NOTES & REFERENCES

Module 234-11

STARTUP AND LOADING

OBJECTIVES:

After completing this module you will be able to:

11.1 Explain the reason(s) why:

- a) The condensate system must be placed in service before the boiler feed system may be started (2); ⇔ ***Page 5***
- b) At least one CEP must be running before the gland sealing steam system may be started (1); ⇔ ***Page 5***
- c) At least one CEP must be in service before the LP turbine exhaust cooling system may be started (1); ⇔ ***Page 5***
- d) The boiler feed system must be placed in service before the boilers and steam piping can be heated to their normal temperature (1); ⇔ ***Page 5***
- e) Warming of the steam piping should, in principle, be completed before steam is admitted to the turbine (2); ⇔ ***Page 6***
- f) Boiler pressure must be sufficiently high (above approximately 1 MPa(g)) before high condenser vacuum can be achieved (2); ⇔ ***Page 6***
- g) The turbine supervisory system is started prior to the other turbine auxiliary systems (1); ⇔ ***Page 7***
- h) The turbine lube oil system must be in service before the turning gear can be started (1); ⇔ ***Page 7***
- i) The gland sealing steam system must not be placed in service when the turbine generator rotor is stationary (1); ⇔ ***Page 8***
- j) The low condenser vacuum trip in the turbine governing system may have to be gagged prior to steam admission to the turbine (1); ⇔ ***Page 8***
- k) Turbine steam valves are tested prior to turbine runup (1); ⇔ ***Page 9***
- l) At least one CCW pump should be running before the gland sealing steam system is started (1); ⇔ ***Page 10***
- m) Requirements for condenser vacuum become more and more stringent with increasing turbine speed (2); ⇔ ***Page 11***
- n) The LP turbine exhaust cooling system should be placed in service before turbine runup is advanced (1). ⇔ ***Pages 11-12***

Page 15 ⇔ 11.2 List six major operational concerns which affect the startup and loading of a turbine generator.

Pages 15-19 ⇔ 11.3 a) Describe two ways in which thermal stresses are created in steam turbines.

Page 19 ⇔ b) Explain the reason why thermal stresses become particularly large during turbine startups, power manoeuvres, and load rejections.

Pages 19-20 ⇔ c) Explain four other operational causes of large thermal stresses.

Pages 21-23 ⇔ d) Describe four adverse consequences/operating concerns caused by excessive thermal stresses.

Pages 24-26 ⇔ e) Describe four general operating practices used to prevent excessive thermal stresses during turbine startup and loading.

Page 27 ⇔ 11.4 a) Explain how the brittleness of the turbine generator at low temperatures affects cold startups.

Page 28 ⇔ b) For each of the following:

i) Turbine rotor;
ii) Generator rotor,

describe two methods of prewarming that can be used to increase its temperature enough to prevent brittle failure.

Pages 29-30 ⇔ 11.5 a) Explain what is meant by axial differential expansion (ADE).

Pages 30-32 ⇔ b) Explain three reasons why ADE occurs in steam turbines.

Page 33 ⇔ c) Explain the reason why ADE becomes particularly large during turbine startups, power manoeuvres, and load rejections.

Pages 33-34 ⇔ d) Explain four other operational causes of abnormal ADE.

Page 34 ⇔ e) Describe three adverse consequences/operating concerns caused by excessive ADE.

Page 35 ⇔ f) Describe four general operating practices used to prevent excessive ADE during turbine startup and loading.

Pages 35-36 ⇔ g) Describe four major actions performed in response to excessive ADE.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Operational experience with large turbine generators shows that once the unit is running in a steady power condition, there is relatively little chance for a major equipment malfunction or failure. However, during startup or shutdown, abrupt load changes or unit upsets, the conditions imposed on the unit are much more severe, reducing the equipment life and increasing the risk of failure. In order to minimize these undesirable effects during turbine generator startup and loading, it is important that you understand the operating practices that are used. While details are left for the station specific training, this module covers the following topics:

- Major actions occurring during startup and loading of the steam and feedwater cycle systems*;
- Major operational concerns affecting the turbine generator startup and loading, including:
  - Thermal stresses;
  - Brittleness at low temperatures;
  - Axial differential expansion.

* Recall that these systems include the boiler, steam system, turbine, condenser, feedheating system and their auxiliaries.

Due to numerous station specific differences, the information presented in this module is very general. This is particularly true with respect to the first topic listed above. As for the second topic, you have probably noticed that its scope is limited only to the turbine generator. This stems from the fact that the major operational problems concerning the boiler, steam system, condenser, feedheating system and their auxiliaries have already been covered in the previous modules.

MAJOR ACTIVITIES DURING STARTUP AND LOADING OF THE STEAM AND FEEDWATER CYCLE SYSTEMS

The intent of this section is to achieve two goals:

1. To give you a general overview of the major activities performed during startup and loading of the steam and feedwater cycle systems.

   This overview is only for orientation purposes (no exam question on this matter will be asked).

2. To explain why most of these activities must be performed in a certain sequence in order to avoid serious operational problems.

   You mav be tested on this material.

You will find that, to a large extent, the information presented in this section is a synthesis of the previous modules where individual systems were discussed, one at a time.

A pullout diagram (Fig. 11.6) at the module end depicts the major activities performed during startup and loading of the steam and feedwater cycle systems*. You are advised to unfold this diagram and keep it in sight for reference, while studying this section. To help you locate individual activities in this diagram, their start and end points are specified in the corresponding description below. The points are numbered in the typical order of their occurrence during a unit startup.

It is assumed in Fig. 11.6 that:

- The initial unit state is an extended shutdown with all major systems in the shutdown state. Note that in the case of a short outage, many of these systems may remain in service (eg. the turbine generator may still be on turning gear).
- The following auxiliary systems are already in service, providing the power and coolant necessary for operation of the remaining systems:
  - All classes of electrical power;
  - The LP and HP service water systems;
  - All compressed air systems.

Initially, startup activities are performed on a few parallel paths to save time:

- Activities 1-4-5-9 which establish the boiler feedwater flow and prepare the steam system for supplies of steam to the turbine and other equipment (eg. reheaters);
- Activities 1-2-3-6 which place the turbine generator on turning gear in preparation for runup;
- Activities 3-7-9 which prepare turbine steam valves for steam admission to the turbine;
- Activity 1-6 which places the CCW system in service;
- Activities 6-8-11 which produce condenser vacuum required for turbine operation.

After the above activities have been completed, most of the remaining activities are performed sequentially. More specifically, activities 9-11-12-13-14 result in turbine generator runup, followed by synchronization with the grid, and finally loading. The only exception is activity 10-11 which places the LP turbine exhaust cooling system in service. This activity can be done in parallel with the initial phase of turbine runup, as shown in Fig. 11.6.

In the text that follows, each activity is described in more detail.

* Note that the reactor, the generator and their auxiliary systems are not included.

NOTES & REFERENCES

Placing the condensate system in service (activity 1-4)

⇔ ***Obj. 11.1 a)***

The condensate system must be placed in service **prior to the boiler feed system** in order to:

- Ensure adequate supplies of condensate to the suction of the BFPs such that the boiler feedwater flow can be sustained;
- Provide injection of cool condensate to the BFP glands, thereby preventing pump damage.

The condensate flow must also be available **before the gland sealing steam and LP turbine exhaust cooling systems can be placed in service.** The reasons are:

⇔ ***Obj. 11.1 b)***

- Cooling of the gland exhaust condenser must be established before any gland leak-off steam enters this condenser. You will recall that this prevents overheating of the gland exhaust fans, steam egress from the turbine and steam valve glands, and formation of steam pockets in the gland exhaust condenser tubes. The latter can lead to steam hammer in the condensate system as explained in module 234-6.

⇔ ***Obj. 11.1 c)***

- The condensate is used as a cooling medium in the LP turbine exhaust cooling system.

The following major steps are performed while placing the condensate system in service. First, the inventory of makeup water is checked and adequate supplies are secured. The feedwater chemical treatment system is placed in service. The whole condensate system, including the DA storage tank, is vented and filled, using the auxiliary CEP.

Once the DA storage tank level is high enough, the electric immersion heaters in the tank are switched on to prewarm the condensate in the tank. Later on, when boiler warming (activity 5-9) is advanced enough, boiler steam (typically referred to as *startup steam*) becomes available for DA heating and the electric heaters are switched off. Meanwhile, one main CEP is started, upon which the auxiliary CEP is shut down and placed in the standby mode. Additional CEPs are started during unit loading, to meet the increasing DA demand for condensate.

Placing the boiler feed system in service (activity 4-5)

⇔ ***Obj. 11.1 d)***

This activity must be completed, **before** the boilers can be used as a long term heat sink for the HT system. Since boiler steam is required for steam pipeline warming, the boilers – and hence, the boiler feed system – must be in service before the warming (activity 5-9) can begin. Therefore, placing the boiler feed system in service is a prerequisite for activity 5-9.

To place the boiler feed system in service, the piping and the boilers are vented and filled, using the auxiliary BFP. If required for accelerated prewarming of the DA storage tank condensate, 1-2 main BFPs can be started*

* Recall from module 234-6 that BFP operation in the recirculation mode is not recommended.

NOTES & REFERENCES

once the tank is filled up. Otherwise, the main BFPs are started later, as required by the increasing boiler demand on feedwater. Once the first main BFP is started, the auxiliary BFP is placed in the standby mode.

Warming up the boilers and steam pipelines (activity 5-9)

Obj. 11.1 e) ⇔

In principle, this activity must be completed **before steam is admitted to the turbine** in order to prevent:

- Excessive thermal stresses in the steam system;
- Water hammer in the steam system and water induction to the turbine*.

* These problems have been explained in module 234-3.

In most stations, it is possible – though not recommended – to begin turbine runup when boiler pressure is slightly below its normal value.

Obj. 11.1 f) ⇔

Warming of the boilers **must also be significantly advanced**, though not necessarily finished, **to enable pulling condenser vacuum** (activity 8-11) to a level required for turbine operation. There are two reasons for this dependence:

- The required high condenser vacuum cannot be achieved without sealing the turbine and steam valve glands. This is performed by the gland sealing steam system which is supplied with boiler steam. For the system to be able to adjust the sealing steam pressure properly, the boiler steam pressure must be sufficiently high*;
- In many stations, the vacuum pumps in the condenser air extraction system are of steam jet air ejector type. For proper operation, they need boiler steam at sufficient pressure*.

* Usually, at least 1 MPa(g).

* Again, at least 1 MPa(g).

Recall that warming of the boilers and steam pipelines is associated with gradual warming of the heat transport (HT) system. During this process, the reactor and HT pumps supply heat, most of which is allowed to remain in the HT system, boilers and steam pipelines, thereby raising their temperature. The heatup rate is controlled by rejecting the surplus heat in boiler steam to atmosphere or – in the stations with CSDVs – to the main condenser (if operative). Note that warming of the steam pipelines includes not only the main steam piping to the turbine, but also the reheat system piping, the CSDV steam piping, the DA startup and poison prevent heating steam piping, etc.

