid system once the fault has been cleared. A load rejection is therefore not a mechanical trip, and the steam flow must not be cut off permanently. The turbine does, however, suffer the same type of transient as during a non-sequential trip.

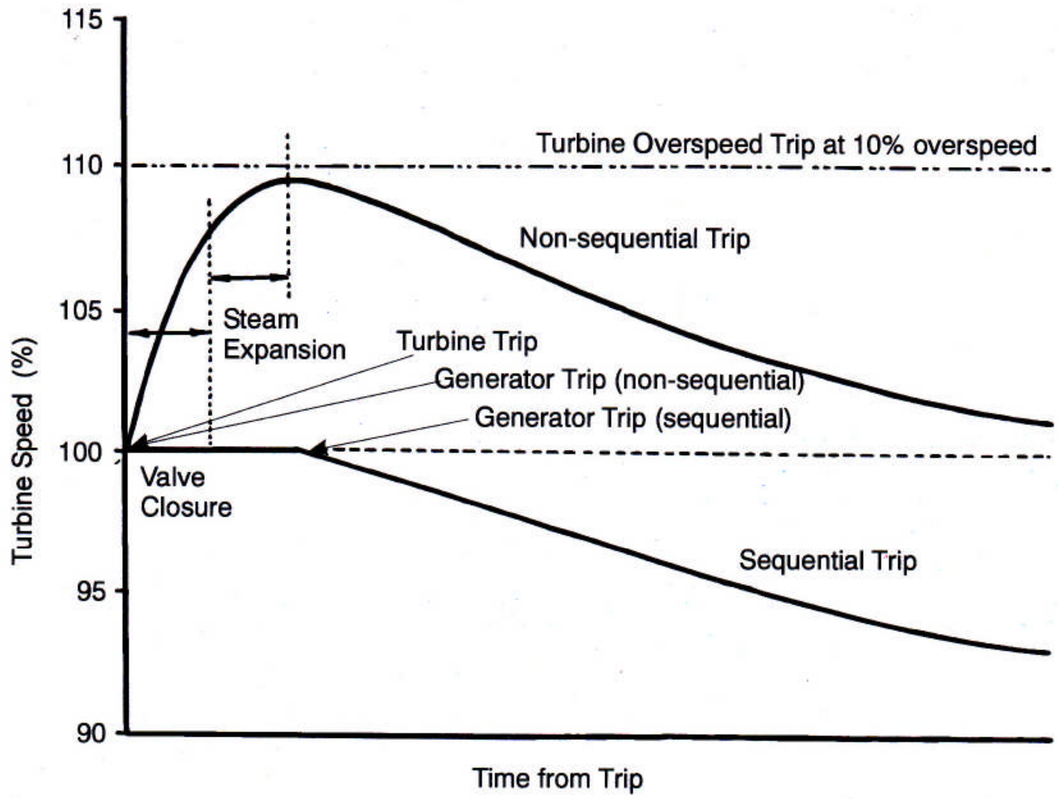


Figure 34 Turbine generator non-sequential and sequential trips

In a load rejection, the power output from the generator is drastically reduced, and closure of the steam inlet valves must be initiated immediately. Even so, the mismatch between power input to the turbine as steam and power output from the generator will accelerate the turbine into an overspeed condition (about 8% above normal speed). This speed transient is not quite as severe as in a non-sequential turbine trip because some surplus power is diverted into the unit services, which account for between 6% and 7% of the full generator power output. Naturally, this speed transient affects the electrical frequency of the supply to the unit services, and the motors of the auxiliaries suffer the same speed transient. Once the speed transient has passed and the turbine speed returned to normal, steam must once again be admitted to the turbine to provide enough power to drive the auxiliaries and to maintain the normal speed condition. The governed speed when supplying only the station load is, however, somewhat above the normal running speed due to the speed droop setting on the governor. The difference between the two speeds is known as the *permanent speed rise*. Returning the speed to normal requires adjustment to the governor. The speed transient arising from a load rejection is illustrated in Figure 35. This assumes no adjustment to the governor settings, but modern control systems initiate a turbine runback to bring the speed back to approximately normal running speed. As before, the speed rise is in seconds and the speed drop in minutes.

