Nuclear Training Course 233
TIMS Ref. 23003

Reactor-Boiler and Auxiliary

Nuclear Training Course 233

Reactor And Auxiliaries

June 1992

Interim Copy - Approved For Use

ABSTRACT OF CURRENT REVISION

June 1992 ⇔

Removed hyphenation of text from previous version. General revision to correct grammatical errors and minor changes to improve clarity. Added revision number to course notes. Included module title with module number in headers. Added Abstract of Previous Revision.

Module 1, Page 3	Changed $MW_{(th)}$ per hour to $MWh_{(th)}$
Module 1, Page 3	Added statement to section on withdrawal of adjuster rods.
Module 2, Page 13	In Figure 2.1, moved Moderator HX TCV from outlet to inlet to reflect actual field location.
Module 4, Page 1	Slight wording change to Objective 4.5 to match intent of all five objective parts.
Module 4, Page 4,5	In Table 4.1 and Table 4.2, changed Gd precipitation pH value from >6 to >7 to agree with 224 course material.
Module 4, Page 7	Added note to Figure 4.2 to indicate that it refers to a unit with adjusters out of the core. Changed other note to indicate that Gd is added to compensate for the lack of Xe.
Module 4, Page 10	Expanded explanation of auto poison addition. Footnote added.
Module 4, Page 12	Material covering Objective 4.5 e) restated.
Module 5, Page 7	Corrected statement about conductivity effect on radiolysis to agree with 224 course material.
Module 5, Page 9	Added summary point to address Objective 5.1 c).
Module 7, Page 15	Bleed condenser major roles item (a) expanded to include HTS supply conditions of 8 MPa, 250°C to reflect other stations.
Module 7, Page 24	Second summary point reworded to match Objective 7.17.
Module 7, Page 25	Summary point added to address Objective 7.21.
Module 7, Page 25	Section on feed pump failure rewritten to be more concise.
Module 7, Page 26	Statement added to cover reactor trip on HTS low flow.

NOTES & REFERENCES

Module 7, Page 27	Note added to include fluctuating TCV on the bleed cooler at some stations.
Module 8, Page 4	Sidenote added to refer reader to other sources for further information.
Module 9, Page 3	Qualified statement about upper limit on HTS isotopic.
Module 10, Page 6	Purification half–life at 25 kg/s corrected to 60 minutes from 20 minutes as previously stated.
Module 10, Page 7	Fourth summary point reworded.
Module 10, Page 9	Footnote added to cross reference with 228 Materials course.
Module 10, Page 14	Summary point added to address Objective 10.5 a).
Module 11, Page 3	Statement added to explanation of fuel centerline melting.
Module 11, Page 6	Expanded summary point for Objective 11.3 c).
Module 13, Page 9	Summary point added to address Objective 13.6.
Module 13, Page 17	In Figure 13.6, moved PRV open point to 3 kPa(g).
Module 13, Page 18	Added chemical equation for steam/zirconium oxidation reaction.
Module 13, Page 18	Added description of hydrogen igniter locations at the various stations with a footnote for details specific to Darlington NGS.
Module 14, Page 7	Changed ΔP to P for trends. Slight rewording of section on annulus gas leakage.
Module 16, Page 2	Added fourth area of CANDU fuel performance assessment – d) performance under major upset conditions.
Module 16, Page 3	Added further explanation to point 7) under "methods to minimize fuel failure mechanisms".
Module 16, Page 9	Added summary point to address Objective 16.1 b).
Module 18, Page 1	Corrected objective numbers.
Module 18, Page 7	Added sidenote to clarify liquid zone response during a reactor stepback.
Module 18, Page 19	Added sidenote to reference discrepancy between actual and indicated boiler level during a main steamline break.

NOTES & REFERENCES

Module 18, Page 22	Sidenote added to refer reader to 235 course for further information on turbine–generator speed response due to power mismatch.

ABSTRACT OF PREVIOUS REVISION

June 1991 ⇔

Added abstract of current revisions. General revision to correct grammatical errors and minor changes for clarity.

Module 7, Page 6	Added references to pressurizer temperature.
Module 17, Page 8	Deleted reference to neutrons in the irradiated fuel bay, since their contribution is insignificant.
Module 18, Page 11	Clarified and separated discussion of large and small LOCAs with respect to crash cooling.
Module 18, Page 12	Qualified pressurizer level decrease statement for LOCAs to exclude leaks from the top of pressurizer.

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Module 233-0

INTRODUCTION TO THE COURSE

AUDIENCE AND PREREQUISITES

The course is for Authorized Nuclear Operators in Training (ANOIT's) and Shift Supervisors in Training (SSIT's) taking the nuclear general part of their authorization training.

The prerequisites include:

1) All NGD generic training courses of level 4 and 3 (for ANOIT's) or PI (for SSIT's), as required by the initial and progression training programs.

2. Concepts from the following NGD generic training courses of level 2, which are a part of the general authorization training, will be used throughout this course:

    223 - Fluid Mechanics,
    224 - Chemistry,
    225 - Heat and Thermodynamics,
    227 - Nuclear Theory,
    228 - Materials Science.

This course builds on the information presented in all the courses mentioned above. This applies particularly to the reactor and auxiliaries (R&A) course(s) which you have taken during your initial and progression training: the 433 and PI33 course. To avoid unnecessary repetition, many references are made in this course to the information covered in the prerequisite R&A course(s). For simplicity, these two courses are referred to in this course as 'previous R&A courses'. It is important that you review these courses thoroughly. Remember that some test questions that you will be asked during this course may be based on the objectives of the previous R&A courses.

NOTES & REFERENCES

COURSE CONTENTS

This course covers a large part of any CANDU plant, namely **the reactor and auxiliary equipment that makes up the "nuclear" side of the unit**. A list of the major topics covered by the course is provided in the table of contents at the beginning of the course notes.

While the previous R&A courses give basic description of this equipment and its normal operation, this course concentrates more on startups, power manoeuvres, shutdowns, operational problems, upsets and incidents.

Good understanding and thorough technical knowledge of these operational aspects by you - a future shift supervisor or first operator - is crucial to ensure safe, reliable and efficient operation of this multi-million dollar equipment that one day you will be entrusted with. This course will help you achieve this by providing you with relevant technical information. For example, you will learn about major upsets and problems, their potential adverse consequences, and major corrective and protective actions to mitigate these consequences. Discussion of these general operational concerns and procedures in this course will prepare you for the station specific part of the authorization training during which you will learn specific indications, alarms, annunciations, actions and procedures.

Being part of the general phase of the authorization training, this course does not favour any particular CANDU station. Only the most typical equipment and operating practices - that apply to most stations - are discussed. Coverage of numerous station specific differences is not the intent of the course, as it would be impractical and confusing. A natural consequence of this approach is that some information presented in this course may not apply to your station. These instances, however, are not frequent. In the few cases where different terminology is used at different stations when referring to essentially the same equipment, the most typical name is used in the course.

COURSE STRUCTURE

The course is made up of 19 self-contained units of instruction called "modules" that are listed in the table of contents at the beginning of the course notes. Except for this module, all the remaining 18 modules are made up of three major parts:

1. Objectives.

The objectives are placed up front of each module. They serve two purposes. First, they **specify the contents** of the module so when you read them, you will get a pretty good idea of what you will learn from the module. Second, they **define the scope of the test** that you will be subjected to **under closed-book conditions** to demonstrate that you have attained the required knowledge by meeting or exceeding the pass mark.

It is important that **after having finished each module** you **review its objectives** to make sure that you can meet their requirements. To help you find the instructional text which addresses each objective, the pages where this text is located are specified in the outer margin right beside each objective (as indicated to the right of this paragraph).

⇔ Pages 6-7

It is worth emphasizing that these objectives have been cross-referenced to detailed analysis of the jobs and tasks performed by the first operator. They have also been reviewed by a panel of authorized first operators, shift operating supervisors and shift supervisors to ensure that they **are relevant to your future job.**

2. Instructional text.

The instructional text is placed right after the objectives and contains all the information that you will need to learn in order to meet them. The text is **cross-referenced to the objectives.** You can easily find these references in the outer margin (as indicated to the right of this paragraph). They indicate the beginning of the text which covers the specified objective.

⇔ Obj. 0.1 c)

In the instructional text, **new terms and key concepts are highlighted** to stand out from the rest of the text and thus attract your attention. They are again **reinforced in summaries** throughout the module (except during short modules, where only one summary is present at the end).

Occasionally, the instructional text is supplemented with a **sidenote.** Sidenotes are placed in the outer margin, and the text they refer to is marked with an asterisk (*). Typically, sidenotes specify references to other sections of the same module, other modules or other courses. This will help you integrate individual modules and courses in one logical set. Other sidenotes provide supporting information, like the typical value of the operating parameter being discussed in the instructional text. The purpose is to help you understand the main concepts or emphasize their importance. You are **not required to remember** any information included in the sidenotes.

* This is a sample of a sidenote.

3. Assignment

The assignment is placed at the module end and consists of several questions that address the objectives. The purpose of the assignment is to give you an opportunity to practice the acquired knowledge and to check for yourself how well you understand and remember the presented material. To find out how much you remember, it is important that you **not** refer to the instructional text when you are working on the assignment. Therefore, if you don't feel confident about your knowledge of the subject matter, it is better to study it again or discuss your doubts with the instructor or your classmates rather than to do the assignment prematurely.

In most cases, to answer the assignment questions you will need to **fill in the blanks and choose the right statement**(s) from those listed in brackets. In the few other cases, the instructions provided explain what you are expected to do. This built in practice may or may not be similar in style to the test questions that you will be required to do.

Except for short modules, you do not have to wait until you finish the whole module in order to work on the assignment. Typically, you can do this right after those summaries of the key concepts where instructions are placed that guide you to specific assignment questions.

No answers are provided to the assignment questions. This is because all the information that you will need to answer them is given twice: first, it is presented in the instructional text and second, it is condensed in the summaries of the key concepts. Thus, you should be able to check your answer easily by referring to the relevant parts of the instructional text and summaries. In case of doubts, consult the instructor or your classmates.

Because all the assignment questions are combined at the module end. You can **easily separate them** from the rest of the module if the instructor wants to mark them or if you want to submit them for instructor's evaluation.

TERMINOLOGY AND SYMBOLS

In case you have doubts about the exact meaning of some terms used in this course, a glossary is given on the next two pages. While the explanations are also valid for other courses, the examples used are specific to this course.

In this glossary, **nouns** of similar meaning are defined one after another so that you can easily see their similarities and differences. The **action verbs** (mainly used in the course objectives and tests) are sorted by the required volume and complexity of the expected answer - starting with the easiest and ending with the most demanding ones.

In the instructional text, many diagrams illustrate major automatic responses to a particular operational event or parameter, eg. HTS pressure error. In these diagrams, the following **symbols** are used:

⇑ ⇓ = Gradual response (eg. of a level controller) whose magnitude increases when the initiating parameter increases or decreases, respectively;

_△ ‾▽ = On-off response (eg. of a level switch) which occurs at a particular value of the initiating parameter when it is rising or dropping, respectively. The 'arrow' side of the symbol indicates the 'on' or 'action' side.

GLOSSARY OF TERMS USED IN THE 233 COURSE

A) NOUNS

TERM	*EXPLANATION*	*EXAMPLE*
Actions	Activities which result in a changed state of a device or a parameter. Can be automatic or performed by the operator.	Start up a pump.
Corrective actions	Actions performed to restore the normal status of a device or to return a controlled parameter to its normal range.	Open a control valve.
Protective actions	Actions performed to protect equipment integrity and personnel safety.	Trip the reactor.
Precautions	Actions taken or to be avoided to prevent some adverse consequences.	Purge moderator cover gas without lowering cover gas pressure to avoid D_2 excursions.
General operating practices	General (not detailed or station specific) actions taken to reach a certain operational goal, eg. to ensure safe operation.	Reduce reactor power to within the capacity of the available heat sink.
Adverse consequences	Undesirable outcome of an event, action(s) or lack of action(s). Consequences can be immediate or long-term effects on unit equipment, operational status or safety.	Structural damage due to excessive ΔT between the end shield and the calandria.
Operating concerns	Concern over a given situation as to its possible adverse consequences.	An explosive D_2 & O_2 mixture being formed in the moderator cover gas.
Upset	Disturbance of the normal status of the equipment.	Reactor stepback.

Abnormal incident	Major upset that seriously jeopardizes equipment integrity and personnel safety.	LOCA, main steam pipeline rupture.
Indications	Any source of information about the equipment status.	Control room or field indicators, alarms,equipment noise.

B) ACTION VERBS

TERM	*EXPLANATION*	*EXAMPLE*
List	To provide a series of items. No further comment on the listed items is required.	List five factors which contribute to fuel failure.
Define	To give (in as few words as possible) the meaning of.	Define direct pressure relief.
State	To set forth. Used when a short response not requiring extensive detail is desired.	State the reasons for limiting power extracted from a fuel bundle.
Describe	To give a detailed account of. Usually used to ask for details of a device, system, principle of operation,etc.	Describe two general techniques for detecting and locating failed fuel in a reactor .
Explain	To give the reason(s) or cause(s) of, to make clear.	Explain how thermosyphoning is achieved in CANDU reactors.

Prepared by: N. Ritter, WNTD

Revised by: P. Bird, WNTD

Revision date: June, 1992

Module 1

MODERATOR HEAVY WATER

OBJECTIVES:

After completing this module you will be able to:

1.1 State the standard method of describing the concentration of heavy water. *⇔ Page 2*

1.2 State the normal range of concentration maintained for moderator D_2O. *⇔ Page 2*

1.3 State the reason for a lower limit on moderator isotopic. *⇔ Page 3*

1.4 Identify one indication available to alert the operator to a low isotopic. *⇔ Page 3*

1.5 State one consequence of sudden (acute) downgrading of the moderator isotopic by: *⇔ Page 4*

- a) less than or equal to 0.3%,
- b) greater than 0.3%.

1.6 During shutdown, identify two primary radiological hazards (source, type) that exist if moderator D_2O has spilled or escaped from the moderator system. *⇔ Page 6*

1.7 For normal power operation, identify the indicated number of primary radiological hazards (source, type) associated with moderator D_2O that: *⇔ Pages 6-7*

- a) Has spilled or escaped from the moderator system (5),
- b) Is contained within moderator pipework (3).

1.8 State two ways the moderator system is used to guarantee the reactor shutdown. *⇔ Page 7*

* * *

NOTES & REFERENCES

INSTRUCTIONAL TEXT

Some characteristics of the moderator heavy water will be discussed in this module. These include:

- Moderator Isotopic,
- Moderator Radiological Concerns,
- Reactor shutdown guarantee.

MODERATOR ISOTOPIC

Isotopic Calculation

Obj. 1.1 ⇔

Isotopic of heavy water is a standard way of describing the **concentration** of heavy water. Isotopic represents the **weight of D_2O divided by the total weight of D_2O and H_2O** in a given sample. For instance, if in a sample of 20 g we have 19.6 g of D_2O and 0.4 g of H_2O, the isotopic will be :

$$\frac{19.60}{19.60+0.40} \times 100 = \frac{19.60}{20} \times 100 = 98\%$$

Acceptable Range

Obj. 1.2 ⇔

High moderator isotopic is required so that the moderator can fulfill its prime function of slowing down fission (fast) neutrons efficiently with a minimum of absorption, ie. be an effective moderator. The acceptable range of isotopic in our plants is ≥ **99.50% purity**.

Moderator isotopic within this range will provide sufficient reactivity to achieve criticality and hence ability to operate at high power. The isotopic strongly affects reactivity and hence fuel costs. Higher isotopic means a smaller number of parasitically absorbed neutrons (see Table 1.1 for a 540 MWe unit).

Table 1.1

Moderator System Isotopic

Change in D_2O Isotopic	+/- 0.1%
Δk Change	+/- 3.6 mk
Fuel Cost Penalty	+/- 700,000 $/year*

* Based on a 1990 cost per fuel bundle of $4750.

A lower fuelling rate is required at a higher isotopic. A lower fuelling rate is the same as saying that the fuel burnup $MWh_{(th)}$ produced per kg uranium is higher. The reference value for zero fuel cost penalty is 99.75%, as this was the standard reactor grade produced by the BHWP. More recently, they are cost effectively producing D_2O at a higher isotopic. In addition, most multi-unit stations have upgraders so that the isotopic is continuously upgraded. Typically, these stations are operating at about 99.9% isotopic.

Isotopic Limit

⇔ Obj. 1.3

If the moderator isotopic is too low, the overall core reactivity is too low. Let us suppose that the moderator isotopic went from 99.75% to 99.40% *. From Table 1.1, the core reactivity change would be - 12.6 mk. This is an enormous amount of reactivity, which cannot be compensated for by the zone levels. An **economic penalty** will occur to **maintain the reactor critical.** To accommodate this large reactivity change and maintain the reactor critical, 2 methods may be used:

* This represents an addition of about 100 kg of H_2O in 300 Mg of moderator.

- **Withdrawal of adjuster rods** (where available). During normal operation, the adjuster rods are fully in core. Removing these neutron absorbers from the core will increase core reactivity (but will probably require derating to keep within normal flux boundaries).
- **Increased fuelling** (reactivity banking). Additional new fuel is added to the core to increase core reactivity. This is associated with a fuel burnup penalty, since fuel is removed before optimum burnup.

⇔ Obj. 1.4

The main indication available to alert the operator to an acute low moderator isotopic change is the average **zone level will decrease** to compensate for the reactivity loss. When the zones reach their lower limit, the withdrawal of adjuster rods will be required (boosters required alarm where there are no adjuster rods). A setback due to a flux tilt or a stepback or setback (depending on the station) on high zone flux may also occur (eventually).

For slow or chronic lowering of isotopic, indications include lab analysis or trending zone level versus fuelling.

There is no upper limit on the moderator isotopic as far as reactor operation is concerned. The isotopic is increased by makeup of higher isotopic moderator D_2O from the moderator upgrader. Individual stations however, have specific restrictions to the percent change of isotopic to accommodate step changes in core reactivity.

Downgrading

Downgrading during normal operation may occur by accidental addition of H_2O, or D_2O downgraded below system isotopic. Equipment failure such as moderator heat exchangers, end shield cooling, or liquid zone leaks could also contribute to downgrading. H_2O vapour may ingress via moderator D_2O collection system tank returns. The effects on normal reactor full power operation are identified in the following chart:

Obj. 1.5 a) ⇔

Obj. 1.5 b) ⇔

Change in moderator isotopic from reference operating value 99.75%.	Short term effect.	Long term effect.
Isotopic slowly increasing from high isotopic moderator makeup.	No observable effect, isotopic change too small.	Fuelling rate reduced slightly. Higher average fuel burnup.
Downgrading of less than or equal to 0.3%.	Operation continues with a drop in average liquid zone level, (adjusters may be required to move out).	Increased fuelling rate needed to return (and maintain) zone levels/adjusters to normal operating positions. Lower average fuel burnup.
Acute downgrading greater than 0.3%.	Shutdown, if Δk from zones/adjusters (boosters) is inadequate to maintain criticality.	Lengthy shutdown until new or upgraded D_2O is supplied.

MODERATOR RADIOLOGICAL CONCERNS

The design of the moderator system has attempted to reduce the radiological concerns in different ways.

The moderator equipment such as pumps, heat exchangers and piping are located in shielded and access controlled areas, mainly because of the nitrogen-16, (N^{16}), and oxygen-19, (O^{19}), high gamma fields. The access controlled areas are not accessible while operating at normal reactor power because of the radiological hazard. The piping is designed to minimize potential leak sources and eliminate pockets and strainers where activated material can build up. All materials used for equipment are low cobalt content.*

* Naturally occurring cobalt-59 converts to a radioactive cobalt-60 isotope in neutron fields.

Two major radiological concerns associated with the moderator system will be discussed in detail. They include:

a) **N^{16} and O^{19} gamma radiation fields;**

b) **Tritium content.**

Figure 1.1 gives an indication of on power radiation field buildup from N^{16} and O^{19} gamma radiation. When operating, the high fields peak at about 10 R/h. After shutdown, the short-lived non radioactive daughters decay away within one minute from shutdown.

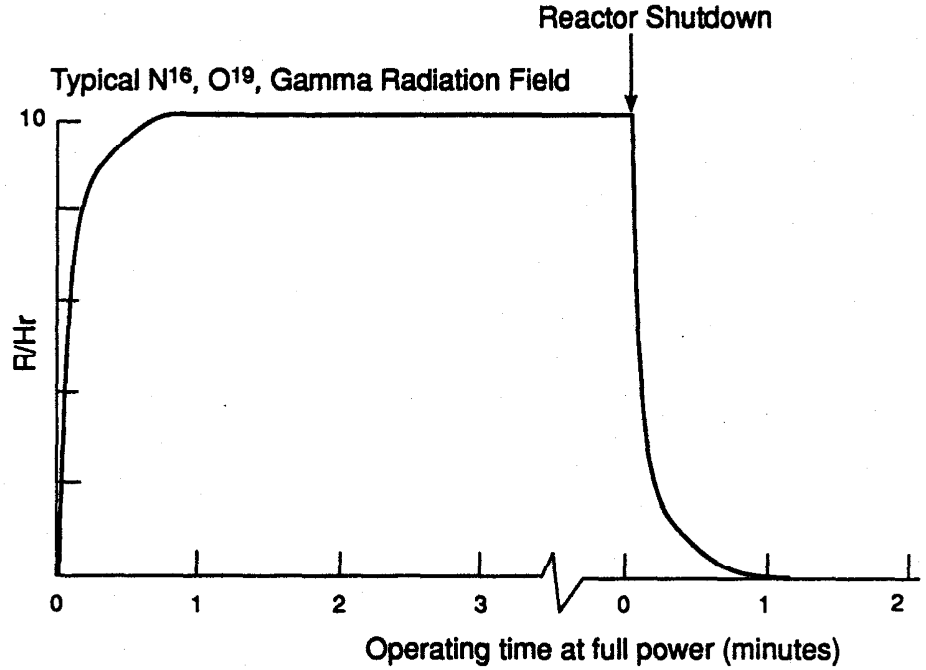


Figure 1.1

Moderator N-16, 0-19 Radiation Field Buildup

Tritium buildup in the moderator is also a major radiological concern. It builds up more quickly in the moderator than in the heat transport system because:

i) Thermal neutron flux is about twice as high in the moderator as in the heat transport system within the core. This is because the moderator is the source of thermal neutrons while the fuel is a sink (HT fluid in the vicinity of the fuel has a "flux depression" for thermal neutrons).

NOTES & REFERENCES

ii) The majority of the moderator D_2O spends a longer time in the core than HT D_2O. Hence the moderator D_2O absorbs more thermal neutrons giving a higher tritium concentration.

When moderator D_2O escapes from the system, tritium concentration is a radiological concern. Because the half life for tritium is about 12 years, the concentration builds up slowly to an equilibrium level. In practice, this concentration is reduced because of:

i) Outages and operation at lower than maximum reactor power;
ii) Low tritium concentration makeup D_2O to the moderator.

Typical equilibrium concentrations of 20 to 40 Ci/kg D_2O (1 to 2 TBq) are experienced at "mature stations". The tritium removal facility is Ontario Hydro's long term solution to reducing the tritium concentration in moderator systems.

The following three conditions are discussed which are particularly hazardous to the operation of the moderator system:

Moderator D_2O spilled during shutdown

Obj. 1.6 ⇔

When moderator D_2O escapes from the reactor or is spilled during shutdown, the following primary radiological hazards exist:

- Tritium
- Activation products - dissolved as ionic impurities and/or entrained insoluble products.

When shut down, the short lived isotopes, N^{16} and O^{19}, decay quickly. Photoneutrons will contribute to the fields for a slightly longer period.

Moderator D_2O spilled on power

Obj. 1.7 a) ⇔

When moderator D_2O escapes from the reactor or is spilled during normal power operation, the following primary radiological hazards exist:

- Gamma radiation (N^{16}, O^{19}) from moderator core and piping;
- Tritium;
- Activation products, dissolved as ionic impurities and/or entrained insoluble products;
- Beta radiation hazard at the hole in the piping system;
- Photoneutrons from N^{16}.

Moderator D_2O contained in pipework on power

⇔ *Obj. 1.7 b)*

The main radiological concerns associated with moderator D_2O sealed in the moderator circuit on power include:

- Gamma radiation (N^{16}, O^{19});
- Gamma radiation from activation products - soluble or insoluble;
- Photoneutrons from N^{16}.

When the reactor is shut down, the gamma radiation from N^{16} and O^{19} will be essentially zero. Activation product radiation will be the only primary concern.

As long as the moderator is contained in the circuit, tritium is of no concern because its beta radiation can not penetrate the pipework. However, in practice, moderator auxiliary rooms have tritium vapourized as an airborne emission, from leaks. Systems are in place to recover D_2O as a vapour or a liquid. This is done to reduce tritium exposure as well as recover D_2O for economic reasons.