Naturally, steam contact with the relatively cool pipework results in **intensive condensation** of the steam. It is, therefore, **very important that the drain valves stay open**. Failure to do this may result in accumulation of water in the lowest points of the pipelines, leading to water hammer in the steam system and water induction to the turbine when the first steam is admitted.

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- The condensate system must be placed in service prior to the boiler feed system for two reasons. First, condensate must be supplied to the suction of the BFPs in order to sustain boiler feedwater flow. Second, cool condensate must be injected to the glands of the BFPs in order to prevent pump damage.
- The condensate system must be in service before the gland sealing steam system is started. Otherwise, lack of cooling of the gland exhaust condenser can result in overheating of this condenser and the gland exhaust fans. Steam hammer in the condensate system could also occur.
- Because the LP turbine exhaust cooling system uses condensate as a cooling medium, it cannot operate without the condensate system in service.
- The boiler feed system must be in service before the boilers can be used as a reactor heat sink, and hence, before the boilers and steam piping can be warmed up to their normal temperature.
- Steam pipelines must be properly warmed and drained before steam is admitted to the turbine in order to prevent excessive thermal stresses and water hammer in the piping, as well as water induction to the turbine.
- Boiler pressure must be sufficiently high to enable pulling condenser vacuum to a level at which turbine runup can begin. This is because the gland sealing steam system and the steam jet air ejectors require boiler steam at sufficient pressure for their proper operation.

Placing the turbine supervisory system in service (activity 1-2)

⇔ Obj. 11.1 g)

Since the turbine supervisory system provides essential data about the operating state of the turbine generator and its auxiliaries, it is **placed in service before other turbine generator auxiliary systems are started.** Note that the system sensors also provide input to DCC software: the Turbine Run-Up (TRU) program and Unit Power Regulator (UPR) which are used in most stations for automatic turbine startup.

Placing the turbine lubricating oil system in service (activity 2-4)

⇔ Obj. 11.1 h)

The turbine lubricating oil system must be running **before the turning gear can be started.** The purpose is to establish adequate lubrication of the turbine generator bearings and the turning gear itself. Recall that to protect this equipment from damage, the control circuit of the turning gear motor has interlocks preventing its operation when the lube and jacking oil pressures are too low.

In the units where the turbine lube oil is also used as a hydraulic fluid in the turbine governing system, the turbine lubricating oil system must be started first. This is why in Fig. 11.6, this activity is shown as a prerequisite for placing the turbine governing system in service (activity 3-7).

If not already running, the purifier and the vapour extraction fans are started. Because the purifier circuit includes a heater, it can be used for prewarming when oil is too cool to be supplied to the turbine generator bearings.

Next, cooling water to the lube oil coolers is valved in, and a lube oil pump (usually, the auxiliary oil pump) is started. Finally, the jacking oil pumps are placed in service.

Placing the turbine on turning gear (activity 3-6)

Recall from module 234-9 that during startup, the turbine is put on turning gear for two purposes:

- To straighten the rotor before runup begins;
- To enable prewarming of the turbine without causing hogging.

In the case of a startup following an extended shutdown, the turbine may have to remain on turning gear for up to 24 hours.

Obj. 11.1 i) ⇔

Note that this activity is **one of the prerequisites for placing the gland sealing steam system in service** (activity 6-8). Otherwise, applying hot sealing steam to the stationary turbine would quickly result in its hogging due to thermal stratification of the steam/air atmosphere inside the machine. This would delay runup until the hogging is rolled out.

Placing the turbine governing system in service (activity 3-7)

This activity must be completed **before turbine steam valves can be tested** (activity 7-9).

Part of the system startup is to make sure the hydraulic fluid for valve actuation is available. In most stations, this is provided by starting up the FRF system (recall that in a few units, the turbine lubricating oil is used instead).

Obj. 11.1 j) ⇔

When the hydraulic fluid is available, the rest of the governing system is placed in service. The no-load speed and load limiter setpoints are properly adjusted, and the tripping mechanism tested. In some stations, **the low condenser vacuum trip is temporarily** disabled (or **gagged** as it is commonly referred to) to prevent it from interfering with the rest of the system. The advantage of doing this is that turbine runup can begin earlier, ie. without having to wait for full condenser vacuum. Later on during runup, the gagging is removed.

Prerunup checks of turbine steam valves (activity 7-9)

⇔ ***Obj. 11.1 k)***

When the turbine governing system is operational, the turbine steam valves can be tested. This is performed prior to turbine runup **in order to detect valve malfunction before steam is admitted to the turbine.** The purpose of this precaution is to minimize chances for operational problems (eg. speed control) and possible equipment damage due to valve failure during turbine runup and loading. Of course, if during these tests any valve is found in poor condition, turbine startup is delayed until the valve is repaired.

During the valve checks, the turbine isolating valves are closed to prevent steam flow through the turbine. Once the tests are complete, the valves are opened to allow prewarming of the steam piping running to the closed emergency stop valves.

SUMMARY OF THE KEY CONCEPTS

- The turbine supervisory system is placed in service before other turbine auxiliary systems are started because it provides essential data about the operational conditions of the turbine generator and its auxiliaries.
- The lube oil system must be placed in service before the turning gear can be started. Otherwise, interlocks in the turning gear motor circuit would not allow for its startup. This prevents damage to the turbine generator bearings and the turning gear itself due to lack of adequate lubrication.
- The turbine must be put on turning gear before gland sealing steam is applied. Otherwise, turbine hogging would result due to thermal stratification of the steam/air atmosphere inside the machine. Turbine runup would have to be delayed until the hogging is removed.
- The turbine governing system must be in service in order to allow for prerunup testing of turbine steam valves.
- The low condenser vacuum trip may have to be gagged prior to steam admission to the turbine to allow turbine runup to begin before full condenser vacuum is pulled. This expedites getting the unit on line.
- Turbine steam valves are tested prior to steam admission to the turbine in order to detect valve malfunction before the turbine is run up. This minimizes the risk of operational problems and possible equipment damage due to valve failure during turbine runup or loading.

NOTES & REFERENCES

Placing the CCW system in service (activity 1-6)

Obj. 11.1 l) ⇔

Placing the CCW system in service establishes cooling of the main condenser before any thermal load is imposed. Note that without this cooling and given enough time, hot steam leaking into the condenser (eg. from the turbine gland seals) could raise its pressure and temperature enough to cause damage. For example, excessive pressure may rupture a bursting disc in a LP turbine exhaust cover. Though it would take a long time* before the leaking gland steam could cause such damage, a prudent precaution is to have **at least one CCW pump running before the gland sealing steam system is started.**

* A few hours.

To place the CCW system in service, the vacuum priming system (if installed) and one CCW pump are started. Gradually, gases are evacuated from the CCW system piping, condenser water boxes and tubes, resulting in their priming with cooling water. Thus, a syphon action is established in the CCW system. The remaining CCW pumps are then started. Their startup procedures must be closely followed to avoid water hammer in the system*.

* This has already been described in module 234-5.

Placing the gland sealing steam system in service (activity 6-8).

Operation of the gland sealing steam system is closely associated with pulling condenser vacuum (activity 8-11). Two **different approaches are used in different stations**, depending on the turbine manufacturer's operational experience.

In some stations, the gland sealing steam system is placed in service before pulling condenser vacuum begins*. The advantage is that air is not sucked into the turbine through the unsealed glands when the vacuum is being pulled. Not only does it facilitate pulling vacuum, but it also prevents contamination of the glands, and ultimately boiler feedwater, with dirt and possibly oil from the adjacent bearings.

* This is reflected in Fig. 11.6 where activity 6-8 is shown as a prerequisite for activity 8-11.

In the other stations, placing the gland sealing steam system in service is delayed until partial condenser vacuum has been drawn. This reduces the period of time during which hot gland sealing steam is applied to the turbine while condenser vacuum is very poor or zero. Note that due to the effect of pressure on saturation temperature, such poor vacuum increases steam temperature inside the turbine exhaust in the direct vicinity of the glands. This is where the gland steam leakoff tends to collect when there is no steam flow through the turbine*. As the leakoff replaces air, the steam partial pressure approaches the turbine exhaust pressure. If this pressure is relatively high (ie. poor condenser vacuum), so is the corresponding saturation temperature. Through localized heating of this part of the turbine, this hot steam can cause excessive axial differential expansion*. This can be avoided by pulling satisfactory condenser vacuum before valving in the gland sealing steam.

* Note that during normal operation, the gland steam leakoff does not collect there because the large turbine steam flow just sweeps it away.

* Axial differential expansion is defined on pages 29-30.

Pulling condenser vacuum (activity 8-11)

Pulling condenser vacuum should begin prior to turbine runup such that condenser pressure is reduced to a satisfactory level* before turbine speed is increased. Then, pulling condenser vacuum and turbine runup are continued together.

* At least, below 50 kPa(a).

⇔ *Obj. 11.1 m)*

With rising turbine speed, the requirements for condenser vacuum become more and more stringent. For example, while turbine runup may begin at a condenser pressure not exceeding 50 kPa(a), the pressure must be reduced to at least 15 kPa(a) at 800-1000 rpm, and 8 kPa(a) at 1500-1600 rpm*.

* These numbers are quoted just to illustrate the point. You do not have to memorize them. The vacuum requirements used in your station may differ slightly.

There are two reasons for increasing the vacuum requirements with rising turbine speed:

1. To reduce the tendency of the LP turbine exhaust to overheat.
2. To prevent excessive flow-induced vibration* of the moving blades in the turbine last stage(s).

* Blade vibration is covered in the last module.

Recall from module 234-1 that both these operational problems are caused by drastic deterioration of the flow pattern in the last stages when the steam moves slower than the turbine blades.

To prevent excessive deterioration of the flow pattern, the steam velocity must increase when the blade velocity increases with rising turbine speed. Recall that for the steam velocity to increase, the pressure ratio in the last stages must increase as well. This happens when condenser vacuum is raised. The higher the condenser vacuum during turbine runup, the better the flow pattern in the last stages.

Condenser vacuum is pulled by the vacuum pumps in the condenser air extraction system. They evacuate air from the condenser shell, LP and HP turbines and associated steam pipelines (incl. extraction steam piping) up to the closed governor valves. To expedite this process, all available vacuum pumps are used.

Placing the LP turbine exhaust cooling system in service (activity 10-11)

⇔ *Obj. 11.1 n)*

The LP turbine exhaust cooling system should be placed in service (ie. ready to supply water to the cooling sprays when turbine exhaust temperature is high enough) before turbine runup is advanced. This ensures that the system is available when needed to protect the LP turbine exhaust from overheating. Recall that with rising turbine speed, more frictional heat is produced in the turbine last stages when the blades churn the steam faster and faster. This heat may raise the turbine exhaust temperature to a level requiring system operation, particularly if the runup is slow or turbine loading deferred.

NOTES & REFERENCES

In practice, the system is usually placed in service before turbine runup begins so that the operator can concentrate on monitoring the runup closely.