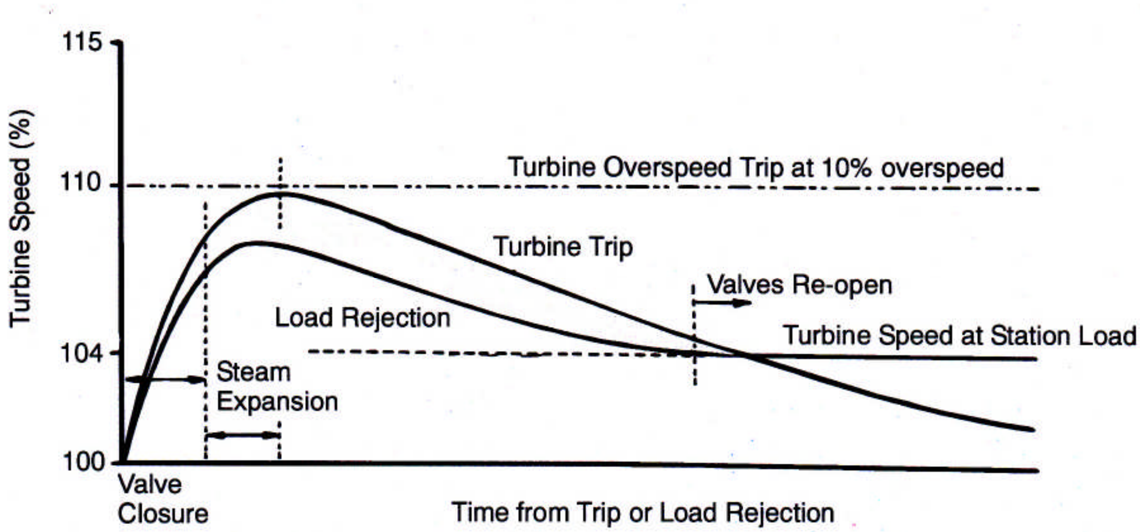


Figure 35 Turbine-generator load rejection

8.12 Turbine Overspeed Protection

All turbines are fitted with direct acting overspeed protection. This usually takes the form of mechanical spring loaded eccentric rings or bolts mounted on the turbine rotor. At an overspeed of about 110% or slightly more of normal speed, they operate and trip the hydraulic circuit of the steam inlet valves. This action is entirely independent of the governing system or other tripping circuits.

In the event of a load rejection and failure of the governing valves to close, the turbine speed would continue to rise. At an overspeed in excess of 110% of normal speed, the overspeed trip would be activated to close the emergency stop valves, and also the governing valves if their failure to close was a governing system failure.

An important aspect regarding the above scenario is that, while a load rejection is initiated at 100% of normal speed, the overspeed trip is activated at about 110% of normal speed. In the event of a governing system failure, the turbine therefore accelerates under full steam flow from 100% to 110% of normal speed before the steam inlet valves begin to close. They take a finite time to close, and after that, the trapped steam expands. During this period, the turbine continues to accelerate into an even higher overspeed condition, as shown in Figure 36. This can be as high as 118% to 120% of normal speed depending upon the turbine design. The turbine overspeed protection does not therefore limit the turbine speed to the settings selected. It is the last line of defence and should be treated accordingly. Any overspeed in excess of the overspeed trip setting should be regarded as dangerous because turbine rotors are overspeeded to only about 125% of normal speed at the manufacturers' facility to confirm their integrity.

The transient overspeed arising from a non-sequential turbine trip or a load rejection should always be below the overspeed trip settings to demonstrate proper operation of the governing system and to avoid a turbine trip following a load rejection.