REACTOR SHUTDOWN GUARANTEE

⇔ *Obj. 1.8*

There are two ways the moderator system is used to guarantee that the reactor is shutdown:

Moderator Poisoning

This method places the reactor in a guaranteed shutdown state due to the very high insertion of negative reactivity. Typically, moderator poisoning inserts hundreds of mk of negative reactivity. A flowpath in the moderator system is set up to ensure: (i) poison is not removed by purification; (ii) poison is not diluted by unpoisoned water; (iii) and poison is not drained out. The moderator D_2O must also be continuously circulated and monitored by sampling for poison concentration and pH* usually twice per shift to ensure the guarantee.

Moderator Draining

Recall** that it is not possible for a natural uranium reactor to achieve criticality without the moderating effect of the D_2O in the calandria. In this case a 'hole' is guaranteed in the calandria by guaranteeing certain drain valves open. This prevents moderator D_2O from inadvertently accumulating in the calandria. Some stations use a moderator dump as a shutdown system.

* Sampled to ensure Gd poison does not precipitate out of solution. See Course 224 for more details.

** This was discussed in the 427 Nuclear Theory course.

SUMMARY OF THE KEY CONCEPTS

- Concentration of heavy water is expressed as a percentage weight of D_2O in a given sample, called isotopic.
- The normal range of isotopic is 99.5% to 100%.
- A low limit on isotopic is imposed to minimize the economic penalty, and to ensure the reactor maintains critical.
- The average zone level will decrease as a result of low isotopic.
- Sudden downgrading of the moderator isotopic will cause a drop in the average zone level. The adjusters (or in some units, boosters) may be signalled to move depending on the average zone level and power error.
- During shutdown, the radiological hazards from spilled moderator D_2O include tritium, and activation products.
- During normal power operation, radiological hazards from spilled moderator D_2O include:
  - Gamma radiation from N^{16} and O^{19};
  - Tritium;
  - Activation products;
  - Beta radiation from the leak;
  - Photoneutrons from N^{16}.
- During normal power operation, radiological hazards from moderator in the pipework include:
  - Gamma radiation from N^{16} and O^{19};
  - Activation products;
  - Photoneutrons from N^{16}.
- The moderator system can guarantee the reactor shutdown by moderator poisoning or by draining the moderator from the core.

Page 9 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. Explain the term isotopic.

____

____

____

____

____

2. a) State the normal range for moderator isotopic.

____

   b) Why is it necessary to impose a lower limit on moderator isotopic?

____

____

3. Indicate one way that an operator may be alerted to a low isotopic.

____

4. What will occur if the moderator isotopic is suddenly downgraded by:

   a) ≤0.3%______________________________

____

   b) >0.3%______________________________

____

NOTES & REFERENCES

5. Indicate radiological hazards in the following chart:

	Shutdown	Normal Power Operation
Spilled Moderator D_2O	a) b)	a) b) c) d) e)
Moderator in pipework	a)	a) b) c)

6. How can the moderator system be used to guarantee that a reactor is shutdown (2 ways)?

a) ____

b) ____

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

Prepared by:	D. Bieman, WNTD
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 2

MODERATOR CIRCULATION SYSTEM

OBJECTIVES:

After completing this module you will be able to:

2.1 a) For each of the following operating states, list the indicated number of major heat sources: *⇔ Page 2*

- i) Full power (2),
- ii) Immediately after shutdown, with the moderator in the calandria (1).

b) For the moderator circulation system, describe the: *⇔ Pages 2, 13*

- i) Heat transfer path,
- ii) Heat sinks,
- iii) Major equipment required for heat removal.

2.2 a) State a typical range for bulk moderator temperature under normal operating conditions. *⇔ Page 3*

b) Explain three possible consequences of operating outside this range. *⇔ Pages 3-4*

2.3 State the possible consequence of localized "hot spots" in the moderator. *⇔ Page 3*

2.4 Under normal operating conditions, state the required level of moderator D_2O (in general terms only) and state the indicated number of adverse consequences of operating with a: *⇔ Page 4*

- a) Moderator level that is too low (5), *⇔ Pages 4-5*
- b) Moderator level that is too high (2). *⇔ Page 5*

2.5 State the indicated number of adverse consequences of the following abnormal conditions:

- a) Loss of service water to the moderator HXs (6), *⇔ Pages 5-6*
- b) Loss of moderator circulation flow (6), *⇔ Pages 5-6*
- c) Moderator heat exchanger leak (2). *⇔ Page 6*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

This module will examine the moderator circulation system. We will cover heat sources, heat removal, bulk moderator temperature, consequences of localized hot spots, improper moderator level, loss of moderator cooling and moderator heat exchanger leaks. Figure 2.1 at the end of the module can be unfolded and kept in sight for your reference.

Heat production

In the process of moderating the nuclear reaction, the moderator is subject to considerable heat production. The heat absorbed by the moderator is approximately 5% of the reactor's gross thermal power production. (Note that in stations using boosters, this value can increase to ~7%. The rest of this discussion will ignore booster heat input to the moderator, as booster are not used for steady state operation).

Obj. 2.1 a) ⇔

Most of the heat in the moderator is generated as a result of the **fission process** (from thermalizing neutrons and absorbing fission γs). The remaining heat is produced by the absorption of γ **from fission products and activated core components.**

Immediately after **shutdown** (with HT D_2O hot), the fission component of the heat production is virtually eliminated and only about 30% of the "at power" heat load remains. Most of this remaining heat is from the absorption of γ **from fission products and activated core components.** Note also that the heat production decreases by a factor of 10 during the first day after a shutdown, mainly due to the decay of short lived fission products.

Heat removal

Heat must be removed from the moderator to prevent the following:

- Temperature increases and boiling, which have an undesirable effect on the core reactivity and cover gas D_2 concentrations.
- Elevated temperatures, since the moderator is not as effective as a heat sink to prevent a pressure tube or calandria tube failure in the event of a LOCA. In addition, large thermal stresses could occur between the end shield and the calandria if moderator temperatures are out of specified ranges.

Each of these problems will be discussed further in the module.

⇔ Obj. 2.1 b)

To prevent the problems mentioned above, the moderator must be cooled while operating and while shut down. This is accomplished by the moderator circulation system. Refer to Figure 2.1 at the end of the module for a typical moderator circulation system.

The moderator D_2O, which is pumped through the moderator heat exchangers, is cooled by service water. Eventually, the heat ends up in the lake (river or sea, depending on the station).

The flow is distributed to various locations in the calandria to minimize the occurrences of local "hot spots", and to ensure all components are cooled.

During normal operation, full flow is maintained through the calandria to keep components cool.

During shutdown periods (and also depending on the amount of time since shutdown), a reduced circulation flow can be used (ie. fewer pumps/heat exchangers or the use of smaller auxiliary moderator circulation pumps) to remove the heat. In stations where the moderator is dumped, cooling to the core components is maintained by calandria sprays, which cool the critical core components (calandria tubes, reactivity mechanisms, dump ports, supports, etc.).

Moderator temperature control

⇔ Obj. 2.2 a)

The moderator temperature is controlled by varying the service water flow through the moderator heat exchangers. The **temperature** at the moderator inlet is controlled to ~40°C. With this inlet temperature, and while operating under normal conditions, the outlet temperature is normally ~60°C. Temperatures outside this operating range must be prevented for the **following reasons:**

⇔ Obj. 2.2 b)

a) Temperature increases must be prevented.

- As the temperature of the moderator increases, the moderator temperature coefficient (positive for equilibrium fuel) causes **core reactivity to increase***.
- If temperature increases to the point of localized boiling, the voids decrease core lattice pitch effectiveness (eg. no moderation will occur in the steam bubbles). Since our reactors are over-moderated, this can cause the **core reactivity to increase** (until the boiling becomes excessive, which will then cause under-moderation).

* This is discussed in the Nuclear Theory course (227).

Obj. 2.3 ⇔

- Boiling would initially be localized to hot spots and be very erratic. This leads to **unstable** reactivity effects in the core localized to the boiling locations.

An elevated moderator temperature will cause the moderator cover gas D_2 levels to increase, as the D_2 comes out of solution. This can lead to an **explosion hazard** in the moderator cover gas.

The maximum temperature also depends on the pressure in the moderator, ie. conditions must be maintained below saturation. Pressure in the moderator is maintained by the cover gas system at approximately 10 to 25 kPa(g) *. Also, we must realize that no heat removal path is perfect, and local hot spots may exist within the calandria. This means that temperatures must be maintained below ~100°C, with a sufficient margin to boiling to accommodate the local "hot spots". (Note, if a higher temperature was desired for the moderator, the calandria would be required to be a large pressure vessel -leading to increased costs).

* At the upper free surface.

b) The thermal temperature range in the moderator must be established to minimize the **thermal stresses** between the end shield and the calandria. Damage to components (such as rolled joints, welds, etc.) could occur if these stresses become large.

c) The moderator may have to act as a reactor **heat sink** under severe accident conditions (severe LOCA). In this situation, fuel channel voiding will cause fuel channel overheating and sagging. And, if fuel cooling is not restored, eventually the fuel channels will contact the calandria tubes. When contact occurs, the heat is conducted through the fuel channel and calandria tube to the moderator D_2O. This will maintain pressure tube integrity. Hence, as the temperature of the moderator increases, its capability as a heat sink is reduced.

Moderator level

Obj. 2.4 ⇔

The major function of the moderator is to thermalize fast neutrons. The function of the moderator circulating system is to cool the moderator and calandria components. Considering these functions, the moderator D_2O level must be **sufficient to minimize neutron leakage from the core and cool the core components.**

Obj. 2.4 a) ⇔

A **low moderator level** can cause the following problems:

a) **Overheating** of the calandria components if they lose their cooling from the moderator D_2O. This is especially true for the calandria tubes.

b) Removal of **reactivity**, especially if calandria tubes are no longer submerged in the moderator D_2O. But, even if all the calandria tubes are still covered, a loss of reactivity can still occur because a lower level results in increased neutron leakage (ie. the moderator performance as a neutron reflector is reduced).

c) **Severe flux tilts** if power is maintained at reduced levels (other reactivity devices will operate to maintain power)

d) The rate of **deuterium evolution** from the top of the moderator D_2O will increase as surface area increases. This will lead to a shutdown if the deuterium concentration in the moderator cover gas reaches the shutdown limit. The normal operating level is kept above the calandria (as illustrated in Figure 2.1) to minimize the D_2O area exposed to the cover gas (ie. due to the shape of the calandria, as level decreases near the top, D_2O surface area increases).

e) In some stations, **ion chamber response** will be affected as the detectors at the top of the calandria become exposed to the cover gas (ie. lose the shielding effect of the moderator D_2O).

A **high moderator level** can cause the following problems: ⇔ *Obj. 2.4 b)*

a) **Insufficient space** in the calandria to accommodate the poison injected when SDS2 fires. This could result in the bursting of the calandria rupture discs. Also, insufficient room could exist for thermal expansion of the moderator as heat input increases during startup.

b) Possible **flooding** of the **SDS2 helium injection header**. (Note that as level in the moderator increases, so does the level in the SDS2 injection tanks.) If the level rises sufficiently, the D_2O/poison mixture will rise into the He injection piping. As the poison tank level increases, the moderator D_2O/poison interface moves away from the calandria. This would result in a delay of poison injection when the Shutdown System initiates. Water in the He injection piping can also cause severe water hammer if SDS2 fires.

ABNORMAL CONDITIONS

In this section, two abnormal conditions are discussed: loss of moderator cooling and a moderator heat exchanger leak.

Loss Of Cooling

Loss of cooling to the moderator will cause the moderator temperature to rise. This could be caused by loss of moderator circulation flow or loss of cooling water to the moderator heat exchangers. This will result in the following: ⇔ *Obj. 2.5 a), b)*

a) The increase in moderator temperature will cause an increase in reactivity due to the positive moderator temperature coefficient (the moderator temperature is positive for equilibrium fuel, but negative for fresh fuel)*. If operation continues, localized boiling will start, causing further **reactivity increases and operational instability**.

* This is discussed in the Nuclear Theory course (227).

b) Equipment will also overheat, resulting in **damage due to thermal stressing.**

c) Also in this case, the moderator **may not be an effective heat sink** (as explained earlier in this module).

d) As boiling occurs, **pressure could increase in the calandria,** causing a burst rupture disc. The required actions would be to shut down the reactor and to cool down the HTS to limit heat input to the moderator. Containment should also be buttoned-up (boxed-up) to ensure that tritium releases to the environment are controlled (in case a rupture disc bursts).

e) As the moderator temperature increases, the D_2O will swell. The **level control** response of the moderator system may not be quick enough to prevent SDS2 injection header flooding.

f) As the moderator temperature increases, **D_2** will come out of solution from the moderator *. This can lead to an **explosive mixture** of D_2 and O_2 in the cover gas.

* This is discussed in more detail in Module 3.

Moderator Heat Exchanger Leak

Obj. 2.5 c) ⇔

In the case of a moderator heat exchanger leak, the moderator D_2O will be lost to the lake. This causes two operating problems:

a) There is a potential for **highly tritiated D_2O reaching the environment.** Continued operation may depend on our target of 1% of the DEL (regulatory limit) for the station.

b) An **economic penalty** exists for the D_2O loss from the station. Continued operation would also depend on the rate of leakage. If the leak is serious enough to require immediate repair, a shutdown will be required to drain and repair the leaking tube(s) or replace the HX tube bundle.

SUMMARY OF THE KEY CONCEPTS

- The major heat sources in the moderator while operating are from thermalizing neutrons, absorption of γ (from fission, fission products and activated core components). The major heat source in the moderator while shut down is from fission product and activated core component γ absorption.
- The optimum temperature range for the moderator D_2O is ~40° C at the inlet and ~60°C at the outlet.
- If the moderator temperature is too low or too high, thermal stresses between the end shield and the calandria will be high, possibly causing equipment damage.
- If moderator temperatures are too high, reactivity will increase. Very high temperatures may cause localized boiling. This could cause reactivity control problems. At high temperatures the moderator would not be an effective heat sink in the event of a LOCA (if fuel channel sagging occurs, due to overheating, until contact with a calandria tubes is made). D_2 excursions can also occur due to high moderator temperatures.
- Normal moderator level must be sufficiently high to minimize neutron leakage and to ensure that core components are cooled.
- Too low a moderator level will result in loss of reactivity, overheating of core components and an increased rate of D_2 evolution due to increased D_2O surface area exposed to the cover gas. In some stations, ion chamber response may be affected.
- Too high a level will result in insufficient space in the calandria to accomodate SDS2 firing without bursting a rupture disc. Possible flooding of the SDS2 He injection header can also occur, which can result in severe water hammer when SDS2 fires.
- Loss of service water to the moderator heat exchangers or loss of moderator circulation flow will cause the moderator temperature to increase. The resultant moderator heating will eventually cause reactivity control problems, equipment overheating and damage. Also in this case, the moderator may not be an effective heat sink in the event of a severe LOCA. As boiling occurs, pressure could also increase in the calandria, causing a rupture disc to burst. D_2 excursions and moderator level increases can occur due to loss of moderator cooling.
- A moderator heat exchanger leak will result in the loss of moderator D_2O. This represent an economic penalty and a radiological emission concern.

You can now **work on the assignment questions.**

⇔ ***Page 9***

ASSIGNMENT

1. The two major moderator heat sources at power are:

   a) ______________________________

   ____

   b) ______________________________

   ____

2. The major moderator heat source with the reactor shut down is

   ____

   ____

3. For the moderator circulation system, describe the heat transfer path and the major components required to remove the heat produced

   ____

   ____

   ____

   ______________________________. The

   ultimate heat sink for the moderator is______________________________

   ____

4. The normal moderator D_2O temperature range is ______________. Low moderator temperature can cause thermal stresses between

   ______________________________.

5. High moderator temperatures can cause the following three effects:

   a) ______________________________

   ____

   ____

   ____

   ____

   ______________________________.

b) ____

____

____

____

____

____.

c) ____

____

____

____

____

____.

6. Localized hot spots in the moderator will cause ______________
This will lead to ______________________________.

7. The normal required level of the moderator (in general terms) is

____

____

8. A low moderator level can cause:

a) ____

____

b) ____

____

c) ____

____

d) ____

____

e) ____

____

9. A high moderator level can cause:

a) ______________________________

____

b) ______________________________

____

10. Loss of cooling to the moderator D_2O can be caused by:

a) ______________________________

b) ______________________________

11. The six consequences of a moderator loss of heat sink are:

a) ______________________________

____

____

b) ______________________________

____

____

c) ______________________________

____

____

d) ______________________________

____

____

e) ______________________________

____

____

f) ______________________________

____

____

12. A moderator heat exchanger leak can cause the following adverse consequences:

    a) ______________________________

    ____

    ____

    b) ______________________________

    ____

    ____

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

Prepared by: N. Ritter, WNTD
Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 3

MODERATOR COVER GAS SYSTEM

OBJECTIVES:

After completing this module you will be able to:

3.1 State the lower explosive limits of D_2 and O_2 in a helium atmosphere. ⇔ *Page 2*

3.2 State six factors that affect the concentration of D_2 and O_2 in the cover gas, and explain how each affects the gas concentrations. ⇔ *Pages 2-3*

3.3 a) List the operating states that require cover gas circulation and explain three reasons for this circulation requirement, ⇔ *Page 3*

b) Explain the three conditions that require cover gas purging, ⇔ *Pages 3-4*

c) Explain the required precaution while purging the cover gas. ⇔ *Page 4*

3.4 State the two methods that are used to ensure that D_2, O_2 and N_2 concentrations in the cover gas are within the allowable limits. ⇔ *Page 4*

3.5 Explain the possible significant consequence and general methods to minimize or offset the consequences for each of the following abnormal conditions in the moderator cover gas:

a) D_2 concentrations between 2% and 4%, ⇔ *Pages 4-5*

b) D_2 concentrations above 4%, ⇔ *Page 5*

c) N_2 concentrations above 2% . ⇔ *Page 5*

3.6 Explain two methods used to determine if a cover gas recombination unit is operating. ⇔ *Page 4*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Recall from your previous R&A courses that the purpose of the moderator cover gas system is to provide a non-corrosive/non-explosive atmosphere for the calandria components. It is for these reasons that helium is used for the moderator cover gas. A typical cover gas system is shown in Figure 3.1 at the end of the module, which can be unfolded and kept in sight for easy reference.

This module will cover the cover gas circulation requirements, cover gas purging, factors affecting cover gas D_2 concentrations and consequences of high D_2 and N_2 concentrations in the cover gas.

Explosive Limits

Obj. 3.1 ⇔

* Note that the recombination units are discussed in the Chemistry 224 course. Recall also the radiolysis reaction: $2D_2O \leftrightarrow 2D_2 + O_2$

The cover gas system facilitates the recombination of D_2 and O_2 created due to radiolysis of the moderator D_2O*. The explosion hazard is eliminated by keeping D_2 and O_2 levels within operating range, which are below the **lower explosive limits** of ~8% D_2 and ~5% O_2 (ie. normal operating levels are maintained well below 1% D_2, with O_2 concentrations slightly higher to ensure a sufficient quantity of O_2 for recombination).

D_2 and O_2 concentrations in the cover gas

The rate of radiolysis and the rate at which the dissolved gases evolve from the moderator are affected by a number of factors.

Obj. 3.2 ⇔

The rate of radiolysis increases with increasing **γ radiation**. Thus, the higher the power level, the greater the rate at which radiolysis occurs. High **conductivity** or impurities (ie. nitric acid, resin fines, oils, etc.) in the moderator will cause the natural rate of D_2 and O_2 recombination to decrease.

Once these gases are produced, the rate at which they come out of solution also depends on a number of other factors:

a) As the **temperature of the moderator** increases, the water is less able to hold the dissolved gases, ie. solubility decreases. Hence, at higher temperatures the rate at which gases leave the water and enter the cover gas is greater than at lower temperatures. The moderator outlet temperature is typically maintained at ~60°C.

b) As the cover gas **pressure of the moderator** decreases, the ability of the moderator to hold the dissolved gases decreases. Again, the gas evolution rate increases as pressure in the cover gas is reduced (ie. a similar effect can be seen in carbonated drinks, as the container is opened and depressurized, the gases come out of solution). The cover gas is normally maintained at a pressure of ~10 to 25 kPa(g).

c) As the **moderator level** decreases, the D_2 and O_2 concentration in the cover gas increases. Recall from module 2 that this effect is caused by the increased surface area between the moderator and the cover gas, from which the D_2 and O_2 can evolve from the moderator to the cover gas.

d) The **concentration of D_2 and O_2 in the moderator**. As the concentration of the gases dissolved in the moderator increase, the gases will attempt to reach a new equilibrium state with the cover gas. This will result in the D_2 in the moderator evolving from the D_2O at a faster rate (as compared to a lower concentration of D_2 in the moderator) to reach the equilibrium state.

Cover gas circulation

⇔ Obj. 3.3 a)

All reactor states require the **circulation of the cover gas**. The reasons for the requirement of continuous circulation are:

a) High decay γ fields exist in the core during shutdowns, which will cause radiolysis to continue (hence allowing D_2 and O_2 concentrations to build up). This can be further aggravated by moderator poisons (impurities) which cause a decrease in the natural recombination rate. This is why D_2 concentrations in the cover gas increase during a reactor restart after an outage (ie. radiolysis exceeds the low rate of natural recombination).

b) Continuous circulation also ensures that any samples taken from the cover gas are representative of the cover gas.

c) The circulation also ensures that a flow is maintained to the recombination units, which will recombine the D_2 and O_2 back into D_2O.

Cover gas purging

⇔ Obj. 3.3 b)

If, during a unit shutdown, the cover gas compressors require maintenance, a helium make-up supply and a method of **purging** must be available. This is to ensure that the removal of D_2 and O_2 can occur (ie. without circulation of the cover gas through the recombination units). Purging while the cover gas compressors are shutdown is referred to as a static purge.

Purging the cover gas is also the only method of removing air or N_2 from the cover gas. This is of particular concern when the system has been opened for maintenance, ie. where air ingress has occurred.

Purging of the cover gas is carried out during reactor operation when concentrations of N_2 or D_2 exceed limits specified in your operating documentation. This is accomplished by bleeding off helium from the system, while making up helium to the system at the same rate (to prevent a drop in cover gas pressure). Purging while the cover gas compressors are operating is referred to as a dynamic purge.

Obj. 3.3 c) ⇔

When purging the cover gas, **care must be taken** to ensure that the **pressure** is not reduced (ie. the normal pressure is maintained at ~10-25 kPa(g)). Recall that lowering the pressure in the cover gas system can cause an increase in D_2 concentration in the cover gas (and evolution of dissolved gases in general).

We should also note that a reduction of cover gas pressure will cause the boiling point of the moderator to decrease. Hence, this will also result in the impairment in the use of the moderator as a heat sink in the event of a severe LOCA *.

* This was discussed in more detail in Module 2.

Cover gas monitoring

Obj. 3.4 ⇔

Cover gas can be monitored by two methods:

a) The first is by the **on line gas chromatograph**, which takes samples upstream and downstream of the recombination units. This will give the operator warning when D_2, O_2 and N_2 concentrations are out of specified ranges. The D_2 and O_2 readings across the recombination units will also indicate to the operator that these units are functioning properly.

b) The other method of sampling is a **manual grab sample** of the cover gas. This manual sample will require analysis by the chem lab.

Abnormal conditions

Obj. 3.5 a) ⇔

Concentration of D_2 between 2% and 4% in the cover gas requires that conditions be established to ensure D_2 levels do not increase further. This **prevents an explosive mixture of D_2 and O_2** being formed. The required methods vary from station to station, but typically include:

- Purging of the cover gas;
- Adding O_2 to ensure there is a sufficient quantity for recombination;
- Check cover gas compressor operation and place another compressor in service if required;
- Check **recombination unit operation**. This could be accomplished by checking that recombination unit temperature is in the correct

Obj. 3.6 ⇔

range, ie. recombination of D_2 and O_2 produces heat. If the recombination unit catalyst becomes wet, the unit will not function (which would require the heaters to be put in service until the unit is functioning). Operation could also be confirmed by D_2 and O_2 levels at the inlet/outlet of the recombination units. If there is a fault with the unit, another unit would have to be placed in service;
- Lowering the moderator temperature;
- Increase moderator level;
- Increase purification or place fresh IX columns in service;
- Do not raise reactor power.

The reasons for these actions have been previously mentioned in this module.

⇔ *Obj. 3.5 b)*

At a concentration of 4% D_2 in the cover gas, the required actions are, again, to ensure that the concentration does not reach the explosive limit. Here, the actions are a bit more drastic, as the margin to the explosive limits of D_2 and O_2 is being reduced. The typical **methods** to reduce D_2 levels will be:

- Continue purging of the cover gas,
- Sample immediately and after the D_2 concentration has been confirmed above 4%, shut down the unit in a controlled manner.