SUMMARY OF THE KEY CONCEPTS

- At least one CCW pump should be running before the gland sealing steam system is started. This prevents the gland leak-off steam from raising condenser pressure and temperature excessively.
- In some stations, the gland sealing steam system must be in service before pulling condenser vacuum begins. This prevents dirt, and possibly bearing oil, from being sucked into the turbine through the unsealed glands. In the other stations, the gland sealing steam system is placed in service only after partial condenser vacuum has been drawn. By shortening the time during which hot gland sealing steam is applied, turbine axial differential expansion is minimized.
- Turbine runup should not begin until proper condenser vacuum has been reached. The vacuum requirements grow with rising turbine speed in order to minimize blade vibration in the turbine last stage(s) and the tendency for overheating of the LP turbine exhaust.
- The LP turbine exhaust cooling system should be placed in service before turbine runup is advanced to ensure the system availability to protect the LP turbine exhaust from overheating. System operation may be required later on during the runup when large quantities of frictional heat are produced in the last stages due to their blades churning the steam at high velocity.

Pages 37-39 ⇔

You may now answer **assignment questions 1-10.**

Turbine runup (activity 9-11-12)

Before turbine runup begins, careful **checks** are performed to make sure the turbine generator and other systems are ready. Some of these checks include the HP turbine rotor eccentricity, condenser vacuum, lube oil pressure and temperature, position of the drain valves in the steam piping, just to name a few.

When the results are satisfactory, the runup can begin. The turbine steam flow is controlled by the turbine governing system whose no-load speed setpoint is adjusted either by the operator or, most often, by the appropriate DCC software*. In both cases, **the target speed and runup rate** must be determined. This is done either by the operator or by the DCC, depending on the station and the type of runup control (manual versus automatic).

In some stations, runup is performed in a few steps, and for each of them, its own target speed is specified. Of course, all target speeds must be outside the turbine generator critical speed ranges in order to prevent excessive

* In most stations, this is the turbine runup program (TRU).

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vibration. Careful checks of the major turbine generator operating parameters are performed by the DCC control software and/or the operator, before the next step of the runup is begun. In the newer stations, with more sophisticated computer software and instrumentation, usually only the final target speed (1800 rpm) is specified, and the runup progresses automatically until it is completed.

As for **the runup rate**, its **selection** is based on turbine metal and steam temperatures such that excessive thermal stresses* can be avoided.

* More information on runup rates is provided on pages 24-25.

When a bearing vibration reaches or exceeds a certain limit, turbine **runup can be inhibited automatically** and speed held (out of the critical speed ranges). A similar action can be done **by the operator** in response to other operating circumstances, as described in the operating manuals. For example, a speed hold may be required by too low condenser vacuum* or by a turbine supervisory parameter (eg. axial differential expansion) in, or approaching, an alarm range.

* Condenser vacuum requirements increase with turbine speed, remember?

Even if the runup is carried out automatically, it is very important that the operator **monitor major operating parameters**, and not rely entirely on automatic protection. Remember that during runup, the turbine generator passes through critical speed ranges and is subjected to increased thermal stresses and axial differential expansion. This increases the risk of damage. An increased potential for other operational problems exists, too. For example, boiler and DA level control is more difficult at low feedwater flow (because of single element control), and intensive steam condensation occurs in the piping. Hence, chances for water induction to the turbine are increased.

Should any problem develop, the operator can take the control over, or trip, the turbine at any time. Normally, however, the operator's role, in addition to monitoring the turbine supervisory parameters, is to **check** that important **automatic actions** are carried out as required, eg:

- The turning gear disengages when runup begins;
- The turning gear motor and the jacking oil pumps quit at the proper turbine speed;
- The main oil pump takes over the bearing oil supply, and the auxiliary pump stops at the appropriate turbine speed.

Synchronization (activity 12-13)

This activity is described in other courses. In summary, it involves adjustments to turbine speed, generator terminal voltage and phase angle, before the main generator circuit breakers are closed. Synchronization can be performed automatically or manually, depending on the station.

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Loading (activity 12-13)

To load the turbine, the operator specifies **the target generator MW load.** The appropriate **loading rate** is selected either by the operator or, more typically, by the appropriate DCC software. The selection is based mainly on the turbine metal and steam temperatures to avoid excessive thermal stresses*. After that, unit loading progresses at the selected rate until the target load is reached.

* Thermal stresses and the selection of the loading rate are discussed in more detail later in this module.

To effect turbine loading, the no-load speed setpoint to the governing system is gradually raised, causing the turbine steam flow to increase accordingly. The setpoint can be controlled by the operator. Normally, however, it is controlled by the appropriate DCC software. In most stations, this software is UPR (when the unit operates in the reactor lagging mode), and BPC (for the reactor leading mode). At any time, **loading can be inhibited** – and in the extreme case, the turbine tripped – if a problem arises.

Even when the loading is performed automatically, it is important that **the operator monitors** closely all **major parameters** as the potential for equipment damage during this large operational transient is greatly increased as compared with steady power operation. The operator must also make sure that the major **automatic actions** are performed at the proper turbine load as specified in the operating manuals. Some of these actions are:

- Various groups of steam pipeline drain valves close at different turbine loads;
- Boiler level setpoint is gradually ramped up;
- Boiler and DA level control switches to the large control valves;
- Moisture separator drains are directed to the appropriate feedheaters rather than dumped to the condenser;
- "Auto" CEPs and BFPs start up;
- Reheaters are gradually loaded and fully in service at a certain turbine load*;
- DA heating switches from boiler steam to turbine extraction steam.

* Recall that in some stations, this is a manual action.

Based on the information presented in the preceding modules, you should be able to recall the reasons why these actions are performed.

You have probably noticed that the above description of turbine runup and loading brings together many facts already covered in the preceding modules. The purpose is to help you get an overall picture of these activities. This will hopefully facilitate studying of the next section.

MAJOR OPERATIONAL CONCERNS WHICH AFFECT THE STARTUP AND LOADING OF A TURBINE GENERATOR

⇔ ***Obj. 11.2***

This section covers three potential operational problems which can damage the turbine generator if it is started or loaded improperly. These problems are:

- Thermal stresses;
- Brittleness at low temperature;
- Axial differential expansion.

For each of these problems, you will learn about its causes, potential consequences to the turbine generator and the general operating practices used to minimize or prevent it.

Three other important operational concerns are:

- Water induction to the turbine;
- Rotor vibration;
- Blade stresses.

Partially addressed in the previous section*, they are covered in more detail in modules 234-13 and 234-14.

* Recall that steam piping must be properly drained (to prevent water induction), and the condenser vacuum requirements increase with turbine speed (to minimize blade stresses).

THERMAL STRESSES

In this subsection, you will learn the following:

- How thermal stresses are created;
- What adverse consequences and operating concerns they cause, and
- What general operating practices are used during turbine startup and loading to prevent excessive thermal stresses.

Causes

Though thermal stresses were mentioned several times in previous modules, no explanation was given about how they are created. Instead, references were made to this module. And hence, the description that follows applies, in principle, to all equipment.

⇔ ***Obj. 11.3 a)***

Thermal stresses can be defined as stresses that are induced in a component when its **thermal expansion or contraction is restrained**. This can be caused by:

- **External constraints**, ie. other equipment or other parts of the same machine, or
- **Uneven temperature distribution** within the same component such that its hotter and cooler parts attempt to expand (or contract) differently.

The first cause of thermal stresses is illustrated in Fig. 11.1, where a simple object (eg. a straight pipe segment or a metal rod) is shown.

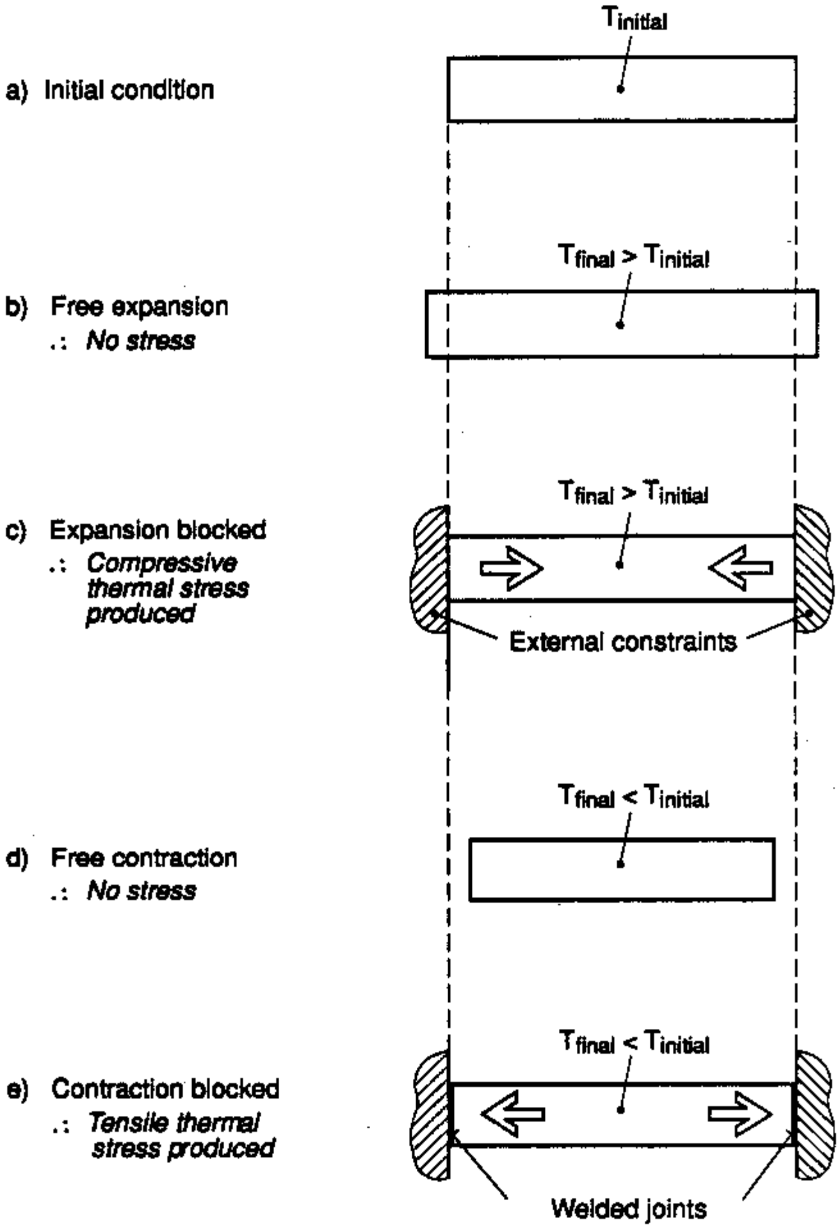

Fig. 11.1. Creation of thermal stresses due to blocking of thermal expansion (contraction) by external constraints.

When there are no external constraints (parts b) and d) of the sketch), heating or cooling of this object produces no thermal stress because the resultant thermal expansion or contraction occurs freely.

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This is not the case in parts c) and e) of the same drawing where the external constraints force the object to retain its initial* length. If you compare parts b) and c) of the sketch, you will see that the external constraints force the object to be shorter than in the case of free expansion. A conclusion can be drawn that blocking of thermal expansion produces compressive thermal stresses. Likewise, comparison of parts d) and e) of the same sketch makes it obvious that tensile stresses are created when thermal contraction is constrained.

