Generators Date Prepared/Revised 8/92 Date Given______

1.0 Reference

PPE Course Manual, Chapter 7, Generators

2.0 Objectives

A. Explain the conditions necessary to produce voltage in a generator.

B. State the relationship between generator frequency and speed.

C. Define the following terms:

1. Field
2. Armature
3. Stator
4. Rotor

D. Explain how generator terminal voltage and frequency are controlled.

E. Explain what determines the power factor for an independent generator supplying various loads.

F. Explain what determines the power factor for a generator on an infinite bus.

G. Describe how real load is changed for a generator on an infinite bus.

H. List the three conditions that must be met in order to parallel a generator with an infinite bus.

I. Explain the limitations associated with generator operation.

Generators | Outline | Notes

3.0 Introduction

A. Most electrical power generated by AC generators

1. Easily stepped up and down using transformers.

2. High voltage used for transmission due to I^2R losses.

B. In order to generate a voltage, there must be a magnetic field, a conductor, and elative motion between the two.

1. Stationary part of generator called the stator.

2. Moving part called the rotor.

3. Conductors into which voltage is induced called the armature.

a. Generator terminals are connected to the armature.

C. Revolving field generators have the magnetic field on the rotor and the armature on the stator. This is because high currents in the armature would result in considerable losses at the slip rings if the armature were on the rotor. — Notes: Figure 7-1

4.0 Polyphase and Multiple Pole Generators

A. DC field input applied to rotor using slip rings and brushes. (Collector assembly)

B. Armature windings can be arranged in either a single phase or three phase configuration. In three phase generators, three sets of armature windings are installed 120 degrees apart. — Notes: Figures 7-2, 7-3

C. Relative motion provided by physically rotating the rotor. Note that peak voltage is produced when there is a maximum amount of relative motion.

1. For each full rotation of the field, the output will complete one full electrical cycle.

2. Relationship between speed and frequency is given by:

$$N = 120\ f/p$$

where N = speed in RPM
f = frequency in Hz
p = number of poles

Note that the number of poles must be even.

D. Three phase generators are preferred due to:

1. Their higher power density (in both generators and motors),

2. The fact that three phase power can be used to create a rotating magnetic field in AC motors,

3. It is economically transmitted.

    a. Large motors operate more smoothly and efficiently.

E. Plant generators typically 22.5 kv (stepped up to 235 kv/345 kv/500 kv on grid).

5.0 Generator Construction

A. Stator

1. Stator bars make up the stator or armature windings — Figures 7-4, 7-5

2. Stator frame is gas-tight and normally pressurized with hydrogen. (May be 60-75 psig).

3. Resistance temperature detectors are placed between the stator bars to measure temperature.

B. Rotor

1. Provides the rotating magnetic field. — Figure 7-6

2. Rotor windings are insulated conductor bars that fit into the slots of the rotor and are supplied current from the exciter.

C. Exciter - supplies direct current to create the rotor magnetic field

1. The amount of excitation current determines the strength of the magnetic field and thus the generator voltage.

2. Typical excitation system is composed of an AC alternator with a DC rectifier. — Figure 7-7

3. A brushless exciter is designed so that all high power components are mounted on the shaft and it eliminates the carbon brushes and collector rings of earlier designs. — Figure 7-8

6.0 Generator Auxiliary Systems - all related to generator cooling

A. Stator water cooling system - deionized water is pumped through hollow stator winding bars to remove heat.

B. Hydrogen cooling system - used to cool the rotor and the inside of the stator.

1. Hydrogen is used due to low density, high thermal conductivity, electrical non-conductivity, and will not cause oxidation (increases insulation life).

2. Major problem is danger of explosion (4.1% - 94.2%). Concentration is normally kept above 97% for safety and efficient cooling.

C. Generator core monitor - senses a breakdown of insulation in the generator using detector which senses when small particles of insulation are suspended in the hydrogen gas.

1. H_2 forced through tube containing α source and a pair of electrodes. The α particles ionize the H_2 gas causing current to flow. When insulation is entrained, i decreases.

D. Gas control system - used to purge hydrogen out of the generator with carbon dioxide and thereby avoid an explosive mixture of hydrogen and air (also restore H_2).

E. Hydrogen Seal Oil System - used to prevent hydrogen from leaking out of the generator where the shaft penetrates the housing.

<u>7.0 Generator Operation</u> - Two parameters to control: frequency and voltage.

A. Speed Regulation

1. Generator frequency is a direct function of the speed of the prime mover (turbine).

2. The prime mover is controlled by a governor which is in turn controlled by a speed regulating circuit.

   a. The speed regulator senses the tendency for the prime mover to slow down with increased load and sends a signal to the governor to increase prime mover speed. — Figure 7-9a

   b. While there is still a reduction in speed with increased load, the speed regulation ensures that it is linear and much less steep than it would otherwise be.

B. Voltage Regulation

1. Generator voltage regulators control excitation in response to changes in reactive load in a manner similar to the way speed regulators control the governor in response to a change in real load. — Figure 7-9b

2. Note that increases in reactive load do not affect generator frequency and that the voltage regulators keeps generator voltage constant for changes in real load.

C. Single generator supplying an isolated load - for example, a diesel generator after a loss of off-site power.

1. Real and reactive power supplied by the generator are the sum of the real and reactive loads. — Figures 7-10a, 7-10b

2. The power factor of the generator is determined by the load.

3. Generator operating frequency is a function of:

   a. No-load frequency set point of the speed regulator. — Figure 7-10c

   b. Speed regulator characteristic (speed droop)

   c. Real power supplied by the generator

4. Generator operating voltage is determined by:

a. No-load voltage set point of the voltage regulator

b. Voltage regulator characteristic (voltage droop)

c. Reactive power supplied by the generator

5. To increase frequency, the operator would adjust the no-load frequency set point of the speed regulator. Figure 7-11

6. To increase voltage, the operator would adjust the no-load voltage set point of the voltage regulator.

7. Emergency diesel generator is unique because its speed regulator has two modes of operation.

a. If the generator is supplying isolated loads, speed droop is set to zero

b. If the generator is operating in parallel with other generators, speed droop is set so the speed drops off as load is increased.

D. Infinite bus - very large power system made up of many generators in parallel that do not exhibit any noticeable decrease in frequency or voltage with increases in real or reactive load. Figure 7-12

1. Any load or generator connected to an infin ite bus will ope rate at the freq uen cy and volt age of the bus.

2. By adjusting the speed and voltage regulators (no-load set points) of a generator in parallel with an infinite bus, we can control the real and reactive power supplied by the generator, and therefore is power factor. — Figures 7-13, 7-14

E. Paralleling generators

1. Oncoming generator voltage must match grid voltage to minimize the potential across the breaker.

2. Oncoming generator frequency must be slightly higher than grid frequency to ensure the generator picks up some real load. — Figure 7-15

3. The generator output breaker must be shut when the generator output is in phase with the grid to minimize the potential across the output breaker.

<u>8.0 Generator Limitations</u> - founded upon operating quadrants that describe generator operation based on real and reactive power loads. — Figure 7-16

A. Operation with negative power (motoring) is not allowed.

B. Most operation occurs with the generator supplying real power and inductive (lagging) reactive loads.

C. Generators are occasionally operated to act as a reactive load on the grid (supply capacitive, leading loads). In this condition, part of the generator's magnetic field is supplied by the grid.

D. Operation with low lagging power factor is limited by heating of the field coils due to the high current from overexcitation. — Figure 7-17

E. Operation with high power factor is generally limited by heating of the armature windings.

F. Operation with low leading power factor is limited by heating in the armature core ends caused by eddy currents that in turn are caused by uneven stator flux distribution.

Motors Date Prepared/Revised 1/92 Date Given______

1.0 Reference

PPE Course Manual, Chapter 8, Motors

2.0 Objectives

A. Describe the factors that affect the synchronous speed of a motor.

B. Define "slip" and explain the factors that cause slip to change.

C. Explain the operation of a three-phase induction motor including its reaction to an increase in load.

D. Describe the operation of a synchronous motor.

E. Explain why starting current is greater than running current in an AC induction motor.

F. Describe the relationship between rotor current, slip, and torque in an AC induction motor.

G. Describe why some motors have starting limits or restart limits.

H. List two methods that can be used to reduce the starting current on an AC motor.

I. State the relative advantage of synchronous and induction motors.

3.0 Introduction

A. Advantages of AC motors

1. Do not require commutators and therefore avoid dangerous sparking and frequent brush replacement.

2. Generally less expensive.

3. Able to take advantage of three phase as well as single phase power.

B. Two AC motor types of particular interest: Three phase induction motors and three phase synchronous motors.

4.0 AC motor theory

A. Rotating magnetic field produced by the motor stator windings (either wye or delta connected).

1. The direction of rotation of the field Figures 8-1 may be reversed by interchanging any two leads to the motor terminals.

2. 2, 4, or 6 poles may be created in the stator at any instant, depending on how the stator is wound.

B. Motor synchronous speed is the speed at which the magnetic field rotates.

1. Applicable to both induction and synchronous motors.

2. Synchronous speed is proportional to applied frequency and inversely proportional to the number of stator poles:

$$N = 120\ f/P$$

Where N = field RPM
f = frequency of applied voltage (Hz)
P = number of poles

3. Note that only the number of poles (normally fixed) and the applied frequency can affect the synchronous speed.

C. Efficiency of any motor is equal to the ratio of output power to input power. The difference between the two is attributable to motor losses.

1. I^2R losses as a result of rotor and stator currents

2. Rotor windage losses

3. Bearing friction losses

4. Magnetic field or core losses

5. Most AC motors are 85%-90% efficient.

<u>5.0 Three phase induction motors</u> - most common type of three phase motor due to simple rugged construction and desirable operating characteristics.

A. Induction motor construction

1. Three phase AC applied to stator to produce a rotating magnetic field. Either wye or delta connected. Similar to the stator of an AC generator.

2. Simplest type of rotor called squirrel cage rotor that consists of copper bars connected at the ends by a copper shorting ring. Squirrel cage rotors are inexpensive, simple, and very rugged. — Figure 8-2a

3. Wound rotor is electrically connected in a manner similar to the squirrel cage rotor. — Figure 8-2b

a. More complex and expensive (slip rings and brushes required)

b. Used for high starting torque loads where low starting current is required or when torque must be applied gradually. Also some speed control.

c. Heavier, less durable, requires more maintenance.

B. Induction motor operation

1. Three phase AC applied to stator causes stator magnetic field to rotate at synchronous speed.

2. Relative motion between stator field and rotor bars cause a voltage to be induced in the conductors of the rotor.

3. Because rotor bars are shorted at their ends, there is a complete path for current flow in the rotor.

4. Rotor current flowing around the conductors creates a rotor magnetic field that interacts with the stator field to produce torque on the rotor.

5. Relative motion must exist between the rotor and the stator field for torque to be generated The difference between synchronous speed and rotor (operating) speed expressed as a fraction of synchronous speed is called slip.

   $$\%S = ((Ns - Nr) / Ns) \times 100\%.$$

   Where S = slip
   Ns = synchronous speed in rpm
   Nr = speed to the rotor in rpm

6. Note that since synchronous speed is normally fixed, slip will change whenever rotor speed changes as a result of a change in load.

7. Slip normally less than 5%.

C. Response to an increase in load

1. Load increases > mismatch between load torque and motor torque > rotor slows > slip increases (more relative motion between rotor and stator field) > more voltage induced in the rotor > rotor current increases > rotor field gets stronger > motor torque increases until torque of motor = torque of load at a new, lower speed.

2. Relatively linear relationship between torque and speed over the motor's operating range.

D. Reactor coolant pumps - 3000-9000 HP induction motors.

E. Sometimes multiple sets of poles are wound on induction motor (stator) to provide speed "control".

1.

Poles	Speed
2	3600
4	1800
6	1200
8	900
10	720
12	600

F. Advantages

1. Inexpensive

2. Simple construction/rugged

3. Low maintenance (no brushes)

4. Good starting torque

5. Desirable torque - speed characteristic

6.0 Synchronous motors

A. Synchronous motor operation

1. Stator windings of the synchronous motor are essentially the same as those of the induction motor with three phase AC applied to create a rotating magnetic field.

2. Rotor of synchronous motor like that of a generator.

   a. Separate DC voltage must be applied to the rotor to create the rotor field.

   b. The poles of the rotor field "lock" in with the opposite polarity stator poles and the rotor is pulled along at synchronous speed.

3. Synchronous motors require special starting components

   a. Rotor inertia prevents the rotor from instantly coming up to synchronous speed - will vibrate back and forth.

   b. To aid in the starting process, small squirrel cage windings (called damper or amortisseur windings) are added to the rotor. The rotor DC field is shorted through a resistor at startup and the motor starts as an induction motor. When the motor approaches synchronous speed, the rotor field is energized and the rotor pulls into synch.

B. Synchronous motors run at synchronous speed determined by the applied line frequency and number of poles of the machine.

Motors	Outline	Notes

C. Overexcited synchronous motors

1. For a fixed mechanical power (load), it is possible to adjust the reactive component of the current drawn by the synchronous motor from the line by varying the DC field current to the rotor (excitation).

2. When the excitation is increased so that it operates with a leading power factor, it is said to be overexcited.

3. Overexcited synchronous motors can be used to improve system power factors in systems composed primarily of inductive (lagging power factor) loads.

D. Advantages

1. Large (~1000 HP) synchronous motors less expensive to build than induction motors (can tolerate larger air gap between rotor and stator).

2. Constant speed.

3. More efficient at slow speed.

4. Can be operated with leading power factor.

E. Synchronous motors are used where constant speed, high efficiency, and power factor control are important. Applications include DC generators, fans, blowers, and centrifugal pumps. — Figure 8-3

7.0 Motor starting current

A. Counter emf results from relative motion between the net (combined stator and rotor) magnetic field and the conductors of the stator. Its direction is such that it opposes the current applied to the stator.

B. At motor start, there is no counter emf to oppose stator current flow with the result that stator current is 7-10 times greater at start than during normal operation.

1. Stator current can be described by:

   $$Is = (Es - Ec) / Zs$$

   where Is = current flowing through the stator — Figure 8-4
   Es = applied voltage to the stator
   Ec = counter emf
   Zs = total impedance of the stator

   As motor speed increases, counter emf increases and stator current returns to normal.

2. To limit starting current most AC motors are started unloaded or with limited load and repeated motor starts are limited in frequency by restart limits.

   a. Starting limits protect the supply/distribution system.

   b. Restart limits protect the motor (overheating).

8.0 Starting circuits

A. Small AC motors, primarily induction motors, may be started by applying full line voltage directly to the motor terminals. Normally this is done through a motor controller in which magnetically operated contacts are opened or shut using a series of relays (called a low-voltage starter. Used for motors < ~7½ HP). It may also be done manually. Figure 8-5

B. Reduced voltage starters are used to minimize the disturbance on the motor supply lines that would result from starting a large motor.

1. Primary resistor starters use resistors connected in series with each stator lead during the starting period. After the motor starts, contacts are closed that short out the starting resistors. Figure 8-6

2. Autotransformer starters are used to step down line voltage at motor startup. Once the motor is running, the operator manually disconnects the transformer from the line and full voltage is applied. Figure 8-7

1.0 References

A. PPE Course Manual, Chapter 9

2.0 Objectives

A. Define and/or explain selective tripping and Class 1E electrical components.

B. Briefly explain the terms redundancy and train separation.

C. Explain the difference between a shunt trip coil and an undervoltage trip coil in relation to tripping a circuit breaker.

D. Explain the need for extinguishing the arc during breaker operation.

E Describe the attributes and applications of the following types of breakers:

1. Air circuit breaker
2. Oil circuit breaker
3. Air-blast circuit breaker
4. Vacuum circuit breaker

F. Describe the attributes and applications of the following devices:

1. Disconnect
2. Breaker control circuit
3. Protective relay
4. Fuse
5. Automatic bus transfer device
6. Uninterruptible power supply

G. Explain the operation of a lead-acid storage battery.

H. Explain why "load shedding" is necessary and how it is accomplished.

I. Explain why "load sequencing" is necessary and how it is accomplished.

3.0 General Discussion

A. Provide redundant, diverse, and dependable power to the many power plant loads.

B. Transport power from the main generator to the utility transmission network.

4.0 Power Distribution Grid

A. General

1. Grid - the transmission network or physical system used to generate and distribute electrical power to utility customers. Figure 9-1

2. Distribution grids have protective schemes designed to ensure this service exists.

3. Protective scheme is an arrangement of bus feeds, circuit breakers, circuit switchers, disconnects, fuses, and other protective and switching devices designed to isolate a faulted line or section as close to the fault as possible, permitting rest of system to operate normally.

4. A protective scheme has three rules:

a. The closest protective device to the fault shall operate first;

b. Selectivity of response time is provided, and

c. Response time is permitted to vary with the severity of the electrical problem.

5. Figure 9-2 shows a simplified distribution system that supplies power to a residential home. The cord running from the TV set to the wall outlet has been broken and shorted to ground. — Figure 9-2

6. If no protective devices existed on the line, the resulting large current could cause a fire in the house and possibly damage the individual pole transformer for the house and the 18-Kv/6900-volt pole transformer that supplies the rest of the neighborhood.

7. Protective devices are progressively harder to trip as you proceed toward power source.

8. Selective tripping is a protective scheme used to isolate the fault as close to the fault source as possible while still protecting the distribution system from damage.