⇔ *Obj. 3.5 c)*

Nitrogen in the cover gas can form **nitric acid** in the presence of moisture and radiation. This acid will also increase **radiolysis** of the moderator D_2O. This could cause a D_2 excursion, resulting in a plant shutdown. Note that this acid will also cause **corrosion** of the moderator components. The N_2 concentration is maintained $\leq 2\%$ (typically $\leq 0.5\%$). When concentrations reach 2%, the typical **methods** to reduce N_2 levels will include:

- Purging the cover gas system until N_2 is within specifications;
- Increasing moderator purification to remove any acids that have formed.

SUMMARY OF THE KEY CONCEPTS

- D_2 concentration in the cover gas increases with:
  - Moderator temperature. As the moderator temperature increases, the D_2 solubility decreases.
  - Decreased moderator cover gas pressure. As the pressure of the cover gas decreases, the D_2 solubility decreases.
  - Decreased moderator level. As the moderator level decreases, the surface area of the moderator exposed to the cover gas increases. This increased surface area makes it easier for the D_2 gas to come out of solution.

  - Increased reactor power. As reactor power increases, so do the γ and neutron fields. The increased fields increase radiolysis.
  - Increased impurities in the moderator. An increase in the impurity level in the moderator will cause the rate of radiolytic recombination to reduce.
  - Moderator D_2 concentration. As the moderator D_2 concentration increases, the D_2 will reach a new equilibrium with the cover gas, resulting in a higher rate of gas evolution from the moderator to the cover gas.

- The lower explosive limits for D_2 and O_2 in a helium environment are 8% D_2 and 5% O_2.
- All reactor states require cover gas circulation. Radiolysis continues during reactor shutdown due to high decay γ fields in the core.
- Purging of the cover gas is required when:
  - Cover gas N_2 or D_2 concentrations are high.
  - The system has been opened for maintenance. This is to purge air (which is mainly N_2) from the cover gas to prevent nitric acid from being formed.
  - Cover gas compressors are not available to circulate the cover gas through the recombination units.
- When purging the cover gas system, care must be taken to ensure that system pressure is not lowered, which could cause a D_2 excursion.
- D_2, O_2 and N_2 concentrations are monitored on line by the gas chromatograph. Grab samples for chem lab analysis can also be taken.
- D_2 concentrations between 2% and 4% may typically require the following to reduce concentrations:
  - Purging of the cover gas,
  - Adding O_2 to ensure there is a sufficient quantity for recombination,
  - Check and place another recombination unit in service as required,
  - Check and place another cover gas compressor in service as required,
  - Increasing the moderator level,
  - Lowering the moderator temperature,
  - Keeping reactor power constant.
- Confirmed D_2 concentrations above 4% will require a unit shutdown (while the purge continues).

- N_2 concentrations above 2% will require a cover gas purge, and may require an increased rate of moderator purification to remove nitric acid that has formed.

You can now **work on the assignment questions.**

⇔ ***Page 9***

ASSIGNMENT

1. The lower explosive limits are _____% D_2 and _______% O_2 in a helium environment.

2. a) As reactor power increases, the production of D_2 in the moderator increases / decreases because ____________________

____

____

____.

b) As moderator impurity levels increase, the concentration of D_2 in the moderator increases because ____________________

____

____

____.

c) As moderator temperature increases, the concentration of the D_2 in the cover gas increases / decreases because ________

____

____

____.

d) As cover gas pressure increases, the concentration of the D_2 in the cover gas increases / decreases because ___________

____

____

____.

e) As moderator level increases, the concentration of the D_2 in the cover gas increases / decreases because _____________

____

____

____.

f) As the concentration of the D_2 in the moderator increases, the concentration of the D_2 in the cover gas increases / decreases because ______________________________

____

____

______________________________.

3. The cover gas must be circulated (only while operating / all the times) because ______________________________

____

______________________________.

4. a) Purging of the cover gas will be required when

i) ______________________________

____

______________________________.

ii) ______________________________

____

______________________________.

iii) ______________________________

____

______________________________.

b) The cover gas compressors can be removed from service only if ______________________________

______________________________.

5. The precaution to be taken when purging the cover gas system is

____

______________. This is because ______________

____

______________________________.

6. Gas concentrations are monitored by the ____________________ on line. The other source of gas analysis is ____________________ ____.

7. High concentrations of N_2 in the cover gas can lead to __________ ______________________________ which will result in ____.

   High concentrations of D_2 in the cover gas can lead to __________ ____.

8. a) D_2 concentrations between 2% and 4% will typically require:

   i) ____.

   ii) ____.

   iii) ____.

   iv) ____.

   v) ____.

   vi) ____.

   vii) ____.

   b) D_2 concentrations above 4%, in addition to the above actions, will also require ______________________________ ____.

   c) N_2 concentrations above 2% will require the following actions:

   i) ____.

   ii) ____.

9. Recombination unit operation can be confirmed by the following:

a) ______________________________

____

____

____

b) ______________________________

____

____

____

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

Prepared by:	N. Ritter, WNTD
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 4

THE MODERATOR LIQUID POISON SYSTEM

OBJECTIVES:

After completing this module you will be able to:

4.1 For each of the following operating conditions: *⇔ Pages 5 - 6*

- a) Prior to initial startup of the unit when it contains fresh fuel,
- b) During fuelling,
- c) During overfuelling,
- d) During an extended outage,
- e) Following startup after a poison outage (Xe transient),
- f) After a large increase in power following sustained operation at a lower power level,
  - i) Explain which poison is preferred and why chosen,
  - ii) Explain why the poison is added to the moderator.

4.2 If poison addition is done manually, list four general indications used to monitor/control poison addition. *⇔ Page 9*

4.3 State the source of information used to ensure that the correct amount of poison has been added to the moderator: *⇔ Page 9*

- a) During any of the operating conditions listed in Objective 4.1, when the reactor is critical,
- b) During an extended outage, or guaranteed shutdown state.

4.4 State the reason why there is an automatic Gd addition feature. *⇔ Page 10*

4.5 State the indicated number of unit responses/concerns, or indications during: *⇔ Pages 11 - 12*

- a) Inadvertent addition of poison at full power operation, (3)
- b) Inadvertent removal of poison at full power operation, (1)
- c) Inadvertent removal of poison at startup operation, (1)
- d) Boron use where gadolinium is preferred, (2)
- e) Poison unavailability. (2, one for each poison)

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Recall from previous Reactor and Auxiliary courses, the moderator liquid poison system is used for reactivity control. Soluble neutron poisons, with large neutron capture cross-sections to absorb neutrons, are added into the moderator in a controlled manner.

Poison may be added for the following reasons:

a) For fresh fuel burnup simulation. The poison compensates for excess fuel reactivity for the first 200 full power days of operation by the addition of a matching negative mk worth of poison.

b) For xenon equilibrium load simulation. Poison is added to compensate for the lack of xenon negative reactivity following a shutdown of about 30 hours or greater. The full xenon equilibrium load may be up to the full 28 mk worth at full power.

c) To overpoison the reactor during a shutdown to obtain a guaranteed shutdown state.

d) To compensate for reactivity due to overfuelling, sometimes called fuelling machine reactivity banking. The additional poison is added to match the extra reactivity from the fresh fuel.

System Description

A sketch of the general system is shown in Figure 4.1. The poison mixing tanks are located in an accessible area while on power. A delay tank is installed in the supply line to allow the gamma fields from nitrogen-16, (N^{16}), and oxygen-19, (O^{19}), isotopes to decay to acceptable levels when the mixing tanks are filled from the moderator system during operation. The poison tanks are equipped with agitators, level gauges, sample valves, poison addition ports and vent lines. Most of this equipment is used in the refilling of the mixing tanks. The agitator, in particular, provides for good mixing and dissolution of poisons. Boron is of particular concern because of its low solubility.

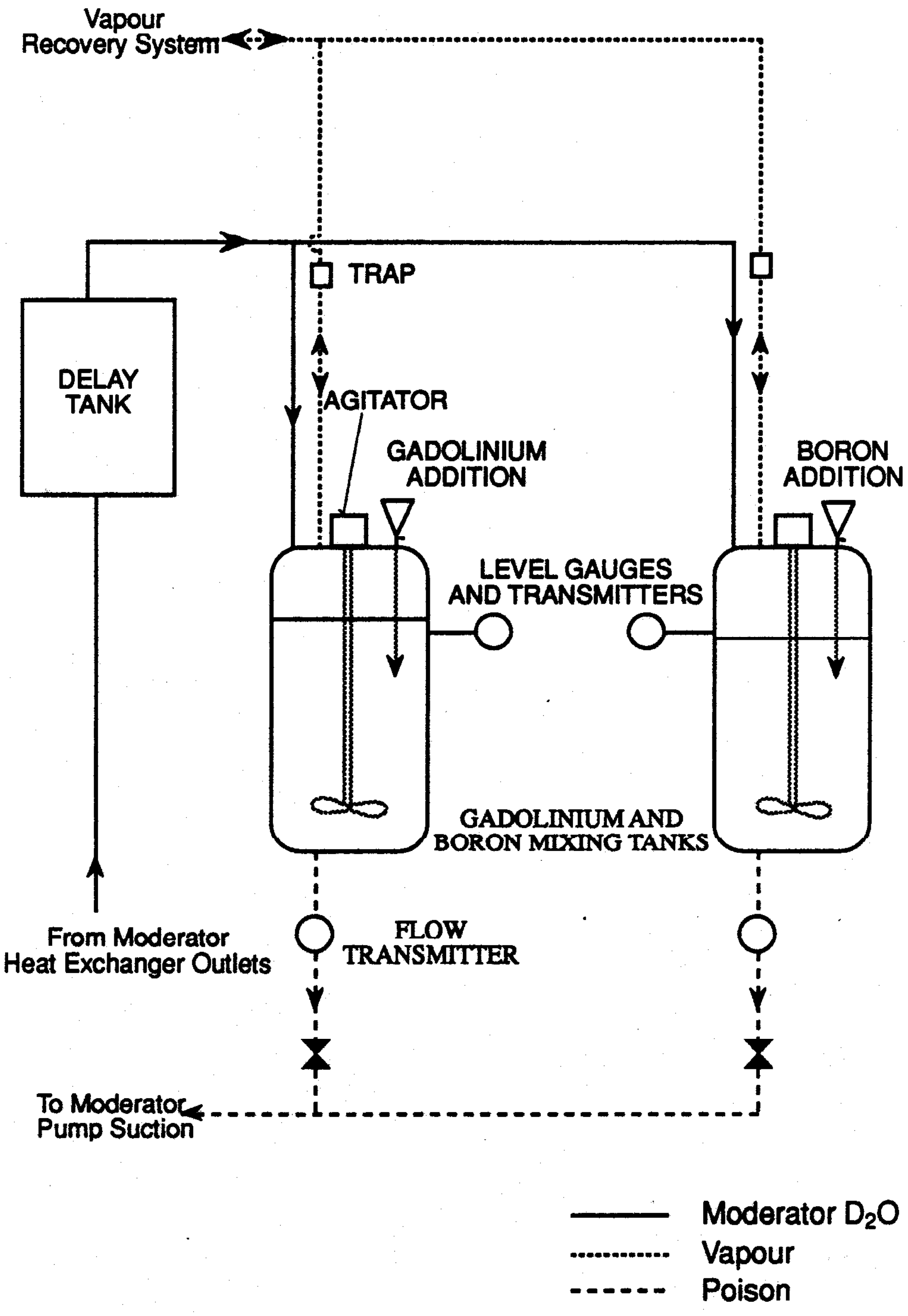


Figure 4.1 Typical Moderator Liquid Poison Addition System

"

NORMAL OPERATION

Choice of Poison

Generally two neutron absorbing poisons are used in the moderator liquid poison system. Depending upon their nuclear and chemical properties, one poison may be more appropriate for a particular application than the other. Table 4.1 summarizes a comparison of the two poisons.

Table 4.1 Comparison of the Advantages and Disadvantages of Boron and Gadolinium Poisons

POISON	ADVANTAGES	DISADVANTAGES
Boron (B)	Preferred for longer term (days) operations due to slower burnout (little makeup needed) and due to slower IX removal. Smaller mk/kg poison in case of inadvertent addition (ie. weaker poison). Because of lower conductivity in solution than Gd, it is less likely to induce a cover gas D_2 excursion.	Less soluble than Gd, undissolved solid could block lines and reduce (unsafely) -ve Δk worth in system. Uses more IX resin to remove than Gd, per mk worth.
Gadolinium (Gd)	Preferred for short term operations (<2 days) due to more rapid burnout and more rapid IX removal. High solubility allows high mk to be achieved without poison precipitating out. Uses less IX resin to remove than B, per mk worth.	Conductivity in solution is higher than B. This increases the risk of D_2 excursions due to enhanced radiolysis. More rapid -ve reactivity insertion (stronger per kg poison) in the case of inadvertent addition. Will precipitate out when solution pH is > 7.

Poison Use

Table 4.2 summarizes different cases where poison may be added to the moderator via the liquid poison addition system for control purposes.

Table 4.2 Specific Applications of Moderator Poisons

APPLICATION	POISON & WHY CHOSEN	WHY POISON ADDED
Fresh fuel burnup simulation – prior to initial startup and during initial operation when the unit contains fresh fuel.	Boron – slow boron burnup rate in neutron fields and slow IX boron removal rate better matches slow fuel burnup rate and slow fuel fission product buildup.	To compensate for extra reactivity of fresh fuel, due to absence of xenon and other fission products and the buildup of plutonium.
During fuelling.	Boron – burnup rate and removal rate of boron more closely match reactivity changes of new fuel.	To compensate for the extra reactivity of new fresh bundles, in part due to absence of xenon and other fission products.
During overfuelling. (fuelling machine reactivity shim control).	Boron – again burnup rate and removal rate of boron more closely match reactivity changes of new fuel.	To compensate for extra reactivity of the excess fuel.
During an extended outage.*	Gadolinium – IX removal rate is faster. Gadolinium is more soluble than boron and has a higher negative mk worth per ppm dissolved. Gd usually does not precipitate unless pH>7.	To make the reactor deeply subcritical. To compensate for loss of xenon and reactivity effects.
Following startup after a poison outage (xenon transient).*	Gadolinium – xenon will buildup at almost the same rate as gadolinium is burned out in neutron flux. The slight mismatch can be compensated by adding Gd or removing Gd with IX column.	To compensate for lack of xenon after the poison outage.**

⇔ *Obj. 4.1 a)*

⇔ *Obj. 4.1 b)*

⇔ *Obj. 4.1 c)*

⇔ *Obj. 4.1 d)*

* This is explained in greater detail on page 6, just after this chart.

⇔ *Obj. 4.1 e)*

** The regulating system is designed to operate with a xenon equilibrium of -28 mk. If this is not present, RRS will be out of zone control range.

Obj. 4.1 f) ⇔

APPLICATION	POISON & WHY CHOSEN	WHY POISON ADDED
After a large increase in power following sustained operation at a lower power level.	Gadolinium – will burnout at almost the same rate as xenon builds up.	Large increase in power after sustained low power operation will initially decrease the xenon level due to increased neutron flux. The poison, if required, will compensate for the loss of xenon. Xenon will, over time, increase to a new higher equilibrium concentration.

Use of poison during a startup following an extended outage includes two durations:

1. Startup following a shutdown of longer than three days,

   A startup to full power following 3 or more days after a shutdown may begin with effectively no xenon in the core as shown in Figure 4.2. The xenon will buildup to about -28 mk worth of reactivity at almost the same rate as gadolinium is burned out by neutron flux removal alone. The match will not be exact as indicated by changes in the average zone level. Any mismatch can be compensated by adding more gadolinium or removing gadolinium by valving in the Gd IX column.

2. Startup between 1.5 and 3 days following a shutdown.

   A startup to full power following 1.5 to 3 days of shutdown from full power, will have a xenon concentration as shown by Figure 4.3 on page 8. Gadolinium must be added as shown during the xenon burnout period. During the subsequent xenon buildup, the gadolinium will burn out at about the same rate. Any mismatch is again detected by the average zone level and is controlled by gadolinium addition or removal as previously discussed. Startup at about 35 hours following shutdown is shown in Figure 4.3.

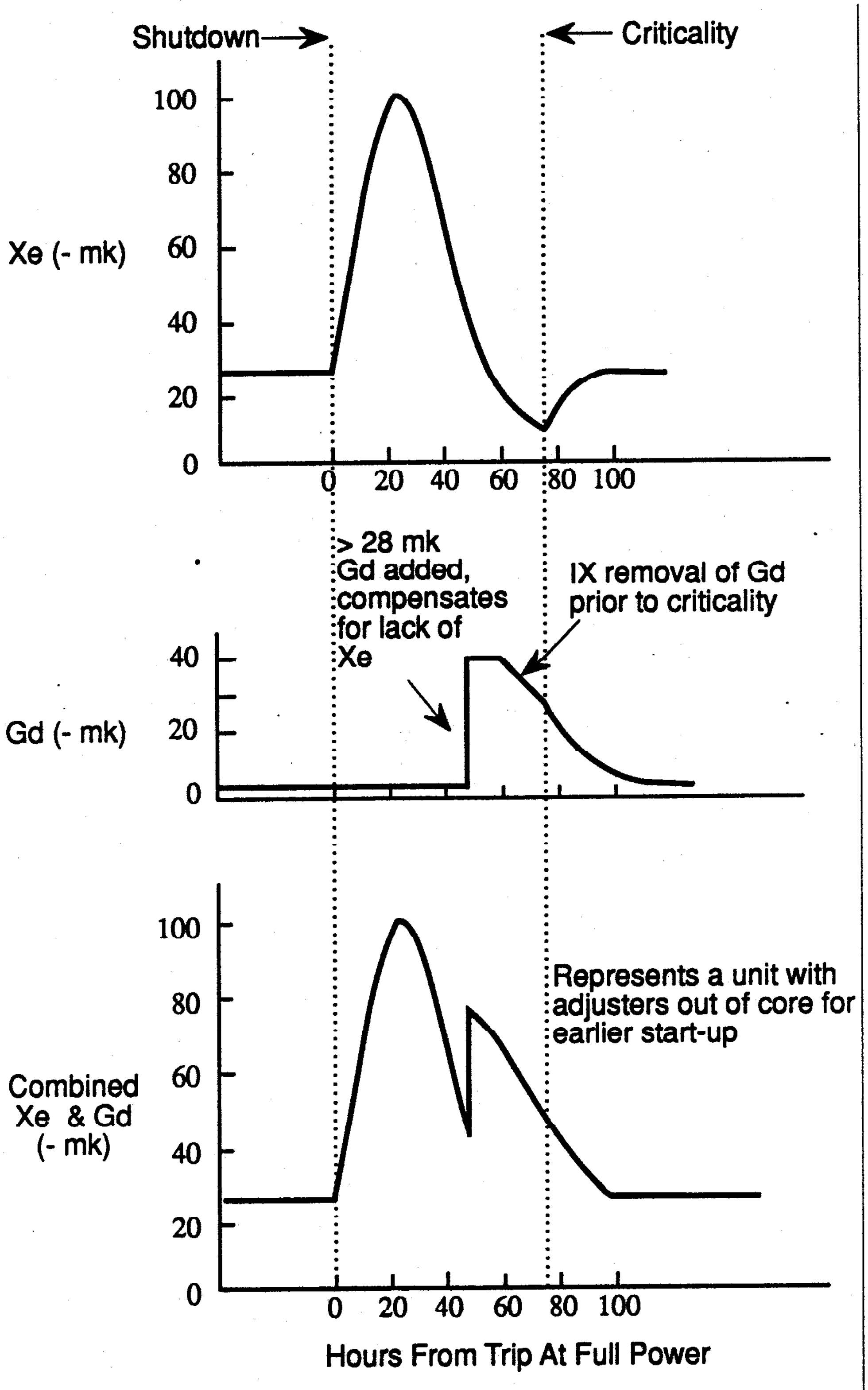


Figure 4.2 Gd Concentration in Moderator After a Shutdown of about Three Days

NOTES & REFERENCES

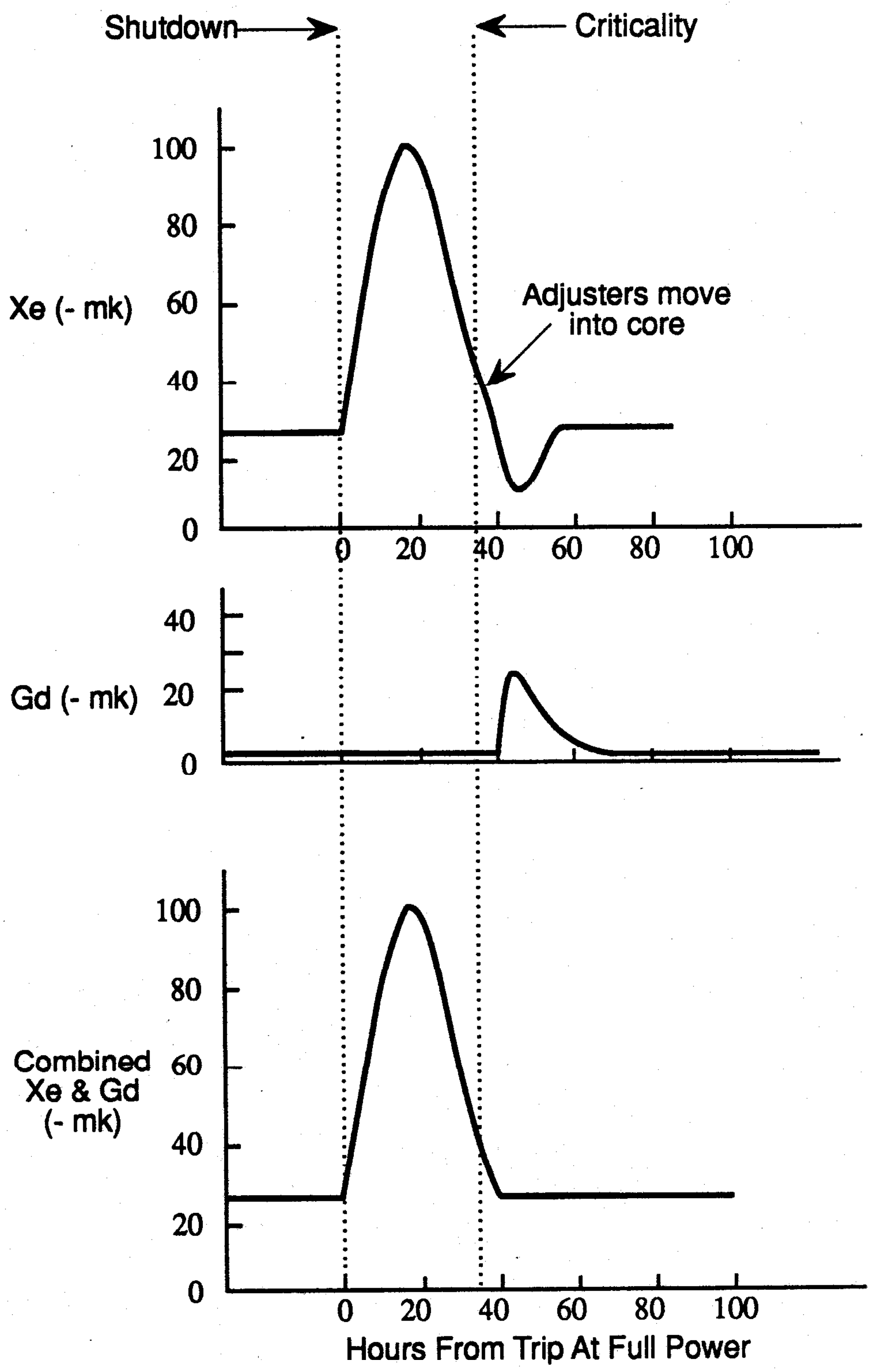


Figure 4.3 **Gd Concentration in Moderator For a Start-Up 1.5 - 3 Days After A Shutdown**

Monitoring and Control

⇔ Obj. 4.2

Manual addition of poison to the moderator is usually done from the control room, although it can also be added from the field. To monitor and control poison addition, the control room operator has four general indications:

The position of the handswitches for the motorized valves on the liquid poison addition lines, downstream of the mixing tanks;

Liquid poison flow rate, from the flow transmitter;

Poison tank level, from the level transmitters with backup from the level gauges in the field; and

Average liquid zone response to the poison addition.

To ensure that the correct amount of poison has been added for conditions requiring poison, there are two sources of information generally available:

1. Ensuring that the average zone level is in an acceptable controlling range for RRS if operating, and
2. Sampling the moderator system for poison concentration using chem lab analysis when shutdown.

⇔ Obj. 4.3 a)

When poison is added while the **reactor is critical**, for any of the reasons listed in Objective 4.1 such as, initial startup with fresh fuel, fuelling, or a xenon transient, it is appropriate to **monitor the average zone level**. This will determine if it is necessary to add or remove poison to ensure the zone levels remain in an acceptable controlling range.