It must be emphasized that **blocking of thermal expansion or contraction** of one component by others **is potentially very dangerous**. It does not take a large temperature change to produce damaging thermal stresses. Therefore, we strive to design and operate equipment in such a way that this cause of thermal stresses is avoided.

For example, thermal expansion joints (usually, bellows) and loops are commonly used in piping to accommodate its thermal expansion/contraction at a safe stress level. In the turbine generator, there is only one thrust bearing to allow the rotor to expand/contract freely in the axial direction. Likewise, turbine casings are supported in such a way that only one end is fixed in the axial direction, whereas the other end can slide in guides. Similar guides are used to accommodate casing expansion/contraction in the radial direction as well as to support diaphragms inside the casing. In operation, care must be taken to ensure that the external guides (which are accessible during turbine operation) are well greased and that no foreign object is jammed in. Otherwise, the casing expansion/contraction will be blocked, resulting in buckling of the casing (leading to rubbing and increased vibration) and/or possible damage to its supports.

Fig. 11.2 on the next page illustrates the second cause of thermal stresses. A thick-wall cylinder or bushing is used here as an example to show how an **uneven temperature distribution** within one component (external constraints are absent) **creates thermal stresses.** You will notice some resemblance of this simple object to a thick turbine casing or a hollow rotor.

* For simplicity, the constraints are assumed infinitely rigid. In reality, they would yield somewhat under stress, thereby reducing thermal stresses in the component placed in between.

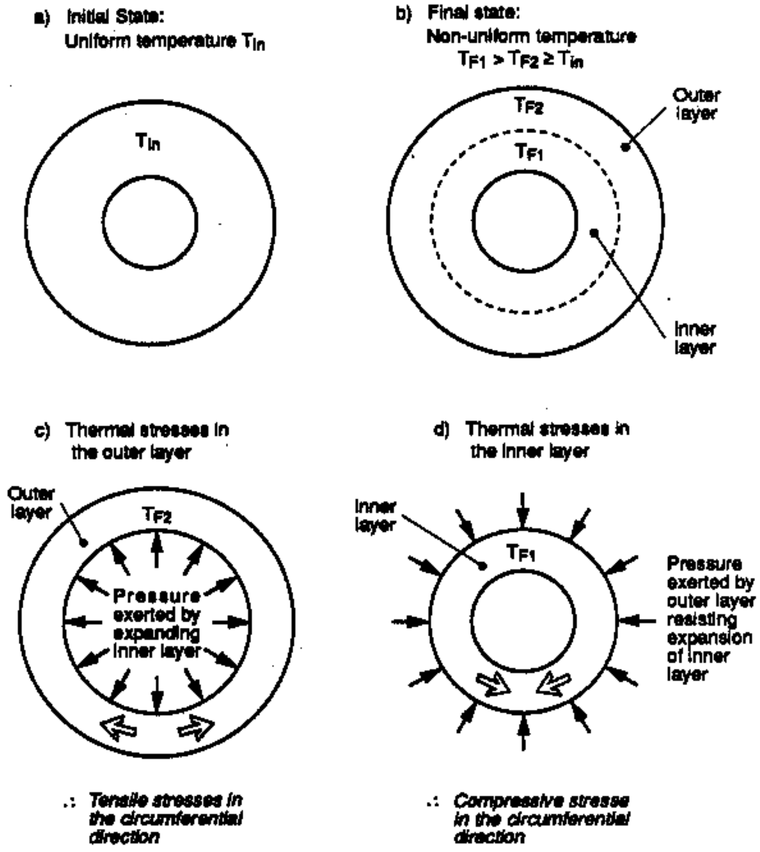

Fig. 11.2. Creation of thermal stresses due to an uneven temperature distribution:
T_{In}, T_{F1}, T_{F2} = Initial and final temperatures.

In the initial state (Fig. 11.2 a), the component is shown at a uniform initial temperature. Of course, it is under no thermal stress. The final stage, shown in part b) of the same sketch, is a result of heating applied to the inner surface (in the bore), as happens in a turbine casing during startup from a cold initial state. You realize that such heating produces a nonuniform temperature distribution. While in reality the temperature would decrease gradually from the inner surface outward, Fig. 11.2 b) simplifies it greatly. Only two temperature zones are assumed to exist: the inner zone which – being closer to the heat source – is hotter, and the outer zone which is cooler. In the drawing, the two zones are separated by an imaginary dashed line. Because the two zones are parts of one undivided body, they cannot expand (or contract) independently, but must reach a compromise.

Since **the inner layer is hotter** than the outer one, it **attempts to expand more**. Thus, it exerts **pressure on the outer layer** as shown in Fig. 11.2 c). The situation is quite similar to a pressurized pipe or vessel. Naturally, such load **produces tensile stresses** in the circumferential direction*.

* Stress analyses show that circumferential stresses exceed all other stresses.

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Due to its lower temperature, **the outer layer** attempts to expand less. Its opposition to the expansion of the inner layer **exerts inward pressure** (Fig. 11.2 d) on the latter, **producing compressive stresses** in the circumferential direction.

In practice, the temperature distribution in any equipment that is much hotter or cooler than its surroundings is always nonuniform. Consequently, some thermal stresses always exist, except for prolonged outages when the temperature stabilizes at the ambient level. Usually, **thermal stresses are fairly low** when the equipment is well insulated and operated **at a steady load**. This is because under such operating conditions, only relatively small local temperature differences (often called *temperature gradients*) exist within the equipment.

⇔ Obj 11.3 b)

However, when equipment is being started up or shut down, or when its load is being changed, thermal stresses increase significantly. Let us now consider a large steam turbine. **During runup, loading, unloading or load rejection, large temperature gradients are set up in the turbine.** This is caused by transient heating or cooling due to changes in the steam temperature and flow*.

Here is how it happens. When the steam temperature changes, **the temperature of the parts** of the turbine casing and rotor which are **in contact with the steam follows quickly**. Then the temperature of the more remote parts changes. This involves transfer of large amounts of heat to or from the metal. The process gradually proceeds towards **the most remote parts** whose **temperature lags behind most**. The larger the turbine, the slower the process, because larger amounts of heat are involved. In the largest turbines, **it may take a few hours** before the most remote parts of the casing and rotor reach their normal operating temperature. Meanwhile, large temperature gradients are created.

⇔ Obj 11.3 c)

Large thermal stresses can also be caused by abnormal operating conditions and accidents. Listed below are four examples:

1. **Water induction to the turbine.**

   If the water is much cooler than the turbine, damaging thermal stresses can be produced due to severe localized quenching of the hot turbine metal. For example, this happens when feedwater enters the turbine via extraction steam piping due to a feedheater tube rupture.

2. **Malfunction or failure of the reheaters, LP turbine exhaust cooling system**, etc.

   Poor performance of this equipment may produce large temperature gradients – and hence, thermal stresses – in some turbine parts. For example, reheater failure could result in an excessive side-to-side temperature difference at the LP turbine inlet, subjecting the casing to large thermal stresses.

* Compared with unloading or load rejection, turbine trips and shutdowns produce smaller thermal stresses because turbine cooling is slower as there is no steam flow through the turbine.

If the LP turbine exhaust cooling system failed (eg. some nozzles plugged), the LP turbine exhaust could experience excessive heating, leading to increased temperature gradients and thermal stresses.

Another example can be failure of the gland sealing steam system to maintain the required gland sealing steam pressure. Recall from module 234-1 that this may upset the flow of air and steam in one or more glands. As a result, some gland segments may be quenched by the leaking air or rapidly heated by the leaking steam. Large temperature gradients and thermal stresses would result.

3. **Casing support feet/keys seized in their guides.**

   Recall from the description of the casing support system (page 17) that inadequate greasing or a foreign object can block a turbine casing support foot. Very large stresses in the casing and its support can result.

4. **Wet thermal insulation.**

   This can cause increased temperature gradients – and hence, thermal stresses – in the turbine casing. Normally, when the insulation is dry, its thermal resistance is much larger than that of the casing. Consequently, the temperature drop across the insulation is several times larger than across the casing wall. As a result, the casing outer surface is only slightly cooler than the inner one.

   However, wetting of the insulation makes it a much better heat conductor. As the heat losses from the casing through the insulation increase, the casing outer surface temperature drops. This leads to larger temperature gradients in the casing. The induced thermal stresses increase accordingly.

SUMMARY OF THE KEY CONCEPTS

- Startup and loading of a turbine generator is affected by the following operational concerns:
  - Thermal stresses;
  - Brittleness at low temperatures;
  - Axial differential expansion;
  - Water induction to the turbine;
  - Rotor vibration;
  - Blade stresses.
- Thermal stresses are caused by blocking of the thermal expansion or contraction of one component by external constraints. The other cause is an uneven temperature distribution within a component, causing its hotter and cooler parts to attempt to expand/contract differently.

- During turbine startups, power manoeuvres and load rejections, thermal stresses can become particularly large. These operating conditions produce large temperature gradients in the turbine because they result in large changes in the steam temperature and flow.
- Large thermal stresses can also be caused by certain abnormal operating conditions and accidents such as water induction, seized casing support feet or wet thermal insulation. Faulty or malfunctioning equipment (such as reheaters, the LP turbine exhaust cooling system or the gland sealing steam system) can also produce excessive thermal stresses in some turbine parts.

Adverse consequences and operating concerns caused by thermal stresses

⇔ Obj 11.3 d)

Excessive thermal stresses, combined with mechanical stresses*, cause the following adverse consequences/operating concerns, listed in the order of decreasing stress magnitude:

* For example, centrifugal stresses in the rotor, and stresses in the casing due to steam pressure.

1. The stressed component can **break instantaneously**.

   This case is very uncommon because it takes a drastic increase in the total stress magnitude to exceed the ultimate tensile strength*. In practice, other failure mechanisms, such as fatigue or stress corrosion cracking, are more common.

   * Recall from the 228 course that the ultimate tensile strength is the maximum tensile stress that a given material can withstand before fracture.

2. The stressed part can **deform plastically** (permanently).

   For this to happen, the total stress must exceed the yield point (also called *elastic limit*)*. The resultant deformation of the casing, a diaphragm or another stationary component, may cause:

   * This term, as defined in the 228 course, means the maximum stress that causes no plastic deformation.

   – **Rubbing** in the turbine due to loss of clearances;

   – Increased **vibration** due to rubbing and/or bearing misalignment – the latter applying to the case where bearing pedestals support the turbine casing, and therefore are subjected to large forces produced due to casing deformation;

   – **A steam leak** through the open half joint (if any).

   Plastic deformation of the rotor due to excessive thermal stress is very rare. The classic case is permanent hogging of the stationary rotor but, as mentioned in module 234-9, it is very unlikely in CANDU stations due to the relatively low temperature of boiler steam. Severe rubbing is a more likely source of thermal stresses that could cause the rotor to bow permanently.