9. The same philosophy used in protective schemes for the grid applies to in-plant power distribution. — Figure 9-3

5.0 Switchyard Bus Arrangements

A. General

1. Large conductors or buses are used in power distribution systems.

2. Common switchyard bus voltages are 22 Kv, 161 Kv, 235 Kv, 345 Kv, and 500 Kv.

3. Many internal plant bus circuits operate at lower voltages (usually 4160 or 6900 volts).

4. Transformers located throughout the plant further reduce the voltage to supply electrical power to lower voltage motors and electrical equipment.

5. To reduce the loss of equipment during bus maintenance or circuit faults, the main bus is normally segmented into several bus sections. — Figure 9-4

6. Separate sections are usually provided with bus-tie circuit breakers to tie or split the bus.

7. A bus-tie breaker arrangement like the one shown in figure 9-4 is sometimes called a "breaker-and-a-half" arrangement because there are three breakers for the two loads that come off each bus-tie between the north and south bus.

8. This arrangement allows isolating any one load while retaining power to all remaining loads.

B. Two Different Arrangements

1. Parallel Bus

   a. Provides redundant power through the "complete spare" concept

   b. Each bus is capable of handling full load capacity

   c. Both busses are usually kept in service at all times so power won't be interrupted if one bus fails — Figure 9-5

   d. Expense is major disadvantage

   e. Used when reliability of power is the highest priority

2. Ring bus

   a. Provides the reliability of the parallel bus arrangement at lower cost

   b. The ring bus is divided into sections by ring bus circuit breakers — Figure 9-6

   c. Each section can be disconnected without interrupting power to the other sections

6.0 System Design Requirement

A. General Design Criterion 17 from 10 CFR 50 Appendix A.

B. Four essential requirements are derived from Criterion 17.

   1. The onsite electrical distribution system must contain at least two separate parts, either of which is capable of providing power to all components required for safe functioning of the reactor.

   2. The onsite distribution system shall be provided with two independent power supplies from the transmission network that are immediately available after a loss of all onsite AC power supplies.

      a. Many nuclear plants operate with the offsite alternate power supply continuously in use for vital safety-related loads.

      b. Other plants have a fast-transfer capability to satisfy this requirement.

   3. Both of the two separate parts shall have a backup power source available within a few seconds following a loss of coolant accident.

4. The two parts of the distribution system must be sufficiently separated to preclude the loss of both parts if one part should suffer a loss of power or severe fault.

7.0 Offsite and Onsite Power Systems

1. Offsite (Preferred) Power System

   a. The preferred source of power to station safety related equipment

   b. Consists of two or more power sources capable of operating independently of the onsite or standby power sources. Essentially 2 or more connections to the grid

   c. The main generator is not available during shutdown and accident conditions, so it is not included in the preferred power system

   d. Class 1E loads

      1) The safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal

      2) Also called safety-related, vital, or essential loads.

   e. Figure 9-7 shows one arrangement for supplying power to the Class 1E loads. Figure 9-7

1) Normally the safety 4160v buses (34C and 34D) are powered from the non-safety 4160v buses (34A and 34B) through the bus-tie breakers.

2) If the supply through the normal station service transformer (NSST A) is lost, the bus-tie breakers will trip open and the breakers from the Engineered Safeguards Features Transformers (ESFTs) to the safety buses will automatically close to effect a fast transfer of the power source.

3) Some plants with similar arrangements keep the safety buses continuously powered from the off-site (grid) source and use the main generator source only for limited time periods when necessary maintenance must be performed on the ESFTs.

   a) The emergency diesel generators (EDGs) provide the backup power source for the safety buses in case the fast transfer does not work properly or offsite (grid) power is lost.

   b) The two separate off-site power sources (two tie-ins to the 345Kv grid) and the two EDGs satisfy two of the essential requirements of General Design Criterion 17.

4) Total functional independence between the two offsite power sources is not maintained in the switchyard itself because all bus sections are electrically connected. However, in the event of an electrical fault, electrical separation is established in a few cycles by circuit breaker operation.

5) The fault isolation and bus transfer scheme is designed to permit automatic fault isolation while still maintaining multiple connections from the plant switchyard to the grid. Therefore, both independent circuits providing offsite (preferred) power will remain energized unless the fault is on one of them, in which case the other independent circuit will remain energized and unaffected.

6) Figure 9-7 also illustrates the concept of redundancy. Note that there are two safety electrical trains: an "A" train including bus 34C, and a "B" train including bus 34D. Each train has its own off-site power supply (ESFT) and its own backup power supply (EDG).

7) Redundancy is achieved by having the like components electrically separated so that one component is on one electrical train and the redundant component is on the other train. The components on each safety train must be capable of performing all functions required for the safety of the reactor, *with the other train deenergized.*

8) <u>Electrical redundancy</u> in a nuclear plant means that either train of the electric distribution system can be lost or faulted, and the other train can perform all functions required for reactor safety.

   a) This objective is achieved in the example plant shown in Figure 9-7 by having half the safety system components powered from the A train and the other half of the safety system components powered from the B train.

   b) Redundancy satisfies one of the essential requirements of General Design Criterion 17.

   INSTRUCTOR NOTE: The term "train" is vernacular or slang. Some facilities use the general term bus instead of train, but most of the nuclear industry use the term bus to identify an electrical entity that is at one specific voltage. The term bus is also sometimes used to mean the physical conductors that carry the bus voltage within an electrical entity. The specific meanings of these two slang terms, bus and train, are often confusing to new plant operators).

f) Another electrical distribution term that is also shown in Figure 9-7 is train separation. — Figure 9-7

1) Note that there is no bus-tie breaker between bus 34C and bus 34D.

2) If there were a bus-tie breaker between bus 34C and 34D, and that breaker suffered a severe short to ground such that the breaker was welded shut, both trains would be faulted.

3) Neither train could be energized until the faulted breaker could be physically disconnected from the two trains.

4) There would be no safety function capability, and the reactor would be unprotected from a major accident.

5) Train separation means that there are no electrical (or physical) connections between the two safety electrical trains.

6) Some nuclear facilities have components that can be powered from either safety train, but they use extensive interlock systems to ensure that the component is fully disconnected from one train before it is connected to the other train.

7) Many facilities may refer to their safety electrical trains by colors or numbers rather than A and B, but the concepts are the same. The two trains carry redundant safety loads and are electrically separated, each with a connection to the offsite power grid and each with an EDG backup power source.)

2. Onsite power system

a. Includes the following: Figure 9-8

1) Conductors that provide paths for distribution of electric power

2) Transformers that step voltage up or down, as required

3) Switchgear that controls the distribution of power and provides fault protection

4) Control and metering equipment required for operation of switchgear

5) Emergency power sources such as EDGs

6) DC components such as batteries, battery chargers, etc.

b. When the main turbine is operating, it supplies all required power to the site as well as power to the grid

c. Following trips or shutdowns or during outages, power must be available from offsite

d. Separated into vital and nonvital distribution systems

e. Nonvital loads: those not required to place the reactor in a safe shutdown condition or prevent the release of radioactivity to the environment

   1) Examples: loads in the turbine building, switchyard, and administrative building

f. Vital distribution system

   1) 6.9 kV shutdown buses

   2) 480 V shutdown motor control centers

   3) Emergency diesel generators

   4) Separated into two redundant load groups or power trains

   5) Each train has both an offsite (preferred) power source and an onsite (standby) power supply (EDGs)

      a) EDG starts automatically if power is lost to the emergency vital buses

      b) Each vital train has its own battery for vital DC loads.

8.0 Switchyard Connection Components

A. Three types of components usually found in nuclear plant switchyard connections may also be found elsewhere in the distribution system: transformers, bus ducts, and disconnects. — Figure 9-4

1. Switchyard Transformers

   a. Electric utility grids normally operate at 235Kv, 345Kv, or 500Kv.

   b. Nuclear plant main generators normally generate power at 22.5Kv.

   c. The large motors used to drive reactor coolant pumps, feed pumps, condensate pumps, and circulating water pumps sometimes use 13.8Kv, but 6.9Kv is used for these motors at most plants.

   d. The emergency diesel generators at most nuclear plants generate power at 4160v and most safety pump motors use 4160v or 480v.

   e. Transformers must be used between all these different operating voltages.

2. High Voltage Buses and Bus Ducts

   a. Power from the normal station service xformers to the inhouse loads is delivered via buses.

   b. Buses, usually made of copper or aluminum, are specially designed conductors in the form of a tube or bar.

   c. Buses that transport high voltages through the plant are normally supported by a protective housing or enclosure called a bus duct.

3. Isolated Phase Bus Ducts

a. The main generator leads of each unit are connected by means of isolated phase bus ducts to the main and normal station service transformers.

b. Using one duct for each of the three generator phases provides physical separation of the three phases to prevent phase-to-phase faults. — Figure 9-9

c. A forced air cooling system is normally used to cool the volume within each isophase duct to carry heat away from the bus operating at relatively low voltage/high current.

4. Protective Bus Ducts

a. Inside the plant, most electricity is carried and distributed by protective bus ducts.

b. The bus duct consists of a metal or nonconductive housing that supports, encloses, and insulates the copper or aluminum bus bars within. — Figure 9-9

c. Metal housings that contain electrical buswork and circuit breakers are called cubicle switchgear or simply switchgear.

d. Buswork is the term used for the metal bus bars inside the switchgear that connect power to (or from) the circuit breakers mounted in the switchgear).

5. Disconnects

a. A <u>disconnect</u> is essentially a piece of conductor that can be easily removed from the circuit (and subsequently replaced) like a removable link.

b. The purpose of a disconnect is to provide an additional, inexpensive way of isolating equipment.

c. Disconnects are *not* used to interrupt circuits under load - too slow.

d. Disconnects used to isolate equipment, such as a large transformer or breaker, by installing a disconnect in series on either side of the equipment or breaker.

e. Breakers associated with a disconnect must be open to isolate the power source or load before the disconnect can be opened (or reclosed).

f. Disconnects are usually operated by insulated levers or gear mechanisms at a convenient location.

g. If the lever is operated by a motor, the disconnect is called a <u>motor-operated disconnect</u> (MOD).

9.0 Circuit breakers

A. General description

1. Current interrupting devices used to direct current and protect circuits from overloads

2. A set of contacts held closed by a mechanical latch; when tripped, large tension springs rapidly force contacts open — Figure 9-10

3. Mechanical latch is normally tripped by the plunger in a solenoid trip coil

    a. Shunt trip coil is energized to trip

    b. Undervoltage trip coil deenergized to trip

4. An arc develops when contacts are opened under load

    a. When breaker contacts first separate, only a thin layer of cool air separates them. Voltage between the contacts is sufficient to overcome the resistance and current begins to flow (arc).

    b. The current flow heats the air to thousands of degrees, reducing the resistance between contacts and allowing continued current flow.

    c. Eventually the contacts move so far apart that air resistance is too great to sustain the arc and the circuit is broken

5. Rapid extinguishing of arc very important

    a. Prevent breaker damage due very high temperatures

    b. Stop current flow to component

6. Lagging power factor affects the load interrupting process due to inductive kick - lagging current prolongs the arc

B. Types of Circuit Breakers

1. Air circuit breakers

    a. Use resistance of air between contacts to extinguish the arc — Figures 9-11, 9-12

    b. Used extensively in low and medium voltage applications

2. Air blast circuit breakers

    a. Compressed air is released through a blast tube directly into the arc path

    b. As the contacts part, the air blast carries the arc up through the arc splitter and into the arc chute where it is extinguished — Figure 9-14

    c. Used for indoor high voltage (> 15 Kv) operations

3. SF-6 gas circuit breakers

   a. Works like air blast circuit breakers but uses sulphur-hexafluoride (SF-6) gas

4. Oil circuit breakers

   a. Contacts are submerged in oil — Figure 9-15

   b. Oil is a much better coolant and insulator than air

5. Vacuum circuit breakers

   a. Opening the contacts in a vacuum prevents arcing by eliminating the conducting path — Figure 9-16

C. Breaker control

1. Operation of control circuit — Figures 9-13, 9-17

   a. The charging motor automatically charges the closing spring when:

      1) The breaker is initially racked in (fully inserted into switchgear),

      2) The breaker is subsequently tripped open

   b. Review functions of a and b contacts

2. Auxiliary contacts can provide breaker position indication to other circuits

3. Compartment switches and limit switches - used to allow breaker testing or maintenance.

10.0 Relays

A. General

1. An electrical switching device with one or more contacts that energize or deenergize control circuits

2. Circuit protection is one use of relays

3. Relay operation — Figure 9-18

   1) Magnetic

   2) Thermal

B. Relay classifications

1. Instantaneous - for very high current short circuits

2. Definite time relay - circuit is designed for current surges of short duration

3. Inverse time relay - the worse the ground, the faster the relay operates

11.0 Fuses

A. General

1. A protective device that automatically breaks a circuit before the wiring and equipment are damaged

2. Consists of a strip of metal with a higher resistance and a lower melting point than the wire in the circuit

3. Not resuable

4. Placed in series with the circuit to be protected

5. Rated according to the continuous current flow it can pass without melting

B. Types of fuses — Figure 9-19

1. Low voltage cartridge fuse

2. High voltage

12.0 Special Onsite Distribution Equipment

A. General

1. Special equipment designed to improve the reliability and continuity of power to selected plant components.

2. Automatic bus transfer devices use two AC power sources to maintain power continuity.

3. Inverters use DC power, normally with a battery backup.

4. Uninterruptible power supplies use both AC and DC power to accomplish the same objective.

B. Automatic Bus Transfer Devices

1. Automatic bus transfer devices have two sources of power available, one supplying power to the equipment and the other in standby

2. Loss of the active power source is sensed and the component is automatically disconnected from the deenergized bus and connected to the standby bus.

3. The transfer may be performed fast enough to prevent deenergizing affected equipment on undervoltage.

4. An automatic bus transfer device is a device which senses normal bus voltage, and automatically transfers the load from the normal bus to another bus when voltage is lost on the normal bus.

C. Inverters and Battery Chargers

1. An inverter is a device that converts DC power to AC power.

2. A battery charger converts AC power to DC power.

3. The relationship of an inverter and battery are shown in figure 9-8. Figure 9-8

4. Normally, the battery charger is supplying all DC bus loads, while maintaining the battery fully charged.

5. If the battery charger suffers a failure or loses power, the electron flow into the battery instantaneously reverses direction, and the battery supplies the 125v DC bus.

6. Inverter continues to use DC power from the DC bus to generate AC power throughout the battery charger failure.

D. Motor-Generator Sets

1. Some older plants may use motor-generator sets to accomplish the same functions as battery chargers and inverters.

2. An AC motor can be used to drive a DC generator to charge a battery

3. A DC motor can be powered from a battery and be used to drive an AC generator to provide special-purpose, reliable AC power.

4. In modern plants, motor-generator sets may be used for these purposes if the load power requirements are greater than a solid-state charger or inverter can provide.

E. Uninterruptible Power Supplies

1. An UPS device uses a battery charger, a battery, an inverter, a regulated AC transformer, and a bypass or transfer switch to supply continuous power to essential, low-power loads such as safety instrumentation. — Figure 9-20

2. The relationship of the battery charger, battery, and inverter in a UPS device was described for Figure 9-8. — Figure 9-8

3. If voltage is lost on the Vital Bus, the battery will instantaneously reverse its current flow direction and send power to the DC bus and inverter.

4. The addition of the regulated transformer and transfer or bypass switch allows the inverter to be bypassed if it develops a fault or needs maintenance. The static bypass switch may be a static transfer switch (automatic device), or it may be set up for manual operation only.

13.0 Batteries

A. General

1. The batteries used for supplying DC voltage and current are made up of voltaic cells.

2. The cells used in station batteries are rechargeable and provide power by electrochemical means.

3. Although differing widely in construction, all battery cells have an electrolyte, anode, and cathode, as well as a non-conducting container.

4. Chemical action, encouraged by the electrolyte, takes place at the anode and the cathode, and produces an electrical potential at the respective terminals.

5. Completing an external connection between the anode and cathode will allow current to flow.

6. One of the more commonly used batteries is composed of cells with a lead peroxide cathode, a sponge lead anode, and a sulfuric acid electrolyte.

7. An electrochemical cell refers to a single unit which converts chemical energy into electrical energy.

8. A battery is a combination of two or more cells.

B. Construction of a Lead-acid Storage Battery

1. A lead-acid battery consists of a number of cells connected together; the number needed depends upon the voltage desired with each cell producing approximately 2.1 volts. — Figure 9-21

2. The plates are formed by applying lead-oxide pastes (PbO) to a grid made of a conductive alloy. The plates are put through an electrochemical process that converts the active material of the positive plates into lead peroxide (PbO_2) and that of the negative plates into spongy elemental lead (Pb).

3. The positive plates (lead peroxide) and the negative plates (sponge lead) are referred to as the active material of the battery.

4. The electrolyte provides the path for interaction and carries the electric current within the battery.

C. Storage Battery Operation

1. In a fully charged battery, the positive plates are pure lead peroxide and the negative plates are pure lead. — Figure 9-22

2. All acid is in the electrolyte so that the specific gravity is at its maximum value.

3. When sulfuric acid (H_2SO_4) is diluted in water, the following dissociation occurs:

$$H_2SO_4 + 2H_2O \longrightarrow 2H_3O^+ + SO_4^{--}.$$

4. The basic chemical reaction occurring at the negative plate when the cell discharges (produces current) is the loss of electrons by the lead (oxidation):

$$Pb + SO_4^{--} \longrightarrow PbSO_4 + 2e^-.$$

5. At the positive plate, lead peroxide gains electrons and passes into solution as Pb^{++} ions (reduction). The Pb^{++} ions combine with SO_4^{--} ions, again forming $PbSO_4$:

$$PbO_2 + 4H_3O^+ + SO_4^{--} + 2e^- \longrightarrow PbSO_4 + 6H_2O$$

6. As the cell discharges, a coating of insoluble lead sulfate ($PbSO_4$) builds up on both the positive and negative plates.