⇔ Obj. 4.3 b)

During an **extended outage** or **guaranteed shutdown state**, to ensure that the poison level is appropriate, it will be necessary to **sample the moderator system for poison concentration** using **chem lab analysis**. Since the zones are no longer controlling in this state and the reactor is deeply subcritical, zone level will no longer indicate poison level.

Chem lab sampling will give a good indication of the actual poison concentration available since only slight irradiation of the poison has taken place. However, when the poisons are irradiated, the neutron absorbing isotopes burn out. The chemical concentration of poison will no longer be related to the mk worth of the poison. Thus sampling during a xenon transient or fuelling reactivity banking, will not clearly indicate whether sufficient poison is in the moderator to provide the mk worth required. Figures 4.4 and 4.5, indicate how poison concentration and poison mk worth vary with irradiation time. Figure 4.4 shows the variation of boron mk worth and boron chemical concentration with irradiation time. Figure 4.5 shows the same variations for Gd.

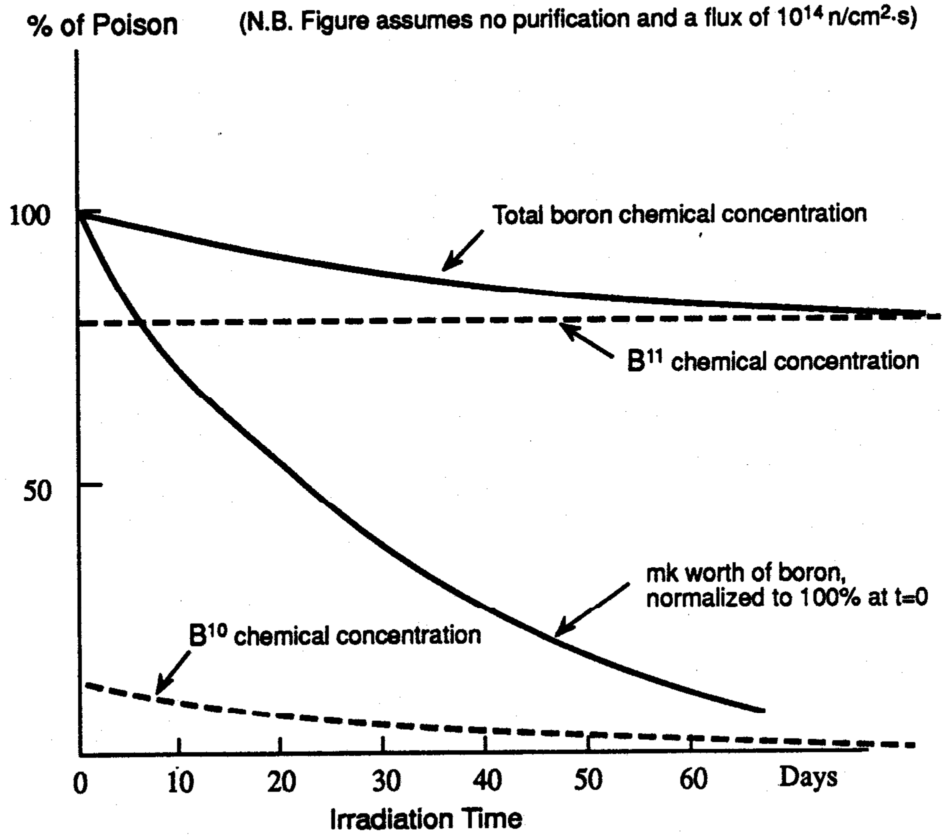


Figure 4.4 Variation of Boron mk Worth and Boron Chemical Concentration with Irradiation Time

Obj. 4.4 ⇔

* This program is known by different names at the various stations, eg. RRSSLO, RCS.

Most plants provide an automatic gadolinium addition feature, where the reactor regulating system regulates the poison addition. This is done automatically by the slow program of RRS* to **control reactor power during a slow uncontrolled increase in reactor power.** The automatic addition feature is intended to bring the reactor back into the controlling range after the zones have filled and the absorbers have been inserted.

At some stations, automatic poison addition may also be initiated if the pressurizer level is low shortly after moderator cover gas pressure becomes high (this is indicative of a possible pressure tube failure).

There is no automatic addition feature for boron. It must be added manually.

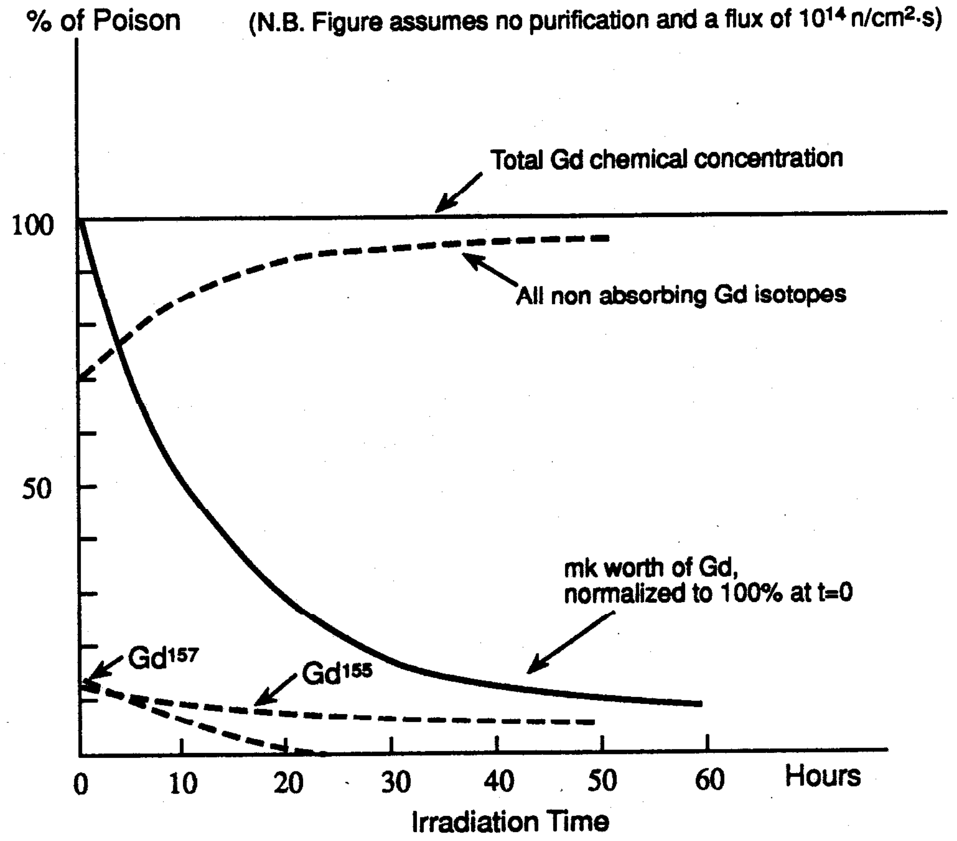


Figure 4.5 **Variation of Gadolinium mk Worth and Chemical Concentration with Irradiation Time**

Abnormal Operational Situations

There are five unusual operational situations for the moderator liquid poison system which will be discussed.

Inadvertent poison addition at full power

⇔ *Obj. 4.5 a)*

When poison is added inadvertently, the following effects of major concern to operation of the unit are likely to occur:

i) **Loss of normal zone control** – the liquid zones will drain to remove light water, a neutron absorber, to compensate for the poison addition. This may lead to other reactivity device movement to compensate for zone draining or loss of spatial control if the adjusters do not drive out;

NOTES & REFERENCES

ii) **Exceeding poison licensing limit** – an upper limit to the moderator poison load at high power and equilibrium conditions exists, to prevent excess positive reactivity from occurring due to voiding in the heat transport system;

iii) **Poison outage** – if the amount of negative reactivity added cannot be compensated for, a forced outage will occur.

Inadvertent poison removal at full power

Obj. 4.5 b) ⇔

When poison is removed inadvertently from the moderator, the **average zone level will rise** to compensate for the poison removal. When the zones fill, absorbers will drive in for further negative reactivity to bring the zones back into control. If more poison is still removed, RRS, in most units, will automatically add gadolinium to insert negative reactivity. Even though power is controlled, a unit upset will result from this event.

Inadvertent poison removal at startup

Obj. 4.5 c) ⇔

With inadvertent poison removal during startup, the reactor will **reach criticality much faster than** normally **expected**. Power again would eventually be controlled, with a unit upset resulting.

Boron use where gadolinium preferred

Obj. 4.5 d) ⇔

Gadolinium is generally preferred for short term effects such as replacement of xenon poison effects. The use of boron instead, would increase the **poison removal time.** The burnup time for boron is much longer than for gadolinium increasing its removal by this method. Boron removal by the purification IX columns is slower and requires more IX columns* which in turn is **more costly.** In fact, purification should be available and in service when boron is inserted. With gadolinium, it is not as important to have the purification system operating as burnup will occur more quickly than with boron.

* Boron removal by purification IX is discussed in Module 5 in more detail.

Poison Unavailability

Obj. 4.5 e) ⇔

With the liquid poison addition system unavailable, the **normal full power poison addition situations** discussed previously, would **be handled with increased difficulty**. Where Boron addition is unavailable, it becomes difficult to compensate for extra reactivity from fresh fuel or fuelling ahead. Where Gadolinium addition is unavailable, it becomes difficult to compensate for xenon following a xenon transient. Unit operation at full power would most likely continue, but replanning of the operating strategy may be necessary.

SUMMARY OF THE KEY CONCEPTS

- Boron is added to the moderator, prior to initial startup when the reactor contains fresh fuel. It may also be added during fuelling, or during overfuelling. Boron has a slower burnup rate, which closely matches the fuel burnup rate and fission product buildup. Poison is necessary to compensate for extra reactivity of fresh fuel.
- Gadolinium is added for extended outages because its removal is faster. Poison is necessary to keep the reactor subcritical and compensate for the loss of xenon.
- Following startup after a poison outage and, after a large increase in power following sustained operation at a lower power level, gadolinium is added since it burns up at about the same rate that xenon builds up. Poison is required to compensate for the lack of, or reduced xenon levels in the fuel.
- When poison is added manually, the control room operator can monitor and control the position of the handswitches for the motorized valves on the liquid poison addition lines, as well as monitor poison flow rate, poison tank level, and average liquid zone response to the poison addition.
- To ensure the proper amount of poison has been added when the reactor is critical, the average zone level should be monitored. During an extended outage, or guaranteed shutdown state, the moderator system poison level should be sampled using chem lab analysis.
- Gadolinium is added automatically by RRS, in most units, to control reactor power during a slow uncontrolled increase in reactor power.
- If poison is inadvertently added, the major effects on unit operation are:
  - loss of normal zone control;
  - exceeding poison licensing limit;
  - poison outage.
- If poison is removed inadvertently at full power, the average zone level will rise. A unit upset may result from this event.
- If poison is removed inadvertently during startup, criticality may occur much faster than normally expected, with a unit upset again possible.
- If boron were added when gadolinium was the preferred poison, the poison removal time would increase substantially because of a longer IX removal time and longer burnup time. Increased cost of removal is also a concern.

NOTES & REFERENCES

- If a poison unavailability occurs, the normal full power poison addition situations could not be handled, which may affect operating flexibility.

Page 15 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. Complete the following chart for poison addition.

Application	Poison	Why Chosen	Why poison required
Extended outage.			
Overfuelling (reactivity shim control)			
Prior to initial startup when unit contains fresh fuel.			
Startup after a poison outage.			
Large increase in power following sustained operation at lower power level.			
Fuelling			

NOTES & REFERENCES

2. When poison is added manually, the control room operator can use the following indications to monitor/control poison addition:

   a) ____________________________

   b) ____________________________

   c) ____________________________

   d) ____________________________

3. a) How does one ensure that the proper amount of poison is added when the reactor is critical?

   ____

   ____

   b) How does one ensure that the required amount of poison is added during an extended outage or a guaranteed shutdown?

   ____

   ____

4. Why is there an automatic gadolinium addition feature?

   ____

   ____

5. a) State two reasons why poison unavailability is a concern?

   i) ____________________________

   ii) ____________________________

   b) What is the main concern for inadvertently removing poison during startup operation?

   ____

   ____

   c) State one concern for inadvertently removing poison during full power operation.

   ____

   ____

   d) What are two main concerns for using boron poison when gadolinium is preferred?

   i) ____________________________

   ii) ____________________________

e) State 3 consequences of inadvertent poison addition during full power operation:

i) ______________________________

ii) ______________________________

iii) ______________________________

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

Prepared by:	D. Bieman
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 5

THE MODERATOR PURIFICATION SYSTEM

OBJECTIVES:

After completing this module you will be able to:

5.1 a) State three reasons why it is important to maintain moderator purity. ⇔ ***Page 2***
    b) State three ways in which moderator purity is controlled. ⇔ ***Page 2***
    c) Describe the term 'purification half life'. ⇔ ***Page 3***
    d) State the primary control for the rate of gadolinium poison removal. ⇔ ***Pages 3-4***

5.2 Explain the reason why a multistage ion exchange technique is required for boron removal. ⇔ ***Page 5***

5.3 State three reasons why boron or gadolinium should be removed when their reactivity effects are no longer required. ⇔ ***Page 6***

5.4 State how each of the following moderator purification parameters is maintained:

    a) Purification flow, ⇔ ***Page 6***
    b) Ion exchange inlet temperature, ⇔ ***Page 7***
    c) Purification pressure, ⇔ ***Page 7***
    d) Conductivity. ⇔ ***Page 7***

5.5 State the indicated number of significant operating consequences for each of the following situations:

    a) High purification flow (2), ⇔ ***Page 7***
    b) Low purification flow (1), ⇔ ***Page 7***
    c) High purification system inlet temperature (2), ⇔ ***Page 7***
    d) IX column differential pressure high (1), ⇔ ***Page 7***
    e) Continued use of spent resin for purification (1), ⇔ ***Page 8***
    f) Use of a saturated boron column for boron cleanup (1), and ⇔ ***Page 8***
    g) Escape of resin into the main moderator system (1). ⇔ ***Page 8***

5.6 State the reason why the moderator purification system must be isolated during unit overpoison guaranteed shutdown state. ⇔ ***Page 8***

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The purification system maintains the purity of moderator heavy water within specified limits by removing dissolved ions and suspended material. How the system performs this function as well as its limitations are discussed in the following major topics:

- Normal system operation;
- Operation during unit guaranteed shutdown state.

NORMAL SYSTEM OPERATION

In this section, you will learn about methods used to remove moderator impurities. Three modes of system operation described are:

- Normal cleanup;
- Gadolinium removal;
- Boron removal.

Finally, important operating parameters that must be maintained in any of the above modes of operation will be discussed. A simplified pullout diagram of a typical system, Figure 5.1, is placed at the module end showing the main components and system flow.

Moderator Purity

Obj. 5.1 a) ⇔

Corrosion products, as impurities to the system, appear as suspended material and dissolved ions. Ions may also be purposely added as neutron absorbing poisons for reactivity control or shutdown. Over the long term, the function of the purification system is to keep the moderator D_2O relatively free of foreign material to ensure: D_2 explosion hazard is minimized by **reduced radiolysis, low corrosion,** and **low neutron absorption.**

Obj. 5.1 b) ⇔

This function is accomplished in three ways by:

1) **controlling pH,**
2) **using strainers and filters,**
3) **using ion exchange columns.**

The **pH** is maintained around 7*, mainly to ensure that moderator poisons do not precipitate out of solution, but also to minimize corrosion of stainless steel components.

* A pH of 7 is neutral on the acid-base scale. More information is available on pH in the 224 course.

There are **strainers** situated on the inlet and outlet of the ion exchange columns are shown in Figure 5.1. They will remove particulate material that may be in the system, especially any resin fines. Some stations have a **filter** at the inlet to the purification loop as well, to collect any corrosion products or suspended material.

The **ion exchange columns** will remove soluble impurities to reduce conductivity as discussed under the heading "conductivity", on page 8. These are usually mixed bed resins removing positive and negative ions (anions and cations).

Modes of System Operation

Removal of gadolinium and boron may employ strong acid/strong base resins as well as different removal techniques. Because of the fact that gadolinium forms strongly charged ions in solution, these are easily attracted to ion exchange columns. Boron, however, forms weakly charged ions in solution which are not as easily removed by ion exchange columns.

Normal Cleanup

To ensure that the ion exchange column removes all ions during normal cleanup, the specification of overall conductivity is monitored. Some specific ions* of concern are also monitored including chloride, nitrate, gadolinium, and radionuclides. Continuous flow through one IX column is adequate to maintain these specifications. The actual flow rate varies from station to station but is most often in the 5 to 7 kg/s range per column. Exceeding this may lead to resin damage and subsequent dispersal of resin fines into the moderator system. If increased flow is required for cleanup, an additional column must be valved into service.

* Ions and concentration may vary, depending upon the station.

A normal cleanup IX column will not be very efficient in removing boron, but will remove any of the above mentioned ions.

Gadolinium Removal

⇔ ***Obj. 5.1 c)***

Gadolinium, being a strong ion, is easily removed by the IX resin. For strong ions, the concept of **purification half life** applies. This term refers to the time required to reduce the ion concentration to one half of the starting value. The time for gadolinium cleanup half life will depend upon the purification flow rate and the total mass of the moderator D_2O. For any unit, the **only normal variable is purification flow rate**, which in turn is dependent upon the number of columns in service.

⇔ ***Obj. 5.1 d)***

Figure 5.2 is a typical curve showing gadolinium concentration versus time for different purification flows. The time to reduce the initial concentration to one half is indicated as purification half life for different purification flows. Of course, to increase the purification flow significantly, the number of parallel IX columns in service must also increase.

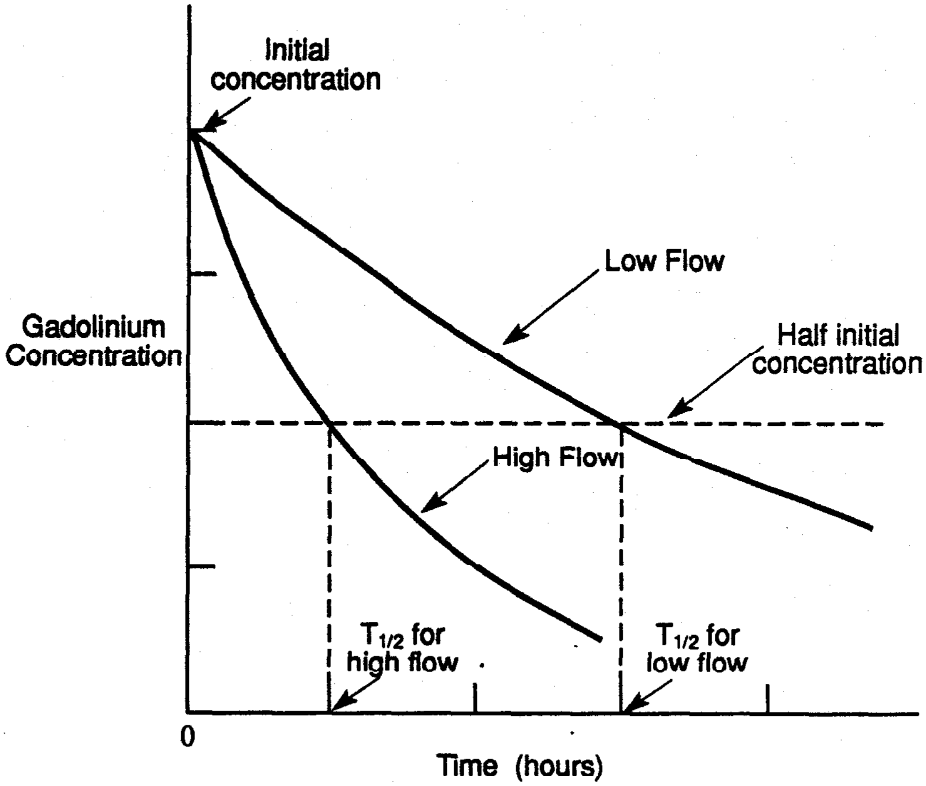


Figure 5.2 Typical Moderator Purification Half Life For Different Purification Flows.

When the poison injection system operates to shut down the reactor, it inserts as much as 600 mk of negative reactivity into the moderator. For example, with a flow rate of 20 kg/s, one cleanup half life will take about 3 1/2 hours. Five half lives will reduce the gadolinium to -19 mk.* Five half lives would take 17 1/2 hours at this flow rate. This cleanup time is too long to prevent a poison outage. However, when this cleanup time is combined with the time to repoise SDS2, 40 to 45 hours will have elapsed. This is enough time to allow the xenon to decay to startup levels.

* Total poison and xenon negative reactivity must be -28mk or -45mk with adjuster removed.

When gadolinium has been added for xenon simulation, the burnup rate closely matches the rate at which xenon reactivity builds up, so that purification removal is not initially required. Gadolinium poison concentration naturally decreases in neutron fields, with a burnout half life of about 8 hours initially, and longer as the largest cross section isotope burns up. Any imbalance between the two rates will be detected by a rise or fall of the average zone level. When the poison has burned out and xenon has built up to its normal level, the gadolinium isotopes must be removed by normal cleanup to keep the moderator D_2O conductivity within specification.

Boron Removal

Because boron forms a weak ion in solution, its removal is more difficult and time consuming. The removal rate depends upon the difference between the boron concentration in solution and the boron concentration in the IX column. An IX column removing boron from the moderator will, over time, form an equilibrium with the boron in solution, so that no further boron can be removed. The column is said to be **saturated or borated.** In the same way, an IX column with a boron concentration higher than that of the moderator will form an equilibrium concentration with the solution and give off boron to the moderator water. Establishing equilibrium concentrations with the solution only occurs with weakly ionized substances and does not occur when a strong ion, such as gadolinium, is attached to an IX column.

⇔ Obj. 5.2

Because boron (B) establishes a equilibrium concentration with the solution, it is removed from the moderator in a **multistage IX technique** using 2 or 3 IX columns operating on different moderator boron concentrations. An example of this would be a two stage removal of 3mg B/kg D_2O or 28 mk worth. One column may reduce the concentration down to 0.5 mg B/kg D_2O at which point it becomes saturated. The column is then isolated and a fresh column is used for the second stage of boron removal to reduce the boron concentration further. This column is then used the next time for first stage boron removal, to maximize the use of the resin. A general rule of thumb for boron removal is that a fresh IX column will leave at least $^1/_7$th of the original boron concentration after the column saturates.

Thus the rate of Boron removal cannot be determined by the normal half life curve of Figure 5.2, since there are other factors beside purification flow rate and total mass of moderator D_2O. Boron removal capacity of the IX columns is also sensitive to temperature. An increase of a few degrees in the IX column will lower the equilibrium concentration in the IX column, reducing its capacity for boron. In fact, it may even release boron from the resin.

Boron concentrations decrease slowly in neutron fields, with a burnout half life of 15 to 20 days depending upon reactor flux. Because of the long burnout time period, IX columns may be required to remove boron. Normal cleanup is required when boron is burned out to reduce the conductivity effects on the moderator.

Obj. 5.3 ⇔

If **boron or gadolinium** are kept in the moderator when their **reactivity effects are no longer required**, additional positive reactivity must be provided to counter the poison effects. The **normal reactivity control span** of the average liquid zone level may **not** allow the zones to **accommodate all reactivity effects.** Keeping gadolinium in the moderator when it is no longer required will **also keep the conductivity high, contributing to increased radiolysis products**. The third concern is **financial.** Fuel costs increase when operating with extra poison.

Operating Parameters

In this section, four important parameters that characterize system operation, are discussed:

- Purification flow,
- Inlet temperature,
- Pressure,
- Moderator conductivity.

For each of these parameters, you will learn how it is maintained and what adverse consequences occur when this parameter goes beyond its limit.

Purification Flow

CANDU stations use a bypass flow purification system around the moderator circulating pumps as shown in Figure 5.1.

Obj. 5.4 a) ⇔

Usually, the purification inlet is downstream from the moderator heat exchanger discharge. The **moderator pump differential pressure** is used as the **driving force for the purification loop**. Typically 4 to 6 columns are available for use in parallel. The extra columns allow for slurrying of resin from a spent column while purification is ongoing. The number of columns in service depends on the poison removal requirements.

Typical purification flows range from 5 to 25 kg/s, depending upon the number of IX columns in service (and station). Exceeding recommended flow rates can lead to resin damage. An individual column inlet motorized valve is the isolation for the column.

NOTES & REFERENCES

In some stations, it has been found that with **high flows**, the quantity of resin fines increase due to mechanical breakdown. The fines can be carried through to the **IX discharge strainer** and cause it to **clog**. The ion **exchange process is** also **less efficient** at higher flows.