3. The stressed part can experience **excessive elastic deformation.**

   Note that some deformation always occurs because whenever there is a stress, there is also an associated strain. A problem may arise when the deformation is too large. This can happen when the total stress, while staying below the yield point, increases too much. In the case of **stationary components**, the effects are similar to, though less dramatic than those outlined in point 2 above.

Though the **rotor** spinning motion tends to equalize its temperature distribution, minor nonuniformities can still occur during fast heating or cooling. The primary reasons are that the rotor material is not perfectly uniform (hence, minor local differences in its thermal conductivity), and the oxides or deposits on its surface can cause slightly uneven rates of local heat transfer from the steam to the rotor surface or vice versa.

Small as they are, rotor deformations can produce **high vibration and possible rubbing**, when turbine speed is sufficiently high or in a critical speed range. Note that these problems do not occur when rotor heating is sufficiently slow because there is enough time for heat transfer to equalize the temperature distribution.

4. The stressed components may suffer **low cycle thermal fatigue damage.**

The term *low cycle thermal fatigue damage* refers to the fatigue damage caused by thermal stresses cycling at a very low frequency (eg. once a day). Cycling of thermal stresses is caused by **alternate heating and cooling** of the turbine during various operating conditions as summarized below:

Startup from a cold initial state	→	Heating;
Loading	→	Heating;
Unloading or load rejection	→	Cooling;
Shutdown or trip	→	Cooling;
Starting from a hot initial state	→	Cooling followed by heating.

Recall that with reduced turbine load, the HP turbine inlet steam temperature decreases due to throttling by the governor valves. This is why during startup from a hot initial state, the hot turbine is initially cooled by the steam flow.

Also recall that during heating, the parts of the turbine that are closer to the steam flow are hotter than the more remote ones. The opposite is true when the turbine is cooled by the steam. Consequently, the thermal stresses in a given location change from tensile to compressive or vice versa. And so, **over the years of turbine operation**, cycles of startups, shutdowns, and power manoeuvres, with occasional load rejections and trips, generate **many cycles** of thermal stresses in the turbine.

If the total stress is large enough, microscopic **cracks** can be **formed** in the material. Subsequent stress cycles produce more cracks and can cause the existing ones to grow and eventually join together, thus forming long and deep cracks. If undetected in time, they could result in a **serious accident** (eg. the rotor could burst into pieces at the normal turbine speed). A **more likely scenario** is that such cracks would be detected, either during a routine major turbine overhaul or by an unusual turbine vibration pattern. Even in this case, a **prolonged outage for repairs/replacement** of the cracked components would result.

It must be emphasized that even a relatively small increase in the magnitude of cyclic thermal stresses **reduces drastically the number of cycles to failure**. The stress magnitude depends on how fast heating or cooling is performed. Though the exact numbers depend on the turbine, an example is given to illustrate this effect. For a certain turbine component, a 70 deg.C/h* heating rate would require about 100,000 cycles to failure. If the heating rate were increased to 105 deg.C/h (ie. by 50%), the number of cycles to failure would drop to about 2000, ie. by 50 times!!!

Among the four adverse consequences of excessive thermal stresses outlined above, thermal fatigue damage and excessive elastic deformations are most common because they occur at the lowest stress level. While excessive elastic deformations can manifest themselves by increased vibration levels, **thermal fatigue damage** remains hidden until cracks are detected. This **absence of acute symptoms** may make the operator believe that the permissible heating/cooling rates can be safely exceeded. From the numerical example in the preceding paragraph, you realize how easily such practices could reduce the number of cycles to failure, and hence shorten the turbine life.

SUMMARY OF THE KEY CONCEPTS

- Thermal stresses combine with mechanical stresses in the turbine.
- In the extreme case, excessive thermal stresses may increase the total stress enough to cause the stressed part to break instantaneously.
- Excessive thermal stresses can also cause plastic deformation of stationary components or (rarely) the rotor. Rubbing, vibration, and possible steam leaks can result from deformation of the casing, diaphragms, etc.
- Large thermal stresses can produce excessive elastic deformation. In the case of stationary components the effects are similar, but less drastic, to those caused by plastic deformation.
- Fast heating or cooling can cause small elastic deformation of the rotor due to minor asymmetry of its temperature distribution. At high turbine speed or in a critical speed range, high vibration levels and possible rubbing can result.

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* This number means that temperature changes by 70 deg.C in an hour.

NOTES & REFERENCES

- Thermal stresses cycle during turbine startups, power manoeuvres, shutdowns, load rejections, and trips. If the stress is high enough, it can cause cracks to form and grow. This is referred to as low cycle thermal fatigue damage.
- If a sufficient number of thermal stress cycles have occurred, large cracks are formed. Usually, they force a prolonged outage for repairs/ replacement of the damaged parts. If not detected in time, the cracks can cause a serious accident.
- The number of cycles to failure decreases rapidly with increasing stress level. Therefore exceeding the permissible heating/cooling rates can reduce the turbine life drastically, leading to premature failure.

Obj. 11.3 e) ⇔

General operating practices used to prevent excessive thermal stresses

The essence of all of these practices is to avoid excessively fast heating or cooling of the turbine. During turbine starting and loading, this is achieved by the following general operating practices:

1. **Proper prewarming** on turning gear and at low turbine speeds.

   Prewarming is used during cold startups, ie. when the initial turbine temperature is low. Because prewarming is **performed when** the turbine is on turning gear or at low speed, the **mechanical stresses** in the rotor and casing **are very low**. Therefore larger thermal stresses can be accommodated. By prewarming the turbine, its further heating during the final stage of runup, and then during loading, is simplified. This is beneficial because during these conditions, centrifugal forces and steam flow produce large mechanical stresses in the turbine rotor and casing. How turbine prewarming is done is described on page 28.

2. **Selection of the proper runup and loading rates.**

   During turbine runup and loading, steam temperature and flow increase as the governor valves open. The rate at which this happens affects the temperature gradients, and hence thermal stresses, in the turbine.

   Selection of the proper runup and loading rates, such that no excessive thermal stresses are generated, **is based on the turbine metal temperature.** The selection can be done differently in different stations, depending on the features of the available DCC software (usually, TRU and UPR) and the mode of startup (automatic or manual).

   In the **simplest method,** three different **runup rates** are available for selection: slow, medium, and fast. Similarly, a few turbine generator **loading** rates are available. In the simplest case of three rates, they are **slow, medium** and **fast***.

* For your orientation, a slow runup takes about 30-45 min., medium – 15-20 min., and fast – 5-10 min., depending on the station.

Similarly, slow loading to full power takes about 50-70 min., medium – 20-30 min., and fast – 8-12 min.

Which of these runup and loading rates are selected depends on the **type of turbine startup**. Traditionally, three types are distinguished: **hot**, **warm** and **cold**. This classification is based on the highest turbine temperature (usually, at the HP turbine inlet) which, in turn, depends on how long the turbine has been shut down*.

In this method, selection of the proper runup and loading rates is very simple: **the cooler the turbine, the slower the runup and loading**:

COLD startup → SLOW runup and loading
WARM startup → MEDIUM runup and loading
HOT startup → FAST runup and loading

Such selection prevents excessively fast heating of the cold or warm turbine, while minimizing the time required to bring the unit to full power. It must be emphasized here that **when the turbine is hot, it must be run up and loaded quickly** in order to minimize cooling of the hot turbine metal by the relatively cool steam. In these circumstances, selection of the slow or medium runup and loading rates would increase thermal fatigue damage by subjecting the turbine to a **thermal cycle**: first prolonged cooling during the runup and initial phase of loading, then heating during the remaining part of loading. This is a rare case when a seemingly gentle operating practice is actually harmful to the machine.

Usually, this simple method of selecting the proper runup and loading rates is used during manual startup. But in practice, turbine startup is most often carried out automatically under control of the proper DCC software such as TRU and UPR. Among many other functions, this software also selects the fastest runup and loading rates at which no excessive thermal stresses will be produced.

In the simplest case, a few rates are available for selection, similarly to the manual selection described above. In newer stations with more sophisticated software, the DCC can request any runup or loading rate between certain minimum and maximum limits. In either case, the selection process is based on monitoring turbine steam and metal temperatures at strategic points such as the HP and LP turbine inlet, the governor and emergency stop valve chests, etc. The number and location of these points vary from one station to another. So do the algorithms used to process the temperature data and calculate the appropriate runup and loading rates. Details are left for the station specific training.

3. **Proper loading of the reheaters.**

Recall from module 234-4 two important points:

a) If we ignore prewarming of the reheat system, boiler steam is not supplied to the reheaters below a certain turbine load. By preventing overheating of the LP turbine exhaust, this practice minimizes thermal stresses in this region of the turbine.

* For your orientation, a **hot** startup refers to the case of the highest turbine temperature being a least 150°C which corresponds to shutdown for up to 12 hours.

A **cold** startup is when the highest temperature i below about 90-100°C which requires a shutdow for at least 48 hours.

Anything in between these two extremes is a **warm** startup.

The values quoted may differ somewhat from those valid in your station.

b) Reheaters are loaded gradually (over a certain range of turbine medium load) while monitoring the side-to-side temperature difference at the LP turbine inlet. This operating practice minimizes thermal stresses at the LP turbine inlet and in the reheaters themselves.

4. **Prevention of abnormal operating conditions and accidents** which could produce excessive thermal stresses.

These abnormal conditions have already been outlined on pages 19-20. In most cases, their prevention is straightforward. For example, operation of the reheat system is monitored, and proper actions are taken in response to its malfunction. Regarding water induction to the turbine, the general operating practices used for its prevention are described in module 234-14.

SUMMARY OF THE KEY CONCEPTS

- During turbine startup and loading, excessive thermal stresses are prevented by the following general operating practices:
  - Proper prewarming;
  - Selection of the proper runup and loading rates;
  - Proper loading of the reheaters;
  - Prevention of abnormal operating conditions and upsets which could produce such stresses.
- Turbine prewarming is performed when the turbine is on turning gear or at a low speed, ie. when mechanical stresses are low. Prewarming simplifies further heating of the turbine during the final stage of runup and during loading when high mechanical stresses are present.
- The cooler the turbine, the slower rates of runup and loading must be selected in order to avoid excessively fast heating of the machine.
- During hot startup, the turbine must be run up and loaded quickly. Otherwise, the machine would be subjected to prolonged cooling, followed by heating. This would reduce the turbine life due to increased thermal fatigue.
- During automatic turbine startups, the proper runup and loading rates are determined by the DCC software (usually, TRU and UPR). This is based on monitoring turbine metal and steam temperatures at certain points.
- To avoid excessive thermal stresses in the LP turbine, reheaters should be gradually loaded after turbine load has reached the proper minimum level.

TURBINE GENERATOR BRITTLENESS AT LOW TEMPERATURES

In this subsection, you will learn why prewarming of the turbine generator is necessary during cold startup, and how it is achieved.

⇔ Obj. 11.4 a)

Turbine and generator **rotors and casings** are usually made of different kinds of low alloy carbon steel. At low temperatures, these materials exhibit increased brittleness, ie: they become more **vulnerable to damage due to shock or fast rising stresses**. If such stresses are sufficiently high, cracks can easily form and rapidly grow, leading to sudden, possibly catastrophic, failure.