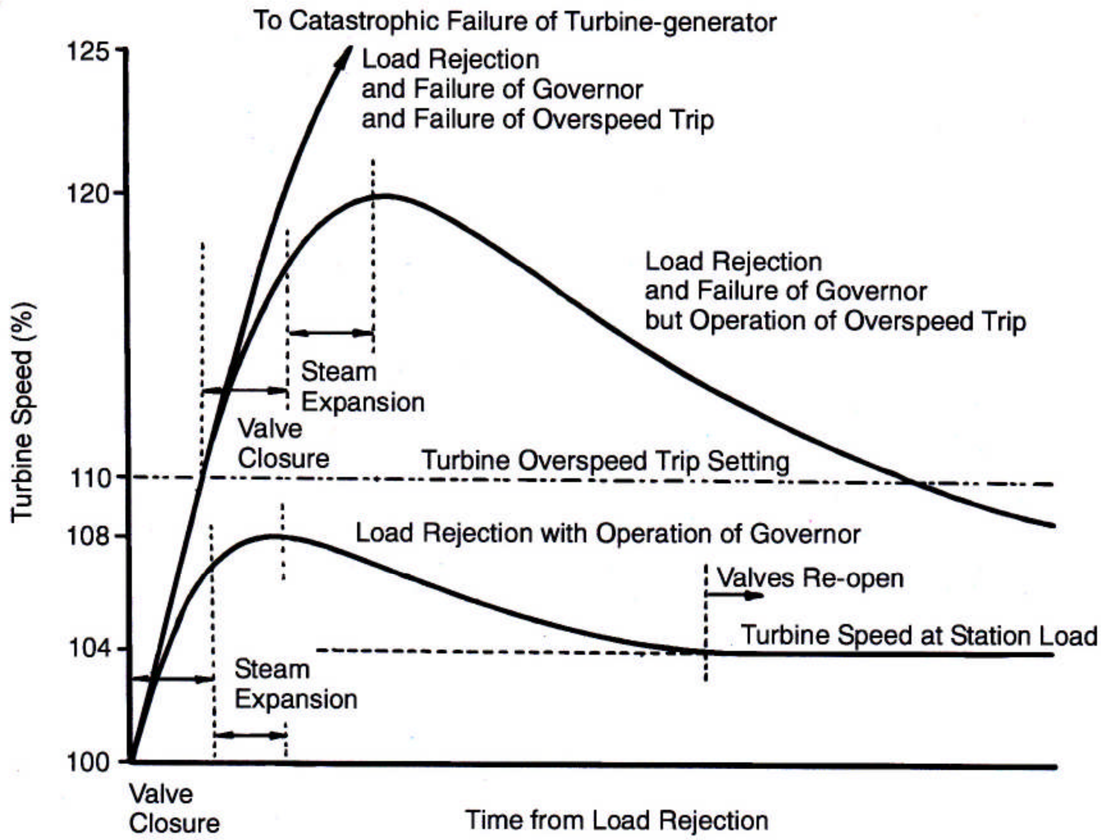


Figure 36 Turbine generator overspeed trip

9 Problems

1. List the key controlling units of a CANDU nuclear plant and explain their function and how they operate. Clarify the difference between normal and alternate modes of operation and explain which controlling units are affected and how they are affected by a change from one mode to the other.
2. Explain how the reactor is protected from abnormal operating conditions and potential accident conditions arising from process excursions or equipment failures.
3. Explain how the turbine is protected from abnormal operating conditions and from potential accident conditions arising from control malfunctions or equipment failures.
4. Explain the theoretical aspects related to the approach to criticality in a reactor, noting in particular the relationship between stabilization time and reactivity added. Explain also how the point of criticality can be predicted and how one knows when criticality has been achieved.
5. Describe the approach to criticality technique used in a CANDU reactor and clarify why this step-wise method has an inherent safety feature.
6. Explain how reactor reactivity changes during operation, noting which key fission products affect reactivity over the life of the fuel. Illustrate these changes in a diagram and

show on the diagram at which point refuelling is necessary. Assume that the reactor initially has new fuel only.

7. Assuming that a hypothetical steam generator operates under the following conditions:

Steam temperature	260°C (saturated steam)
Feedwater temperature	260°C (saturated water)
Steam flow	500 kg/s
Primary coolant pressure	10 MPa
Primary inlet temperature	290°C
Primary outlet temperature	270°C.

   a. Calculate the primary coolant mass flow rate.

   Assuming that the primary coolant mass flow rate is constant and that the heat transfer coefficients remain constant, determine the following:

   b. Primary system temperatures when the steam flow rate is increased to 1000 kg/s, assuming that the steam pressure is kept constant.
   c. Secondary steam pressure when the steam flow rate is increased to 1000 kg/s if a temperature of 300°C in the primary system is not to be exceeded.

   For both (b) and (c) above, sketch the temperature variation along the length of the tube bundle and show terminal temperatures. Assume a linear rise in temperature of the primary coolant.

8. Illustrate the two modes of operation of a typical CANDU unit as follows:
   a. Sketch a typical pressure control system for a steam generator when operating in the reactor leading mode.
   b. Sketch a typical pressure control system for a steam generator when operating in the turbine leading mode.

   Each sketch should show the nuclear reactor, steam generator, and turbine generator as well as the primary sensors and control elements. For each, describe how the system would respond to a transient load condition (increase or decrease in load).