⇔ Obj. 5.5 a)

Low purification flow would take a **longer time for moderator cleanup**. In fact, for very low flows, the **rate** at which **impurities are produced may exceed the purification rate** so that even though purification is occurring, the impurity level may be increasing.

⇔ Obj. 5.5 b)

Inlet Temperature

⇔ Obj. 5.4 b)

⇔ Obj. 5.5 c)

Most stations take advantage of the **cooling provided by the moderator heat exchanger.** The purification inlet is downstream of the main moderator heat exchanger outlet. IX resins are temperature sensitive. They should be kept below about 60°C to **prevent damage and subsequent release of contaminants** such as chlorides, boron, and gadolinium. Borated IX columns are particularly sensitive to temperature changes when they are at equilibrium with the moderator D_2O. A **small temperature increase can release boron poison into the system.** Typical purification inlet temperatures are 30°C to 35°C.

Pressure

⇔ Obj. 5.4 c)

⇔ Obj. 5.5 d)

The moderator purification **pressure** is **maintained** by the **moderator circulation pumps.** The pump differential pressure is at least 650 kPa with the pressure reduced at the calandria by flow restricting devices. Since a typical system purification pressure drop is about 400 kPa, the pump differential pressure will provide sufficient pressure for an adequate flow. When the ΔP across an individual strainer (filter) **increases, this component requires changing or cleaning.** If they are not changed, the **flow will gradually decrease** until no purification flow occurs.

Conductivity

⇔ Obj. 5.4 d)

Moderator conductivity is a measure of the concentration of ionic impurities. It is **monitored by in line conductivity cells and by chem lab sampling.** Conductivity must be kept low because as dissolved impurities increase, the natural rate of D_2 and O_2 recombination decreases. In addition, increased neutron absorption and possible corrosion will result.

NOTES & REFERENCES

The conductivity is usually kept below 0.1 mS/m by continuous IX purification. An increase in moderator conductivity normally indicates spent IX resin in the column. Other methods which may identify that an IX column is spent are:

- Checking for high ΔP across the IX column (plugging),
- Observing average zone level reduction (boron leaching from resin),
- Checking for increased chloride readings at the column outlet.

Obj. 5.5 e) ⇔

The **continued use of spent resin** for purification **will result in increased conductivity at the outlet which in turn can cause a D_2 excursion.** This is because impurities are not removed or further impurities may be released from the resins. Other ways of detecting spent resin are indicated above.

Obj. 5.5 f) ⇔

Continued use of a **saturated boron column will not reduce the boron content further**. In fact, as ionic impurities replace the loosely bonded boron, more **boron poison and contaminant is released** to the system.

Obj. 5.5 g) ⇔

Another contributing factor to conductivity is **resin fines escaping into the main moderator system.** If not removed, they will increase conductivity by releasing ions to solution. Increased conductivity results in increased radiolysis products, producing a higher D_2 concentration and possible **D_2 excursion.** If D_2 levels in the cover gas are high, an explosion hazard may exist prompting a unit shutdown.

System Operation During Unit Guaranteed Shutdown State

Obj. 5.6 ⇔

One method of placing the reactor in the guaranteed shutdown state is by adding an excess of neutron absorbing poison to the moderator to ensure that the reactor will not reach criticality. During this state, the **moderator purification system must be isolated** as part of the guaranteed shutdown state. This is to **ensure** that the **poison** will **not be removed inadvertently.**

SUMMARY OF THE KEY CONCEPTS

- Moderator purity is maintained to minimize radiolysis products, corrosion, and neutron absorption. Moderator purity is controlled by neutral pH control, strainers and filters, and ion exchange columns.
- Purification half-life refers to the time required to reduce the ion concentration to one half of its original value.
- Gadolinium removal depends upon purification flow rate.
- Boron is removed in a multistage technique because ion exchange columns easily saturate with boron.
- Boron or gadolinium should be removed when they are no longer required because the normal reactivity control span may be affected. Gadolinium nitrate contributes to the conductivity which in turn causes increased radiolysis products. Both poisons can produce increased fuel costs.
- Flow is maintained by using the main moderator circulation pump ΔP as the driving force for the purification loop. High purification flows result in a less efficient exchange process and may damage resin leading to plugged strainers or filters and increased impurities in the moderator. Low purification flow may not remove impurities as fast as they are formed.
- Ion exchange inlet temperature must be controlled to ensure high inlet temperature does not damage the resin. Boron removal columns are particularly sensitive to boron release when temperature is increased.
- Purification pressure is maintained by using the main moderator pump discharge pressure and monitoring the ΔP across components in the purification loop. High ΔP will result in reduced purification flow.
- Low conductivity is maintained by the IX columns. Outlet conductivity and other parameters are sampled by the Chem Lab to determine if the column is spent. Continued use of a spent resin will result in increased outlet conductivity. Other indications of a spent resin include reduced IX flow (damaged resin), decreasing zone levels, or increased chloride levels. Continued use of a saturated boron column may release more boron into the system as it is displaced by stronger ionic impurities on the column.
- Resin escape into the moderator may contribute to cover gas D_2 excursions.

NOTES & REFERENCES

- The moderator purification system is isolated as part of the overpoisoned guaranteed shutdown state to ensure the poison will not be removed inadvertently.

Page 11 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. a) State three reasons for keeping moderator water pure?

i) ______________________________

ii) ______________________________

iii) ______________________________

b) Indicate three ways moderator water purity is maintained.

i) ______________________________

ii) ______________________________

iii) ______________________________

2. How would you increase the rate of gadolinium removal?

____

3. Why is a multistage technique required for boron removal?

____

____

____

4. Why should boron or gadolinium be removed when their reactivity effects are no longer required?

____

____

____

5. a) How is purification flow maintained?

____

b) What are two consequences of high purification flow?

i) ______________________________

ii) ______________________________

c) What is the consequence of low purification flow?

____

6. a) How is the ion exchange inlet temperature maintained?

____

b) What are three consequences of a high purification inlet temperature?

i) ______________________________

ii)______________________________

iii) ______________________________

7. a) What provides the driving force for flow through purification?

____

b) What is the consequence of high differential pressure across a purification system component?

____

8. a) How is low conductivity maintained?

____

b) What is the consequence of continued use of spent resin for purification?______________________________

____

c) How would you know if you valved in a boron saturated column?

____

d) What is the consequence of resin escape into the main moderator system?

____

9. Why must the moderator purification be isolated during the overpoison guaranteed shutdown state?

____

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

Prepared by: D. Bieman
Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 6

HTS HEAT SOURCES & HEAT TRANSFER PATHS

OBJECTIVES:

After completing this module you will be able to:

6.1 For each of the operating states listed below, label a power flow block diagram (given) that shows the role of the heat transport system in transporting heat energy:

- a) At full power, with rated electrical output to the grid (two major pathways); ⇔ *Pages 2-4*
- b) During poison prevent operation (major pathway only) for stations using SRV's and for stations using CSDV's; ⇔ *Pages 4-5*

The diagrams must show:

- i) Major heat sources;
- ii) Heat carriers;
- iii) Required pumps;
- iv) Heat energy transfer points;
- v) Heat sinks.

6.2 State and explain the general constraints on HT system operation for the prevention of Delayed Hydride Cracking (DHC). ⇔ *Page 6*

6.3 Explain the two major potential hazards associated with the HT system. ⇔ *Page 6*

6.4 State two hazards associated with hydrogen when the HTS is cold. ⇔ *Pages 6-7*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

We have discussed in earlier levels of this course the main purpose of the Heat Transport System (HTS), ie. to transport the heat produced in the fission process to the steam generators by means of pressurized D_2O. The general layout of the various systems in use was also discussed as well as the three basic formats of Heat Transport Systems used in current CANDU reactors. To recap, these are:

1) Double loop, with counterflow through the reactor, and pressure control by feed and bleed;

2) Double loop, with counterflow through the reactor, and pressure control by means of a pressurizer;

3) Single loop, with counterflow through the reactor, and pressure control by pressurizer.

Also noted was the use of zirconium alloy pressure tubes for neutron economy, with the remainder of the system constructed mainly from carbon steel.

An additional function of the Heat Transport System (HTS) is to provide a barrier to the release of radioactivity to the environment.

The HTS must have the capability of removing both full power heat from the reactor and the decay heat following a shutdown. In this module we will describe the pathways by which the HTS can remove the full power output from the reactor and the alternative operational state when the unit is forced into the poison prevent mode. The shutdown operational function will be discussed in a later module.

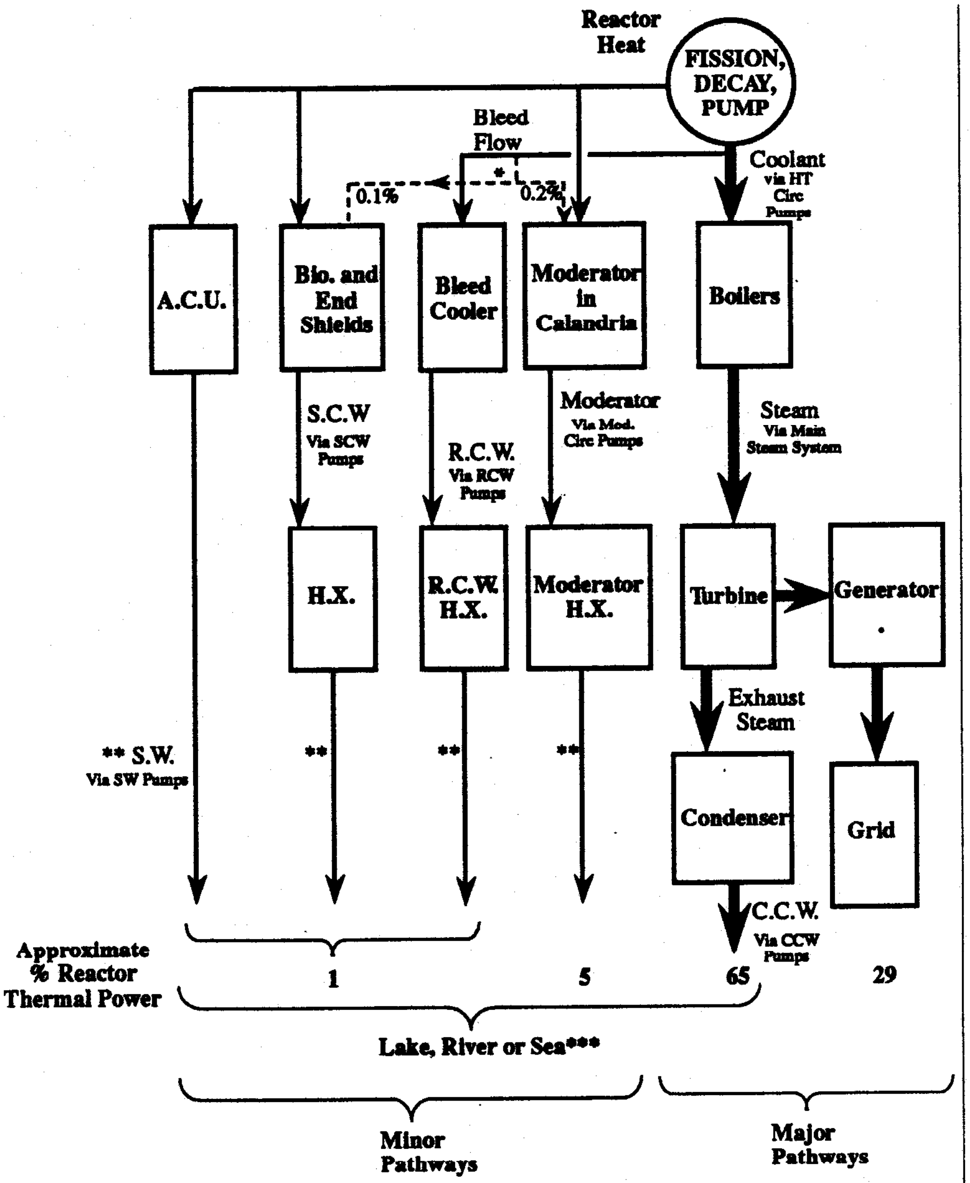
REACTOR AT FULL POWER

The approximate division of the heat produced in a CANDU reactor at full power is:

Heat from the fission process	~ 92-93%
Heat from the fission products	~ 6-7%
Heat from the HTS pumps	~ 1%

Obj. 6.1 a) ⇔

At full power, the heat from the above sources is transported by the HTS coolant (D_2O) to the boilers where the feedwater inventory, being converted into steam, provides the main intermediate heat sink (Fig. 6.1).



Key	
A.C.U.	Air Cooling Unit
S.W.	Service Water
S.C.W	Shield Cooling Water
R.C.W	Recirculated Cooling Water
C.C.W	Condenser Cooling Water

* Some channel heat will be transferred to the moderator and end shields by conduction and radiation.

*** An additional heat exchange is required for cooling to the sea, ie. Recirculated Cooling Water to Raw Sea Water

Figure 6.1 Full Power Heat Removal Chain

Steam produced in the boilers provides the driving source for the turbine generator. About **30%** of the energy **leaving the boilers** will be converted to **electrical energy** for the grid during normal operation. The remaining **70%** of the steam's thermal energy is transferred via the condenser and condenser cooling water (CCW) to the **lake, river or sea.** Note, this energy (heat) is released as the exhaust steam from the turbine is reconverted to a liquid state.

There are also other pathways, all ultimately ending at the lake (river or sea), for various auxiliary systems. As seen in Fig. 6.1, most of these pathways do not remove a large amount of heat ("minor pathway"). The only significant "minor pathway" auxiliary system is that for the moderator, which accounts for approximately 5% of reactor power output. Recall that this heat is generated by a combination of thermalizing neutrons and absorbing γs from fission, fission products, and activated core components.

Note that these "minor" heat paths will not be shown in subsequent diagrams although you should assume that they are still available for heat removal unless otherwise specifically stated.

The various shield systems at different locations (End and Biological/Thermal) have been lumped into a single category.

The circulation of the various heat transport mediums, such as Condenser Cooling Water (CCW), Recirc. Cooling Water (RCW), etc., requires the operation of circulating pumps for the overall heat transport mechanism to remain viable. The heat transfer diagrams shown in this module, and subsequent modules, will assume the correct ("normal") operation of various pumping sources.

POISON PREVENT MODE

Obj. 6.1 b) ⇔

This mode of operation is especially useful when steam flow to the turbine is lost with the reactor at power (eg, on a turbine or generator trip), and the prospects are good for returning the turbine generator to service within a few hours. As an alternative to a unit outage, this mode is used to prevent the reactor from poisoning out * due to higher than normal xenon levels.

* Recall from your Nuclear Theory course (227) that reactor power must be maintained high enough to prevent a poison outage.

Clearly, the **steam** must **be discharged elsewhere** in order to keep the boiler heat output via the steam equal to the heat input from the coolant (Fig. 6.2). At some stations, the steam is discharged to atmosphere via **Steam Reject Valves** (SRVs); at other locations, the steam is discharged directly to the condenser via **Condenser Steam Discharge** (Dump) **Valves** (CSDVs). The SRVs are rated for 100% full power and CSDVs are rated for 75-100% full power.

Ideally, reactor power could be maintained at full power to be absolutely certain that a poison outage does not occur. In practice, **reactor power**, hence steam flow, is **maintained** at the minimum - about **60% to 70%** - at which the Xe transient can be overridden. The reasons for operating at reduced power are as follows:

1) At stations using SRV's - to conserve feedwater, which is being lost to the atmosphere.
2) At stations using CSDV's having condensers with limited thermal capacity - to avoid overloading the condenser and excessive piping vibrations (note that some stations have condensers with 100% full power capacity).
3) Economic savings due to lower fuel and fuelling costs

Figure 6.2 a) depicts the Poison Prevent heat transfer chain for stations using SRV's. The coolant transports fuel and pump heat to the boiler, and steam transports the heat from the boiler to the atmosphere via the SRVs.

Figure 6.2 b) depicts the corresponding process at other stations. Steam transports the heat from the boiler to the condenser via the CSDVs, and the CCW transports the heat from the condenser to the lake, river or sea, depending on the station.

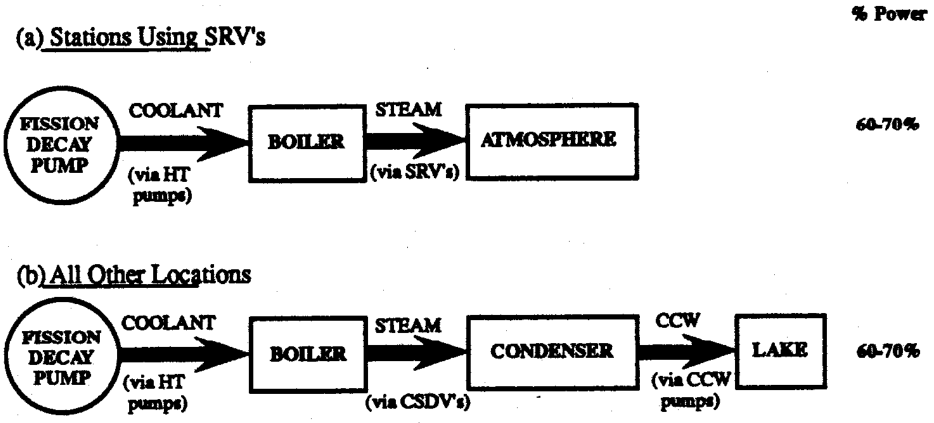


Figure 6.2
Poison Prevent Mode Heat Removal Chain

DELAYED HYDRIDE CRACKING

The movement between various reactor operating states is carefully controlled and is detailed in the various station operating manuals. One general constraint imposed on HT system operation between states is concerned with Delayed Hydride Cracking (DHC).

The phenomena of DHC has been discussed in detail in the 228 Materials course. In this course we will address only the general methods adopted to minimize the onset of DHC in the pressure tubes.

Obj. 6.2 ⇔

Experience indicates that the problem is essentially temperature/stress related. The highest risk is present when HTS temperatures are in the area **~100-200°C**. Operating procedures are, therefore, designed to **avoid operation** in this area and also to **pass through** this temperature band as quickly as possible (and in a continuous manner) both during heatup and cooldown of the unit. To further limit stress levels, this transition may also occur at pressures lower than normal operating pressure.

HAZARDS

Obj. 6.3 ⇔

The heat transport system is normally operated at **high temperature and pressure** and, therefore, has all the **"conventional"** hazards due to these effects.

In addition there are **radiation hazards** generated as a result of reactor operation. These include both activation and fission products. These materials are then distributed throughout the system resulting in:

a) Contaminated D_2O containing:

   i) Tritium;
   ii) Fission products as a result of any fuel failures or "tramp" uranium on fuel bundles;
   iii) Activation products.

b) Contaminated surfaces due to:

   i) Plating out of activation products;
   ii) Crud deposits;
   iii) Collection in IX columns and filters.

Contaminated D_2O is a significant hazard when leaks or spills occur, when the system is opened, or when adding or removing coolant.

Contaminated surfaces are hazardous when working with an open, drained system or during component maintenance.

In addition, when at power, there is a danger of elevated gamma and neutron fields around the system components (due to N^{16} and O^{19}).

Hydrogen Hazards When Cold

Obj. 6.4 ⇔

The necessary addition of **hydrogen gas** * to the system when operating can cause two major **problems when the system is cold:**

* More detail about hydrogen addition is given in Module 10

a) **Hydrogen embrittlement** of the zirconium alloy components - fully discussed in the materials course (228).

b) All the hydrogen related **explosion hazards** as the hydrogen comes out of solution following system depressurization. This is of particular concern if the system is to be opened for repairs. This is why the hydrogen addition system is isolated before the unit is depressurized during a shutdown. Purging, etc, may be required particularly if welding operations are to be undertaken.

These two problems require that H_2 additions to the HTS be limited to that required to maintain the system specifications for H_2 concentrations.

SUMMARY OF THE KEY CONCEPTS

- The two major heat removal pathways at full power are power output to grid and rejection of heat to the lake (river or sea).
- For poison prevent operation the major heat removal path is via the steam rejected directly to the condenser or to the atmosphere.
- The general operational method to combat DHC in pressure tube components is to avoid operation with the HTS in the temperature range 100°C-200°C and pass through this range quickly and continuously when required to do so.
- The HTS has potential hazards from both conventional and radiological sources.
- H_2 increases the risk of hydrogen embrittlement of zirconium alloy components when the HTS is cold. H_2 poses an explosion hazard as it comes out of solution when the HTS is cold and depressurized.

You can now **work on the assignment questions.**

⇔ ***Page 9***

ASSIGNMENT

1) For each of the operating states listed below, label the power flow block diagram that show the role of the HTS in transporting heat energy.

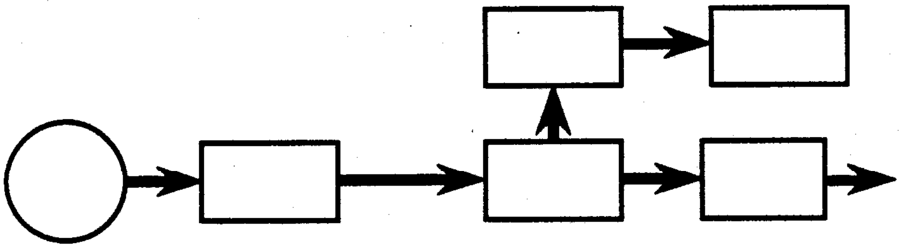
   a) At full power, with rated electrical output to the grid (two major pathways),

   b) During poison prevent (major pathway only), for a station using CSDV's and for a station using SRV's.

   The labels must show:

   i) Major heat source,
   ii) Heat carriers,
   iii) Required pumps,
   iv) Heat energy transfer points,
   v) Heat sinks.

Power Flow Diagram: Normal Operation - Major Pathways.



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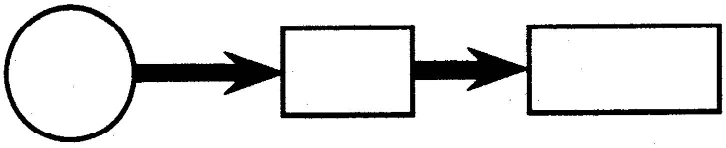
Power Flow Diagram: Poison Prevent Operation For Stations Using SRV's - Major Pathway.



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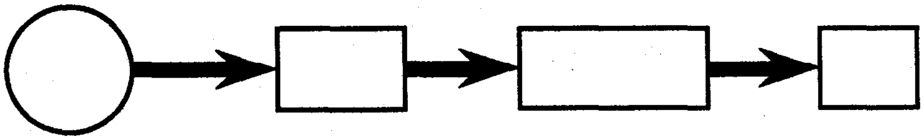
Power Flow Diagram: Poison Prevent Operation For Stations Using CSDV's - Major Pathway.



____

2) The general constraints on the operation of the HTS for the prevention of DHC (Delayed Hydride Cracking) are:

a) ______________________________

____

b) ______________________________

____

The reason for these constraints is

____

____

______________________________.

3) Explain the potential hazards associated with the HTS:

a) ______________________________

____

____

____

____

b) ______________________________

____

____

____

____

4) When the HTS is cold, H_2 causes an increased risk of ______________________ of ______________ alloy components. It also poses an ______________ hazard as H_2 comes out of solution from the HT coolant at lower temperatures (and hence, lower pressures).

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

Prepared by:	D. Tennant, N. Ritter, WNTD
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 7

HTS PRESSURE & INVENTORY CONTROL

OBJECTIVES:

After completing this module you will be able to:

7.1 Explain the concern of HT pressures that are:

- a) Too high and, ⇔ *Page 3*
- b) Too low. ⇔ *Pages 3-4*

7.2 Explain two concerns with blocked or restricted coolant paths. ⇔ *Page 4*

7.3
- a) State the three effects of boiling in the HTS and, ⇔ *Page 4*
- b) State when boiling in the HTS is permissible at some stations. ⇔ *Page 4*

7.4 State why it is necessary to have HT system pressure/inventory control. ⇔ *Page 4*

7.5 State four purposes of the feed and bleed system for units with a pressurizer while in "solid" mode pressure control. ⇔ *Pages 5-6*

7.6 State the purpose of the pressurizer during "normal" heat transport operational mode. ⇔ *Page 6*

7.7 Explain how a pressurizer maintains HT system pressure to a predetermined set point. ⇔ *Page 6*

7.8 State five purposes of the feed and bleed system for units with a pressurizer while in "normal" mode pressure control. ⇔ *Page 8*

7.9 State five purposes of the feed and bleed system for units without a pressurizer. ⇔ *Page 8*

7.10
- a) Explain the three reasons why the pressurizer level is controlled. ⇔ *Page 9*
- b) State how the pressurizer level varies with reactor power. ⇔ *Page 10*
- c) For units with a pressurizer, explain how shrink and swell are made up between cold pressurized and zero power hot. ⇔ *Page 11*

7.11
- a) Explain the two methods how feed and bleed system demands are minimized during operation on units that do not use pressurizers. ⇔ *Page 11*

Page 12 ⇔ b) For units without a pressurizer, explain how shrink and swell are made up between cold pressurized and zero power hot.