7. During the discharge, the conversion of the electrolyte ions to lead sulfate and water causes the acid concentration of the electrolyte to decrease, which decreases the specific gravity of the electrolyte.

8. When so much of the active material has been converted into lead sulfate that the cell can no longer produce sufficient current, the cell is discharged.

9. If the discharged cell is then connected to a DC charging source with a voltage slightly higher than battery voltage, electrons will flow to the cell in the opposite direction from that of discharge, and the cell will charge, i.e., *use* the electrons to convert the lead sulfate and water back into the initial constituents.

10. During charging operations, lead sulfate goes to lead at the negative plate and to lead peroxide at the positive plate, resulting in a reduction in weight and a gain in porosity of the plates.

11. At the same time, the sulfate is restored to the electrolyte with the result that the specific gravity of the electrolyte increases.

12. The chemical reactions occurring during the charging process are as follows:

$PbSO_4 + 2e^- \text{ ---> } Pb + SO_4^{--}$

(Negative plate),

$PbSO_4 + 6H_2O \text{ ---> } PbO_2 + 4H_3O^+ + SO_4^{--} + 2e^-$ (Positive plate)

13. Because the amount of sulfuric acid combining with the plates at any time during discharge is in direct proportion to the amount of discharge, the specific gravity of the electrolyte is a guide in determining the state of discharge of the lead-acid cell.

14. The specific gravity of the electrolyte in battery cells is routinely measured to determine the state of charge of the battery.

15. Summary of operation

    a. Chemical reactions in a lead-acid storage battery during charge and discharge may be conveniently summarized by a combined, reversible chemical equation:

       Discharge --->

       $PbO_2 + Pb + 2H_2SO_4 \leftrightarrow 2\ PbSO_4 + 2H_2O$

       <--- Charge

    b. During discharge the combined reaction proceeds from left to right as both the positive plates (lead peroxide) and the negative plates (sponge lead) react with the sulfuric acid to *produce current flow*.

    c. During discharge *both* plates become coated with lead sulfate ($PbSO_4$) and the electrolyte (H_2SO_4) is diluted by the formation of water.

    d. During charging operations the combined reaction proceeds from right to left as electrical current *from an outside source* is used to convert the lead sulfate and water back into the original constituents.

D. Other Storage Battery Information

1. Hydrometer

a. The specific gravity of a cell can be determined by use of a hydrometer, which consists of a float within a syringe.

b. The distance that the float stem protrudes above the level of the liquid depends upon the specific gravity of the solution.

2. Potential Difference and Current

a. The potential difference of a cell is determined by the ease with which the electrodes yield positive or negative ions, which is determined by the types of materials used.

b. The size of the cell or any of its parts does not affect the potential difference the cell is capable of producing. As an example, the materials used in the lead-acid cell will always produce a potential difference of 2.1 volts per cell.

c. On the other hand, the amount of current is determined by the size of the electrodes (assuming the concentration (specific gravity) and quantity of the electrolyte is adequate).

3. Capacity

a. The capacity of a storage cell, expressed in ampere hours, is the product of the discharge current in amperes multiplied by the number of hours the cell will maintain that current.

b. The ampere hours that may be obtained from a battery are greater for a long, low rate or itermittent rate of discharge, than for a short, high rate of discharge.

c. All batteries are given a capacity rating, which is the ampere hours obtainable under certain working conditions.

d. The capacity of a cell is affected by the temperature at which it is operated. Usually, the capacity decreases when a cell is operated at low temperatures. In fact, at about -30°C, most electrochemical cells stop supplying energy because the electrolyte freezes.

4. Battery Charges

a. A normal or regular charge is given to the battery on a periodic basis, or if necessary to restore the energy taken out on a discharge.

b. An equalizing charge is an extended normal charge. This type of charge is performed periodically to ensure that all the sulfate is driven from the plates and that all the cells are restored to a maximum specific gravity.

14.0 Emergency Responses

A. General

1. The electrical distribution system is needed for normal operations.

2. The critical design functions for the system involve the provision of reliable power to the safety-related equipment during emergencies.

B. Plant Trip

1. For a plant trip, the main generator will be promptly tripped off the line (sometimes after a 30-second delay), and the main generator breakers to the grid will be tripped open. — Figure 9-8

2. If the main generator was supplying onsite loads through an auxiliary transformer, the opening of the generator breakers will initiate an automatic fast transfer such that the reserve supply breakers will close to provide power to the plant directly from the grid.

3. If the transformers for plant loads are located on a branch off the line from the switchyard to the main generator as shown in figure 9-7, there is normally no need for a fast transfer on a plant trip; power is instantaneously backfed from the grid through the main transformers to the normal service station transformers so there is no loss of power. — Figure 9-7

4. The emergency diesel generators remain shut down on a normal plant trip, and there is no significant perturbation on the safety buses.

C. Loss of Offsite Power

1. For a loss of offsite power, the plant will trip, and the emergency diesel generators will be automatically started when the loss of voltage on the emergency buses is sensed.

2. Each diesel generator breaker will close automatically when the associated diesel generator approaches rated speed and voltage output.

3. If all the emergency pump motors were still connected to the emergency buses, they would all try to start the instant the breaker closed.

4. The combined starting currents of all the emergency motors would put a serious overload on the diesel, causing a diesel trip and/or other possible damage.

5. This unsatisfactory situation is prevented by using an automatic function called <u>load shedding</u>, or disconnecting all the major loads on the emergency buses when the loss of voltage is initially sensed.

6. Note that if the normal supply for the emergency buses is from the non-vital buses as shown in figure 9-8, the load shedding will also include disconnecting all the non-vital connections from the emergency buses. — Figure 9-8

7. Also note that some loads will remain continuously connected to the emergency buses, but these will be small, essential loads such as instrumentation and communications.

8. <u>Load sequencing</u> is the term applied to the staggered time sequence that is used for reloading the major emergency loads back onto the emergency buses after the diesel generator breaker has closed.

9. The loads are sequenced to start in a predetermined order with a spacing of 5 to 10 seconds.

10. The time spacing allows the large motor starting currents to subside before each additional motor is started.

D. Safety Injection Actuation

1. For a safety injection actuation, the plant is tripped, and the emergency diesel generators are automatically started as a precautionary measure.

2. The electrical power supply response is essentially identical to that for a plant trip, except that the diesel generator is running unloaded.

3. If offsite power is subsequently lost during a safety injection actuation, load shedding is again actuated, causing all the major loads (and any non-vital bus ties) connected to the emergency buses to be automatically disconnected.

4. Because the diesel generators are already running, the output breakers will close almost immediately and load sequencing will begin.

5. The order in which the emergency loads are sequenced onto the emergency buses on a loss of offsite power after a safety injection actuation signal normally differs from the simple loss of offsite power situation.

6. Loads used for a loss of coolant accident need priority during a safety injection, but not during a simple loss of offsite power situation.

15.0 Summary

A. Review objectives

1.0 References

A. PPE Course Manual, Chapter 10

B. Power Plant Piping Systems Handout

C. Valves Handout

D. Valve Actuators Handout

2.0 Learning Objectives

A. Explain the following piping terms: Learning objectives

1. Nominal pipe size

2. Pipe schedule

B. Describe the functions of piping snubbers.

C. Describe the purpose of the following valve components:

1. Disk

2. Seat

3. Body

4. Bonnet

5. Stem

6. Packing

7. Actuator

8. Yoke

D. Describe attributes and applications of the following valve types:

1. Gate

2. Globe

3. Check

4. Stop-check

5. Butterfly

6. Safety

7. Relief

8. Solenoid

9. Plug/Ball

10. Diaphragm

E. Define the following pressure-relief valve terms:

1. Blowdown

2. Chatter

F. Describe attributes and applications of the following valve actuator types:

1. Manual

2. Electric

3. Pneumatic

4. Hydraulic

G. Describe the following terms concerning motor-operated valves:

1. Seal-in feature

2. Throttle feature

3. Position limit switches

4. Torque limit switches

5. Worm

6. Clutch

3.0 Introduction

A. In nuclear power plants, high pressure/high temperature piping is a high-technology field.

B. Piping systems are used to transport fluids that may be at high temperatures, high pressures, highly corrosive, or any combination of these.

C. The term "piping system" applies to a connected assembly of pressure retaining pipes, fittings, valves, strainers, and traps that is resting on supports or suspended on hangers.

D. Basically this course makes no distinction between piping and tubing

1. Basically, piping is made of straight pieces of pipe joined by elbows, tees, or other fittings

2. Tubing is often flexible enough to be bent into desired shape without use of fittings.

3. Plant drawings prescribe the exact location and the size of all piping, but size and shape of tubing, especially air tubing, is frequently decided by construction personnel.

E. In this presentation, we will discuss

1. Pipe - types, materials, and applications

2. Piping supports - hangers, supports, and snubbers

3. Various types of valves and their applications

4. Various types of valve actuators

5. Motor - operated valves

4.0 Pipe

A. Piping Standards

1. Pipe material requirements are established by industry standards,

which are published by organizations such as:

a. ASTM - American Society for Testing & Materials

b. ANSI - American National Standards Institute

2. ANSI standards deal with overall piping systems that provide a code of minimum requirements for safety and reliability of a system.

B. Pipe Size and Schedule

1. Nominal Pipe Size - refers to diameter

a. Normally a steel pipe of a standard thickness has an inside diameter close to nominal pipe size — Table 10-1

b. For 14 inches and larger, outside diameter and nominal pipe size are equal.

2. Schedule - refers to the thickness of the pipewall

a. No direct conversion between schedule number and thickness - depends on pipe size - must go to appropriate table.

b. The text provides an equation that a system designer can use for rough determination of pipe schedule required for his system:

$$\text{Schedule} = 1000 \times \frac{\text{Operating Pressure}}{\text{Allowable Stress}}$$

Table 10-2

3. Much nuclear auxiliary piping is schedule 80S - stainless steel

a. Schedule 80S is about .5 inch thick for nominal 6- to 14-inch pipe sizes

b. For actual reactor coolant piping in PWRs which is about 30 inches ID, the thickness is about 1.5 inches.

C. Pipe materials and applications

1. Carbon steel - most widely used in steam/feed piping in PWR plants - but will corrode

2. Stainless steel

   a. This is what sets nuclear systems apart from non-nuclear

      1) Need to limit corrosion

      2) Prevent leaks, flow blockages, heat transfer surface fouling

      3) Prevent irradiation/ activation of corroded metal particles in core

   b. Pressure vessels are carbon steel or chromium-molybdenum steel clad with stainless steel weld material - some very large pipes done same way.

   c. Nuclear auxiliary and some reactor coolant piping all stainless steel.

3. Chromium-molybdenum - used in high pressure, high temperature applications.

4. Cast iron - now used only for underground water or gas distribution, sewage.

5. Concrete - sewers, circulating water system.

5.0 Pipe Hangers, Supports, and Snubbers

A. General

1. Where there is no need for personnel access thru a piping area, piping may be supported on floor supports; where there is need for access, piping is normally supported by hangers from overhead.

2. Pipe hangers prevent the sagging of pipe but allow for slight movement of piping that results from expansion/ contraction and normal vibration.

3. Must carry the weight of pipe, valves, fluid, etc.

B. Use many different types of hangers to provide for or restrict pipe movement in certain directions.

C. Adjustable hangers — Figure 10-1

1. Also called rigid hangers

2. Prevent perpendicular movement but allow slight translational movement.

D. Variable spring hangers allow controlled vertical movement/some horizontal movement. — Figure 10-2

E. Constant supports restrict large amount of movement of very large pipes-main steam. — Figure 10-3

Puts a constant load or spring force on pipe to hold it near a desired position.

F. Roller stand supports allow unrestricted movement in one direction. Used where there — Figure 10-4

is frequent large expansion/contraction of small bore piping system.

G. Pipe Snubbers

1. Special supports designed to allow gradual/slow movement such as thermal growth, but resist sudden/rapid pipe movement from events such as

earthquake, pipe whip, vibration, or shock

2. Used extensively on safety-related systems in nuclear plants

3. Two main types:

   a. Hydraulic - orifice prevents rapid oil flow - check valves shut on sudden rapid oil flow causing hydraulic lock - prevents further movement. Figure 10-5

   b. Mechanical - senses acceleration, tightens up brake on operating shaft - also has dashpot or orifice to slowly release brake.

4. Both types have failed

   a. Oil leakage/contamination

   b. Seal failure

   c. Rusting, binding

5. Reanalyzing the number of snubbers required - used to use them everywhere, but that may hurt more than help; puts excessive loading on piping

6.0 Valves

A. General

1. A valve is a device used to shut off fluid flow, or control the rate of flow into, inside of, or out of a piping system.

2. An open or throttled valve is a source of head loss in a system due to friction

B. Valve parts — Figure 10-6

1. Disk

2. Seat

3. Body, connection to system

4. Bonnet

5. Stem

6. Packing, stuffing box

7. Actuator (hand wheel or mechanized)

8. Yoke - prevent bending of stem

Note: Stems may be

a. Rising

b. Non-rising

C. Gate valves

1. Purpose - stop or start flow - frequently used in feed/condensate systems — Figure 10-6

2. Distinguishing characteristic - gate disk

3. Basic disk types - parallel disk or wedge disk

4. Advantages

   a. Low differential pressure (low friction resistance)

   b. Long life

5. Disadvantages

   a. Poor throttling

   b. Difficult operation at high differential pressure

   c. Longer stroke time

   d. Packing leakage

D. Globe valves

1. Purpose - throttle and/or stop flow — Figure 10-7

2. Plug disk - more contact with seat

   a. Throttle flow more effectively

b. Resists wire drawing - grit holds disk off seat, then leakage cuts groove in disk/seat

3. Metal disk with narrow conical seat — Figure 10-8

4. Angle valves - reduces flow direction changes — Figure 10-9

5. Needle valves - small, many turns to adjust — Figure 10-10

6. Advantages of globe valves

   a. Can throttle flow without valve damage

   b. Can be arranged so system pressure will tend to seat the valve tighter

   c. Parts are easy to replace/repair

7. Disadvantages

   a. High differential pressure

   b. High flow => high pressure under disc => more force to close.

   c. Foreign matter can plug the valve.

E. Check valves

1. General

   a. Purpose - prevent reverse flow

   b. Reliability must be very high

   c. An ideal check valve should:

      1) Open easily and quickly

      2) Have little pressure drop when open

      3) Have little effect on flow patterns

      4) Resist damage to seat disc, disc hanging, or disc guiding

5) Close quickly without valve injury or water hammer

d. Water hammer is scary phenomenon where slug of water moving at high speed is suddenly stopped by a valve, pipe bend, or another mass of water within a piping system.

e. The probability of valve damage and water hammer has caused many nuclear piping designers to try to stay away from swing-check valves.

2. Swing check — Figure 10-11

3. Lift check — Figure 10-12

4. Stop check can also be manually closed — Figure 10-13

F. Butterfly valves — Figure 10-14

1. General - used in low differential pressure situations

a. Extremely durable, efficient, reliable

b. Disc to body seal is not leak tight.

c. Some valves have resilient seats/rubber gaskets for better leak tightness, or metal seats for longer life.

2. Example - ventilation/circ water systems

G. Safety and relief valves

1. Provide automatic overpressure protection for piping systems and components

2. Safety valves

a. Gas/vapor system

b. Pop fully open when set pressure is reached.

c. Terms:

1) Blowdown - pressure drop before shuts

2) Chatter - repeated partial opening/closing

d. Principle of increased surface area (force) causes pop opening; valve starts to open, exposing more area to pressure, overcoming spring compression completely.

e. Steam safety valve discharges are normally to roof with big mufflers; PWR RCS and BWR safeties discharge to controlled container with water seal.

f. Nozzle reaction safety valve — Figure 10-15

g. Huddling chamber safety valve — Figure 10-16

3. Relief valves — Figure 10-17

a. Liquid system or power operated

b. In liquid systems opens gradually in proportion to pressure - allows "chatter", but liquid cushions

c. In steam/air systems - are power operated to prevent chatter

4. Use of relief and safety valves together (pressurizer, main steam): power-operated reliefs have isolation valves, safeties do not

H. Specialty valves

1. Solenoid valves - air to control valves - start/stop air without stem leakage — Figure 10-18

   a. Direct acting

   b. Pilot operated - for high pressure systems

2. Plug valves - dirty systems — Figure 10-19

3. Ball valves - air systems — Figure 10-20

4. Diaphragm valves - eliminate stem leaks — Figure 10-21

   a. Used in gas, refrigeration systems where leaks are not allowed

   b Weir-type

   c. Straightway-type

5. Control valves - have actuators that Figure 10-22 respond to an input signal

   a. Globe valve is the most common body style

      1) Single seated - for small pipes

      2) Double seated - Used for larger valves for balanced forces — Figure 10-23

6. Pressure reducing valves - a type of control valve

   a. Self-contained pressure reducing uses auxiliary valve and piston - inlet/outlet system pressures control valve — Figure 10-24 valves -

7. Three-way valves - Cooling water systems

   a. Diverting service — Figure 10-25

   b. Combining service — Figure 10-26

8. Deluge valve - Fire protection systems — Figure 10-27

- uses system press to hold closed

7.0 Packing

A. Slippery dense material that is pressed tightly/packed around a valve stem to keep operating fluid in. Figure 10-6

B. Must be slippery to allow stem to move or turn.

C. Teflon or graphite impregnated asbestos often used

D. Squeezed down by a packing gland

8.0 Gaskets

A. Replaceable material to seal joints Figure 10-6

B. Common materials

1. Rubber-bonded asbestos used for pressures under 300 psi

2. Metal-clad asbestos used for higher pressures and temperature over 250°F

3. Spiral-wound (flex) gaskets very common for power plant use for higher temperatures and pressures.
   a. Teflon filler - $T \leq 450°F$
   b. Asbestos filler - $T \leq 1000°F$

9.0 Valve Operators (Actuators)

A. General

1. Actuators are devices that convert energy into the work of valve stem movement

2. Types of actuators

a. Manual

b. Power

1) Electric

2) Air

3) Hydraulic

B. Manual actuator — Figure 10-6

1. Handwheel

2. Lever

3. "Hammer" hand wheel - moves freely for portion of travel before striking lug on secondary wheel

4. Gears

a. Air motor

b. Electric wrench

5. Chain wheel

C. Electric actuators — Figure 10-28

1. Advantages

a. Remote operation

b. Rapid opening or closing

c. Automatic operation

2. Electric valve operator or motor-operated valve

Figure 10-29

3. Limitorque valve operators - limitorque refers to a vendor product line. The term is sometimes used generically to refer to electric motor-operated valves

a. General

1) Controls and limits the opening and closing travel/torque of the valve

2) Proper valve seating very important - prevent valve damage and ensure leak tightness

3) Torque limit switches - stop valve movement if obstruction encountered.