9. Explain the terms “swelling” and “shrinking” when applied to a boiler or steam generator. Clarify the difference between steady state and transient conditions and explain what causes each to occur. As clarification, review the sequence of events following a load change on the system. Explain briefly what effect this has on a single element level control system.
10. If the pressure in the steam generator drops from 4.0 MPa to 3.9 MPa, determine what percentage by mass of the water in the steam generator will immediately be converted to steam. If this steam remains in suspension in the water in the form of bubbles, by what percentage will the water swell (transient swelling)?
11. In large CANDU plants, the steam generator level set point is usually programmed so that the water level is lower at low power levels than at high power levels. Explain why the water level set point is different for different power conditions. Clarify how the water inventory in the steam generator changes as the level set point is ramped up and down.
12. Show in a sketch how steam generator level varies with load in a typical CANDU steam generator. Show also in a separate sketch how steam generator inventory would be expected to vary with load. Discuss the relative merits of maintaining constant level or

constant inventory in the steam generator and clarify to what extent these are achieved with the current arrangement.

13. Consider a typical three element controller for a steam generator.
    a. Sketch the control system used to control the water level. Show what measurements are taken and how the signals are processed by the control system. The diagram must be sufficiently detailed and fully labelled so as to be self-explanatory.
    b. Explain why a three element controller is used instead of a single element (level only) controller. Support the explanation with an example demonstrating when and why a single element controller may give an incorrect response.
14. In the event of a turbine-generator trip or load rejection from full load, the reactor power is decreased and maintained at a certain level to prevent excessive buildup of xenon in the reactor and surplus steam is dumped to the condenser.
    a. Explain what limits the maximum amount of steam that can be rejected and state the usual limit.
    b. Explain why water is mixed with the steam before release into the condenser. Estimate the condition of the steam before mixing with water and hence determine how much water must be added per kilogram of steam.
15. Consider a condenser operating under the following conditions:

Cooling water inlet temperature	10°C
Cooling water outlet temperature	20°C
Steam inlet (saturation) temperature	30°C.

    Sketch the anticipated temperature profiles for both cooling water and steam across the condenser (that is, along the tubes) for each of the following conditions:
    a. Given or normal conditions.
    b. Cooling water inlet temperature increased to 16°C.
    c. Cooling water flow reduced to 1/2 its original value.
    d. Turbine load reduced to 1/2 its original value.

    Assume a linear change in cooling water temperature along the tubes.
16. Consider a condenser which operates at 0.005 MPa and condenses steam with a moisture content of 10% at a rate of 600 kg/s. Cooling water enters the condenser at 13°C and leaves at 23°C. Determine the following:
    a. Temperature profile (sketch) across the condenser (along the tubes from inlet to outlet).
    b. Average temperature difference between steam and cooling water.

    Having established the basic condenser parameters given above, determine what changes in these parameters would occur and what their magnitude would be for the following new conditions:
    c. Cooling water inlet temperature increase to 18°C.
    d. Cooling water flow rate decrease to 50%.
    e. Fouling of condenser tubes which decreases overall heat transfer coefficient by 25%.
    f. Reduction in steam flow to condenser to 400 kg/s.

For each case, sketch the new temperature profile across the condenser, assuming a linear change in cooling water temperature along the tubes and average temperature differences.

17. The condenser of a large steam turbine receives exhaust steam at varying flows depending upon the prevailing turbine output. On axes of condenser pressure versus condenser steam flow, sketch the following:
    a. Variation in condenser pressure with steam flow into the condenser (due to variation in turbine output).
    b. Variation in condenser pressure with steam flow into the condenser at a cooling water temperature <u>higher</u> than that in (a) above.

    Explain why the condenser performance curve has the shape shown and why the variation shown in (b) is different from that shown in (a).
18. Explain how the flow of steam through the turbine is affected by low load operation. Clarify what adverse conditions arise in the last stage blading under low load conditions and how this affects turbine performance. Explain how these adverse effects can be minimized.
19. Describe motoring and explain under what conditions the turbine would be subject to motoring. Give the advantages of motoring and note the precautions that must be taken when motoring.
20. Consider the start-up phase of turbine operation.
    a. Explain in detail the cause of sagging and clarify under what circumstances sagging of the turbine shaft can occur.
    b. Explain in detail the cause of hogging and clarify under what circumstances hogging of the turbine shaft can occur.
    c. Explain why such states are not desirable and the adverse consequences arising from such deformation.
    d. Explain how such states can be prevented from occurring or alleviated if such conditions exist.
21. Explain axial differential expansion in a large steam turbine. Explain how this can be minimized by proper location of the thrust bearing in the case of a large nuclear unit. Support the explanation with a suitable sketch showing the direction of expansion of rotor and casing. Show the fixing points of the casing and the location of the thrust bearing. Clarify under what conditions excessive axial differential expansion can occur. Describe the adverse consequences caused by excessive axial differential expansion.
22. Explain the operation of the following and clarify under what circumstances each would be used:
    a. Regular governor when controlling speed.
    b. Regular governor when controlling load.
    c. Emergency overspeed governor.
23. Describe the sequence of events and the turbine response during the following tripping modes. Clarify under which circumstances each would occur and sketch the speed response of the turbine in each case.
    a. Sequential turbine trip.
    b. Non-sequential turbine trip.
    c. Turbine load rejection.