Page 12 ⇔ 7.12 a) Explain the two major purposes of the interunit D_2O transfer system.

Page 13 ⇔ b) Explain the three major purposes of the HT D_2O storage tank.

Page 13 ⇔ i) Explain two reasons that a lower operating limit is placed on the D_2O storage tank level.

Page 13 ⇔ ii) Explain two reasons that an upper operating limit is placed on the D_2O storage tank level.

Page 15 ⇔ 7.13 a) State the two methods for controlling bleed condenser pressure.

Page 15 ⇔ b) Specify which method is used as a backup and explain two reasons why it is the backup method.

Page 16 ⇔ 7.14 State the method used to control degasser condenser pressure.

Pages 17-18 ⇔ 7.15 For both types of HT system (pressurizer and no pressurizer) state the response during slow power manoeuvres, of:

a) HTS Pressure,
b) HTS Average Temperature,
c) Feed and bleed flows,
d) Pressurizer level,
e) Boiler pressure.

Page 19 ⇔ 7.16 State why it is necessary to have HT system pressure relief.

Page 20 ⇔ 7.17 Explain the concern over rapid increases in HTS pressure.

Page 20 ⇔ 7.18 State the two major causes of HTS over-pressurization and give an example of each type of over-pressurization.

Page 21 ⇔ 7.19 Explain the concern over heat sink capability reduction.

Page 21 ⇔ 7.20 a) Explain what is meant by direct pressure reduction and,

Page 21 ⇔ b) State two methods of direct pressure reduction.

Page 22 ⇔ c) Explain how each of these two methods affects HTS pressure.

Page 23 ⇔ 7.21 a) State the type of events the HTS pressure relief valves are sized for.

Page 23 ⇔ b) Explain why these relief valves are not sized to handle all types of overpressure events.

7.22 a) Explain what is meant by indirect pressure reduction. ⇔ *Page 21*

b) State how this method of pressure reduction is achieved. ⇔ *Page 22*

c) Explain how this method affects HTS pressure. ⇔ *Page 22*

7.23 Explain the concerns and possible consequences of:

a) A failed open pressure relief valve, ⇔ *Page 25*

b) A feed pump failure,

c) A steam bleed valve failed open (pressurizer system), ⇔ *Page 26*

d) Failed HT main circulation pump(s), ⇔ *Page 26*

e) Isolation of bleed condenser on high temperature. ⇔ *Page 27*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

As stated in Module 6, the primary role of the Heat Transport System (HTS) is to transport the heat generated by fission and decay heat from the reactor to the boilers, which produce steam to run the turbine generator.

The turbine requires saturated steam at a pressure of approximately 4.5 MPa. If the HT system is to remain subcooled, ie. a liquid, this means that the HTS must also be a pressurized system. Also, taking into account the ΔT required to transfer heat from the HT system to the boilers, the HTS has to be pressurized to approximately 9 to 10 MPa.

These high pressures dictate the need for a pressure control system with operating requirements which must satisfy both mechanical and nuclear concerns.

PRESSURE CONTROL

Mechanical Concerns

⇔ *Obj. 7.1 a)*

The HT system is a pressure boundary and must remain intact. Operating at a **higher pressure** than normal in the HT system increases the likelihood of a **rupture** of the HT system and thus, a **Loss Of Coolant Accident** (LOCA). A LOCA results in a loss of coolant inventory, which may also result in insufficient coolant being available to cool the fuel.

Nuclear Concerns

Obj. 7.1 b) ⇔ *Obj. 7.3 a)* ⇔ On the other hand, operating at too **low a pressure** in the system will result in excessive boiling. This inevitably would lead to **fuel overheating** either as a direct result of **film boiling** (dryout) or through **loss** of coolant **flow** in the channels caused by pump cavitation. In addition, due to the positive void coefficient, channel voiding leads to large increases in reactor power output, which will tend to further promote boiling and fuel overheating if no protective action is taken. *Obj. 7.2* ⇔ Note that excessive boiling, resulting in **fuel overheating and voiding**, can also occur at normal system pressures with **blocked or restricted coolant passages**.

Obj. 7.3 b) ⇔ Note that this requirement, ie, to avoid excessive boiling, still allows for the HTS, at most stations, to be operated at high power with a **limited** amount of boiling (nucleate boiling) occurring at the exits of some channels. Typically, in a number of channels, 3-5% boiling occurs. This improves heat transfer from the fuel and adds to the extractable heat available to the boilers.

Even at stations where limited boiling occurs at full power, it ceases once the reactor power output falls to ~<90% FP.

Obj. 7.4 ⇔ Given a totally enclosed heat transport system, **pressure** will **vary directly** with the average **temperature** of the HTS. Coolant pressure increases due to swell as the average temperature increases during reactor power increases. Conversely, pressure decreases as a result of coolant shrinkage during power reductions.

Coolant **swell and shrink** are a major phenomena. A typical unit's HTS swell may be as much as 60 m^3 on warmup with an additional 10 to 20 m^3 as power is raised from 0 to 100% full power. Given the incompressible nature of the coolant, the addition of even 1 m^3 of coolant to a non-boiling pressurized heat transport system would increase pressure significantly.

These conditions dictate the need for HTS **pressure and inventory control system.** This system ensures that there is adequate coolant at the correct conditions to remove the heat from the fuel.

HEAT TRANSPORT PRESSURE CONTROL

In the previous module we discussed the normal operational states of the HTS. Recall that it is necessary for the HTS pressure to be controlled at all power levels - from a cold shutdown condition to 100% Full Power.

We have already mentioned in this module, the relative amount of D_2O inventory changes which occur as the unit is maneuvered between 0%

full power cold and 100% full power hot and vice versa. It was also stated that the major inventory change occurred on warmup of the unit to about 250°C(approximately three times that change which occurs between 0% and 100% FP).

This latter fact is the reason why two methods of pressure control are required on most CANDU reactors, depending on the power level of the reactor.

These two pressure control methods are known as **solid mode** and **normal mode.**

Solid Mode Pressure Control

⇔ *Obj. 7.5*

Solid mode describes the pressure control of the HTS while the pressurizer is isolated (in stations using pressurizers). In this mode, **pressure control** is by **feed and bleed action**, ie. inventory addition and removal. The significance of the word 'solid' is that no compressible vapour space exists within the system to 'cushion' pressure transients (the system is totally non-boiling and the pressurizer is isolated).

With the HTS pressure at its setpoint, neither feed nor bleed action is required. If pressure rises above the setpoint, bleed action will remove inventory from the HTS and lower the pressure. Should pressure fall below the setpoint, the opposite occurs, ie. feed valve opens and inventory is added to the HTS (refer to Figure 7.1 for a simplified feed and bleed controller).

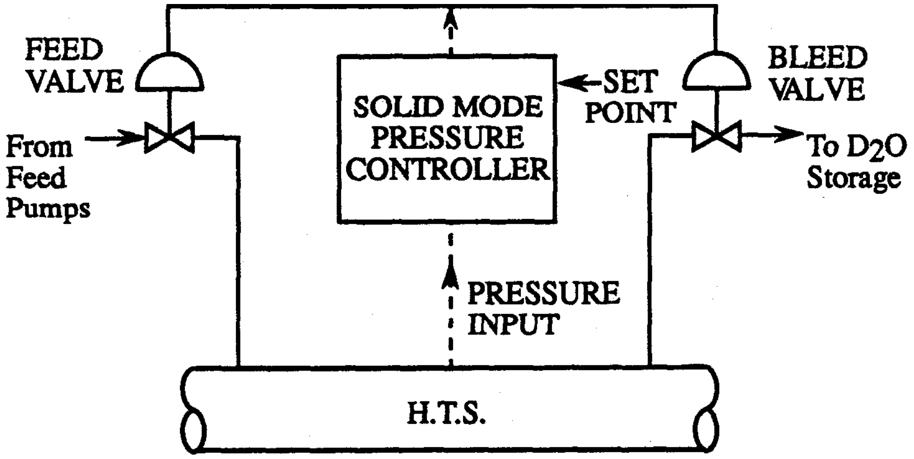


Figure 7.1
Simplified Feed and Bleed Controller

Note that during unit warmup, the bleed valve will be at or near the fully open condition to remove the swelling D_2O from the HTS. On unit cool down, the opposite will occur, ie. the feed valve will be open fully.

In practice, it is desirable to have a percentage of the HTS D_2O circulated through the **purification** system to remove crud, fission products, and impurities. The bleed valve is biased open a small amount to achieve this (except for CANDU 600, which is discussed later in the module). This will result in a drop in system pressure so the feed valve will be opened by the controller to maintain system pressure at the setpoint.

During solid mode operation, the feed and bleed system, in addition to the above, performs the following functions:

a) It supplies **D_2O to the Pump Gland Seal** Cooling System.

b) The bleed condenser (or degasser condenser in some stations) **accepts coolant discharge from the HTS** (bleed valves, HT relief valves, steam bleed valves, pressurizer relief valves, depending on the station). This ensures that this coolant is available for use when required.

During **solid mode** operation, the **pressurizer** is **isolated** from the HTS by a motorized valve. At this time, saturation conditions are established in the pressurizer at normal operating pressure by manipulation of the electric heaters and steam bleed valves (in preparation for valving into the HT system).

Normal Mode Pressure Control

Obj. 7.6 ⇔

Normal mode control is selected during "normal" operation. In this mode, the pressurizer is no longer isolated and HTS **pressure** is **controlled** by the **pressurizer** (sometimes called the surge tank).

The pressurizer is shown in Figure 7.2. It is connected to the HTS, at a reactor outlet header, by means of a large diameter pipe.

Obj. 7.7 ⇔

Heat transport system pressure is controlled by **regulating the steam pressure in the vapour space** above the liquid.

To **increase** HT system **pressure**, the steam pressure must be increased. This is achieved by switching on the **electric heaters**, thus increasing the temperature of water in the pressurizer. This causes the saturation temperature, and hence pressure to increase.

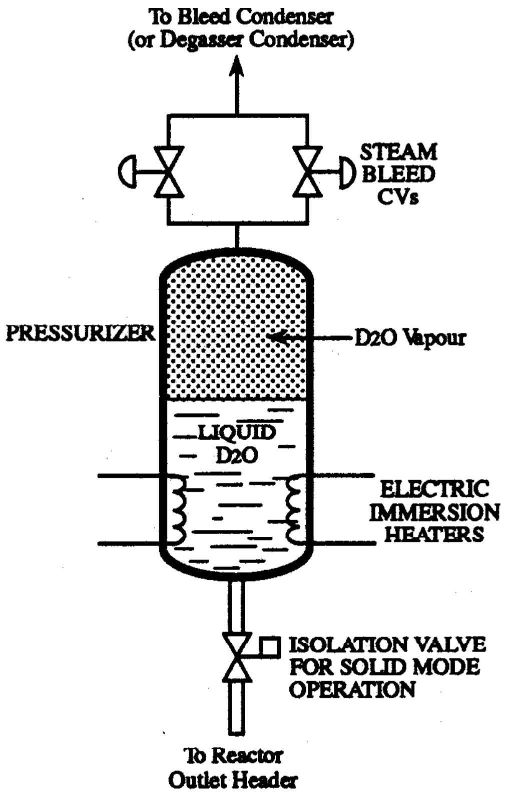


Figure 7.2
Typical Pressurizer

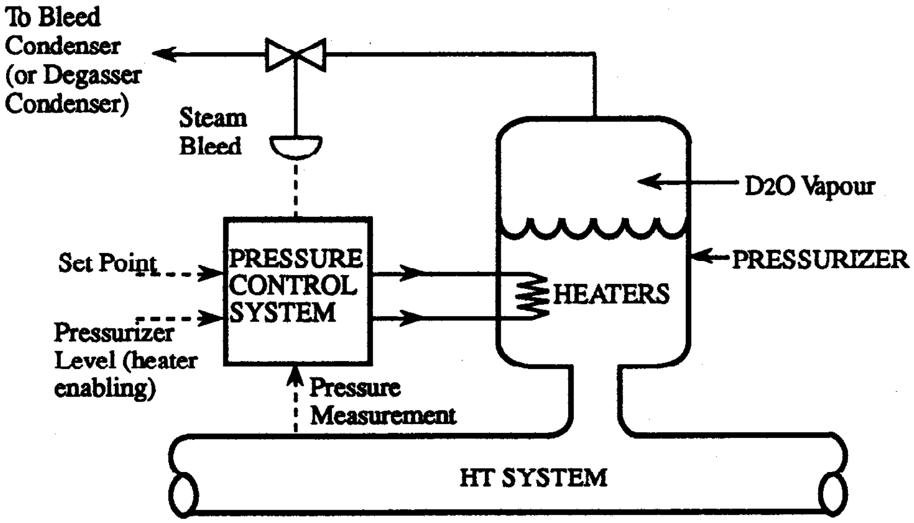


Figure 7.3
HTS Pressure Control (Normal Mode)

To **reduce HT pressure, steam** is **discharged** from the pressurizer's vapour space to the bleed condenser (or degasser condenser in some stations) via the steam bleed valves. This causes the the saturation temperature and pressure to decrease. The control system is shown in Figure 7.3.

Obj. 7.8 ⇔

During normal mode operation, the feed and bleed system doesn't control HTS pressure, but performs the following functions.

a) It adjusts coolant inventory to **maintain pressurizer D_2O level** at its setpoint (see following section on level control);

b) It returns D_2O to the system (via feed) to **make up for losses** via steam bleed valves (or degas flow in some stations);

c) It supplies cool D_2O to the **purification system** in most stations;

d) It supplies **D_2O to the Pump Gland Seal** System;

e) The bleed condenser (or degasser condenser in some stations) **accepts coolant discharge from the HTS** (bleed valves, HT relief valves, steam bleed valves, pressurizer relief valves, depending on the station). This ensures that this coolant is available for use when required.

Note that functions (c), (d) and (e) are carried out by the Feed and Bleed system in either control mode.

One of the major **advantages of pressurizer control** is that it provides a **faster control** in response to HTS pressure transients than a feed and bleed system. (ie. Large quantities of coolant can be quickly transferred to/from the pressurizer through the large diameter connection to the HTS. This is in comparison to using a feed and bleed system, which will have a more limited capacity.)

Pressure Control Totally by Feed And Bleed

Obj. 7.9 ⇔

The HTS used at some stations is **non-boiling and solid. Pressure control** in these stations, at all power states, is by **feed and bleed control** (ie. inventory transfer). Basically, this is the **same as solid mode** control at other locations. The feed and bleed system may also provide a **D_2O supply** for the **fuelling machines**.

However, in this case the pressure control function is divided into two ranges, termed **wide and narrow range**.

The wide range covers the warmup and cooldown of the system when the pressure can range from full working pressure to a much lower pressure, ie. control uses a low gain, resulting in **coarse control - Wide Range**.

For normal full power operation, when "tight" control about the setpoint is required, control is switched to a higher gain, resulting in **finer control - Narrow Range**. More details of this control system will be presented in Instrumentation and Control courses.

SUMMARY OF THE KEY CONCEPTS

- HT pressures that are too high can cause HTS ruptures (LOCA). Low HTS pressure will result in fuel overheating due to film boiling, and/or loss of coolant circulation due to pump cavitation. Voiding will promote fuel overheating because it introduces positive reactivity, thereby increasing heat production in the fuel.
- Fuel overheating due to film boiling is also possible at full system pressure if a coolant blockage or restriction exists.
- Pressure control is required since the pressure in the HTS varies directly with the HTS average temperature. Inventory control is required because of coolant shrink and swell as the HTS temperature varies.
- For units with pressurizers, the feed and bleed system controls HTS pressure in "solid" mode. It also provides purification flow (in most stations) and D_2O to the HTS pump glands. The bleed condenser (or degasser condenser in some stations) accepts D_2O from the HTS relief valves to prevent the loss of this coolant.
- For units with pressurizers, the feed and bleed system controls pressurizer level in "normal" mode. It also provides make-up for losses, purification flow (in most stations), D_2O to the HTS pump glands, and maintains the bleed condenser (or degasser condenser in some stations) as a pressure relief vessel.
- For units without pressurizers, the feed and bleed system controls HTS pressure. It also provides the same functions as it does in solid mode in units with pressurizers. It may also provide a D_2O supply for the fuelling machines.

Pressurizer Level Control

Level control of D_2O in the pressurizer is important for the following reasons:

⇔ *Obj. 7.10 a)*

a) It **prevents** the **uncovering** of the **electric heaters** (on low level) therefore reducing the risk of burning out the heating elements (automatically switched off on low level). This results in the loss of pressure control (ie. cannot increase pressure without the heaters);

b) It **prevents** the system from **going solid** as a result of too high a level. Loss of the vapour space results in loss of pressure control;

c) Taking account of the limits imposed by a) and b), **maintains a maximum HTS inventory.**

Obj. 7.10 b) ⇔

An additional function carried out by the **level controller** is to **ramp up level in the pressurizer as reactor power is increased.** This means that **shrink or swell** as a result of power maneuvers can be accommodated directly by transfer **to and from the pressurizer** with minimal resort to feed or bleed action. A simplified control system is shown in Figure 7.4.

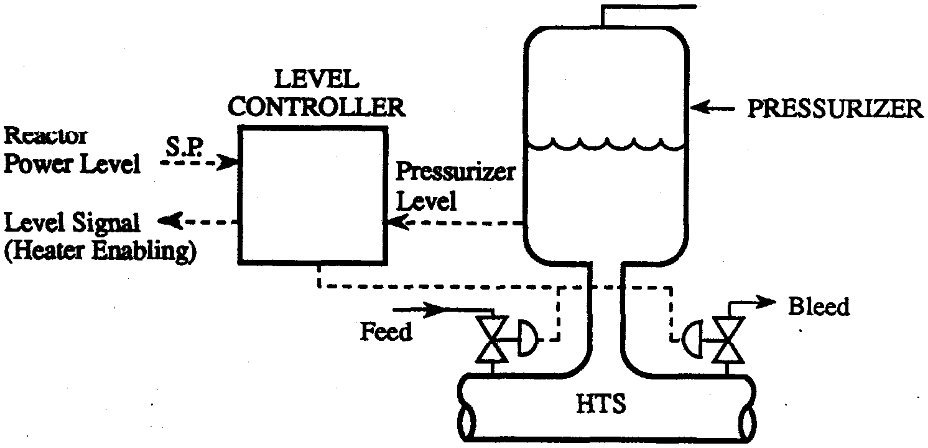


Figure 7.4
Pressurizer Level Control

* This is discussed in the 234 Turbine and Auxiliaries course.

Similar to boiler level changes with reactor power *, the level is at its lowest at low power. This is because the HT inventory will swell as reactor power is increased. The low level leaves room for the "excess" coolant that will enter the pressurizer. The requirement to make up shrinkage while at low power is a minimum, hence a lower level is not a major operating concern. On the other hand, the level is highest at full power. This takes into account the shrinkage that could occur if power is reduced. While at full power, the risk of further swell is minimal, hence the higher level in the pressurizer is not a major operating concern.

Pressurizer level is controlled by use of the feed and bleed valves.

For example, on a **power increase**, the pressurizer level **set point** will be **ramped upwards**. The **swell**, as a result of the power increase, will be **accommodated within the pressurizer** and will **satisfy** the increased **level requirement**. **Feed and Bleed** system **action** will be minimized to adjust HTS inventory. The opposite is true for a reduction in reactor power. The HTS shrink will be supplied from the pressurizer.

An additional **advantage**, achieved by ramping pressurizer level upwards as power increases, is that, should a reactor trip occur, the resultant **shrink** in the HTS can be **replenished quickly** from the pressurizer. Note that it is not practical to provide a pressurizer that is sufficiently large enough to accommodate all the swell from 0% power cold to 100% full power hot. It does, however, handle the inventory changes that occur in the on-power condition (zero power hot to full power), with minimum recourse to feed and bleed action. The inventory transfer between **cold pressurized and zero power hot**, to accommodate shrink and swell, is via the feed and bleed system and D_2O storage tank inventory.

⇔ *Obj. 7.10 c)*

Another advantage of the use of a pressurizer is that it results in addition/removal of inventory at HTS operating temperature directly to/from the pressurizer during transients. This minimizes heat losses and thermal stresses as compared to a solid system (ie. where inventory is cooled as it leaves the system and heated as it returns to the system via the bleed/feed path).

Response of Feed And Bleed Systems To Reactor Power Changes

For fine control using feed and bleed, and at the high working pressures used in the HTS, fairly small sized valves are used. Inventory transfer rates, and thus control of pressure transients, are limited.

⇔ *Obj. 7.11 a)*

At stations **without pressurizers**, the **demands on the Feed and Bleed** system are **reduced by** using the following techniques:

a) **Operating the station** (for the maximum possible time) as a **base load unit**, thus reducing the need for power manoeuvres and resulting changes in HTS temperature, and therefore pressure changes.

b) **Maintaining HTS average temperature** essentially constant in the at-power condition. This is achieved **by ramping down boiler pressure**, and therefore boiler temperature, as reactor power is increased. Boiler temperature and reactor inlet temperature can be assumed equal, since there should be little ΔT between the HT D_2O at the boiler outlet and the boiler temperature. Thus, as reactor outlet temperature increases (with an increase in reactor power) reactor inlet temperature, under the same conditions, will decrease. The average HTS temperature, ie. the mean of the inlet and outlet temperatures, will remain essentially constant over the power range. System shrink and swell, and therefore feed and bleed requirements, are thus minimized. This effect is shown in Figure 7.5 at the top of the next page.

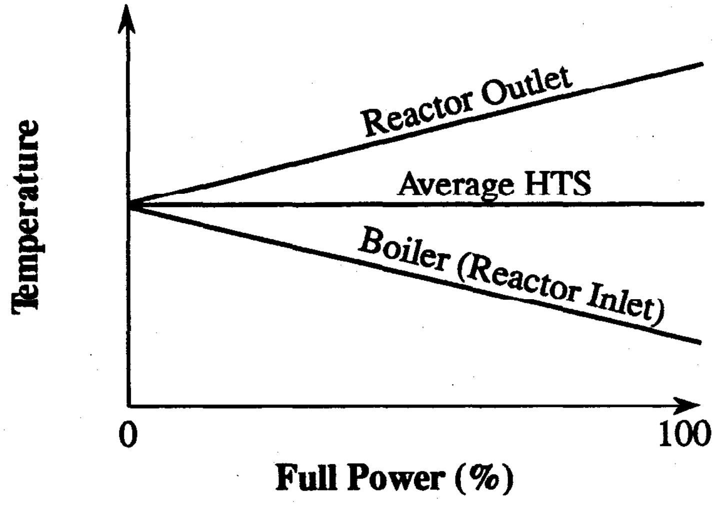


Figure 7.5
Reactor, Boiler and HTS Temperature Trends

Obj. 7.11 b) ⇔

The inventory transfer between **cold pressurized and zero power hot**, to accommodate shrink and swell, is via the feed and bleed system and D_2O storage tank inventory.

D_2O TRANSFER AND STORAGE

Obj. 7.12 a) ⇔

D_2O Transfer System (Interunit Tie)

At a typical CANDU generating station (single or multi-unit), provision must be made to ensure that **sufficient quantity and quality of D_2O is available for extended, and safe unit operation.**

Each station (multi-unit) has a **central D_2O storage facility** to receive shipments of D_2O from the manufacturing plants. It can be **pumped** from this central location to the reactor systems as required. This facility is also capable of **holding** the D_2O from one moderator or one HTS, should a reactor system require draining.

This central supply and distribution system reduces handling of D_2O **drums** and, therefore, reduces personal exposure to tritium from any spills that may occur. It is also a **faster** method of transferring D_2O. It also allows transfer of D_2O **between units.**

Separate storage is supplied for any **downgraded D_2O** which may have escaped or have been removed from the reactor systems. This is the usual source of D_2O for the station upgrading facility. Note, that since **HTS** D_2O has a lower tritium content than the **moderator, separate storage** is provided for each system.

D_2O Storage Tanks

⇔ Obj. 7.12 b)

Each unit's HTS has its own individual D_2O storage tank. Its **purposes** are to:

a) Provide enclosed **storage** for D_2O to **makeup leakage** from the HTS.

b) **Accommodate** system D_2O **shrink and swell** during reactor power manoeuvres.

c) Provide a **positive suction head** to the HTS feed (pressurizing) pumps.

As indicated in (b) above, the storage tank level will vary with reactor operating state.