During turbine generator startup, fast changing stresses can be **created in a number of ways:**

- A **fast runup** produces centrifugal stresses that are rising even faster because they are proportional to the square of speed. For example, when speed increases from 12 rpm to 1800 rpm (ie. 150 times), the stresses rise 22,500 times – most of this, in the high speed region.
- **Fast heating or cooling** produces large thermal stresses in the surface in contact with the steam flow. Recall that a change in steam temperature is quickly followed by a similar change in the metal surface temperature, whereas the temperature of the underlying metal lags behind. This produces a large temperature gradient in the metal surface. Initially, the gradient rapidly increases. Then, it slowly decreases when the temperature of the underlying material approaches that of the surface. In other words, fast heating or cooling results, nearly instantaneously, in large and fast changing thermal stresses at the heated (or cooled) surface.
- **High vibration, and possibly rubbing,** can occur particularly when passing through a critical speed range.

To prevent brittle failure, the turbine generator must be warm enough before it is exposed to large and fast changing stresses. The required minimum temperature depends on the material*. Compared with casings, rotors are of primary concern because they are subjected to higher stresses and the consequences of their brittle failure are more serious. Due to some material differences, the HP turbine rotor must be prewarmed more than the LP turbine rotors. This is one of the reasons why turbine prewarming focuses on the HP turbine.

It is obvious that the temperature requirements quoted above are met during hot and warm startups. However, **during cold startup, adequate prewarming is necessary** to prevent brittle failure. Such prewarming is carried out when the turbine generator is on turning gear and/or during the initial phase of runup when mechanical stresses are low. Incidentally, no heat should be supplied to the turbine generator when its rotor is stationary because it would cause hogging.

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* This temperature is about 50-100°C for the HP turbine rotor, and about 20-30°C for the generator rotor.

NOTES & REFERENCES

Obj. 11.4 b) ⇔

Different heat sources are used in different stations for prewarming of the turbine rotor and the generator rotor. Let us first discuss the methods used to prewarm the **turbine rotor:**

1. The most common method consists of two stages:
    a) **Initial prewarming** when the turbine generator is on turning gear. Heat is supplied **with the gland sealing steam.** Recall that in most stations, this prewarming is quite short* in order to avoid excessive axial differential expansion.
    b) **Further prewarming by low steam flow** during the initial phase of runup when mechanical stresses are very low.
2. In some stations, **prewarming of the HP turbine** is accomplished **by a very small flow of boiler steam** throttled to a very low pressure*. In this method, the intercept valves are shut, and the heating steam flow should be so small that the turbine does not roll off the turning gear (though this sometimes occurs). Up to four hours is usually enough to raise the turbine temperature enough to turn a cold startup into a warm one.

* About 15-20 minutes.

* About 200-300 kPa(g).

Depending on the station, prewarming of the **generator rotor** is achieved by:

1. **Electric heaters** located in the lower half of the generator casing. They warm the generator hydrogen which, in turn, heats up the rotor. This is the typical method of prewarming.
2. **A small excitation current** which warms the rotor windings and eventually the rotor body. To prevent generator damage due to overfluxing, the current must be manually adjusted and kept quite low compared with its normal level. The automatic voltage regulator (AVR) must be "off". Otherwise, it would apply excessive excitation in a futile attempt to reach the normal generator terminal voltage despite the low speed*.

* For more details, refer to the electrical equipment courses.

SUMMARY OF THE KEY CONCEPTS

- To prevent brittle failure of the turbine generator rotor during a cold startup, it must be properly prewarmed before it is subjected to large and fast changing stresses, ie. before high turbine speeds are attained.
- Prewarming is performed when the turbine generator is on turning gear or at a low speed, ie. when mechanical stresses are very low.
- Typically, turbine rotor prewarming starts when gland sealing steam is valved in. When the runup begins, the small flow of turbine steam becomes the main heat source.

- In some units, the HP turbine is prewarmed with a very small flow of low pressure steam. The intercept valves stay closed, and the turbine should remain on turning gear.
- The generator rotor is prewarmed by a small excitation current (in some stations) and/or by electric heaters which warm the generator hydrogen which, in turn, heats the rotor.

You may now work on **assignment questions 11-17.**

⇔ Pages 40-45

AXIAL DIFFERENTIAL EXPANSION

You will learn now what axial differential expansion is, why it occurs in steam turbines, what operating concerns it causes, how it is minimized during turbine startup and loading, and what corrective and protective actions are taken when it becomes excessive.

General description

⇔ Obj. 11.5 a)

Whenever the turbine rotor and casings change their temperature, they expand or contract accordingly. In addition, they experience mechanical deformations which change during some operating conditions. Both the thermal expansion (or contraction) and mechanical deformations occur in all directions: radial, circumferential and axial. But since the total length of the turbine generator (up to 60 meters) exceeds its other dimensions considerably, the combined thermal and mechanical deformations in the axial direction exceed those in the remaining directions.

Depending on the operating conditions, the rotor and casings can expand (eg. during a cold startup) or contract (eg. during unloading). For simplicity, one term – ***axial expansion*** – covers both cases. Axial expansion of the turbine rotor and casing is illustrated in Fig. 11.3 on the next page.

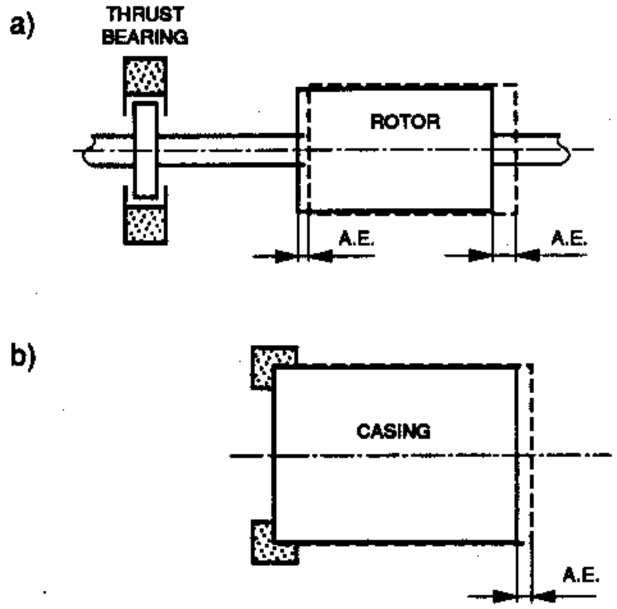

Fig.11.3. Axial expansion (A.E.) of the turbine rotor and casing:
——— Cold state; - - - - - - Hot state;
▨ Points fixed in the axial direction.

The major problem with the axial expansion is that the turbine rotor and casing expand differently as you might notice in the above sketch. This changes the axial clearances between the moving and stationary parts of the turbine and, if excessive, may result in rubbing. Because of this hazard, the difference between the rotor and casing expansions is closely monitored. The difference is commonly referred to as ***axial differential expansion*** (ADE, for short).

In ADE measurements, various sign conventions are used in individual stations. In some, expansion towards the generator is considered positive. In other stations, expansion towards the front pedestal (the HP turbine outboard bearing) is taken as positive. In yet other stations, expansion away from the thrust bearing is positive. You will learn during the station specific training which of these conventions is used in your station.

Obj. 11.5 b) ⇔

Reasons why ADE occurs in steam turbines

The turbine rotor and casings expand differently in the axial direction because of the following reasons:

1. **Different axial supporting of the rotor and the casings on the foundation.**

   This is illustrated in Fig. 11.4 which shows a simplified top view of a large turbine. You can see that all the **casings** are supported individual-

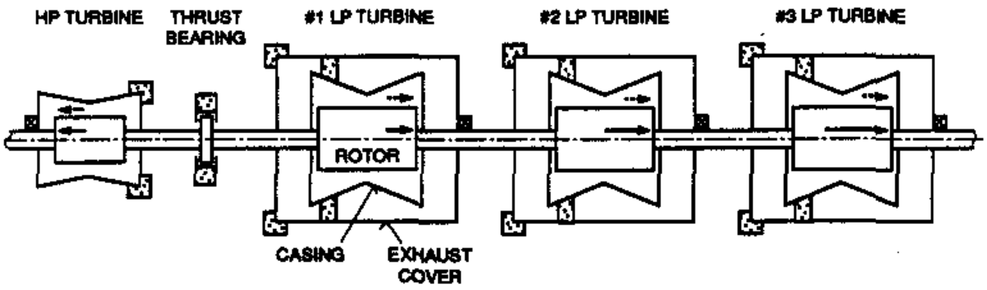

Fig.11.4. Simplified arrangement of the turbine fixed axial supports and their effect on turbine axial expansion:

▨ Points fixed in the axial direction;

—▸ Rotor expansion during cold startup;

····▸ Casing expansion during cold startup;

■ Typical location of ADE transducers.

Note:
In some stations, the LP turbine ADE is measured at the #3 LP turbine only.

ly. Hence, they **expand independently** from one another. For example, the axial expansion of the #1 LP turbine casing has no effect on the axial expansion of the HP or #2 LP turbine.

Unlike the casings, all the rotors are coupled together and supported axially in one common thrust bearing located between the HP and #1 LP turbines. While this arrangement allows the HP turbine rotor to expand independently, it makes the **LP turbine rotor expansion cumulative.** For example, the axial expansion of the #3 LP turbine rotor is the sum of its own expansion plus those in the #1 and #2 LP turbines. As you can see, the further away from the thrust bearing, the larger the rotor expansion (note the length of the arrows in Fig. 11.4), and hence, the ADE. This is why ADE transducers are located at the casing end which is more remote from the thrust bearing as shown in the same sketch.

2. **Different temperatures of the rotor and casing.**

   Recall that the amount of thermal expansion depends on the temperature difference between the initial and final conditions. While during a prolonged shutdown, the rotor and casing temperatures are identical, their operating temperatures are not. There are two reasons for this.

   First, **at steady power, the rotor is hotter than the casing.** It is easy to understand this when one realizes that nearly the whole rotor surface is in contact with steam, whereas the large casing outer surface is not. *Thus, despite the use of thermal insulation, heat losses from the casing are larger than those from the rotor.* The latter are relatively small because they occur only through the relatively small surface of the shaft where it protrudes from the casing.

NOTES & REFERENCES

Second, much larger temperature differences between the casing and rotor occur **during transient operating conditions** (eg. startup, load changes) when **the two components change their temperature at different rates.** In most turbines, it is the rotor which does it faster. This is due to its smaller mass (hence, less heat is required to change its temperature) and more intimate contact with steam as mentioned above.

3. **Different mechanical deformations of the rotor and casing.**

When a turbine rotor is subjected to large centrifugal stresses, it stretches radially (as shown exaggerated in Fig. 11.5). This results in a corresponding **contraction in the axial direction** as if the rotor tried to maintain a constant volume. A similar effect can be easily observed when a rubber band is stretched. This contraction in the direction perpendicular to the direction of the tensile stress is sometimes referred to as ***Poisson's effect.*** In some stations, this term is used in the operating manuals.