4) Travel position limit switches - normal method of stopping valve motion

b. Operation of SMB-0 or larger operators

Figure 10-30
Show NRC video-tape, if available.

1) High motor speed is geared down to useful operating speed.

Figure 10-31

2) Electrical drive shaft motion is transmitted to the worm through a clutch - clutch can be disengaged with handle to allow manual operation.

3) If clutch has been disengaged for manual operation, receipt of an electrical signal - either from a control switch or an actuation signal - will automatically reengage the clutch (allowing motor operation) and disconnect the handwheel.

4) Worm turns worm gear which is splined to a drive sleeve that engages the threads on valve stem.

5) The trick is to get the valve to shut tightly, but not to jam it shut causing damage to the valve - or preventing it from opening.

6) Use position limit switches and torque limit switches to do this.

a) Position limit switches are just gear driven from worm shaft.

b) Torque limit switches take advantage of worm's ability to slide along worm shaft when operating shaft meets resistance.

Figure 10-31

c) Worm movement (due to obstruction) compresses Belleville springs causing turn of torque limit switch shaft - closes torque switch, which interrupts power to the motor.

c. Hand Operation - a handwheel is provided for emergency hand operation of the Limitorque valve actuator.

1) Figure 10-32 shows the declutching arrangement when the declutch level is pulled downward. Figure 10-32

2) When the handwheel is rotated, it turns the handwheel clutch pinion which is engaged with the worm shaft clutch, which turns the worm shaft and rotates the worm gear.

3) When the electric motor is energized, the worm shaft clutch is released and driven along the splines on the worm shaft to engage with the worm shaft clutch gear. Power is again transmitted through the motor pinion to the worm shaft clutch gear to the worm shaft clutch,and on through the worm shaft.

4) When the handwheel is turned it does not rotate the motor. Similarly, when the motor is in operation, the handwheel does not turn. Because the handwheel drives through the same train as the motor, it will operate the torque switch.

d. SMB-000 Actuator Differences Figure 10-33 Figure 10-34

1) SMB-000 smaller; SMB-0 larger (up to SMB-5)

2) From a mechanical standpoint, differences are in the declutch assembly parts, the handwheel gearing, and the actuation gearing for the torque and limit switches.

3) Unlike the SMB-0, which has a clutch splined to the worm shaft, the SMB-000 has a clutch ring, which is mounted on the drive sleeve just above the worm gear and is moved upward by the clutch fork assembly (for hand operation). When the declutch lever is depressed, the clutch ring moves the clutch keys upward until they engage with the lugs on the bottom of the handwheel.

4) In the SMB-0 and larger operators, the handwheel drives through the same train as the motor and will operate the torque switch; however, in the SMB-000 and SMB-00, the handwheel turns the drive sleeve directly and will not operate the torque switch.

e. MOV Problems - Because these valves are normally quite large and in many applications they must move full stroke in less than 10 seconds,

1) Hard to get torque and limit switches adjusted exactly

2) Valve cycling or pipe movement causes switch misadjustment

f. Motor Operator Control circuits — Figure 10-35

1) Like a normal motor controller - has separate open and close paths

2) Seal-in contact - simply a contact around the operating switch that allows the spring-return-to-neutral switch to be released by the operator while valve keeps moving to full open or full shut position

3) Switches with the spring- return-to-neutral feature can have automatic safety features incorporated - normally not used where valve has to be throttled by an operator.

4) Close/open limit switches normally interrupt power to motor.

5) Torque switches interrupt power if torque too high.

a) Torque bypass switches allow using extra torque to get valve off seat or backseat.

b) Torque bypass switches also used during safety injection actuation to ensure valve strokes to emergency condition.

6) If the valve can be used as a throttle valve, delete the seal-in feature - valve moves only when switch is turned to open or closed position — Figure 10-36

7) The valve position indication can come directly from the actuator or can come from limit switches operated by a follower arm on valve. In either case, red is normally open, green is closed, and a combination red/green or both dark means intermediate - can also have percentage indication.

D. Pneumatic Actuators - control air operates on a diaphragm that moves disk against spring pressure. — Figure 10-37

1. Used on many smaller piping systems (4 inches or smaller)

2. Frequently used on small/medium valves that control flow, but can be used for isolation valves. These are the type of valve actuators that are controlled by the controllers discussed in the controllers chapter.

3. Frequently use solenoid valves to turn on/bleed off air pressure above or below diaphragm - diaphragm movement is opposed by spring pressure

4. Plant operators normally expected to know what would happen to valve if air pressure is lost or power to solenoid is lost. Normally, valves are set up so these

failures would put valve in safe position or would cause least perturbation on system.

5. Pneumatic control valves that are throttle valves normally have electronic-to-pneumatic (EP) converters (about a foot square gray box) that

Figure 10-38

convert an electrical signal to an output air pressure.

6. E/P converters adjust air pressure to hold valve at position that will cause the right flow - must have feedback device

E. Hydraulic Actuators - control oil operates on a piston that moves valve through a mechanical linkage that is opposed by spring pressure. — Figure 10-39

1. Used on very large valves with large possible differential pressure - main turbine control valves, stop valves, main steam stops

2. Hydraulic actuators normally have self-contained hydraulic system

   a. Systems normally have an accumulator pressurized by air/nitrogen, a pump to restore system accumulator pressure after a valve stroke, and valves to port oil pressure to top or bottom of a piston that moves the valve through the lever linkage

   b. Normally have reservoir to catch oil vented from other side of piston

3. As in turbine control valves, a hydraulic lock can be used to hold a control valve in an exact position.

4. A solenoid trip valve can be used to suddenly vent off one side causing closure.

5. Not normally used in containment - don't like high press oil systems in containment with possibility of leakage causing fire and/or contamination problems.

10.0 Summary

A. Review learning objectives — Learning objectives

1.0 References

PPE Course Manual Chapter 11 (Turbines)

2.0 Learning Objectives

Learning objectives

A. State the purpose of a turbine

B. Define or describe the following as appropriate:

1. Stop valve
2. Control valve
3. Combined intermediate valves (includes reheat stop valve and intercept valve)
4. Extraction non-return valve
5. Governor
6. Front standard
7. Critical speed
8. Journal bearing
9. Thrust bearing
10. Labyrinth seal

C. Explain the purpose of the following turbine auxiliary system/components

1. Moisture Separator/Reheater
2. Lubricating Oil System
3. Turning Gear and Lift Pumps
4. Gland Seal Steam System

D. Explain why a turbine is tripped under the following conditions:

1. High vibration
2. Overspeed

3. Low lube oil pressure
4. High thrust bearing wear

5. Reactor trip

6. High reactor vessel (steam generator) level

E. Explain how the addition of water to a Terry turbine can lead to turbine overspeed.

3.0 Introduction

A. A nuclear power plant produces saturated steam for transporting thermal energy to the turbine where the energy is converted to mechanical energy. The generator converts the mechanical energy to electrical energy.

B. Steam flow to the turbine is controlled by the governing valves and quick acting stop valves which will rapidly close in an emergency.

C. The basic function of a steam turbine is to convert the thermal energy of steam into mechanical work.

4.0 Turbine Design Types

A. Impulse turbines — Figure 11-1

1. In a pure impulse turbine the entire pressure drop for each stage occurs in the nozzle. The nozzles are arranged in a ring and are stationary, and feed steam into the rotating baskets at an angle to the moving bucket. The buckets change the speed and direction of the steam, but do not cause a pressure drop.

B. Reaction turbines

1. In a reaction turbine, the nozzles rotate. Figure 11-3
In an ideal reaction turbine all of the pressure drop occurs across the rotating nozzles. In large turbines this design is impractical.

2. Figure 11-2 shows the characteristics of both an impulse turbine and a reaction turbine. Note: the reaction turbine exhibits some of the characteristics of the impulse turbine. — Figure 11-2

3. In a pure reaction turbine, the pressure drop occurs as the steam moving across the moving blades. The only purpose of the stationary blades is to redirect the steam. The pure reaction state used relatively infrequently. Most reaction turbines have a pressure and enthalpy drop in both the fixed and moving blades. The degree of reaction is defined as the fraction of the enthalpy drop that occurs across the moving blades.

C. Turbine Staging

1. Multiple stages are used to extract maximum energy from the steam.

   a. A typical turbine must extract 400 BTU/lb of work from the incoming steam. Because a single impulse stage is capable of extracting about 40 BTU/lb, 10 or more stages would be needed for the typical turbine.

2. Impulse turbine compounding has two ways of extracting more energy:

   a. Velocity compounding - Curtis stages Figure 11-4

      Multiple rows of rotating blades with stationary buckets in between. The stationary buckets are not nozzles.

   b. Pressure compounding - Rateau turbine Figure 11-5

      Multiple nozzles each followed by one row of moving buckets. Each stage is designed as a single stage impulse turbine.

3. Reaction turbine compounding

   a. Compounding is simple multiple staging.

   b. Maximum efficiency occurs when blade speed is equal (and opposite in direction) to steam speed - twice the speed of impulse turbine.

4. Stage efficiencies in a practical turbine

a. The relative efficiencies of various types of turbines can be seen in Figure 11-6. Figure 11-6

b. It can be seen that while peak efficiency for the reaction element is better than either type of impulse turbine, it falls off very quickly with the size of the enthalpy drop. Because large enthalpy drops are common in the first stage of a large turbine, it is common to see a Curtis stage as the first stage of a multistage turbine.

5.0 Construction Details

A. Stage sealing — Figure 11-7

1. As previously stated, the largest pressure drop in an impulse turbine is across the stationary nozzles. And the largest pressure drop in a reaction turbine is across the moving buckets. Therefore, the problem of sealing these two types of turbines so that all of the steam goes through the blading is slightly different.

2. In a reaction turbine equal attention is paid to the stationary and moving buckets.

3. In an impulse turbine most of the shaft packing is at the stationary nozzles while there is only abbreviated packing on the rotating blade tips.

B. Axial thrust loading

Figure 11-7

1. Because of the large pressure drop across the rotating blades of a reaction turbine, considerable force is generated on the rotor. One method of dealing with this force is to have a large thrust bearing. This is frequently impractical. Another way Figure 11-8 of dealing with this force is to use a double flow rotor. The flow splits and goes in opposite directions. This balances the axial thrust and decreases the need for large thrust bearings.

C. Rotor Design — Figure 11-9

1. Rotors are fabricated by three different processes:

a. Single Forging

b. Rotors shrunk and keyed onto the shaft

c. Hollow forged sections are welded together.

2. The shaft is supported by journal bearings at each end. A thrust bearing maintains the shaft axial position. Bi-directional thrust bearing. A low speed turning gear will rotate the shaft when the turbine is shut down.

D. Shaft sealing systems — Figure 11-10

1. The shaft sealing system is designed to prevent steam from leaking out of the turbine at high power and to keep air from leaking into the turbine at low power. This is accomplished by maintaining a controlled leakage into a gland area inside of the seal.

2. This gland area is maintained at a vacuum by the gland steam condenser.

3. Sealing steam is provided by either the main steam system or an auxiliary source.

E. Rotor Glands — Figure 11-11

1. Labyrinth seals encircle the rotor at each end. The seals provide a torturous path that inhibits the flow of steam and air.

2. At low loads, the the HP and LP exhaust chambers are below atmospheric pressure. Sealing steam is supplied to chamber X, which effectively seals steam leaking out of the turbine and air leaking into the turbine. — Figure 11-12

3. At high loads, the high pressure turbine supplies all sealing steam for both the high and low pressure turbines. At this point, the turbine is said to be self-sealing.

F. Gland Seal Condenser

1. Maintains slight negative pressure in gland leak-off system

6.0 Practical Turbine Types — Figure 11-13

A. Condensing versus non-condensing

Some of the oldest power plants did not condense the turbine exhaust.

B. Extraction versus non-extraction

1. Many turbines are now designed such that steam can be extracted from the turbine at various points. The extraction steam can be used for feedwater heaters or other applications.

C. Reheat versus non-reheat

1. In some multistage units the steam is piped back to a reheater to improve its quality before it enters the last stages of the turbine. This improves the cycle efficiency of the plant.

D. Single Casing versus Compound Turbines

1. Small turbines are usually built with all of the stages housed in one casing.

2. Larger turbines may have up to six separate casings. If all of the shafts from the separate casings are bolted together in line, the generator is called "tandem compound."

3. Two small generators may be driven side by side, this is called "cross compound".

E. Single versus Multiple Flow

1. Small single casing turbines are generally single flow; large turbines generally use multiple flow.

7.0 Modern Turbines

Figure 11-14
Figure 11-15

A. A typical large turbine is shown in figure 11-14. It consists of one high pressure turbine and three dual exhaust low pressure turbines mounted on one shaft. This is an 1800 rpm, tandem-compounded, six-flow turbine.

B. Steam approaches the turbine through four main steam lines that are connected by an equalizing header, then through four stop valves and four control valves. Flow splits and enters the center of the high pressure turbine. Figure 11-16

C. After passing through the HP turbine, the steam has provided approximately 70% of the work accomplished by the turbine.

D. The steam then passes through the two moisture separators/reheaters and finally through the low pressure turbines.

E. Turbine Valves — Figure 11-16

1. Stop Valves - There are four stop valves that are normally fully open during turbine operation. On a turbine trip signal these valves will rapidly close (0.1 sec) to shut off the steam supply to the turbine.

2. Control Valves

   a. Regulate the flow of steam to the turbine.

   b. For a BWR the turbine control system will maintain a constant reactor pressure for a given reactor power. Turbine power follows reactor power.

   c. For a PWR the turbine control system maintains a constant generator output. Reactor power follows turbine load.

3. Combined Intermediate Valves

   a. Two valves in one: a reheat stop valve and an intermediate control valve (intercept valve).

   b. Both valves are normally fully open during high power operation. During low power operation, the intercept valves may be throttled to control steam flow to the LP turbines. The intercept valves will also start to throttle closed during a turbine overspeed condition. Both valves will close on a turbine trip with the stop valve acting fastest.

B. Electro-Hydraulic Control System — Figure 11-17

1. Uses oil to position the turbine valves as required. A turbine trip is accomplished by venting the oil from all of the valves, which allows spring pressure to close the valves.

C. Lube Oil System — Figure 11-18

1. Supplies oil to the bearings of the turbine and the generator. It also supplies oil to several safety trip devices.

2. During low speed operations, lift pumps supply oil to the bearings.

3. As turbine speed increases to rated speed, a shaft driven oil pump supplies bearing oil pressure.

4. Oil from the shaft driven oil pump also drives a booster pump which supplies oil to the shaft driven pump.

5. Two electrical pumps supply oil to the bearings when the turbine is on the turbine gear, accelerating, or in an emergency condition.

   a. The turning gear oil pump - A.C.

   b. The emergency bearing oil pump - D.C.

8.0 Turbine Bearings

A. Main Bearings — Figure 11-19

1. Provided at the ends of each turbine to support the main shaft weight and allow for alignment of the shaft.

B. Thrust Bearings — Figure 11-20

1. One thrust bearing is provided, usually between the HP and LP turbine casings.

2. This bearing maintains the position of the shaft during changing load conditions.

3. A leveling plate distributes the thrust load equally around the bearing.

9.0 Extraction Steam Figure 11-13 Sheet 1

A. Provides a heat source for feedwater heaters. Remove moisture from turbine stages.

The extraction steam lines are equipped with extraction non-return valves (ENR) that will trip during a turbine trip to prevent damage to the turbine from water induction or overspeed.

10.0 Exhaust Hood Spray

A. Sprays water onto the hoods of the last stage of the LP turbine to help cool the blades which have heated up due to friction at low loads.