⇔ Obj. 7.12 b) i)

It is important to maintain a **minimum level** in order to ensure **adequate feed pump suction head**, and to provide an inventory to **cover expected "normal" losses.**

⇔ Obj. 7.12 b) ii)

Too high a level at low power may result in the tank being completely filled by the swell as power increases. The tank forms part of the sealed HTS system, even though at a lower pressure (typically 10-20 kPa(g)). The **vapour space** above the D_2O is filled with **helium** and providing both a non corrosive, non explosive atmosphere with the ability to remove any D_2 (produced by radiolysis) by purging. This space would be lost on very high level, allowing this tank to pressurize. Any **overpressure** is relieved initially by **valving** to the recovery/collection system. Extreme overpressure protection is provided by a rupture disc, which will **discharge** excess **coolant to containment.**

SUMMARY OF THE KEY CONCEPTS

- Low pressurizer level could cause exposing the electric heaters to the steam causing burnout. Also the level must be maximized to ensure that there is sufficient inventory for rapid shrinkage make-up. High pressurizer level could cause the pressurizer to go solid, hence losing pressure control.
- Pressurizer level is ramped with power changes to accommodate shrink and swell and to minimize feed and bleed requirements.
- Feed and bleed requirements are minimized for systems without pressurizers by ramping down boiler pressure as reactor power is increased. This maintains HTS average temperature constant to minimize swell. To further help, these units are run as base load units.
- The feed and bleed system provides the inventory transfer between the cold pressurized state and zero power hot conditions.

- The purpose of the inter-unit D_2O tie is to centrally store and distribute D_2O and allows transfers of D_2O between units.
- The purpose of the D_2O storage tank is to provide D_2O for loss make-up, accommodate shrink and swell and provide a positive suction head to the feed pumps. A minimum level must be maintained to make-up D_2O for losses and to ensure adequate suction head at the feed pump. A high level could cause the tank to go "solid" resulting in loss of coolant to collection/recovery or to containment through the rupture disc.

Pages 29-32 ⇔

You can now work on **assignment questions 1-18.**

BLEED FROM THE SYSTEM

We have already mentioned that a **portion of the HTS inventory** is diverted from the system on a continuous basis, and put through a **purification** process.

This clean up will be performed by a combination of **filters, ion exchange columns and strainers**. Ion exchange resins are generally **not able to tolerate excessive temperatures.** Temperatures greater than ~60°C may cause resin efficiency to decrease and perhaps cause resin breakdown with the release of, typically, fluorides and chlorides. These ions can promote stress corrosion cracking in the zirconium and stainless steel components of the HTS (discussed in the Materials course). Note that in some stations purification is performed at full system pressure, at other stations it is performed at a reduced pressure.

The purified D_2O is either returned to the HT system or it can be held in the D_2O storage tank at nearly atmospheric pressure and cooled (as previously mentioned). This tank is maintained at a pressure close to atmospheric. It also accommodates the excess D_2O due to swell on a unit warmup from a cold state (the D_2O transfer and storage system is used, as required, to maintain the D_2O storage tank level in the correct range).

Therefore, for storage at all stations and purification at most stations, it is necessary to both cool and depressurize any bleed from the HTS. This is accomplished differently at different locations, but there are two basic methods described below.

Bleed/Purification Using Bleed Condensers

A representative pressure and inventory control/purification system is shown in Figure 7.6 *.

* This diagram is provided at the end of the module. It can be unfolded and kept in sight for your reference.

The bleed condenser has two major roles:

a) To reduce the pressure and temperature of any bleed from the HTS from approximately 9-10 MPa and ~300°C (8 MPa, 250°C at some stations) to 2 MPa and ~200°C.

b) To accommodate any discharge of D_2O from the HTS. This can be in either liquid (via the HT pressure relief valves) or vapour (from the pressurizer via the steam bleed valves).

The bleed condenser will, as its name implies, condense any bleed flow from the HTS. There are **two methods** of achieving this condensing action:

⇔ ***Obj. 7.13 a)***

Reflux Cooling

a) This is achieved by taking a flow of already cooled and purified D_2O which is being recirculated or returned to the HTS by the pressurizing (feed) pumps and passing it through a tube bundle located in the bleed condenser. As well as condensing the steam, this heats the D_2O that is returning to the HTS, thus efficiently recovering this heat.

Spray Cooling

b) This is achieved by spraying cooled D_2O into direct contact with the incoming bleed flow (note the bleed flow will flash to steam as it encounters the lower pressure of the bleed condenser).

Spray cooling is used as a backup to reflux cooling, should reflux cooling not be able to maintain the process at its required setpoint. If the reflux flow is at a maximum and pressure continues to increase in the bleed condenser, spraying will commence. This direct contact method of condensing should quickly lower pressure but at the **expense of mixing already cooled and purified D_2O with that yet to be treated.** This places a **heavier load on the purification circuit**. Spray cooling would also likely add to degassing of the coolant in the bleed cooler. This will result in the impairment of reflux cooling. This will also lead to **level control problems** in the bleed condenser, since the incoming bleed will be at a high rate, with spray cooling adding to the inventory.

⇔ ***Obj. 7.13 b)***

As previously noted, the D_2O leaving the Bleed Condenser will be at a pressure of approximately 2.0 MPa and a temperature of about 200°C.

Further cooling to less than 50°C, required before passing to the ion exchange columns, is performed by the Bleed Cooler.

Details of the control systems used in the bleed condenser and cooler will be covered in the I&C Course 236. The control requirements cover bleed condenser level and pressure, plus bleed cooler exit temperature.

Note that electric immersion heaters can be used to establish the initial saturation conditions in the bleed condenser (only at some stations). **Relief valves** are necessary to provide pressure relief for the bleed condenser, when the level rises enough to cause the bleed condenser to go "solid". The bleed condenser relief valves **discharge into recovery sumps** (or tanks in some stations) within containment. (These component are not shown in Figure 7.6.)

BLEED/PURIFICATION USING A DEGASSING CONDENSER

A representative pressure and inventory/purification circuit using a degassing condenser is shown in Figure 7.7 *.

* This diagram is provided at the end of the module. It can be unfolded and kept in sight for your reference.

Note that purification in this type of arrangement is conducted at full system pressure. Because this purification flow is driven by the HT pumps, it is independent of the bleed circuit. Hence bleed flows can be quite small during system operation. This type of purification will be discussed in more detail in a later module of this course.

For this system the degassing condenser has the following major roles:

a) To accommodate any discharge of D_2O from the HTS. This can be in either liquid (via the HT pressure relief valves) or vapour (from the pressurizer via the steam bleed or steam relief valves).

b) To reduce the pressure and temperature of any flows from the HTS from approximately 9-10 MPa and ~300°C to 1.2 MPa and ~190°C.

c) To degas flows from the HTS. This degassing function will be discussed in a later module of this course.

Obj. 7.14 ⇔

The degasser condenser will condense flow from the HTS by **spraying cooled D_2O** into direct contact with the incoming flows (which will flash to steam as it encounters the lower pressure of the degassing condenser).

Further cooling to less than <~70°C (typically ≤30 °C) will be performed by the Degassing Cooler before the D_2O is returned to the HTS or D_2O storage tank. This further cooling is required because high temperatures at this point would cause net positive suction head problems at the feed pump. Note there is no temperature control on the degasser cooler (other than the high temperature over-ride on the level control valves). The recirculating cooling water is always at a maximum flow rate to ensure maximum cooling.

Note that the electric immersion heaters can be used to maintain the conditions in the degasser condenser for degassing (when steam bleed flows are insufficient to maintain pressure). Just like the bleed condenser, **relief valves** are necessary to provide pressure relief for the degasser condenser when the level rises enough to cause the degasser condenser to go "solid" (these are not shown in Figure 7.7). The degasser condenser relief valves discharge into **recovery sumps** within containment.

POWER MANOEUVRES

Figures 7.6 and 7.7 show, in a very simple format, two types of pressurizer systems and a feed and bleed system fitted to CANDU units. We can use these diagrams to explain how the different systems will respond to normal power manoeuvres (between 0% and 100% FP) and a limited number of system upsets.

Pressurizer System

⇔ *Obj. 7.15*

As mentioned previously, an **increase in reactor power** raises **average HTS temperature.** This causes a corresponding **coolant swell** causing an increase in pressure. The increase in pressure and inventory will cause:

a) Additional D_2O **inventory** to **enter** the **pressurizer,**

b) The **steam space** above the liquid in the pressurizer to be further **compressed.**

Effect (b) will be countered by the control system **opening the steam bleed valves** in the pressurizer until pressure is once again at the setpoint.

Since pressurizer level setpoint is ramped upwards as reactor power increases, the inventory transferred to the pressurizer will provide the extra D_2O required to bring the level to its new setpoint. Any **discrepancy will be made up with bleed valve opening.**

The steam discharged to the bleed condenser, plus any additional bleed flow input, will cause **pressure and level in the bleed condenser to increase.** In the case of the **degasser condenser,** the steam discharge and any additional degassing flow will similarly cause its **pressure and level to rise.**

Pressure will be returned to setpoint by some **additional reflux flow** while the bleed condenser input is at its increased level. **Spray action is not likely** to occur for a normal power manoeuvre. For the **degasser condenser case,** the pressure reduction will be performed by **spray cooling.**

The increase in bleed condenser/degasser condenser level will be removed by an increased **opening of the level control valves.**

The additional outflow from the bleed condenser/degasser condenser will **increase the loading on the bleed/degasser cooler**. In the case of the bleed cooler, **additional cooling water flow** will be required to maintain the temperature at its setpoint. For the degasser condenser, **the temperature at the degasser cooler outlet will increase** slightly as the thermal load increases (recall that RCW valves are always fully open).

Once the new steady state power has been established, it is probable that reflux, level and cooling water control valves (if any) will return to their pre-manoeuvre positions.

On a large power reduction, HTS coolant shrink will result in a decrease in pressurizer level and a slight pressure reduction in the pressurizer steam space. Pressurizer heaters will come on to restore system pressure to setpoint.

Obj. 7.15 ⇔

Feed and Bleed System

For a feed and bleed system, an **increase in reactor power** output will cause a new, **lower boiler pressure setpoint to be generated.** Recall that this is intended to keep the average heat transport system temperature relatively constant during normal power maneuvering. However, the range of boiler pressure adjustment is limited - to achieve reasonable thicknesses of boiler vessels (high pressure limit) and maintain high thermal efficiency of the cycle (low pressure limit).

Because of these limitations, average **heat transport system temperature will increase slightly** during reactor loading. Therefore, HTS pressure will also increase. **Opening the bleed valve** will be necessary to reduce pressure to the setpoint.

The additional bleed flow will bring about a similar response (as discussed earlier in the pressurizer section) from bleed condenser pressure and level controllers and bleed cooler temperature controller.

Note that for a reduction in power, an opposite response will occur. HTS average temperature will reduce, resulting in a drop in HTS pressure. This pressure decrease will require feed action to restore pressure to the setpoint.

Bleed action will reduce, resulting in less reflux flow to prevent bleed condenser pressure falling. Outflow from the bleed condenser will be reduced to maintain level which will in turn reduce loading on the bleed cooler.

SUMMARY OF THE KEY CONCEPTS

- Bleed condenser pressure is controlled by condensing D_2O by reflux cooling and spray cooling. Spray cooling is used as a backup since it increases load on the purification circuit and creates level control problems. For stations using a degasser condenser, cooling is by spray cooling only.
- As reactor power increases, pressurizer systems will respond as follows:
  - HTS temperature increases, causing swell and an increase in HTS pressure,
  - Steam bleed valves open to reduce HTS pressure,
  - Pressurizer level increases due to swell (level setpoint is also ramped up),
  - Bleed condenser (or degasser condenser) level increases and load on the bleed (or degasser) cooler increases,
  - Bleed system action should be minimized.
- As reactor power increases, for a feed and bleed system (no pressurizer), response will be as follows:
  - Boiler pressure is ramped downward to maintain HTS average temperature constant, hence HTS pressure increase is minimized,
  - Bleed condenser level increases due to increased bleed flow and load on the bleed cooler increases.

You can now work on **assignment questions 19-21.**

⇔ ***Pages 32-33***

HT Pressure Relief

⇔ ***Obj. 7.16***

Pressure relief must be provided to **prevent overpressurization**, with subsequent rupture of components in the HTS.

Rupture of components could result in one or a combination of the following:

1) A HT coolant spill requiring Emergency Coolant Injection if the loss of coolant is large enough (ie. loss of heat transfer medium),

2) Fuel failures due to the decrease in cooling capacity (as a result of voiding in the HTS due to reduced system pressure),

3) A reactor power increase due to an increase in reactivity as a result of the positive voiding coefficient. This situation would require the operation of shutdown systems to reduce power if the Reactor Regulating System (RRS) is not capable of control.

Pressure relief obviously reduces the possibility of these undesirable events occurring.

Obj. 7.17 ⇔

Note that events causing slow HTS swell (pressure increases) are not normally of major concern since these events are handled within the capacity of the pressure and inventory control system. On the other hand, **rapid pressure increases** (beyond the capacity of the pressure and inventory control system), if not counteracted, will cause serious overpressurization.

Obj. 7.18 ⇔

Overpressurization in the HTS can be caused by:

1) **Mechanical Compression of the Coolant**

   This could be the result of the pressurizing feed pumps supplying D_2O to the system at a rate above that which pressure and inventory control can accommodate (eg. insufficient bleed from the HTS due to bleed valve malfunction).

   In some stations this condition is also possible during refuelling due to overpressurization by the fuelling machine pressurizing pumps. This would only be a concern if the overpressure relief devices on the fuelling machines failed to function.

2) **Coolant Swell Due to Increases in HTS Temperature**

   If the coolant swell, as a result of an increase in HTS average temperature, cannot be contained by the pressure and inventory control systems, major overpressurization of the HTS can occur.

   These events are potentially more hazardous than mechanical over-pressurization, because the levels of over pressure achievable may be very large (ie. greater than the capacity of the relief valves).

   Events leading to this type of overpressurization include:

   a) Pressurizer heaters failing to turn off as the HTS pressure setpoint is reached. The increased boiling in the pressurizer will increase D_2O pressure in the pressurizer. Since the pressurizer and HT system are connected, pressure will also increase in the main HTS.

   b) Loss of reactor regulation leading to reactor power increasing above normal full power setpoint. Assuming that the heat production rate is greater than the heat removal rate, this results in HTS swell and accompanying pressure rise (protected against by shutdown system trip).

   c) Loss of HTS circulating pumps while at power. The loss of coolant flow will result in an immediate increase in HTS average temperature leading to high HTS pressure (again protected against by shutdown system trip- Protected by both low HT flow and high HT pressure trips.).

d) Conventional (Boiler) System Upsets

  i) Cessation of steam flow from boilers due to turbine trip or load rejection. This occurrence is normally countered by providing an alternate heat sink (steam discharge) and by reducing the heat input to the system by means of a reactor stepback or setback. If the remedial measures do not occur, heat removal from the HTS will be impaired, resulting in an increase in HTS average temperature and a corresponding rise in HTS pressure.

  ii) Loss or reduction of boiler feedwater and consequent loss of **heat sink capability**. As heat sink capacity in the boilers reduces, HTS temperature and pressure will increase rapidly. This is mainly due to the loss of the cooling effect from the preheaters (approximately 20% of the heat sink). *⇔ Obj. 7.19*

Further details on unit upsets will be given in Module 18 of this course.

Methods Of Reducing HTS Pressure

Two basic methods of obtaining pressure reductions exist:

1) **Direct** pressure reduction,
2) **Indirect** pressure reduction.

Direct pressure reduction refers to methods which are **applied directly** to the **HTS**. *⇔ Obj. 7.20 a)*

Indirect methods are **secondary effects** from actions to control the **steam system**. By first influencing the steam system, there will be a variation in heat sink capacity, which affects HTS D_2O pressure. *⇔ Obj. 7.22 a)*

Basically, direct pressure reduction mechanisms can handle HTS over-pressures resulting from both mechanical and HT temperature increases while indirect methods are capable of handling only events resulting from HTS temperature increases. The reason for this limitation is explained later in this section.

DIRECT PRESSURE REDUCTION

HTS pressure, usually measured at the reactor outlet header, is used to initiate the various relief actions. These are shown in Figure 7.8 on the next page.

HT Pressure Relief Valves

The **HT pressure relief valves** are the first line of defence against an uncontrolled pressure rise. There are generally a number of them, *Obj. 7.20 c)* ⇔

Obj. 7.20 b) ⇔

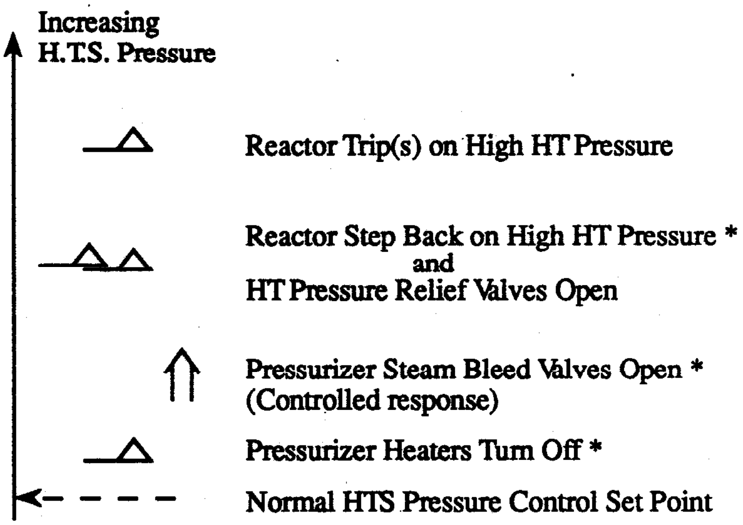
mounted in parallel, discharging from the reactor outlet header(s) into the bleed condenser (or in some stations, the degasser condenser). These valves **discharge** the "excess" **coolant** from the HTS, thus **limiting** the **over-pressure**. Although the boiler safety valves must be capable of discharging the steam produced by 100% or greater reactor power output, the HTS relief valves have only a limited discharge capacity.

Obj. 7.21 a) ⇔

Obj. 7.21 b) ⇔

The reason for this apparent discrepancy is that the HT relief valves are **sized** to match the overpressurization capability caused only by **mechanical** (pump) **methods**. To provide sufficient relief valve capacity for all likely events would not be desirable as it would increase the risk of **overrelief**, with excessive **loss of inventory**. This would lead to saturated conditions being reached in the main HTS and excessive boiling in the HTS. This could lead to **steam blanketing** and **fuel overheating.**

Note that the relief valves may have staggered set points to provide progressive action as HTS pressure increases.



* Not in all stations

Figure 7.8
Some Direct Methods of H.T.S. Pressure Reduction

Reactor Power Reductions

Obj. 7.20 b) ⇔
Obj. 7.20 c) ⇔

If the pressure relief valves are unable to stop the pressure rise, reactor power may be **stepped back**, ie. a step decrease in reactor power (typically 30%). This would result in a rapid coolant **shrink** with associated rapid drop in HTS pressure. This feature is only available for reactors fitted with control absorbers .

At stations without control absorbers, initial attempts to reduce HTS pressure is by coolant discharge via bleed and pressure relief valves. This will cause a high level in the bleed condenser. This will result in a reactor setback on high bleed condenser level. A **setback** is a power ramp down which results in a more gradual coolant **shrink** than that achieved by a stepback, ie. pressure reduction will be slower than that for a stepback.

A pressure rise not terminated by either relief valves or reactor setback/stepback will eventually **trip** the reactor. This quickly reduces thermal power to decay levels (~ 7% FP) causing a **rapid** HTS D_2O **shrink** and pressure reduction.

Indirect Methods Of Pressure Reduction

⇔ *Obj. 7.22 b)*

⇔ *Obj. 7.22 c)*

Indirect methods, as mentioned earlier, reduce HTS average temperature by first affecting the steam system. This temperature decrease results in coolant shrink which in turn leads to a decrease in HTS pressure.

The temperature reduction is achieved by **lowering boiler pressure** (and therefore boiler temperature since the boilers are saturated). The higher ΔT between HTS D_2O and boiler H_2O will result in a higher rate of heat transfer from the HTS and therefore, a reduction in the average HTS D_2O temperature.

Boiler pressure is lowered by discharging steam from the secondary side. Figure 7.9 illustrates the methods available. Note that a rise in HTS pressure due solely to mechanical over-pressure mechanisms cannot be handled by indirect methods (unless manual intervention is used) and will not, by itself, cause any steam valves to open.

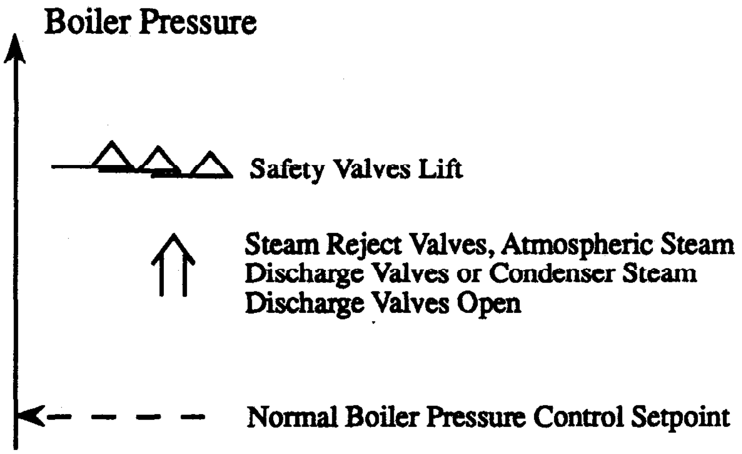


Figure 7.9
Indirect HT Pressure Reduction Methods

At most stations, atmospheric steam discharge valves and condenser steam discharge valves are used. The other stations use steam reject valves which discharge only to atmosphere. All plants, of course, use safety valves.

Discharging steam (to atmosphere or condenser) merely provides an additional or **alternative heat sink** to the turbine. If the heat removal provided by steam discharge is equal to power input to the boilers, then no HTS pressure rise will occur.

The **steam reject valves** at some stations, or the combined atmospheric and condenser steam discharge valves at other stations have at least 75% full power steam capacity. Thus, they are **capable of handling fairly large upsets**. However, should they prove inadequate to control steam pressure, the steam safety valves (set at higher relief pressures) will provide a further heat sink. The safeties are required by law to be capable of >100% steam power removal (ie, this takes into account reactor trip setpoints and channel power variation [ripple] effects).

Steam rejection can also be used, **together with direct methods** of pressure reduction, to cope with coolant swell upsets. In such cases, the steam reject valves (SRVs) could be opened manually by the unit operator. **Manual** SRV opening is a slow response, but the effect is of large capacity. Note that depending on the station, opening of the SRVs (or ASDVs) may also be used as an initiating parameter for a reactor setback to supplement the pressure reduction by reducing the heat input to the HTS.

Automatic opening of the SRVs could be employed on a HT pressure rise. But due to the time delay [~10 seconds] from steam discharge to HT average temperature change, rapid HT overpressures caused by primary system events could not be controlled automatically by this method. With the reactor shutdown and the **heat transport system cold, steam rejection is not capable** of assisting relief devices for heat transport mechanical overpressurization, since there will be no steam to discharge.

SUMMARY OF THE KEY CONCEPTS

- Pressure relief must be provided to prevent damage to the HTS.
- Rapid HTS swells are beyond the capability of the pressure and inventory control system.
- Over-pressurization is caused by mechanical compression of the coolant or by coolant swell.
- Direct methods of HTS pressure reduction act directly on the HTS D_2O (ie. relief valves, reactor power reduction causing HTS D_2O shrink).

- Indirect methods of HTS pressure reduction act on the steam system to control HTS pressure (ie. boiler pressure reduction also reduces HTS temperature, hence HTS D_2O shrinks).
- HTS pressure relief valves are sized for mechanical overpressure events only. To provide pressure relief capacity for all possible events would increase the risk of over relief yielding excessive inventory loss.

MAJOR UPSETS

Failed Open Pressure Relief Valve (PRV)

⇔ *Obj. 7.23 a)*

Should a PRV fail open, **coolant is being lost** from the system. **Heat transport pressure will fall** rapidly and efforts to restore pressure will commence, ie. pressurizer heaters on (where applicable), feed action to restore inventory.

The flow through the PRV will cause **bleed condenser (or degasser condenser) pressure and level to increase.** Control action, as discussed earlier in the module will be required. A setback on high bleed condenser level may result. High temperature over-ride of the bleed/degasser condenser is also possible *.

* This will be discussed later in this module.

Boiling in the HTS will occur when saturation conditions are reached. The **increased boiling** will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

If the valve does not reclose, a **reactor trip** will eventually be generated on low pressurizer level (or low HT pressure where no pressurizer is installed).

Feed Pump Failure

⇔ *Obj. 7.23 b)*

On failure of the feed pumps, **no makeup to the HTS** will be available (assume for this example that no back-up pumps are available). Where pressurizers are installed, the pressurizer level will decrease while maintaining HTS pressure. This will continue until the level falls sufficiently to limit the pressurizer's ability to react to a major upset. The unit must then be shutdown and cooled down.