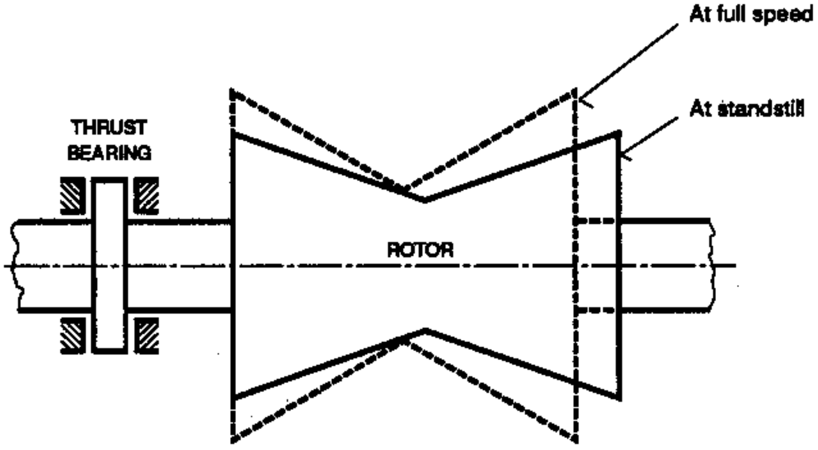

Fig. 11.5. Axial contraction of a turbine rotor due to centrifugal stresses.

The Poisson's effect influences ADE during turbine runup (when it tries to shorten the shaft) and rundown (when it attempts to elongate it). In the HP turbine, the effect is negligible due to a relatively low level of centrifugal stresses. However, **in the LP turbines,** where centrifugal stresses are much higher (particularly in the last stages with very long blades), the Poisson's effect that occurs at the normal turbine speed is much larger. Without this effect, the rotor axial expansion would be substantially higher.

In most cases, the mechanical deformations of the sturdy HP turbine casing (mainly due to steam pressure) are negligible. But in the LP turbines, the exhaust cover deformations caused by pulling or breaking condenser vacuum are large enough to affect ADE (note in Fig. 11.4 on page 31 that ADE transducers are attached to the exhaust covers).

SUMMARY OF THE KEY CONCEPTS

- ADE is the difference between the axial expansion of the rotor and casing.
- There are three reasons why ADE occurs: different axial supporting of the turbine rotor and casing, their different operating temperatures, and different mechanical deformations.
- Because turbine casings are supported independently from one another, their axial expansion is also independent. But, since all the LP turbine rotors are coupled together, their axial expansion is cumulative.
- At steady power, the rotor is usually hotter than the casing because the latter loses more heat. During transient operating conditions, the casing and rotor change their temperature at different rates. In most turbines, the rotor does it faster.
- When speed rises, the LP turbine rotors experience mechanical axial contraction due to Poisson's effect. During rundown, the same effect causes mechanical elongation.
- The effect on ADE of the mechanical deformations of the HP turbine casing is usually negligible, but LP turbine ADEs are noticeably affected by condenser vacuum pulling and breaking.

Operational causes of ADE

At steady power operation, ADE is relatively small because the temperature difference between the rotor and casing is not large. This **steady state ADE** changes with turbine load, since the load influences the turbine temperature distribution. The ADE also depends on which turbine (HP, #1 LP, etc.) it is measured at. But for a given turbine and a given load, the steady state ADE is fixed and cannot be reduced*.

⇔ *Obj. 11.5 c)*

Much larger ADE occurs, however, when the turbine undergoes **transient heating or cooling**. This happens, for example, during startup, power manoeuvres or load rejections. Recall that during these conditions, the casing and rotor change their temperature at different rates, the rotor typically being faster. As a result, the rotor and casing expand at different rates. This **produces a transient ADE** which eventually subsides when the turbine temperature has stabilized.

Naturally, this transient ADE increases with the rate of heating or cooling. For example, fast heating of the turbine can result in a transient ADE peaking at 150%, or even more, of the steady state ADE at full power. Since the axial clearances in the turbine are limited, proper operating practices must be used during turbine startup and loading to keep the transient ADE within safe limits.

⇔ *Obj. 11.5 d)*

In addition to the aforementioned operating transients, certain abnormal operating conditions and accidents can also cause abnormal ADE. In most

* For your orientation, the typical full power values of ADE in individual turbines are as follows:

HP – about 1 mm;
#1 LP – " 5 mm;
#2 LP – " 10 mm;
#3 LP – " 15 mm.

In your station, the exact values of the steady state ADE at full power may be somewhat different.

cases, they are **the same conditions which also cause large thermal stresses.** You can easily see it in the following list:

1. Water induction to the turbine.
2. Malfunction or failure of the reheaters, gland sealing steam system, etc.
3. Casing support feet/keys seized in their guides.
4. LP turbine exhaust overheating which can be caused by many reasons, such as:
   - Failure of the LP turbine exhaust cooling system when the turbine needs its operation;
   - Poor condenser vacuum, particularly at light loads;
   - Prolonged operation on turning gear with gland sealing steam valved in when condenser vacuum is very low or nonexistent.

Except for the third item in the list, the others raise ADE by increasing the temperature difference between the rotor and casing. As for the third item, it can produce increased ADE by restricting the casing axial expansion.

Obj. 11.5 e) ⇔

Adverse consequences and operating concerns caused by excessive ADE

Excessive ADE causes the following three major consequences/operating concerns:

* More information on this action is on page 36.

1. A **turbine trip*** to protect the machine from damage outlined below.

   This protective action results in a loss of production. In many cases, this could have been avoided by use of proper operating practices such that excessive ADE would not have occurred in the first place.

2. **Increased risk of damage to turbine seals, blades, etc.**, due to axial rubbing between the moving and stationary parts.

   This could result in secondary effects such as:

   - Seal deterioration;
   - Blade failure;
   - Increased vibration due to forces generated by the rubbing and thermal bowing of the shaft as described in module 234-1.

   Usually, rubbing occurs first in seals because their axial clearances are smaller than those between the other components.

3. In case of severe rubbing, **the thrust bearing can get damaged due to overloading.**

   Note that the shaft expansion is blocked when severe axial rubbing occurs. This can produce a very large load on the thrust bearing.

NOTES & REFERENCES

General operating practices used to prevent excessive ADE during a turbine startup and loading

⇔ *Obj. 11.5 f)*

Recall that during turbine startup and loading, the machine experiences a transient ADE which increases with the rate of heating or cooling. Hence, prevention of excessive ADE is **achieved by prevention of excessive rates of heating or cooling**. As this is exactly what we do to prevent excessive thermal stresses, the very same operating practices are used. Below they are quoted again, for your convenience:

1. Proper prewarming during cold startups.
2. Selection of proper rates of runup and loading.
3. Proper loading of the reheaters.
4. Prevention of abnormal operating conditions and accidents which could produce excessive ADE.

Typically, thermal stresses are more demanding than ADE. In other words, the heatup rates (ie. prewarming, runup and loading rates) which are appropriate from the point of view of thermal stresses, are also fine for ADE.

Major actions performed in response to excessive ADE

⇔ *Obj. 11.5 g)*

The actions below are listed in the order of increasing magnitude of ADE. Except for the second action, they apply to all operating conditions, not just startup.

1. An **alarm is given** to alert the operator about the problem.

   If the ADE is not changing quickly, the operator has a chance to investigate the cause and rectify it if possible. Recall that excessive ADE can be caused by a several reasons such as poor condenser vacuum or reheater problems. Elimination of the cause can prevent the other, more drastic actions listed below.

2. **Turbine runup or loading is inhibited.**

   As steam temperature and flow stabilize, the turbine has time to equalize temperatures (this condition is often referred to as *heat soaking*). This gives the slower responding casing a chance to catch up with the rotor. Thus, the transient ADE is reduced, and the runup or loading can be resumed.

3. **Turbine load is appropriately changed.**

   When the ADE indicates that the rotor is too long with respect to the casing, it implies too fast heating. This can be compensated for by a reduction in turbine load. The opposite holds true for the case of the rotor being too short.

Note that changing the load removes the symptoms but not necessarily the cause of excessive ADE. It also subjects the turbine to thermal cycling.

4. **The turbine is tripped.**

In most stations, the automatic trip feature (if any) is disabled. Instead, the operator can trip the turbine manually after he/she has been alerted by the turbine supervisory system, UPR or TRU, etc.

However, **the decision to trip the turbine is not as obvious** as it may appear. Note that when the ADE indicates a long LP turbine rotor, tripping the machine may actually cause damage because the rotor will expand further with decreasing turbine speed due to **Poisson's effect.** In these circumstances, a load reduction may be more appropriate. Therefore, before any decision is made, the trend of the ADE should be examined to see if it has peaked and how fast it is changing.

SUMMARY OF THE KEY CONCEPTS

- During startup, power manoeuvres and load rejections, ADE can become particularly large because during these operating transients, the turbine rotor and casing do not change their temperature at the same rate.
- Large ADE can also be caused by many abnormal operating conditions and accidents such as water induction, reheater problems, seized casing keys or LP turbine exhaust overheating.
- An excessive ADE can damage turbine seals, blades, discs, etc. due to axial rubbing. Severe rubbing can also damage the thrust bearing due to its overloading. To prevent damage, the turbine may have to be tripped which causes a loss of production.
- The same operating practices that prevent excessive thermal stresses during turbine startup and loading, are also effective in prevention of excessive ADE. Usually, thermal stresses are more limiting than ADE.
- When ADE is excessive, an alarm is given first. Next, turbine runup or loading is inhibited. If that does not help, turbine load may have to be changed appropriately. In the extreme case, the operator is advised to trip the turbine. Poisson's effect must be taken into consideration when making a decision about tripping the machine.