11.0 Turning Gear

A. Turns the turbine shaft at 1 to 2 rpm to prevent shaft bowing due to the weight of the shaft or differential expansion. Figure 11-21

12.0 Front Standard Figure 11-14

A. Supports the high pressure shell and the the high pressure turbine.

B. Houses various devices and control components, including:

a. Overspeed trip

b. Mechanical trip valve

c. Lockout valve

d. Oil trip valve

e. Mechanical trip solenoid

f. Low speed switch

g. Mechanical manual trip

h. Shaft grounding devices

i. Oil sights

j. Main oil pump

k. Speed sensing head

13.0 Turbine Governor

A. Controls steam flow to the turbine to maintain shaft speed constant under varying load conditions.

B. Simplest type of governor is the flyweight governor. Flyweights spin proportional to turbine rotor speed. Centrifugal force pushes the weights outward, causing a speeder rod to be lifted up against spring pressure. As speeder rod moves, a steam control valve will be repositioned, changing steam flow. This is typically used in small turbines or as an overspeed protection device on larger turbines. — Figure 11-22

C. Most large turbines use a hydraulic governor system.

14.0 Turbine Operational Problems

A. Vibration is a major concern to the operator. Causes include:

1. Unbalanced shaft
2. Poor alignment
3. Bad foundation
4. Loose parts
5. Internal rubbing
6. Steam troubles
7. Packing troubles
8. Oil troubles

B. Critical Speeds — Figure 11-23

1. Vibration induced in a turbine due to natural harmonics associated with operating the turbine at certain speeds.

C. Water Induction

1. Water entrained in the steam may cause damage to the turbine.

2. Sources of water include:

   a. Extraction lines

   b. Steam seal system

   c. Moisture carryover

D. Overspeed

1. If the generator circuit breaker is opened when reactor power exceeds the bypass valve capacity, the turbine should trip by closing all of its stop and control valves and the extraction non-return valves. If the turbine does not trip, an overspeed will occur. Two backup overspeed trips are usually provided.

E. Low Lube Oil Pressure/High Thrust Bearings Wear

1. Loss of lubrication for even a short period can destroy a bearing surface.

2. To prevent bearing damage, turbines are immediately tripped when there are indications of low lube oil pressure.

3. High thrust bearing wear is usually an indication of a lube oil system malfunction. To prevent damage, turbines are immediately tripped when there are indications of high thrust bearing wear.

F. Reactor Trip

1. PWR plants automatically trip the turbine on a reactor trip. This prevents rapid cool down of the reactor system.

2. On BWR plants, a reactor trip also secures steam to the turbine.

15.0 Auxiliary Turbines

A. Auxiliary turbines for emergency use must be capable of starting up and obtaining rated flow in less than 25 seconds.

B. This type of turbine can use steam of very low quality but entrained water can lead to overspeed problems due to the increased mass of the water on the turbine blading.

C. Protected against overspeed by a mechanical tripping mechanism. A mechanical key, whose position is a function of the centrifugal force generated by motor speed will trip a mechanical lever in the turbine casing during turbine overspeed conditions. This will shut the turbine steam supply valve.

16.0 Summary

A. Review objectives — Learning objectives

1.0 Reference

A. PPE Course Manual, Chapter 12

2.0 Learning Objectives

Learning objectives

A. Define and/or explain the following:

1. Head
2. Net positive suction head (NPSH)
3. Cavitation
4. Shutoff head
5. Pump runout

B. Describe the construction/operation of a centrifugal pump.

C. Describe the causes/effects of cavitation on the operation and internal components of a centrifugal pump.

D. Describe the construction/operation of a reciprocating positive displacement pump.

E. Describe the purpose/operation of the following:

1. Stuffing Box
2. Shaft sleeve
3. Sealing water
4. Mechanical seals

F. Draw an operating characteristics curve for a typical centrifugal pump and explain the shape of the curve; combine the pump curve with a typical system head loss curve and explain the location of the operating point.

G. Discuss factors which shift the operating point on a pump curve.

H. Draw operating characteristics curves for centrifugal pumps in series or parallel operation.

I. Draw an operating characteristics curve for a typical positive displacement pump and explain the shape of the curve and the location of the operating point.

J. Use the centrifugal pump laws to determine new pump operating conditions created by a change in pump speed.

K. Describe the construction and operation of a jet pump.

3.0 Introduction

A. Fluid mechanics principles

1. Head - the height of water needed to produce a fluid pressure equal to the actual fluid pressure at a certain point in a piping system

2. Head can be expressed in feet of water or pounds per square inch (using fluid density in conversion)

3. The term head was originally applied to the static head that existed in stationary fluid. Static head comprises the potential head due the height of the water column above the measurement point plus the pressure head due to any gas overpressure on the surface of the water (converted to the equivalent water column height).

4. Water that is moving also has a velocity head which is the distance this water stream could be bent straight up by a frictionless elbow.

5. Velocity head can be related to pressure head through the equation

$$V^2 = 2gh$$

B. Pump is a moving mechanical device that does work on a fluid thereby giving it energy to move.

C. Pump head - the measure of the energy the pump must supply to the fluid to enable the fluid to overcome all the friction losses resisting its flow around the system.

$$z_1 + \frac{(v_1)^2}{2g} + \underline{p_1} + h_p = z_2 + \frac{(v_2)^2}{2g} + \underline{p_2} + H_f$$

D. Three basic types of pumps used in nuclear plants

1. Centrifugal pumps that use a rotating impeller to impart centrifugal force to fluid.

2. Positive displacement pumps that use a reciprocating piston to displace successive volumes of incompressible fluid.

3. Jet pumps that use an operating or motive fluid to impart momentum to the suction or pumped fluid

4.0 Centrifugal Pump Basics

Figure 12-1

A. Two basic functions

1. Impart kinetic energy of an impeller to fluid by centrifugal force

2. Convert part of the kinetic energy to pressure energy by reducing fluid velocity in an expanding area volute

B. Operation

1. System pressure moves fluid axially into the eye or open center of the impeller

2. Impeller construction prevents further axial movement so fluid is forced out into the moving vanes

3. The rotation of the vanes and contained fluid imparts centrifugal force and very high velocity to fluid

4. The fast moving fluid is allowed to expand in the volute where it slows down

5. Because no work is done in the volute, energy remains constant; therefore, the reduction in kinetic energy causes an increase in pressure energy, which is the desired effect.

C. Centrifugal Pump Characteristics

1. Discharge relatively free of pulsations
2. Capable of high capacity
3. Efficient performance over a wide range of conditions
4. Not self-priming. Cannot pump air or vapor.

5.0 Centrifugal Pump Mechanical Details

A. Two mechanical parts — Figure 12-1

1. Rotating element - impeller - imparts kinetic energy
2. Stationary element - casing/volute - changes part of kinetic energy to pressure
3. Multistage centrifugal pumps have a series of impeller-volute combinations with each stage impeller taking its suction from discharge of preceding volute. — Figure 12-2

B. Radial forces on impeller controlled by volute — Figure 12-3, Figure 12-4

1. Volute designed so radial forces are counterbalanced when pump is operating at design capacity
2. At capacities below and above design capacity, the radial forces are not balanced - causes increased wear on shaft sleeves, shaft bearings.
3. Double-volute casings are designed to balance the radial forces. — Figure 12-5

C. Impeller classifications

1. Impeller suction type
   a. Single suction cheaper and simpler
   b. Double suction helps balance — Figure 12-6

axial thrust forces and can permit operation with smaller suction head.

c. Multistage pumps normally use single-suction impellers, but subsequent stage suction directions are alternated to balance axial thrust forces.

2. Impeller design type

a. Open - like windmill

b. Closed - two disks with vane membranes between them

c. Semiopen is somewhere in between

D. Shafts and shaft sleeves

1. Critical speed - pump rotor shaft rotating at a speed corresponding to its natural frequency of vibration

2. Rigid shaft - operating speed less than first critical speed

3. Flexible shaft - operating speed greater than first critical speed

4. Shaft sleeve - a sacrificial wear sleeve that is keyed or fastened to shaft to protect shaft at areas of high wear — Figure 12-7

6.0 Centrifugal Pump Stuffing Boxes

A. Normally have two functions

1. Reduce pumped fluid outleakage along shaft

2. Prevent air inleakage along shaft, which could collect in low pressure impeller eye and cause air binding

B. On nuclear pumps, stuffing boxes normally have two parts: — Figure 12-7

1. Rings of packing to squeeze the shaft sleeve

2. A lantern ring or seal cage to distribute sealing (or injection) water — Figure 12-8

a. Sealing water prevents escape of steam or radioactive gases

b. Sealing water also prevents air inleakage

3. Sealing water normally injected under pressure into middle of packing rings.

a. Doesn't need higher pressure than operating pressure

4. Sealing water can come from discharge of pump or from an external source — Figure 12-8

a. Text gives some situations where external source is normally used

1) Large suction lift

2) Low discharge pressure

3) Hot pumped fluid

4) Hotwell (condensate) pumps, which may frequently operate with cavitation

5. Packing - similar to valve packing

a. Soft, pliable so won't damage shaft

b. Won't break down with friction heat

c. Normally use asbestos or metallic packing

6. Stuffing box gland

a. Like packing gland in a valve

b. Tighten down gland to squeeze packing against shaft

7.0 Centrifugal Pump Mechanical Seals

A. Used in applications having very high pressure or overriding need to have minimum leakage — Figure 12-9

1. These conditions will rapidly cause leakage or shaft damage or both if normal stuffing boxes are used - no shaft is perfectly round.

2. Engineers developed mechanical seals which use mating surfaces on plane perpendicular to shaft axis - can be more forgiving of manufacturing tolerances

3. Many pumps that have mechanical seals also have a stuffing box as backup.

B. Principles of Mechanical Seals

1. Two sealing surfaces located in a plane perpendicular to the shaft

2. One of the surfaces is attached to shaft and rotates; other surface is attached to pump casing.

3. Mating surfaces are often pushed against each other by leveling springs behind rotating surface.

4. Plenty of sealing surface to accommodate any shaft eccentricities

5. Use of springs causes surfaces to grind each other smooth.

6. Rotating element is usually made of a hard material - stellite.

7. Stationary element is often made of carbon or some other material that will wear slightly to form better seal.

8. Actually must be some leakage between surfaces for lubrication and cooling

9. The leakage film between the surfaces can be either pumped fluid or injected sealing fluid.

C. Details of Mechanical Seals   Figure 12-10

1. Rotating element can be either inside seal assembly box (internal) or outside seal assembly box (external).

2. Pumped liquid pressure tightens seal

in internal assembly; pumped liquid pressure opens seal in external assembly.

3. Some pumps have double seals inside the sealing box - normally with an injected sealing liquid. Figure 12-11

8.0 Centrifugal Pump Bearings

A. Two basic types required

1. Radial (or line) bearings - maintain radial position of rotor

2. Thrust bearings - maintain axial position of rotor

B. Most radial bearings are ball bearings

1. Ball bearings consist of three parts

a. Inner race - attached to and spins with shaft

b. Outer race - attached to casing - stationary

c. Bearing balls - rotate and travel so there is no sliding friction - it is a rolling action

d. Packed with grease for lubrication and cooling

2. Ball bearings can be self-aligning to accommodate slight angular misalignment of shaft

3. Ball bearings cannot accommodate thrust forces unless specially designed

9.0 Cavitation

A. The formation of vapor-filled cavities in the pumped liquid due to the impeller dynamic action coupled with the subsequent collapse of these cavities is called cavitation.

B. Cavities may be bubbles, vapor-filled pockets, or combination of these.

C. Local pressure must dip below vapor pressure of liquid for cavity formation to begin; and then must increase above the vapor pressure for cavity collapse to occur.

D. Even minor cavitation causes pump damage over period of time - millions of little water hammers beating on the vanes.

E. Heavy cavitation can cause rapid pump damage due to motor imbalances - also causes discharge pressure fluctuations and flow slugging.

10.0 Pump Head

A. Suction head - head available at the pump suction

B. Discharge head - head available at pump discharge - equals suction head plus head added by pump

C. Net Positive Suction Head

1. NPSH is the pressure head available - or required - to force a given flow (gpm) of pumped liquid into the impeller of a pump

2. For uniformity NPSH is stated as feet of water equivalent to the available- or required-pressure above the vapor pressure of water at the pumping temperature

3. An adequate or minimum required NPSH implies that the total static and dynamic head of the liquid at the suction of the pump is sufficiently above the temperature-dependent vapor pressure of the liquid to preclude vapor bubble formation anywhere in the pump.

4. The pump manufacturer determines the minimum required NPSH empirically; the system designer and operator must then operate the system such that the available NPSH always exceeds the minimum required NPSH.

5. A word expression for available NPSH is the sum of the static head plus the velocity head minus the liquid saturation pressure. The following would be the equation form:

$$NPSH_{avail} = \frac{P}{\gamma} + \frac{V^2}{2g} - \frac{P_{sat}}{\gamma}$$

D. Cavitation Prevention

1. Required NPSH states the minimum pressure conditions required at a pump suction to prevent cavitation.

2. Required or minimum NPSH is determined by test and specified by the pump manufacturer.

3. The available NPSH must be at least equal to the required NPSH to prevent cavitation.

4. Remember - vapor pressure of liquid increases as temperature increases

5. Positive factors contributing to available NPSH

   a. Height of expansion tank level above pump suction

   b. Overpressure on expansion tank liquid

   c. Temperature reduction in pumped fluid

6. Negative factors deducting from available NPSH

   a. Friction losses between expansion tank and pump suction - connect expansion tank close to pump suction

7. The positive factors do not vary with flow rate, but friction loss increases as the square of flow rate; therefore, the available NPSH normally decreases as flow rate increases.

11.0 Positive Displacement Pumps (PDPs)

A. Basic principle - A solid will displace an equal volume of liquid. — Figure 12-12

B. Components of the liquid end of a reciprocating PDP

1. Displacing solid - piston/plunger
2. Container holding liquid - cylinder
3. Suction check valve
4. Discharge check valve
5. Packing around piston - keep water in and air out

C. Operation of PDP liquid end — Figure 12-13

1. Plunger moves out, dropping pressure
2. Suction check valve opens, admitting liquid
3. Plunger moves in, increasing pressure
4. Discharge check valve opens, releasing liquid
5. Volume of liquid forced into discharge pipe essentially equal to plunger displacement

D. PDPs can also be double acting — Figure 12-14

1. Need piston rings or piston packing
2. Need two suction valves and two discharge valves

E. Most nuclear PDPs use electric motor with a crank-and-throw device for moving pistons

1. Must also have speed reduction system to get piston speeds down to efficient speed

F. Construction of PDP liquid end — Figure 12-15, Figure 12-16

G. Characteristics of PDPs

1. Adaptable to high pressure operation
2. Pulsating discharge normally requires damping
3. Capable of efficient performance at extremely low through-put rates.

4. Flow rate is constant over a wide range of discharge pressures. Larger pistons, more cylinders, or increased speed can increase flow.

H. Pulsations are inherent disadvantage of PDPs

1. Two methods of reducing pulsations

a. Multiple pistons — Figure 12-17

b. Pulsation dampener on discharge — Figure 12-18

I. PDPs have a required NPSH to prevent cavitation in suction passages. — Figure 12-19

12.0 Jet Pumps

A. Jet pumps are similar to an air ejector or water eductor and have no moving parts - instead a high-pressure stream of motive fluid is directed through a nozzle designed to produce a very high velocity — Figure 12-20

B. The nozzle converts much of the motive fluid pressure energy to kinetic energy and significantly reduces the pressure in the suction chamber.

C. The suction fluid is allowed to flow into the low pressure suction chamber, mixes with the motive fluid, and takes some of the momentum of motive fluid.

D. The resultant mix is then sent to a diffuser where much of the velocity is converted back to pressure.

E. Three basic parts of jet pump are nozzle, suction chamber, and diffuser.

F. Jet pumps are most specifically referred to in BWRs where the motive fluid is supplied by the recirculation pumps.

G. Characteristics

1. Inefficient - can't get real high flow rate or pressure

2. Lack of moving parts makes them reliable.

3. High reliability makes them useful in inaccessible locations.

13.0 Operating Characteristics of Centrifugal Pumps

A. Operating characteristics curves

1. Pump head curve

a. Discharge head is high at low flow (shutoff head) and low at high flow (runout). Figure 12-21

b. Plateau section is longer for pumps with higher speeds and larger impellers.

2. System head loss curve - due to fluid friction with pipe walls and valves - varies as square of flow rate.

3. Where these two curves cross is the system operating point.

4. The operating point can be varied by changing either the pump curve or system curve.

5. Shutoff head

a. As previously stated, the pressure at the outlet of a centrifugal pump (divided by the fluid density to convert to feet) is the pump head.

b. There is an upper limit on the discharge pressure that a centrifugal pump can develop - determined by

1) Pump speed

2) Size of impeller and volute

3) Tolerances between impeller and pump casing

c. This upper-limit discharge pressure of a centrifugal pump can be determined by shutting off the discharge of the pump; hence, the upper-limit head is referred to as the shutoff head.

1) Shutting off the discharge can be done by shutting discharge valve or increasing downstream pressure above discharge pressure capability of pump.

2) Used to think that operation at shutoff head would not instantaneously harm pump. Impeller essentially windmills in the fluid - friction between windmilling impeller and fluid produces heat, causing rapid temperature rise in fluid, impeller, and casing - decreasing clearances - metal contact possible after short time

3) Recent licensee reports indicate that pump damage can occur rapidly due to flow/pressure imbalances causing unbalanced radial forces and vibration.