Show on each sketch the period during which the governor valve closes and the period of steam expansion in the turbine.

24. Explain how a turbine is protected against excessive overspeed. Describe a potential sequence of events with associated physical phenomena that could lead to the total destruction of the turbine.

Answer Guide for Chapter 9

1. See Section 2.1 CANDU Plant Control Systems and Figure 2 Basic plant control system.
2. See Section 2.2 Reactor Protection Systems, Section 2.3 Reactor Shutdown Systems and Section 2.4 Emergency Coolant Injection.
3. See Section 2.5 Turbine Protection System.
4. See Section 3.3 Approach to Criticality as well as Figure 4 Stabilization time for different subcritical multiplication factors and Figure 6 Approach to critical – inverse count rate change.
5. See Section 3.4 Approach Technique and Section 3.5 Reactor Start-up.
6. See Section 3.7 Fuel Burnup and Figure 8 Effects of fuel burnup on reactivity.
7. See Section 5.1 Plant Control and Figure 9 Steam generator temperature profile.
   Use Steam Tables. (a) Flow rate M = 8008 kg/s assuming light water. (b) Inlet temperature t = 290°C. Outlet temperature t = 310°C. (c) Steam Temperature t = 250°C. Steam pressure p = 3.97 MPa.
8. See Section 5.2 Steam Generator Pressure Control and Figure 2 Basic plant control system.
9. See Section 5.3 Swelling and Shrinking as well as Figure 10 Steady state swelling due to different load conditions and Figure 11 Transient swelling due to changing load conditions.
10. Use Steam Tables. Amount of water converted to steam = 0.26%. Degree of swelling = 10%.
11. See Section 5.4 Steam Generator Level Control as well as Figure 12 Constant steam generator water level and Figure 13 Ramped steam generator water level.
12. See Section 5.4 Steam Generator Level Control and Figure 15 Steam generator level alarms and set points.
13. See Section 5.4 Steam Generator Level Control and Figure 14 Three element steam generator level control system.
14. See Section 6.1 Characteristics and Function and Section 6.2 Atmospheric and Condenser Steam Discharge Valves. Use Steam Tables. Assume a steam generator pressure of 5 MPa and a condenser pressure of 0.005 MPa. Water required = 0.10 kg water per kg steam.
15. See Section 7.1 Thermodynamics and Heat Transfer and Figure 18 Changes in condenser temperature profile. (a) Steam temperature = 30°C. (b) Steam temperature = 36°C. (a) Steam temperature = 35°C. (a) Steam temperature = 20°C.
16. See Section 7.1 Thermodynamics and Heat Transfer and Section 7.4 Condenser Tube Fouling as well as Figure 18 Changes in condenser temperature profile. (a) Steam temperature = 33°C. (b) Average temperature difference θ = 15°C. (c) Steam temperature = 38°C. (d) Steam temperature = 38°C. (e) Steam temperature = 38°C. (f) Steam temperature = 26°C.

17. See Section 7.1 Thermodynamics and Heat Transfer as well as Figure 19 Variation in condenser pressure and Figure 20 Condenser performance curves.
18. See Section 8.4 Turbine Load Variation as well as Figure 31 Change in whirl velocity at low loads and Figure 32 Recirculation of steam at low loads.
19. See Section 8.4 Turbine Load Variation.
20. See Section 8.1 General Operational Considerations.
21. See Section 8.5 Differential Expansion and Figure 33 Differential axial expansion of turbine rotors and casings.
22. See Section 8.6 Turbine Governing.
23. See Section 8.9 Turbiine Trip.
24. See Section 8.12 and Figure 36 Turbine generator overspeed trip.

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