Pages 45-48 ⇔

You may now go to **assignment questions 18-27.**

NOTES & REFERENCES

ASSIGNMENT

1. If the boiler feed system were started when the condensate system is still shut down, the following problems would occur:.

   a) ______________________________

   ____

   b) ______________________________

   ____

2. a) The reason why at least one CEP should be running before the gland sealing steam system may be started is ______________

   ____

   ____

   ____

   ____

   b) Another precaution taken prior to the gland sealing steam system startup is placing at least one CCW pump in service. The reason:

   ____

   ____

   ____

   ____

   ____

   c) If the gland sealing steam system were started before placing the turbine on turning gear, the following problem would occur:

   ____

   ____

   ____

   ____

3. Prior to starting the turning gear, the turbine lube oil system must be in service because ______________________________

   ____

   ____

   ____

4. The turbine supervisory system is placed in service before the other turbine auxiliary systems because ______________________

5. Prior to turbine runup, turbine steam valves are checked in order to ______________________

6. The reason why the low condenser vacuum trip is typically gagged before turbine runup begins is ______________________

7. At least one CEP must be running before the LP turbine exhaust cooling system may be placed in service because ______________________

8. a) The boiler feed system must be in service before the boilers and steam piping can be heated to their normal operating temperature. The reason for this dependence is ______________________

   b) Warming of the steam piping should be completed before steam is admitted to the turbine because otherwise the following problems could occur:

      i) ______________________

      ii) ______________________

9. High condenser vacuum cannot be pulled if boiler pressure is too low because:

   a) ______________________________

   ____

   ____

   b) ______________________________

   ____

   ____

10. a) Two reasons why condenser vacuum requirements increase with turbine speed are:

    i) ______________________________

    ____

    ii) ______________________________

    ____

    b) Both problems are caused by deteriorated ______________

    in the turbine last stages where the steam moves too __________

    relative to the moving blades.

    c) The higher the turbine speed, the (higher / lower) the blade velocity, and hence the (higher / lower) the steam velocity that is required to avoid the problems listed in point a).

    d) Raising of the condenser vacuum requirements with turbine speed promotes a better flow pattern in the last stages because

    ____

    ____

    ____

    ____

    e) The LP turbine exhaust cooling system should be placed in service

    before high turbine speeds are reached because __________

    ____

    ____

    ____

    ____

NOTES & REFERENCES

11. The major operational concerns that affect the startup and loading of a turbine generator are:

    a) ______________________________

    b) ______________________________

    c) ______________________________

    d) ______________________________

    e) ______________________________

    f) ______________________________

12. a) Thermal stresses are created when thermal ______________ or ______________ is blocked. This can be caused by:

    i) ______________________________

    ____

    ____

    ii) ______________________________

    ____

    ____

    b) An uneven temperature distribution within one component produces:

    i) Tensile thermal stresses in its (cooler / hotter) parts because

    ____

    ____

    ____

    ____

    ii) Compressive thermal stresses in its (cooler / hotter) parts because ______________________________

    ____

    ____

    ____

    c) Maximum thermal stresses exist during steady operation at full power when the HP turbine inlet steam is at its highest temperature. (False / true)

d) During runup, loading, unloading or load rejection, large thermal stresses are produced. (False / true) The reason for this is

e) In large turbines, it may take a few hours before the most remote parts of the casing and rotor reach their normal operating temperature. (False / true)

13. The following abnormal operating conditions or accidents can produce large thermal stresses:

a) Condition: __________

It can produce large thermal stresses because __________

b) Condition: __________

It can produce large thermal stresses because __________

c) Condition: __________

It can produce large thermal stresses because __________

d) Condition: ____________________

It can produce large thermal stresses because ____________________

____

____

____

____

14\. a) Excessive thermal stresses cause the following adverse consequences and operating concerns:

i) ____________________

ii) ____________________

iii) ____________________

iv) ____________________

b) Excessive deformations of the casing can cause:

i) ____________________

ii) ____________________

iii) ____________________

c) Fast heating or cooling of the rotor can result in its thermal deformation due to:

i) ____________________

____

____

____

ii) ____________________

____

____

____

d) These deformations can damage the turbine through __________

and possibly ____________________ when turbine speed is

____

____

15\. a) Cycling of thermal stresses is caused by alternate __________ and __________ of the turbine during operating conditions such as ____________________________________

____

b) Thermal cycling, if large enough, can result in formation of

____

c) If not repaired in time, they can cause __________________

____

d) The number of cycles to failure can be drastically reduced when the stress level is ____________________________

e) If there are no acute symptoms, the permissible runup and loading rates can be safely exceeded with no adverse consequences to the turbine. (False / true)

16\. a) During turbine startup and loading, excessive thermal stresses are prevented by the following general operating practices:

i) ____

____

ii) ____

____

iii) ____

____

iv) ____

____

b) Three types of turbine startups are: ____________________

They are based on ______________________________

____

c) The proper runup and loading rates are selected as follows:

i) SLOW rates for _____________ startup;

ii) MEDIUM rates for _____________ startup;

i) FAST rates for _____________ startup.

d) A cold turbine must be run up and loaded (slowly / quickly) to prevent ______________________________

____

e) A hot turbine must be run up and loaded (slowly / quickly) to prevent ______________________________

____

____

17. a) When the turbine generator is cold, its rotor and casings can be too __________ to withstand ______________ stresses.

b) During turbine startup, such stresses can be created due to:

i) ______________________________

____

ii) ______________________________

____

iii) ______________________________

____

c) To avoid catastrophic failure, the turbine generator must be properly prewarmed. This is performed when the turbine is ______________ and continued during __________

____

d) Turbine rotors are prewarmed in the following ways:

i) ______________________________

____

____

ii) ______________________________

____

____

NOTES & REFERENCES

e) For generator rotors, the following methods of prewarming are used:

i) ______________________________

____

____

ii) ______________________________

____

____

18. a) The term axial differential expansion means ______________

____

____

b) There are three reasons why ADE occurs in steam turbines:

i) ______________________________

____

ii) ______________________________

____

iii) ______________________________

____

19. a) The HP and LP turbine casings (do / do not) expand independently from one another because ______________

____

b) The HP turbine rotor (does / does not) expand independently from the other rotors because ______________

____

c) The LP turbine rotor expansion (is / is not) cumulative because

____

____

20. a) At steady power, the rotor is usually (cooler / hotter) than the casing because ______________

____

____

b) During transient operating conditions, the rotor expands (faster / more slowly) than the casing because ______________________

____

____

21. a) The Poisson's effect can be described as ______________________

____

____

b) This effect influences the ADE of the (HP / LP / all) turbine(s) during ____

22. a) Except for accidents, the maximum ADE occurs at full power. (False / true)

b) The steady state ADE can be defined as ______________________

____

c) The transient ADE can be defined as ______________________

____

____

23. a) During startup, power manoeuvres or load rejections, ADE can become particularly large because ______________________

____

____

b) Examples of some other operational causes of large ADE are:

i) ____

It can increase ADE because ______________________

____

____

ii) ____

It can increase ADE because ______________________

____

____

iii) ______________________________

It can increase ADE because ______________________________

____

____

iv) ______________________________

It can increase ADE because ______________________________

____

____

24. a) Excessive ADE causes the following adverse consequences and operating concerns:

i) ______________________________

____

ii) ______________________________

____

iii) ______________________________

____

b) Axial rubbing between the turbine stationary and moving parts can damage components such as ______________________________

It can also increase rotor vibration due to ______________________________

____

____

25. The following general operating practices are used during turbine start-up and loading in order to prevent excessive ADE:

a) ______________________________

b) ______________________________

c) ______________________________

d) ______________________________

26. The following actions may have to be performed in response to excessive ADE:

    a) ______________________________

    b) ______________________________

    c) ______________________________

    d) ______________________________

27. a) Holding turbine speed or load constant when excessive ADE is indicated during turbine runup or loading, respectively, can reduce the ADE because ______________________________

    ____

    ____

    b) When the ADE indicates that the rotor is too short relative to the casing, a load (increase / reduction) can return the ADE to normal because ______________________________

    ____

    ____

    c) Tripping the turbine when the ADE indicates a long LP turbine rotor may actually cause damage because ______________________________

    ____

    ____

Before you move on to the next module, **review the objectives** and make sure that you can meet their requirements.

Prepared by: J. Jung, ENTD
Revised by: J. Jung, ENTD
Revision date: July, 1994

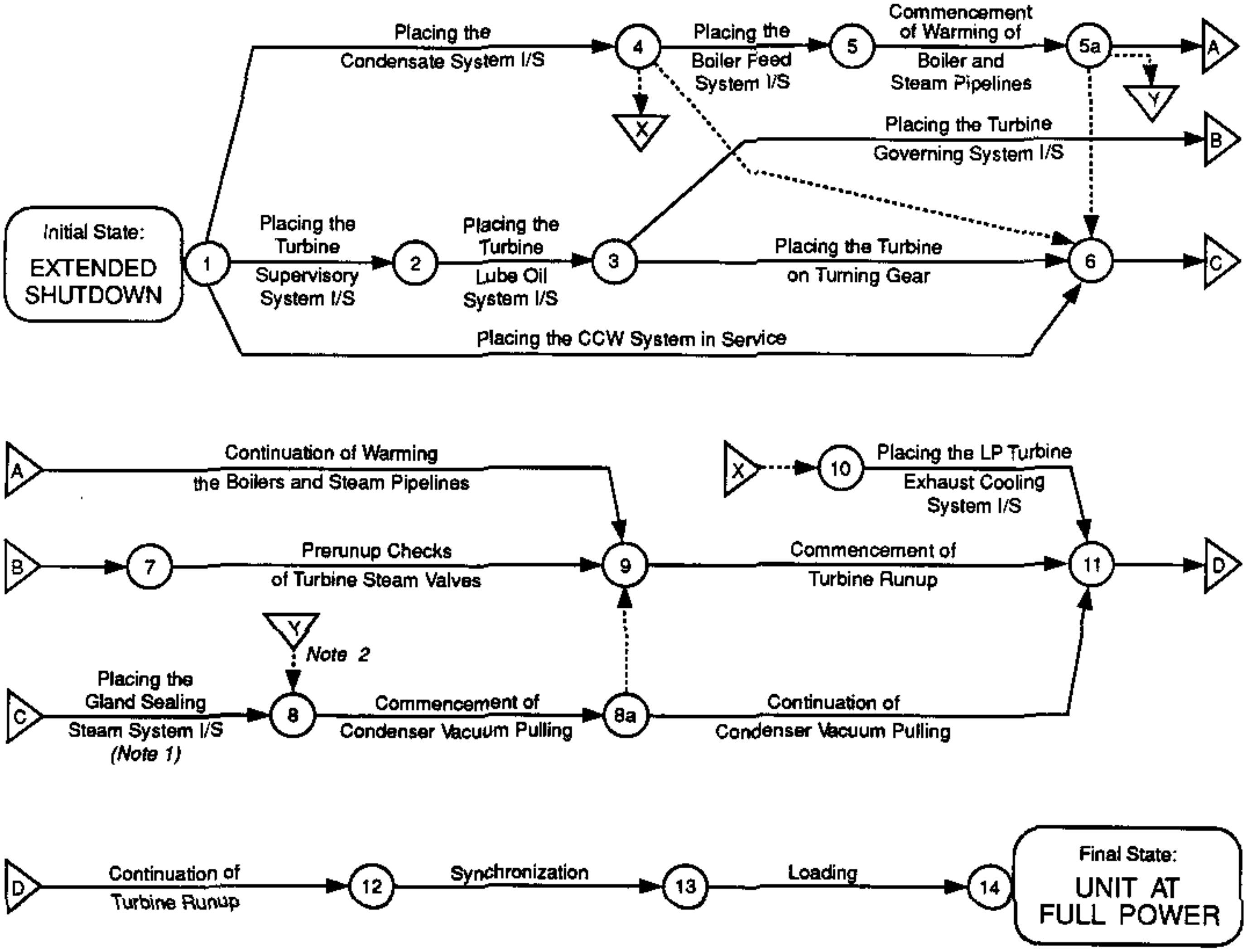

Fig. 11.6. Major activities during startup and loading of the steam and feedwater cycle systems.

——————► Activities ···················► Additional cross-links

Notes:

1. *In some stations, this activity is delayed until a certain level of condenser vacuum has been reached.*
2. *Applies to the stations where steam jet air ejectors are used.*