4) System must be designed to provide some minimum cooling flow through pump under all conditions even with discharge valve shut - normally done with a small recirculation line called a mini-flow. Recent licensee reports have also indicated that larger mini-flow or recirculation flow rates are required to prevent the flow/pressure imbalances described above.

6. Pump Runout

a. Just as there is an upper limit on discharge pressure that a centrifugal pump can face and still have flow, there is also a lower limit on discharge pressure to ensure that the flow rate does not become excessive.

b. When the discharge pressure goes below this lower limit, and flow becomes excessive, the unbalanced radial forces can cause excessive vibration and rapidly damage the pump. Also, the large electrical current flow can cause motor winding overheating. Pumps that use the pump discharge pressure to supply shaft seal cooling or sealing water may lose this cooling under runout conditions.

c. Normally, system design prevents runout conditions under all foreseen operating conditions, but a pipe rupture or other event that drops discharge pressure to near-zero can cause very rapid increase in flow rate to runout conditions.

B. Factors which shift system operating point

1. Shifting pump curve

a. Speed of pump — Figure 12-22

b. Number of stages — Figure 12-23

c. Number of pumps

d. Series or parallel arrangement

e. Internal changes in pump - cavitation, wear — Figure 12-25

f. Density/temperature of fluid

2. Shifting system curve — Figure 12-24

a. Valve types, position

b. Pipe wall friction: crud, erosion, corrosion

c. Series or parallel operation of components

d. Density/temperature of fluid

C. Single pump operations

1. Although there are pumps with variable impeller/vane sizes, almost all nuclear pumps have constant size

impellers - so must change pump speed to change pump curve significantly.

2. Both discharge pressure and flow rate increase if pump speed is increased - but recall head is related to flow velocity squared.

3. The pump laws

   a. Flow rate is proportional to pump (motor) speed

   b. Pump head is proportional to pump (motor) speed squared

   c. Pump power is proportional to pump (motor) speed cubed

4. Normally, pump speed is changed by varying number of poles used in motor windings.

   a. 2-pole motors rotate at nearly 3600 rpm

   b. 4-pole motors rotate at nearly 1800 rpm

   c. 6-pole motors rotate at nearly 1200 rpm

D. Multiple pump operations

1. Parallel operations

   a. Both pumps develop same shutoff head, but same flow rates in each branch comprise total system flow. — Figure 12-26

   b. Height of plateau constant, but plateau length is increased and flow rate approaches doubling

   c. Because system curve changed only slightly by adding parallel branch, operating point flow rate is increased significantly and resultant pump head less so. — Figure 12-27

2. Series operations

   a. Because total system flow rate — Figure 12-28 must go through each pump, the runout flow rate for series operation is same as for single pump, but the pump heads are additive so shutoff head of pump curve is doubled.

b. Height of pump curve is doubled, but length remains constant.

c. System curve is again changed only slightly so operating point pump head is increased significantly and flow rate less so. — Figure 12-29

14.0 Operating Characteristics of Positive Displacement Pumps (PDPs)

A. A PDP will produce essentially constant flow rate despite increases in system back pressure, friction losses, or any other impediment, even a closed discharge valve. — Figure 12-30

B. Because pumped water is almost incompressible, the discharge pressure will increase rapidly to match the system backpressure.

C. If the outlet valve is shut or system back pressure is allowed to increase, the pump discharge pressure will continue to increase until system or pump damage occurs, unless prevented by a relief valve.

15.0 Summary

Learning objectives

A. Review objectives

1.0 References

A. PPE Course Manual, Chapter 13, Diesels

2.0 Learning Objectives

Learning objectives

A. Describe the purpose and basic operation of an emergency diesel generator.

B. Describe the purpose and basic characteristics of the following emergency diesel generator auxiliary systems

1. Starting system
2. Fuel transfer system
3. Fuel injection system
4. Cooling water system
5. Lubricating oil system

C. Explain the terms scavenging, supercharging, and turbocharging.

D. Explain measures taken to allow an emergency diesel generator to be started and loaded within 10 seconds without damage.

3.0 Introduction

A. All nuclear plants must have reliable 10CFR50 App.A emergency power source; must be on line Criterion 17 supplying safeguards equipment within seconds Reg. Guide 1.9 of loss of normal and backup power; must be wholly independent of normal and backup power. Reliable source of emergency power (5 MW) of medium voltage for operating safety related systems.

B. Each plant is required to have at least two separate and redundant emergency power systems and each must be supplied by a diesel or equivalent emergency power source. Some dual reactor plants still have three diesels so one acts as a swing diesel. These plants are in the process of buying additional diesels so each plant has at least two machines.

4.0 General

A. Diesel engine generator is normal choice.

   1. Ability to accept rapid loading

   2. Superior reliability after repeated operations

   3. Independent of outside power

B. A few plants have gas turbines - disadvantages: exhaust hydrocarbons, volatile fuel storage problems, poor reliability.

5.0 Diesel Cycles

A. Four-stroke diesel engine — Figure 13-1

   1. All events occur during four strokes of the piston and two revolutions of the crankshaft.

      a. Air intake

      b. Compression

      c. Expansion (power)

      d. Exhaust

B. Two-stroke diesel engine — Figure 13-2

   1. Most nuclear power plants use a two- stroke diesel.

   2. All cycle events occur during two strokes of the piston and one revolution of the crankshaft.

      a. Both valves are exhaust valves.

      b. Air is forced into the cylinder under pressure.

   3. Exhaust, air intake, and compression occur on the same stroke. To do this quickly, normally use compressed scavenging air.

6.0 Diesel Systems

A. Systems described are for diesels in common use as emergency or standby power sources.

B. Describe in general terms

6.1 Starting System

A. Starting depends on development of high air temperature on compression stroke to ignite fuel - starting system must be able to turn engine over rapidly. Use some type of stored energy, typically compressed air or battery. Figure 13-3

B. Stored capacity must provide several sucessive starts - normally at least five.

C. Types

1. Direct cylinder injection with compressed air Figure 13-4

   a. Timed distribution valves

   b. Air pushes pistons causing crankshaft rotation - other pistons are now compressing, causing ignition when fuel is injected.

2. Air-driven motors - requires big air motor

3. Battery-powered dc motors - require large battery - not used for large diesels.

4. Redundancy is normally most important requirement in starting air systems: two air receivers, two or four solenoid valves, two separate air distribution half-systems - either of which can start the engine. Air start lines have check valves to prevent combustion pressure from going backward into the compressed air line.

6.2 Fuel Systems

A. Main supply tanks Figure 13-5

1. 7-day full load capacity

2. "Day tanks" - only about 6-8 hours

B. Supply pumps, filters, and purifiers.

6.2.1 Injection System

A. Fuel injection must start and end abruptly. Figure 13-1

1. High pressure - some systems develop up to 5000 psi. Figure 13-2

2. Accurate metering - quantity must be accurate and variable to control load.

3. Exact timing - early or late injection results in loss of power.

4. Injection rate - not a spurt but extended over a period of time.

5. Proper atomization - increases surface area of fuel exposed to air for combustion, resulting in improved combustion and maximum power.

B. Common fuel injection system

1. Unit injector system (most common) - combines pump and injector at each cylinder. Injection pump at each cylinder is driven by camshaft using push rods and rocker arms.

a. High pressure fuel lines are eliminated.

b. Dirty fuel can clog injectors.

c. Fuel flow rate controlled by push rod rotation.

6.3 Diesel Engine Lube Oil System

Figure 13-6

A. Provides oil flow to all surfaces requiring lubrication and cooling.

B. Commonly supplied by an electrically- powered and a shaft-powered pump. Lube oil kept warm for quick starts.

1. Rocker Lube Oil System

a. Provides shutdown oil supply to valves and rockers

b. Protects bearing oil system from contamination due to fuel or cooling water leaks

6.4 Cooling System

A. Heat generated by friction and combustion — Figure 13-7

1. Friction heat is removed by lube oil then to the service water through the oil cooler.

2. Heat of combustion is removed by cylinder water jackets and jacket water heat exchanger.

3. Heat of compression of turbo-charged air is removed in intercooler.

B. Cooling water temperature range controlled for efficient operation and quick starts.

C. Most diesels have a self-contained cooling water system that is cooled by a safety-grade service water system.

1. The self-contained system is normally kept warm by heaters while the service water system is normally cut in only when the diesel is producing power.

2. The service water valves automatically open during accidents.

6.5 Scavenging Air, Supercharging, or Turbocharging System — Figure 13-8

A. Removes exhaust gases and re-supplies combustion chambers with air

B. Aids in keeping piston heads cooler- improves efficiency

6.5.1 Crankcase Scavenging

A. Uses engine pistons as air pumping devices

1. Atmosphere-to-crankcase check valves allow air into crankcase.

2. Crankcase pressure builds up and is directed to upper cylinder area by aspirator check valves.

B. Inefficient and generally not found on large modern diesels

6.5.2 Blower Scavenging

A. Air is blown into the intake ports which pushes exhaust gas out exhaust ports and cools cylinder heads. — Figure 13-9

B. In simple scavenging, the air intakes close when the exhaust ports close.

6.5.3 Supercharging and Turbocharging

A. By increasing rate of air flow to engine, fuel is burned more efficiently or fuel can be burned at higher rate - more power is produced. Also scavenging of exhaust gases is done better so more efficient/higher fuel rate - more power. Figure 13-10

B. Blowers driven by an auxiliary shaft are generally called superchargers.

C. Blowers driven by exhaust gases driving a turbine are called turbochargers.

D. Supercharging and turbocharging does scavenging, but also builds up pressure because exhaust ports are shut before air intakes.

1. Pressures are much greater.

2. Scavenging is normally done on two-cycle engines only, while
supercharging is done on two-and-four cycle engines.

E. Turbocharging may increase power as much as 50%, especially if an intercooler is used.

1. Greater air density due to intercooler

2. Bearing loads and heat stresses are not materially increased.

3. Use of exhaust gases rather than auxiliary shaft more efficient

6.6 Governor Systems

A. A governor is a device designed to control the speed of an engine by varying the flow of fuel.

1. Isochronous operation: speed maintained at a constant value regardless of load - only this machine is carrying a bus.

2. Speed-droop operation: speed droop is designed into diesel governors so diesel generator can operate in parallel with another generator and share the system load.

B. Speed decreases from no-load to full load is "speed-droop." Draw speed-droop diagram

$$Speed\ droop = \frac{N_{NL} - N_{FL}}{N_{NL}} \times 100$$

6.6.1 Engine Controls

A. Isochronous control means to keep an engine running at a desired constant speed, regardless of changes in load.

B. A varying amount of fuel is mixed with a constant amount of air.

6.6.2 Mechanical Governor

A. Rotational speed of fly-weights control fuel flow. — Figure 13-11

1. Steady speed falls when load is applied.

2. Steady speed rises when load is reduced.

B. Built-in speed droop

1. Centrifugal force will not return fuel valve to original position after a load change.

2. Precise speed control is not possible.

6.6.3 Hydraulic Governor — Figure 13-12, Figure 13-13

A. Meet requirements of sensitivity, speed of operation, and true isochronous control

B. Smaller flyweights are required to move smaller pilot valve.

C. Speed droop is reduced by feedback mechanism.

6.6.4 Hydraulic Governor With Compensating Device

A. Provide more accurate regulation than mechanical or hydraulic — Figure 13-14

B. Discontinues changing the fuel control setting slightly before new setting is reached to minimize "overshoot"

6.6.5 Electric Governor — Figure 13-15

A. Required to maintain precise control over frequency and voltage

B. Electric governors allow control in three modes:

1. Starting (acceleration) control - a programmed rate of increase for startup

2. Speed control - senses engine RPM or bus frequency

3. Load control - senses generator KW output and reduces the speed control signal accordingly. In load control - droop circuit must be in there or engine would

attempt to overload or trip on reverese power depending on the frequency setting to grid frequency.

C. Speed control

1. Maintains unit speed regardless of load - runs at 450 RPM continuously

2. Droop circuit is bypassed.

3. Load sensor does not operate in speed control mode.

D. Starting Control

1. Speed setting adjustment for non-emergency unit warmup and gradual cooldown

7.0 Emergency Starts

A. NRC requires that emergency diesel generators rapidly accelerate to rated speed/voltage and be capable of being loaded within 10 seconds of starting. Causes significant maintenance problems over time unless pre-start measures are taken to keep the diesel warm and ready for an emergeny start.

B. Measures employed to keep diesel warm and ready for an emergency start

1. Cooling water is heated and circulated through water jackets keeping cylinders warm.

2. Lube oil circulation pump pushes sump oil through heater and back to sump.

3. Turbocharger intercooler cooling water kept warm so scavenging air is initially warm.

8.0 Emergency Response

A. At most nuclear power plants, the following signals will automatically start the emergency diesel generator.

1. Loss of power or sustained undervoltage on the diesel generator vital bus

2. Safety injection (emergency core cooling) actuation signal

9.0 SUMMARY

Learning objectives

A. Review learning objectives

1.0 References

A. PPE Course Manual, Chapter 14, Process Instrumentation

2.0 Learning Objectives

Learning objectives

A. List and state the functions of the 4 major components in a basic instrument channel.

B. Regarding the temperature indication from a resistance temperature detector (RTD) or thermocouple, explain the effect caused by:

1. Open circuits
2. Short circuits

C. List and explain the basic operation of the detectors used to sense:

1. Pressure
2. Level
3. Temperature
4. Flow

D. Regarding the level indication of a D/P cell, explain the effect caused by:

1. Opening the equalizing valve
2. A change in reference leg level
3. A change in reference leg density
4. A change in monitored water level
5. A change in monitored water density

E. Regarding the flow indication of a D/P cell, explain the effect caused by:

1. Opening the D/P equalizing valve

2. Erosion or obstruction of the primary element

F. Describe the purpose of environmental qualification.

G. Describe the methods used to compensate for instrument inaccuracies during accident conditions.

3.0 Introduction

A. Process parameters

1. Examples of process parameters:

   a. Temperature
   b. Pressure
   c. Level
   d. Flow

2. Applications:

   a. Indication: The value at a given time is an important indicator of conditions in the process being observed.

   b. Control: Because of the interdependency of events in a process, the conditions at one point can be used to control the conditions at another point.

   c. Alarms

   d. Protective devices

B. Two types of parameter measurement,

1. Direct measurement

   a. Examples

      1) Sight glass
      2) Dip stick

   b. Provides indication only, no control, alarm, or protective functions (unless float switches are used, which is really a separate system).

2. Indirect measurement

   a. Develops an output proportional to the condition of the monitored parameter.
   b. Most indirect measurements produce an electrical signal as its output.

3. Instrument channel develops the electrical signal.

   a. Basic instrument channel: Figure 14-1

      (1) Detector - senses the condition at the monitored point and produces an output that is proportional to the parameter.

      (2) Transducer - for detectors that do not produce an electrical output, converts the output to an electrical signal.

      (3) Amplifier - increases the process signal to a usable magnitude.

      (4) Indicator - displays the process variable so it can be monitored.

4.0 Temperature

A. "Temperature" refers to a thermal state of molecules (heat content) that can't be measured directly. It is a measurement of
the average kinetic energy of the molecules or atoms contained in a system.

B. Uses of temperature vary from inputs to the reactor protection system to measurement and control of the station air conditioning system.

C. Temperature detectors types:

   1. Thermocouples: Figure 14-2

      a. Thermocouples are instruments for measuring temperature that operate on the principle that when two dissimilar metals are joined together, a voltage is developed across the junction. This voltage changes with temperature.

b. To form a thermocouple circuit, dissimilar metals X and Y are used to create a junction.

c. The total circuit voltage is the difference of the voltages at the junctions, as determined by the temperatures of each junction.

d. Current flows in the thermocouple circuit proportional to the temperature difference between the junctions.

e. At least two junctions are required for temperature measurement.

1) The unknown or desired temperature is referred to as the hot or measuring junction.

2) The second junction is known as the cold or reference junction and is usually maintained at a fixed temperature.

f. Figure 14-3 illustrates in more detail a thermocouple circuit in which M_1 and M_2 are dissimilar metals.

Figure 14-3

g. The extension wires, L_1 and L_2, (usually made of copper), connect the thermocouple to a potentiometer (voltage measuring device).

h. For a given set of dissimilar materials the only variable left is the temperature differential between junctions and, if the temperature of the reference junction (T_{REF}) is held constant, then the net voltage in the thermocouple circuit will be affected only by a change in T_H.

i. Because the reference junction temperature does not change, changes in the temperature of the hot junction will generate a voltage proportional to the change in temperature of the hot junction.

1) Voltage $_{(C\text{-}D)} \propto T_H - T_{REF}$

2) Δ Voltage $_{(C\text{-}D)} \propto \Delta T_H$

j. For proper operation it is necessary that connections C and D be at the same temperature. The same is necessary for connections A and B which is normally the case.

k. If changes in ambient temperature cause a temperature change of the reference junction, the net voltage in the thermocouple circuit will be affected and will no longer be proportional to the temperature at the hot junction. To compensate for this event, some thermocouple applications monitor the temperature of the reference junction and automatically correct the temperature reading from the potentiometer.

l. Thermocouples are used in plant applications where rugged instrumentation is required. They are installed in reactor vessels at the top of the reactor core to measure the temperature of the coolant exiting the fuel assemblies.

m. A special application of thermocouples (heated junction thermocouples) are installed in the reactor vessel to monitor vessel water level.

n. Reactor vessel level can be determined based on the installed height of any uncovered (unwetted) thermocouples.

o. Thermocouple failure modes.

2. Resistance Temperature Detector (RTD)

a. Operates on the principle that a metal's resistance to current flow will change with temperature and that this change is proportional to the change in temperature.

b. As a metal wire is heated, the molecular activity within the wire increases. The increase in molecular activity hinders the flow of electrons, resulting in increased resistance.

c. For most metals, the relationship between a metal's resistance and its temperature is nearly linear, so temperature can be determined by measuring the resistance of a wire. — Figure 14-4

d. Construction: Basically a coil of wire placed in a bulb — Figure 14-5

e. For most PWR applications, the wire is either nickel or platinum. Both metals exhibit nearly linear temperature resistance relationships over plant operating temperatures, but nickel tends to lose this linear relationship as the temperature approaches 300°C (~570°F).

f. Nickel is relatively inexpensive and available, so it is used to measure temperatures below 300°C (~570°F).

g. Pure platinum has a linear and stable resistance-to-temperature relationship. It is the international standard of temperature measurement usually used in power plants. Commonly used for temperatures >300°C (~570°F).

h. Other materials:

* Copper
* Tungsten

i. The thermal bulb is expensive and delicate; it is usually placed in a protective sheath of material compatible with the planned environment. The sheath is filled with a material such as magnesium oxide or aluminum oxide, then hermetically sealed.

j. RTDs are constructed for installation either directly in the sensed medium or into a thermowell (usual method unless extreme sensitivity is required.).

k. Thermowell provides more protection and ease of maintenance but slower response.

l. Example: RCS RTDs; both immersion and thermowell, explain difference in function

m. Operation: RTD connected as one leg of Wheatstone bridge. Bridge is balanced (zeroed) using the variable resistor, subsequent changes in RTD resistance due to temperature changes

Figure 14-6

unbalance the bridge causing the voltmeter to indicate. The output voltage is calibrated to read out in temperature.

n. Explain two wire systems. Point out how lead resistance can affect accuracy. — Figure 14-7A

o. Explain three wire systems. Point out compensation for lead resistance. — Figure 14-7B

p. RTD failure modes.

5.0 Pressure

A. Units and their meaning

1. Pressure, defined as force per unit area, is measured in one of the following units: Figure 14-8
   a. Gage pressure
   b. Absolute pressure
   c. Vacuum pressure
   d. Differential pressure

2. Gage pressure: indicates the pressure of a system with respect to the pressure surrounding the detector. Expressed in units of psi-gage (psig).

3. Absolute pressure: indicates the pressure of a system with respect to absolute vacuum. Expressed in units of psi-absolute (psia).

4. Relationship between gage and absolute pressure, assuming the pressure surrounding the gage is atmospheric, is:

$$P_{gage} = P_{absolute} - P_{atmosphere}$$

5. Vacuum pressure: a measure of pressure below atmospheric pressure.
   a. As pressure decreases below atmospheric, vacuum pressure increases.
   b. Example: 9 psia = -5.7 psig = 5.7 psi-vacuum
   c. Unit systems
      (1) Inches of mercury vacuum
      (2) Feet of water vacuum
      (3) Inches of water vacuum

6. Differential pressure: pressure difference between two systems; expressed in psi-differential (psid).

B. Types of Detectors

1. Bourdon tube

   a. Curve shaped tube with a non-circular Figure 14-9 cross-section and sealed at one end, so the surface area of the inside curve is less than the surface area of the outside curve

b. Applying an internal pressure results in a larger net force on the outside curve, which tends to straighten the tube. $P = F/A$ $F = PA$

c. The displacement of the tube tip varies in proportion to the exerted pressure. Movement is transmitted through a linkage to a pointer or transmitter.

d. Suitable for high pressures (12 psig - 100,000 psig) but cannot measure vacuum

2. Metallic bellows — Figure 14-10

a. One-piece, collapsible, seamless metallic unit formed from very thin-walled tubing and having deep accordian folds

b. Linear relationship between increments of load (changes in pressure) and deflection up to the elastic limit

(1) Linear only when bellows movement is on the compressive side of the point of pressure equilibrium

(2) Compressive force assured by using a spring to oppose the bellows

c. Characteristics

(1) More sensitive than the Bourdon tube to low pressures

(2) Most suited to pressures from .5 to 75 psig

3. Diaphragm — Figure 14-10

a. Similar to the bellows gage, but uses a diaphragm opposed by a spring

b. Works the same as the bellows gage

c. Course manual describes and pictures a "slack" diaphragm.

d. Measures both pressure and vacuum but must be designed for specific application.

C. Mechanical - electrical conversion

1. Contrast temperature detectors with pressure detectors

a. The operation of temperature detectors is based on the principles of electrical theory. The detector outputs are inherently electrical so no transducer is required.

b. The operation of pressure detectors is based on the principle of mechanical deflection in response to applied force. The output produced is mechanical so a transducer is required for outputs other than local indication.

c. Transducer: converts a mechanical signal to an electric signal.

2. Transducer types

a. Force balance transmitter — Figure 14-11

b. Movable core transmitter — Figure 14-12

1) Detector linked mechanically to a linear variable differential transformer (LVDT) consisting of a primary coil and two secondary coils.

2) The movement of the coil changes the magnetic coupling between the pri and sec coils, which causes a change in the voltage output of the secondary coils.

c. Variable capacitance D/P sensor — Figure 14-13

d. Strain gage — Figure 14-14

1) A semiconductor resistor is bonded to a diaphragm and sealed.

2) When pressure is applied to the diaphragm, the resistor is distorted by elastic deformation causing its length to increase and cross-sectional area to decrease.

3) Results in increased resistance.

4) The resistor is attached to a balanced Wheatstone bridge, so increased resistance causes a current proportional to the pressure.

5) Installing a second resistor to the other side of the diaphragm will allow measurement of pressure and vacuum.

6.0 Flow

A. Flow detection: A differential pressure is created by a primary device such as a nozzle or orifice and measured by a pressure detector.

B. Primary devices — Figure 14-15

1. Orifice plate

a. A circular hole in a thin, flat plate that is inserted in the flow stream

b. One side of a differential pressure detector is connected upstream; the other side is connected downstream.

c. The flow is proportional to the <u>square root</u> of the D/P across the orifice, or, the D/P is proportional to the square of the flow.

e.g. 10 psid at 100 gpm. If D/P increases to 40 psid, what is flow?

Ans. 200 gpm

d. Inexpensive and accurate, but has large pressure drop

2. Flow nozzle — Figure 14-15

a. A convergent nozzle with a rounded inlet core

b. Moderate permanent pressure drop and moderate cost, but can measure higher flow rates than an orifice

3. Flow venturi — Figure 14-15

a. Convergent-divergent nozzle

b. The diverging section of the nozzle allows for a gradual recovery of pressure. The gradual increase in cross- sectional area reduces turbulence resulting in a permanent downstream pressure drop of only 10%-25%.

c. Very high cost

4. Elbow meters — Figure 14-16

a. Operate on the principle that centrifugal force is exerted along the outer edges of a liquid traveling in a circular path.

b. Pressure taps are taken off the inside of the elbow (low speed, low pressure) and the outside of the elbow (high speed, high pressure).

c. Device accuracy is poor, but cost is relatively low and the numbers of loops of penetrations may be reduced. — Used in RCS Westinghouse PWRS.

5. Pitometer — Figure 14-17

a. The main advantage of the pitometer is that it produces such a low unrecoverable pressure drop as to be undetectable.

b. The actual pitometer tube more closely resembles a piece of pipe with eight fins on the inside circumference.

c. The fins are equally spaced radially with one-half pointed into the flow stream and the other half pointed away from the flow stream. These two types of fins alternate around the inside of the tube.

d. The pitometer is reversible. It makes absolutely no difference which way the tube is installed in the piping.

e. Assume that flow is from left to right. The top fin will sense system pressure and transmit that pressure to the left piezometer ring (or chamber).

f. The bottom fin faces upstream and is exposed to system pressure and will transmit that pressure to the right piezometer ring. This impact pressure is proportional to the square of the flow rate.

g. Both piezometer rings run the full circumference of the insert.

   1) Each ring has five ports connected to it.

   2) Four come from the fins and the fifth connects to an access tap.

   3) The access tap is the point where a differential pressure transmitter will be connected.

h. Both piezometer rings are exposed to system pressure; therefore, a differential pressure transmitter connected to each will cancel out the system pressure.

i. The output of the transmitter will be proportional to only the impact pressure seen by the upstream nozzles.

Used in RCS loops of B&W PWRs.

6. Obstructional erosion of primary element

C. Flow sensors (differential pressure detectors)

1. Bellows flow sensor — Figure 14-18

   a. Two bellows, high pressure, and low pressure

   b. The difference in force exerted by the two bellows is proportional to the ΔP across the primary element.

   c. Mechanically connected to a transducer

   d. Because flow rate is proportional to the square root of ΔP, the detector output is sent to a square root extractor.

2. Diaphragm flow sensor — Figure 14-19

   a. One diaphragm with a connection to the high pressure side and a connection to the low pressure side of the primary flow device

   b. Principle that opposing forces generate signal in the same way as the bellows flow sensor: also requires square root circuitry

   c. The most common type of flow sensor in nuclear plants

3. Magnetic flow sensor — Figure 14-20

4. Differential pressure detectors have an equalizing, or "bypass" valve that is used during maintenance.

   a. If the valve is open, there can be no ΔP sensed, regardless of the actual values at the high and low pressure connections. — Same effect if diaphragm ruptures.

7.0 Level

A. Level measurement

1. Most level measurements are based on a pressure measurement of the liquid's hydrostatic head (the weight of the liquid above a reference line).

2. At any point, the hydrostatic force is $P = HD$

exerted equally in all directions and is independent of the volume of liquid or the shape of the tank.

$P = (ft)\ (lbm/ft^3)$

$P = lbm/ft^2$

$P = lbm/in^2$

3. H = P/D where H is height of water, P is pressure resulting from hydrostatic head, and D is fluid density.

B. Detection systems

1. Vented tanks — Figure 14-21

   a. Low side of detector is open to atmosphere.

2. Unvented/pressurized tanks — Figure 14-22

   a. Differential pressure detector used to compensate for variable pressure in top of the tank

      1) Low pressure side of the ΔP detector is connected to the top of the tank.

      2) High pressure side is connected to bottom of the tank.

      3) Since pressure from the top of the tank is felt on both sides of the detector, its effect is canceled.

      4) Unvented tanks containing saturated water will cause condensation in the sensing line connected to the top of the tank.

      5) As water collects in sensing line, sensed D/P and, therefore, indicated level will change.

      6) Need to maintain constant water level in upper sensing line.

   b. Reference leg system — Figure 14-23

      1) The low pressure side of a D/P cell is connected to the bottom of a closed tank (variable leg).

2) The high pressure side is connected to the reference leg.

3) $\Delta P = z_r \gamma_r - z_v \gamma_v$
where z_r is height of reference leg, γ_r leg is density of the reference leg, z_v is height of the variable leg, and γ_v is density of the variable leg.

If D/P ↑,
indicated
level ↓. If D/P ↓ indicated level ↑.

4) Typical examples of reference leg systems.

a) PWR - pressurizer and steam generator — Figure 14-24

b) BWR - reactor vessel

3. Sources of level indication error

a. Heating/cooling of tank contents

b. Loss of reference leg level (leak or depressurization)

c. Reference leg density (temperature)

d. Loss of D/P (equalizing valve opens or diaphragm ruptures)

8.0 Signal Processing

A. Current output of one transmitter can be used to supply input signals to several systems. — Figure 14-25

B. The arrangement in Figure 14-25 is known as a current loop.

9.0 Calibration

A. Calibration is a recurring and important activity related to plant instrumentation and control maintenance.

   1. The instrument must be "zeroed" to ensure that the lowest response or indicating ranges are accurate.

   2. The instrument range must be verified, with instrument accuracy determined over the entire operating range or span.

   3. The setpoints of the instrument, or the alarm readings, must be adjusted and properly set.

   4. The repeatability of the instrument must be verified.

10.0 Environmental Qualification

A. Qualification of safety-related equipment

   1. Reduce the potential for common mode failures due to environmental effects.

   2. Demonstrate that ESF electrical equipment is capable of performing its designated safety-related functions.

B. Equipment must be designed to perform with a certain degree of accuracy during normal operations, abnormal operating conditions, accident conditions, and for a specified time after an accident.

C. Qualification methods

   1. Type testing - an identical instrument is actually subjected to the various environments and operating conditions for which it was designed, and its performance is measured.

   2. Operating experience

      a. Limited as a sole means of qualification

b. Serves as a useful supplement to other tests in that it may show how materials and equipment change with time under actual service and maintenance conditions.

c. Most widely used in qualification of equipment outside the containment.

3. Analysis

a. Requires a mathematical model to predict the response of the instrument to environmental influences.

b. Validity of the model must be justified by test data, operating experience, or physical laws.

c. Usual analysis case predicts the response of the instrument to a single input (i.e., seismic event) while holding all the other inputs constant.

d. Other partial type tests are done and the results are combined to provide the necessary qualification data.

4. By far the most preferred is type testing - NUREG-0588 states that the NRC will not accept analysis in lieu of test data unless testing of the component is impractical.

11.0 Compensating Measures for Adverse Environment

A. Even with the best design and construction, instrument channel accuracy is still affected by adverse environmental conditions.

B. However, because of environmental testing, these effects are predictable and the maximum expected inaccuracies can be determined.

C. Once the maximum expected inaccuracy for an instrument is known, the instrument reading can be corrected to yield a conservative value for the monitored parameter.

D. Emergency operating procedures (EOPs) use a variety of process instrument indications to direct operator actions during an accident condition.

E. If an accident causes an adverse containment environment, then many instrument readings may become inaccurate.

F. EOPs provide alternate, more conservative, parameter values for use in directing the operators upon adverse containment.

G. In other EOP applications, graphs in the procedures provide a correction for indicated parameter values based on the value of the adverse parameter.

H. The graphs provide a more accurate indication of the actual monitored parameter but are somewhat time consuming and are only used when accuracy of measurement is vital.

12.0 Summary

Learning objectives

A. Review objectives

B. Answer final questions

C. Dismiss class

1.0 Reference

PPE Course Manual, Chapter 15, Controllers

2.0 Objectives

1. Explain the difference between open-loop and closed-loop control systems.

2. Explain the principles of operation and the relative advantages/disadvantages of the following types of controllers:

   a. Proportional

   b. PI

   c. PD

   d. PID

   e. Bistable

3. Define or explain various controller terms such as time constant, dead time, gain, reset rate, reset time, rate gain, and setpoint.

4. Explain the functions of bistable controllers, including the neutral zone and deadband.

5. Explain the change in output response to step and ramp changes in error signals for the following types of controllers:

   a. Proportional
   b. Proportional integral
   c. Proportional integral derivative

3.0 Introduction

A. Open loop (open cycle) - A control system in which the controlling element is unaware of the effect it is producing on the controlled element.

B. An example is an automobile that has no speedometer but does have a calibrated throttle.

4.0 Controller Terminology

A. Five elements of a feedback system Figure 15-1

1. Setpoint: determines the desired value of the output or controlled or process variable.

2. Controlled or process variable.

3. Feedback: measurement of the output and feeding it back to the input, either directly or in a modified but proportional form.

4. Comparison (summation): its function is to compare the input signal with the signal fed back from the output.

5. Output signal to the controller.

B. General Terminology

1. Regulator-Designed to keep the output or controlled variable constant in the face of load variations.

2. servomechanism-control systems whose inputs are time varying.

3. A single capacity process is one which contains one element of capacitance and one element of resistance Figure 15-2

4. Time constants - The combined effects of resistance and capacitance produce time delays. The time constant is the time required for a process to reach 63.2% of the total process change. Figure 15-2

5. Dead time - the time difference between when a change occurs and when it is detected.

6. Gain - the percent change in output divided by the percent change in input
K = (% output change)/(% input change)

5.0 Feedback Control

A. Closed-loop feedback — Figure 15-3a/b

1. The output signal has a direct effect upon the control action. The error signal is the difference between the input signal and the measurement feedback signa. This is fed to the controller to reduce the error and bring the output of the system to a desired value.

2. Closed loop systems more accurate than an open loop system, but stability can be a problem because it can overcorrect errors and cause oscillations.

3. Negative feedback can correct the oscillation problem.

6.0 Controller Operation

A. General

1. Five types of controllers: (1) bistable, (2) proportional control, (3) proportional integral control, (4) proportional derivative control, (5) proportional derivative integral control.

2. Figure 15-4 will be used to demonstrate the various types of controllers. — Figure 15-4

B. Bistable Control

1. The simplest controller - either completely on or completely off

2. Consider the water level controller in figure 15-5. — Figure 15-5

3. Assume setpoint is 100 inches and we are initially at steady state flow. A decrease in steam demand occurs at time zero. Water level increases which causes an error signal. This will shut the regulating valve completely. This will result in rapid valve oscillations.

4. The oscillations can be reduced by use of a dead band or neutral zone. — Figure 15-6

5. The response of a step input to a bistable controller is illustrated in figure 15-7. — Figure 15-7

C. Proportional Controller

1. Output to input ratio is proportional (linear) - not a step change as in bistable.

2. Proportional band - Defined as % change in input/% change in output

3. Proportional band is the inverse of gain

   P.B. = 1/gain

4. Position = $K_pE + P_o$

   Where K_p = controller gain

   E = Error (setpoint - measured variable)

   P_o = Initial Position with no error signal present

   P = controller output

5. The input/output characteristics for various proportional bands are shown Figure 15-8. — Figure 15-8

6. Consider the example in figure 15-9. Steam flow decreases from 50% to 25%. Regulator responds by closing the regulating valve proportionally as level rises above the setpoint. — Figure 15-9

7. Steady state will be reached when feed flow matches steam flow. This corresponds to an error of 50% or 150 inches.

8. If gain is set at 2, the controller will maintain level between 75 inches and 125 inches.

9. A proportional controller will not control at its setpoint.

10. The response of proportional controller to a step change in input is illustrated in Figure 15-10. Figure 15-10

D. Proportional Integral Controller

1. The output is a function of not only how large the error signal is, but also how long the error signal has existed.

2. Refer to figure 15-11 Figure 15-11
Causes the controller to control at the desired setpoint.The proportional output is integrated and added to the controller signal.

3. K = Reset Rate =the number of times the output amplitude is repeated each minute

4. T = Reset Time = the time required for the proportional output amplitude to be repeated once

$$K = 1/T$$

5. Proportional controller has a proportional band of 200% and a reset rate of 2 rpm. A step change of 20% occurs in the error signal, the magnitude of the change in the controller output due to proportional action is 10%. A reset rate of 20% will cause an additional 20% every minute the error exists. Figure 15-12

6. This controllers response to a step change in the setpoint from 100 inches to 125 inches is shown in figure 15-13. Figure 15-13

E. Proportional Derivative Controller

1. Allows the system to anticipate changes in the process variable and produces an output that is proportional to the rate of change of the input.

2. $P_d = K_d\, di/dt$

   Where P_d = controller output

   K_d = derivative constant

   di/dt = rate of change of the input

3. K_d - The derivative constant specifies the function of differentiation and is called the rate gain. Expressed as %/%/sec.

4. See figure 15-14. Discuss derivative action of the controller. Figure 15-14

5. The systems response to a decrease in steam flow is shown in figure 15-15. With a gain of 1, steady state will eventually be reached with a constant 50% level error to match the 50% change in valve position. Figure 15-15

6. Time required to reach steady state is reduced due to the derivative action of the controller.

7. Figure 15-16 demonstrates the effect of a step change in the setpoint to 125 inches. Since steam flow did not change, in steady state the feed regulator will be 50% open as before. The error will therefore be zero. The steady state level will therefore equal the new setpoint. Figure 15-16

Error (E) = setpoint - measured value
= 125 inches - 125 inches

$$P-P_0 = K_pE$$

$$50\% - 50\% = K_p(0) = 0$$

F. Proportional Integral Derivative Controller

1. Most common type of controller. Combines the three types of control modes. — Figure 15-17

2. Figure 15-18 illustrates how the PID actions combine to produce the controller output. Four different types of error signals are examined. — Figure 15-18

G. Combined Operation

1. Figure 15-19 shows the effects of an increase in steam flow above the original steady-state feed flow and compares the results using the four different control modes. — Figure 15-19

2. Proportional mode (trace a) - Oscillates several cycles before stabilization is reached. Residual offset exists.

3. Proportional Integral mode (trace b) - Zero offset error, higher initial overshoot amplitude, longer period until stabilization.

4. Proportional derivative mode (trace c) - shorter period until stabilization is reached.

5. Proportional Integral Derivative (trace d) - zero offset error, rapid stabilization. Note that the addition of the integral function caused some decrease in stability from trace (c) due to the integral-derivative interaction, but overall, the type of controller provides superior performance.

7.0 Summary

A. Review Objectives

1.0 Reference

A. PPE Course Manual, Chapter 16, Nuclear Instrumentation

2.0 Learning Objectives

Learning objectives

A. Describe the characteristics of a gas-filled detector operating in each region of the gas ionization curve.

B. Explain the three types of neutron reactions used to create charged particles.

C. State the region of the gas ionization curve in which each of the following detectors operate:

1. BF_3 Detector
2. Compensated ion chamber (CIC)
3. Uncompensated ion chamber (UIC)
4. Fission chamber

D. Explain how each of the following detectors provide a signal proportional to reactor power:

1. BF_3 Detector
2. CIC
3. UIC
4. Fission chamber
5. Self-powered neutron detector (SPND)

E. Explain how gamma compensation is provided for each of the following:

1. BF_3 Detector
2. CIC
3. Fission chamber
4. SPND

3.0 Introduction

A. Power measurement

- 10^{20} fissions/sec during normal operation

1. $\dot{m} c_p \Delta T$ or $\dot{m} \Delta h$

   a. Accurate

   - Most accurate measure of power level - heat balance

   b. Too slow to protect fuel

   1) Loop (core) transit time

   2) Instrument delays (RTDs or T/Cs)

   - Delays in parameter indication changes jeopardize reactor safety

   c. Invalid if RCS reaches saturation (as with BWRs)

2. Reactor power is directly proportional to rate of fission in core.

   - Must monitor fission rate to quickly shut down reactor.

3. Neutron flux is directly proportional to fission rate.

   - n flux $\propto$ fission rate

4. Therefore, reactor power is directly proportional to neutron flux.

5. Neutron flux changes instantaneously as reactor power changes.

6. Instruments are available to measure neutron flux both inside and outside the core.

7. These instruments are used to provide indications of reactor power and inputs to reactor protection circuits.

B. Ranges of reactor power indication

Figure 16-1

1. PWRs

   a. Source

   b. Intermediate

   c. Power

2. BWRs

   a. Startup

   b. Heating

   c. Power

3. Some CE plants combine source and intermediate ranges into a wide range.

4. Detectors used may be excore or incore.

   a. Excore detectors measure neutron flux leakage from the core.

   b. Incore detectors measure actual neutron flux from within the core.

   c. Excore and incore detectors rely on the production of ion pairs for neutron measurement.

2.0 Ion Chamber Operation

Figure 16-2

A. Circuit description

1. Chamber filled with inert gas (N_2)

2. Electrode in center of chamber

3. Chamber walls form second electrode

4. dc voltage applied to electrodes

   a. Center electrode is positive (anode)

   b. Outer electrode is negative (cathode)

5. Variable dc power supply to adjust sensitivity of circuit

6. Resistor (meter) as the circuit load

B. Circuit operation

1. Radiation ionizes gas and produces ion pairs.

    a. Electron is stripped from atom - negative charge.

    b. Atom is left with positive charge.

2. Positive ions migrate to cathode to collect electrons.

3. Negative ions (electrons) collect on anode.

4. Ion collection results in a pulse across resistor (meter).

5. Pulse size affected by:

    a. Type of ionizing radiation

    b. Value of applied dc voltage

3.0 Gas-Filled Detector Characteristic Curve Figure 16-3

A. Recombination region

1. Applied voltage near zero

2. Ion pairs are formed by ionizing radiation but most recombine without collecting on electrodes.

3. As voltage is increased, current will increase until essentially all ions formed are being collected on the electrodes.

4. When current flow remains stable for an increase in applied voltage, saturation voltage has been reached.

5. Saturation voltage marks the beginning of the ion chamber region.

6. Detectors are not used in the recombination region because output is

    not proportional to ionizing events (flux).

B. Ionization region

1. An increase in voltage does not cause a substantial increase in current - plateau voltage.

2. Essentially every ion pair produced is collected on the electrodes.

3. Applied voltage is high enough to prevent recombination but not high enough to cause gas amplification.

4. This region is commonly used in radiation detection instruments because a small voltage variation will not affect the detector output.

C. Proportional region

1. An increase in applied voltage results in gas amplification.

   a. Electrons travelling toward anode cause further ionizing events.

   b. Secondary ions are also collected by electrodes.

2. Detector output is proportional to the rate of primary ionizations.

3. Increased sensitivity as some ionization events may go undetected without gas amplification.

4. Applied voltage must be kept constant.

5. This region commonly used in radiation detection instruments due to sensitivity at low radiation levels.

D. Limited proportional region

1. At these increased voltages, gas amplification can no longer increase at a rate proportional to the rate of primary ionizations.

2. Space charge effect

   a. Electrons are much lighter than positive ions.

   b. Electrons are collected much faster than positive ions.

   c. Positive ions form a "cloud" or space charge.

d. Positive cloud masks center electrode from electrons.

e. Gas amplification increases at a slower rate than primary ionizations.

3. At upper end of region, space charge effect is controlling the amount of ions collected.

4. This region not used for radiation detection.

E. Geiger-Mueller region

1. Applied voltage is so high that each ionization results in maximum gas amplification and maximum detector output.

2. Space charge effect limits gas amplification and detector output on each ionization.

3. Geiger plateau - where an increase in voltage no longer produces an increase in ion pairs collected

4. Threshold voltage - the voltage that results in the Geiger plateau (approx. 1000 Vdc)

5. Advantage - larger pulse heights are obtained

6. This region is commonly used in radiation detection instruments.

F. Continuous discharge region

1. Voltage is so high that once an ionization occurs, the voltage is sufficient to cause further ionizations such that the detector is saturated continuously.

2. This region is not used for radiation detection.

4.0 Neutron Detection

A. Neutrons cannot be measured directly.

B. Neutrons create charged particles.

1. Ionization

2. Fission

C. Ions can be collected

D. Neutron reactions

1. n - alpha

$_0n^1 + {_5B^{10}} \dashrightarrow {_5B^{11}} \dashrightarrow {_3Li^7} + {_2He^4}$

a. Neutron strikes B-10 atom, absorbed into nucleus.

b. B-11 immediately decays into Li-7 and an alpha particle.

c. Charged particles cause ionizations.

d. KE of charged particles also contributes to ionizations

e. High microscopic cross section for absorption of thermal neutrons (3850 barns)

2. n - fission

$_0n^1 + {_{92}U^{235}} \dashrightarrow {_{92}U^{236}} \dashrightarrow$ FFs

a. Neutron is absorbed into a U-235 nucleus.

b. Fission results in at least two charged fission fragments.

c. Fission fragments cause ionizations.

3. n - activation

$_0n^1 + {_{45}Rh^{103}} \dashrightarrow {_{45}Rh^{104}}$ + gamma

$_{45}Rh^{104} \dashrightarrow {_{46}Pd^{104}} + {_{-1}B^0}$

a. Neutron is absorbed into the nucleus of Rh-103.

b. Rh-104 is radioactive and decays into Pd-104 by beta emission.

c. Beta particle causes ionizations.

d. Rh-104 has 42.5-second half-life, which causes an inherent delay in detection

4. n - alpha and n - fission most widely used in neutron detection

C. Proportional detectors

1. Used for measuring source range neutron flux

2. Each ionization results in a pulse of current.

3. Pulse rate is proportional to neutron flux.

4. Pulse rate is proportional to reactor power.

D. BF_3 proportional counter — Figure 16-4

1. One of simplest types of proportional detectors

2. Aluminum walls serve as negative electrode (cathode).

3. Tungsten center wire serves as the positive electrode (anode).

4. Center electrode insulated from aluminum can.

5. Cable supplies voltage to electrodes and carries away current from ionizations.

6. Operating voltage determines that detector will operate in the Proportional Region.

7. Operation

a. Neutron absorbed by B-10 nucleus results in charged particles.

b. Charged particles cause ionizations.

c. As ions travel toward electrodes, secondary ionizations occur, which result in gas amplification.

d. Higher voltage causes more gas amplification, which causes a larger pulse.

e. Pulses are sent to integrating circuitry that counts the pulses and determines a rate which is proportional to the neutron flux.

8. Quenching

a. After each ionization, an electron and a positive ion are formed.

b. Electrons travel rapidly toward anode.

c. Positive ions travel much more slowly toward cathode.

d. Positive ions are still travelling after all electrons are collected.

e. Positive ions reach the chamber walls where they are neutralized by gaining electrons.

f. When positive ions are neutralized, energy is liberated, which causes further ionizations.

g. Newly freed electrons are collected, thereby adding to duration of the original pulse or causing additional pulses.

h. Quenching gas (usually organic gas such as methane)is added to chamber gas to quench extended or additional pulses.

i. Quench gas molecules have lesser affinity for electrons than chamber gas.

j. Positive ions of chamber gas take electrons from quench gas.

k. Quench gas ions then travel to chamber walls to pick up electrons and become neutralized.

l. When quench gas ions are neutralized, the energy liberated disassociates the quench gas molecules instead of causing additional ionizations - limits the useful life of most proportional detectors.

9. Gamma compensation — Figure 16-5

    1. Proportional detectors used in startup or source range

    2. Gamma radiation is significant relative to neutron flux.

    3. Must eliminate gamma pulses

    4. Preamplifier increases magnitude of detector pulses.

    5. Pulse height discrimimator

        a. Passes only the larger neutron pulses

        b. Converts pulses into square waves

    6. Log integrator converts square waves into logarithmic signal.

    7. Log amplifier increases magnitude of log signal.

    8. Output of circuit supplies meters, protection circuitry, and a differentiator.

    9. Differentiator determines rate of change of log signal and supplies startup rate or period indication.

6.0 Ion Chamber Detectors

A. Why different from proportional detectors?

    1. Different regions of six-region curve

    2. Applied voltage less than proportional detectors

    3. No gas amplification occurs.

    4. Only ions (electrons) actually created by event are collected.

    5. Pulses are smaller than proportional detector (i.e., less sensitive to low flux levels).

B. Ion chambers are used in higher neutron flux.

1. Intermediate and power range - PWR

2. Heating and power range - BWR

C. Higher neutron flux results in rapid pulses.

1. Impossible to count individual pulses

2. Rapid pulse rate produces an electric current

D. Current is proportional to number of ionizing events detected.

E. Impossible to discriminate between ions caused by neutrons and ions caused by gammas.

F. Gamma compensation by construction of detector

G. Fission chambers — Figure 16-6

1. Coated with U_3O_8, uranium oxide.

2. Chamber is filled with argon gas.

3. Percentage of thermal neutrons entering chamber will result in fission of U-235 in U_3O_8.

4. High energy and highly charged fission fragments cause ionizations in the argon gas.

5. Electrons are collected resulting in a pulse.

6. Fission chambers produce pulses much larger than other ion chambers, which can be used in low neutron flux fields.

7. Fission chamber can be used in much higher gamma fields than ion chambers.

8. Capable of operating over source and intermediate ranges

9. Often used as Wide Range channels in Nuclear Instrumentation Systems

a. As Rx power increases, circuitry automatically shifts from pulse counting to current.

b. In frequency band of amplifier (5 kHz to 100 kHz), frequency of pulses can be converted to a current that is proportional to Rx power.

c. Process is called Campbelling.

10. Gamma interactions

a. Gamma radiation will also cause ionizations in the argon gas.

b. Pulses resulting from gamma ionizations are smaller than pulses from fission fragment ionizations.

c. Must be negated to result in detector output that is proportional to neutron flux

1) Source range - use pulse height discriminating circuitry.

2) Intermediate/Power ranges use campbelling.

H. Compensated ion chamber — Figure 16-7

1. Two detectors in one case

2. One chamber coated with B-10 - sensitive to neutrons and gammas

3. Other chamber uncoated - sensitive only to gammas

4. Output from chambers electrically opposed - gamma output cancels

5. Compensating voltage adjusted to cancel the effects of gamma flux

6. Output proportional to neutron flux

7. Overcompensated

a. Compensating voltage set too high

b. Detector output lower than actual neutron level

8. Undercompensated

a. Compensating voltage set too low

b. Detector output higher than actual neutron level

9. Log current amplifier produces logarithmic output for indication.

10 Differentiator determines rate of change of log signal and supplies startup rate or period indication.

I. Uncompensated ion chamber — Figure 16-8

1. Used in power range where gammas do not need to be negated

a. Gammas insignificant compared to neutrons (.1% at 100% power)

b. Gamma current proportional to reactor power

2. Single chamber

3. Sensitive to both neutrons and gammas

7.0 Self-Powered Neutron Detectors

A. Do not require external voltage

B. Current is produced due to activation and decay of the isotope whithin the detector.

C. Example activation reaction

$_0n^1 + {}_{45}Rh^{103} \dashrightarrow {}_{45}Rh^{104}$ + gamma

$_{45}Rh^{104} \dashrightarrow {}_{46}Pd^{104} + {}_{-1}B^0$

1. Neutron causes Rh-103 nucleus to become radioactive Rh-104.

2. Rh-104 decays into Pd-104 and a beta particle.

3. Beta is emitted with a 42.5 second half-life.

D. Operation — Figure 16-9

1. Emitter

   a. Located in center of tube

   b. Surrounded by aluminum oxide insulation

   c. Made of Rhodium-103

2. Collector

   a. Metal walls of tube

   b. Encase emitter and insulation

3. Neutron activates a Rh-103 nucleus.

4. Rh-104 emits a beta particle with a 42.5 second half-life.

5. Beta passes through insulator and is collected by collector.

6. Electrons flow through meter and back to emitter.

7. Strength of current is proportional to neutron flux and reactor power.

8. Background correction

   a. Gamma reactions occur in the detector and leadwire, which result in free electrons.

   b. Portion of current from gamma reactions

   c. Background detector installed in each detector assembly

   d. Essentially replica of detector except no rhodium

   e. Output of background detector equal to gamma output of detector

f. Output of both detectors sent to plant computer where detector gamma current is removed

9. Advantages

a. Fairly simple operation

b. Provides accurate measurement of neutron flux

10. Disadvantage - Slow response time due to 42.5 second half-life

Used for average power calc. only

8.0 Summary

Learning objectives

A. Review objectives

B. Answer final questions

C. Dismiss class