In units without pressurizers, heat transport pressure will immediately begin to fall. Boiling in the HTS will occur when saturation conditions are reached. The **increased boiling** will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

If the feed pump is not restored, a **reactor trip** will eventually be generated on low HT pressure or HTS low flow while pumps are cavitating.

Obj. 7.23 c) ⇔

Pressurizer Steam Bleed Valve Fails Open

This fault will immediately reduce the pressure in the steam space of the pressurizer and HTS pressure will fall.

Boiling in the HTS will occur when saturation conditions are reached. The **increased boiling** will impair fuel cooling due to film boiling and decreased coolant flow (due to pump cavitation caused by decreased suction head).

In the pressurizer, the intensive boiling will cause the **level** in the **pressurizer to increase,** causing **feed valves to close and bleed valves to open** (ie. level increases due to boiling, but actual inventory is being lost through valve). A reactor **trip** on **low heat transport** system **pressure** is likely. Also, a setback on high pressurizer level is possible.

The flow through the steam bleed valve will cause **bleed condenser (or degasser condenser) pressure and level** to **increase.** Control action, as discussed earlier in the module will be required. A setback on high bleed condenser level may result. High temperature over-ride of the bleed/degasser condenser is also possible *.

* This will be discussed later in this module.

Obj. 7.23 d) ⇔

Failed HT Main Circulation Pump

The majority of operating CANDU reactors require the use of all (typically four) main HT pumps for full power operation. **Loss of one pump** or more will seriously **impair the heat removal capability of the HTS** due to low flow (ie. coolant circulation reduces while the heat input to the HTS continues). **Continued operation** at full power would result in **film boiling** in the fuel channels with a high probability of fuel failures and a large pressure increase.

On the loss of a single circulating pump at these units, **a reactor stepback** will occur to reduce reactor power output to approximately ~65% FP. Note that in two loop systems, trip of a symmetric pump will be required (in some situations, depending on which pump trips, a shutdown cannot be avoided).

At stations where normal operation requires 12 of 16 pumps to be operative (three out of each bank of four), the loss of any single pump in a bank, would require that a **standby pump be started.** Continued operation without sufficient coolant circulation would result in boiling and potential damage as stated above.

For a unit using a feed and bleed system, the resulting increase in pressure would probably overwhelm the bleed condenser capacity. The reactor may **trip** on **high HTS pressure or temperature** before the **high bleed condenser level setback** function is initiated.

Over-ride of Bleed/Degasser Condenser Level Control

⇔ ***Obj. 7.23 e)***

The description of bleed condenser and bleed cooler operation given earlier, indicates that bleed (or degasser) cooler loading is dependent upon flow (which controls level) out of the bleed (or degasser) condenser.

Thus, efforts to control a **high level** in the bleed condenser may produce **outflows**, such, that the bleed cooler **can no longer cool** the D_2O to 50°C or lower. Because ion exchange resins breakdown at high temperatures, additional control action is initiated to enable the bleed cooler to cool the D_2O to a temperature below that which could cause damage.

Since recirculating service water flow through the bleed cooler is always at a maximum, the only alternative to regain control is to **reduce the mass flow rate** of the hot D_2O through the bleed condenser (some stations have a normal fluctuating TCV on the bleed cooler). This mass flow reduction must remain in effect until the **temperature at the bleed cooler outlet is again acceptable**. This action will cause **level control to be lost** in the bleed condenser. If the condition causing the increased bleed flow·is short term, things will soon return to normal. If the condition persists, rising bleed condenser level will eventually cause a **reactor setback** in some stations.

The details of this control system are given in the 236 Instrumentation and Control course .

Similarly, temperature protection for the degasser condenser/purification design is provided in two stages. The IX **resins are protected** from high temperature via a similar **high temperature override** at the **purification cooler outlet**. A **high temperature override** also exist at the outlet of the **degasser cooler** to **protect the feed pumps** from net positive suction head problems. If the steam bleed continues (ie. HT high pressure continues, or a valve failure occurs) a reactor **stepback** will occur on **high HT pressure** (the HT relief valves also open at this point).

SUMMARY OF THE KEY CONCEPTS

- A failed open PRV will cause HTS pressure to fall. Film boiling and fuel failures are possible. Bleed condenser pressure and level will increase, with a possible setback on bleed condenser high level and high temperature over-ride. A reactor low pressure/low pressurizer level trip is possible.
- A feed pump failure will cause the HTS pressure to fall . Film boiling and fuel failures are possible. A reactor will trip on low HTS pressure or low pressurizer level/low HT pressure.
- A failed open steam bleed valve will cause the HTS pressure to fall. Film boiling and fuel failures are possible. Bleed condenser pressure and level will increase, with a possible setback on bleed condenser high level and high temperature over-ride. A reactor setback on high pressurizer level and/or a reactor trip on low HTS pressure is possible.
- The loss of a HTS pump reduces coolant flow through the reactor. Continued operation at full power would result in film boiling. Reactor power reductions are required by either stepback on pump loss, setback on high bleed condenser level or high HT pressure or temperature trip.
- The bleed condenser has a high temperature over-ride to protect purification resins from damage, but this causes level control in the bleed condenser to be lost. If the HTS pressure is still high, bleed condenser level will continue to increase (bleed continues) until a setback on high bleed condenser level occurs.
- The degasser condenser has a high temperature over-ride to protect the feed pumps from damage, but this causes level control in the degasser condenser to be lost. If the HTS pressure is still high, degasser condenser level will continue to increase (steam bleed continues) until a stepback on high HTS pressure occurs (HT liquid RV's will also open at that point). Purification resins are protected from damage by a high temperature over-ride at the purification cooler outlet.

Pages 33-36 ⇔

You can now work on **assignment questions 22-31.**

ASSIGNMENT

1. a) The concern with HT pressure that is too low is ________

   b) A HT pressure that is too high may cause ________

2. Coolant flow blockages are a major concern because:

   a) ________

   b) ________

3. Boiling in the HTS is allowed in (large amounts / small amounts). This boiling (helps / hinders) heat transfer in the channels.

4. It is necessary to have a HT pressure and inventory control system to ensure that ________

5. The purpose of the feed and bleed system for a unit with a pressurizer in "solid" mode of pressure control are:

   a) ________

   b) ________

   c) ________

   d) ________

6. The purpose of the pressurizer during "normal" heat transport pressure control mode is ______________________________

____

7. For a pressurizer system in normal mode a HTS pressure rise above the setpoint causes ______________________________

____

____

____

____

8. When HTS pressure reduces below the setpoint the pressurizer heaters will come (on / off) until pressure reaches __________.

9. The purpose of the feed and bleed system for a unit with a pressurizer in "normal" mode of pressure control are:

   a) ______________________________
   b) ______________________________
   c) ______________________________
   d) ______________________________
   e) ______________________________

10. The purposes of the feed and bleed system for a unit without a pressurizer are the same as (normal / solid) mode control in units with a pressurizer. An additional function is to supply the ______ ______________________________ with D_2O.

11. a) Pressurizer level setpoint is ramped (up/down) for increases in reactor power. This minimizes the requirements for _____

    ____

    ______________________________.

    b) Low level protection is provided to prevent ______________

    ____

    ______________________________.

c) High level protection prevents ____.

12. The operating concern for a pressurizer level that is too high is ____.

13. The operating concerns for pressurizer levels that is too low are:

    a) ____.

    b) ____.

14. For stations not using pressurizers, feed and bleed system requirements are (minimized / maximized) during increases in reactor power by:

    a) ________________________.
    This reduces system swell by (increasing / decreasing / maintaining) average HTS temperature which is achieved by (increasing / decreasing) D_2O temperature at the reactor inlet.

    b) ____.

15. The purpose of the inter-unit D_2O transfer system is to:

    i) ____.

    ii) ____.

16. The purpose of the D_2O storage tank is to ____.

17. The problems with operating with a D_2O storage tank that is too low are:

    i) ____
    ____.

    ii) ____
    ____.

18. The problems with operating with a D_2O storage tank that is too high are:

    i) ____
    ____.

    ii) ____
    ____.

19. Two methods for controlling bleed condenser pressure are:

    a) ______________________________ which reduces
    pressure by ______________________________________
    ____.

    This method (is / is not) used as a backup.

    b) ______________________________ which reduces
    pressure by ______________________________________
    ____.

    This method (is / is not) used as a backup.

    c) The backup method is not preferred because:

    i) ____
    ii) ____

20. Degasser condenser pressure is maintained by the use of ________
______________, which reduces pressure by ______________
____
____.

21. For HT systems with and without pressurizers, indicate on the following table, where applicable, the response of pressurizer levels, feed and bleed flows, HTS pressure and temperature, feed/bleed response and boiler pressure for a reactor power increase.

	Units with Pressurizer	Units without Pressurizer
HTS Pressure		
HTS Avg. Temperature		
Boiler Pressure		
Feed and Bleed Action		
Pressurizer Level		

22. a) HTS pressure relief is required because ________________

____.

b) Rapid changes to HTS pressure are a major concern because

____

____.

23. The two major causes of HTS overpressurization are:

a) ____

An example of this type of overpressurization is ________

____.

b) ______________________________

An example of this type of overpressurization is __________

______________________________.

24. a) "Direct " methods of HTS pressure relief means:

____

____

______________________________.

b) Two examples of direct methods of pressure relief are:

i) ______________________________.

This reduces the pressure by ______________________________

____

ii) ______________________________

This reduces the pressure by ______________________________

____

25. a) "Indirect " methods of HTS pressure relief. ______________

____

______________________________.

b) An example of an indirect method of pressure relief is

______________________________.

This reduces pressure by ______________________________

____

____

______________________________.

26. The HTS pressure relief valves are sized for ____________________

____. The reason they

are not sized to handle all over-pressure events is ______________

____

____

____.

27. A failed open pressure relief valve will cause________________

____

____

________________. In stations using bleed condensers, the reactor

may setback on ___________________________________.

28. A failed HT feed pump will cause ___________________________

____

____

____

____

____. A reactor trip

will occur on ______________________ or _________________.

29. A failed open steam bleed valve will cause ___________________

____

____

____

____

____

____

____

____.

30. A failed HT pump will cause a ______________________________

____

____

____

____.

HTS pressure would (rise / fall) because ____________________

____

____.

31. The purpose of the bleed/degasser condenser high temperature override is ____

____

____

____

____

____

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

Prepared by:	D. Tennant, N. Ritter, WNTD
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 8

HEAT TRANSPORT SYSTEM SHUTDOWN OPERATION

OBJECTIVES:

After completing this module you will be able to:

8.1 Explain the reason why a heat removal path must be available when the unit is shut down. *⇔ Page 2*

8.2 Explain the reason for the class of power supply provided for the direct and indirect shutdown cooling systems. *⇔ Page 2*

8.3 Explain the operation of the two current types of shutdown cooling systems used in CANDU reactors, ie, indirect and direct. *⇔ Page 3*

8.4 State the function of the:

- a) Shutdown Cooling System, *⇔ Page 4*
- b) Maintenance Cooling System. *⇔ Pages 3, 8*

8.5 Explain the need for a maintenance cooling system when the method of shutdown cooling is indirect. *⇔ Page 8*

8.6 For each of the operating states listed below, label a block diagram that shows the role of the HT system in transferring heat energy (major pathway only) from the heat source to the heat sink.

- a) Zero power hot, pressurized when using a direct shutdown cooling system, *⇔ Pages 5-6*
- b) Zero power hot, pressurized when using an indirect shutdown cooling system, *⇔ Pages 6-7*
- c) Thermosyphoning, *⇔ Pages 9-10*
- d) Crash cooldown. *⇔ Page 11*

The diagram must show:

- i) Major heat sources,
- ii) Heat carriers,

(Continued Next Page)

iii) Required pumps,
iv) Heat energy transfer points,
v) Heat sinks,
vi) Normal capacity of these systems in terms of percent full power (approximate).

Page 9 ⇔ 8.7 a) Explain how thermosyphoning is achieved in a CANDU reactor.

Page 10 ⇔ b) State the four conditions required to maintain thermosyphoning.

Page 12 ⇔ 8.8 Explain how, in the absence of the boiler systems as heat sink, an emergency cooldown may be achieved. State the capacity of the system required to perform this emergency cooldown.

8.9 Explain the consequences of violating or exceeding the following constraints:

Page 11 ⇔ a) Too frequent use of the shutdown cooling system for emergency cooldowns,

Page 11 ⇔ b) Temperatures at which shutdown cooling may be normally valved in.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Obj. 8.1 ⇔ At power, a significant portion (typically 6-7%) of a CANDU reactor's full power output is due to the heating effects of fission product decay. Following a shutdown of the reactor, these fission products will continue as a thermal power source. Although radioactive decay will decrease the magnitude of this source (typically to about 1% Full Power (FP) in about 1 hour) it will still produce a significant amount of power (~20-30 MWt, depending on the station).

This unique feature of nuclear powered generating stations **requires a heat removal path and heat sink at all times** when the reactor contains used fuel. This means that at least a portion of the HTS must be available to remove the decay heat from the fuel.

Obj. 8.2 ⇔ Since this decay heat is always present, the cooling systems required to remove decay heat are **supplied by Class III power** (or at least backed up with Class III power) to ensure a **reliable power supply** (ie. a **reliable heat sink**).

Without this continuous cooling, it is easily possible to fail fuel even with the reactor shutdown. For example, the massive fuel failures which occurred at Three Mile Island were caused by insufficient cooling of a tripped reactor. Fuel failure will inevitably release fission products into the HTS, reducing the multiple barriers to the release of radioactive contaminants.

This module will deal with the heat removal paths while shutting down the reactor, and while the reactor is shutdown. The emergency use of shutdown cooling and maintenance cooling systems will also be covered.

TYPES OF SHUTDOWN COOLING SYSTEMS

The systems in use vary between stations and are known either as "directly" cooled or "indirectly" cooled. All make use of at least a portion of the heat transport system with one or more heat exchange points before arriving at the final heat sink (lake, river, or sea).

"Directly cooled" refers to systems where the HT D_2O is **cooled directly by service water.** This type of cooling is used for shutdown cooling in stations where the preheaters are not external to the boiler.

⇔ ***Obj. 8.3***

For the "**indirectly cooled**" case of shutdown cooling, the **initial heat exchange** is from HTS coolant to boiler feedwater. This heat exchange occurs in preheaters external to the boilers (installed only in some stations), while the boilers themselves are not involved. The second heat exchange is from the feedwater to service water, which carries heat away to the final heat sink (the lake, river, or sea). This is an **"indirect"** system. Note that this method of cooling requires the boiler feedwater system to be in service, and HT pumps operating.

⇔ ***Obj. 8.3***

A separate directly cooled system, known as the Maintenance Cooling System (MCS) is available on units with indirect shutdown cooling systems. This system **allows the feedwater system and HT pumps to be shut down when maintenance on the feedwater or HT system is required.** This system has a heat removal capacity of approximately **1% FP.**

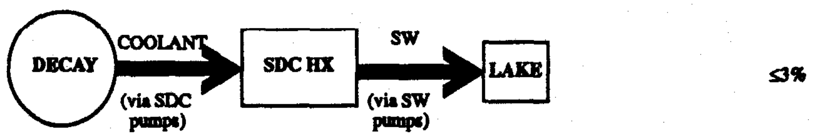
⇔ ***Obj. 8.4 b)***

Partial draining of the HTS (down to header levels) for maintenance purposes may also be performed on some units with direct shutdown cooling systems (or maintenance cooling systems) .

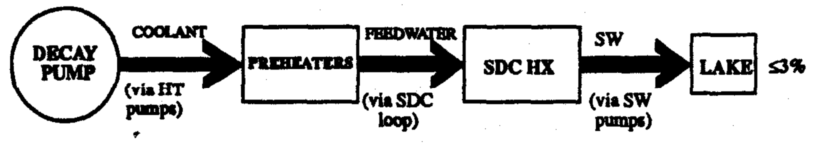
The representative heat removal chains for the above are shown in Figure 8.1 on the next page.

% Reactor Thermal Power

(a) Direct Shutdown Cooling (SDC) System



(b) (i) Indirect Shutdown Cooling (SDC) System



(b) (ii) Maintenance Cooling System (MCS) for Indirect Shutdown Cooling

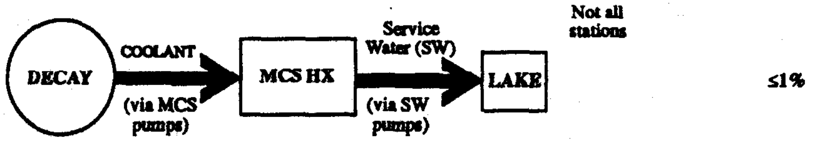


Figure 8.1: Heat Removal Chains

Steam Reject Cooling

Obj. 8.4 a) ⇔

For both types of systems (direct and indirect), the **initial HTS cooldown** from full power operation (ie. from 300°C to between 150°C - 165°C) is normally achieved **by Boiler Pressure Control (BPC)** system using steam discharge* to the atmosphere or condenser**. The **shutdown cooling system will then continue the cooldown.**

It should be noted that steam reject cooling could (theoretically) continue to near 100°C as boiler pressure is lowered, but is no desirable (since the steam volume produced would be enormous). As the temperature decreases, the rate of HTS cooling would also decrease because the differential temperature between the HTS and the boilers decreases. The large volumetric flow of steam produced at lower boiler pressures may "choke" the steam valves and limit cooldown rate. This would result in spending too much time in the higher risk temperature range for pressure tube delayed hydride cracking.

* Recall that boiler pressure, hence temperature, is reduced by steam discharge. The HTS temperature reduces with boiler temperature.

** Further information on steam discharge to the condenser is found in the 234 Turbines course and Module 6 of this course.

DIRECTLY COOLED SHUTDOWN COOLING SYSTEM

⇔ *Obj. 8.6 a)*

System Description

A typical system is shown in Figure 8.2 and consists of a pump and heat exchanger combination in parallel with the normal full power heat removal path. The number of shutdown coolers varies from location to location, but there are a minimum of two cooler loops at any location. Note that the normal flow direction through the reactor is maintained by the shutdown cooling pumps. No redundancy of shutdown cooling pumps (in a loop) is provided, as the total shutdown cooling flow is typically 10-15% of the main system flow. Adequate shutdown cooling flow can be maintained with a single shutdown cooling loop unavailable.

On a controlled cooldown, the capacity requirement is for approximately **1-3% of reactor full power.**

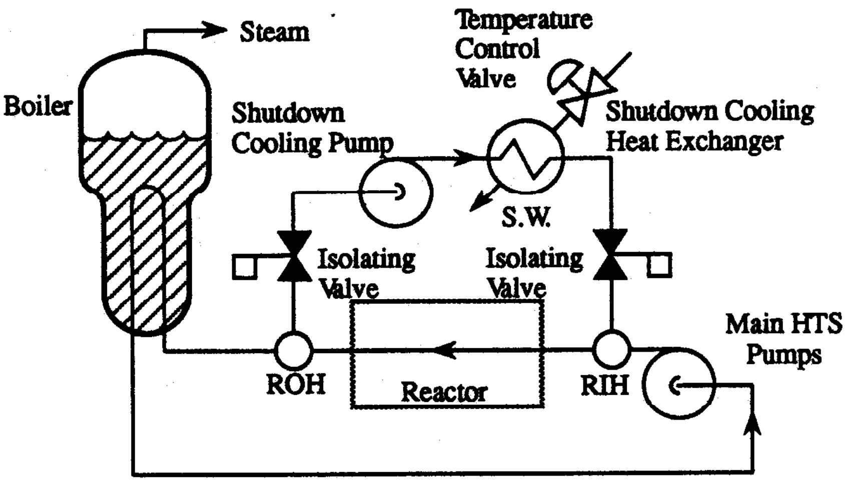


Figure 8.2: Simplified "Directly Cooled" Shutdown Cooling System

Typical Operation

With the reactor at power, the shutdown cooling isolation valves will be closed. The shutdown cooling loops will be filled with pressurized D_2O via small lines from the reactor outlet headers. The shutdown cooling loops are also warmed to a temperature close to the HTS temperature by the use of warmup lines from the HTS (not shown in the diagram), before being slowly valved into service. This avoids thermal shocks to the system.

During a cooldown of the HT system following a reactor shutdown, the shutdown cooling system will be used to **cool down the HTS from ~165°C to 60°C** (remember that cooldown from operating temperature to ~165°C is by steam reject). **Temperature control** of the shutdown cooling system is achieved by automatic **control of service water flow** through the heat exchangers.(In some plants, 2 or 4 main HT circulating pumps will continue to operate until a low system temperature is achieved. Shutdown cooling can then continue with the HT pumps shut off).

Note that it is important to establish a cooling water flow prior to placing the system in service. Failure to do this could result in boiling on the cooling water side of the heat exchanger. When the cooling water flow is established, the vapour pockets would collapse (due to condensation), which could result in water hammer.

Obj. 8.6 b) ⇔

INDIRECTLY COOLED SHUTDOWN COOLING SYSTEM

System Description

External preheaters are used at some stations to provide cooler D_2O to the inner zone of the reactor, where the channel temperature differentials (ΔTs) are higher than those for the outer zone. Other stations use increased coolant flow rate in the channels with higher ΔTs (inner zone).

In stations with preheaters, coolant for the inner zone channels, which has already passed through the boiler tubes, is routed through the preheater tubes. Here it releases additional heat to preheat the boiler feedwater on the shell side. Thus, pre-cooling of HTS D_2O (for the inner zone of the core) and preheating of boiler feedwater are accomplished in the preheater.

The basic system for indirect cooling is shown in Figure 8.3 on the next page. It is somewhat more complicated than the direct method because **two heat exchange points** are required (refer back to Figure 8.1). The initial heat removal path is from the HT D_2O to the boiler feedwater in the **preheaters**, with a secondary heat exchange from the boiler feedwater to service water in the **shutdown coolers** (heat exchangers).

Note that the system must remove the heat input to the HTS by the main HTS pumps, as well as the decay heat. This increases the **heat removal capacity to ~3% FP.**

Typically the system consists of 2 x 50% heat exchangers and 2 x 100% pumps. Power supplies are typically Class III to ensure a reliable power source for fuel cooling.

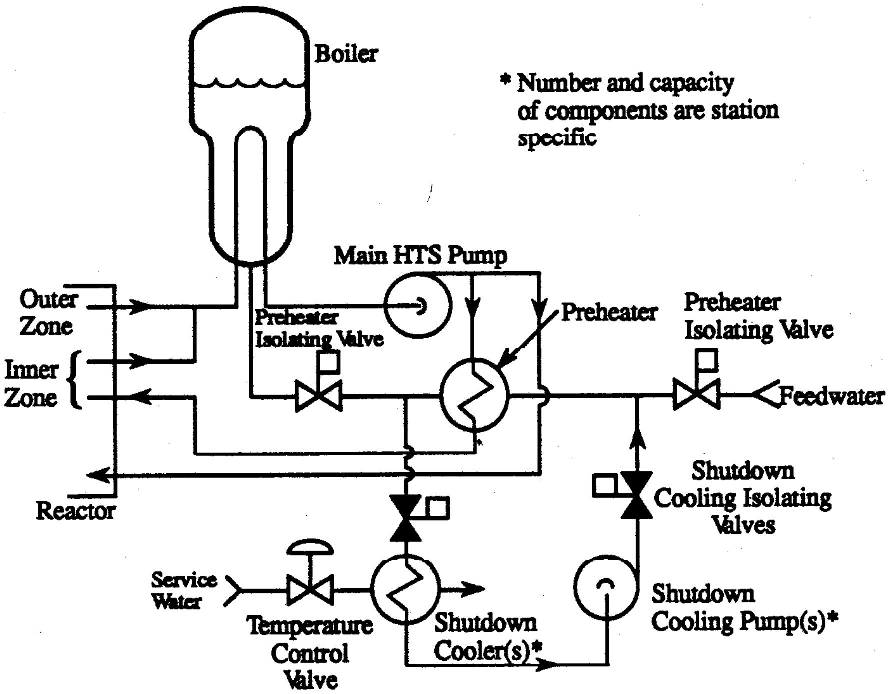


Figure 8.3:
Indirect System for Shutdown Cooling

Typical Operation

With the reactor at power, the shutdown cooling loop is kept in a cold depressurized state and isolated from the preheaters. The system must be filled and vented prior to use, to prevent water hammer due to slugs of water being forced through the system.

As with the direct system, the shutdown cooling system normally cools the HTS from ~170°C to 60°C.

The system is brought into operation by opening the shutdown cooling isolation valves. HTS temperature control is provided by a temperature control valve on the service water line to the heat exchanger.

It is important to keep the feedwater portion of the system pressurized. Failure to do this will result in boiling in the system. The vapour pockets formed will collapse when the vapour is condensed in the heat exchanger, or if the system is pressurized quickly, resulting in water hammer.

Note that the **HT pumps must remain in operation** to circulate D_2O through the preheater. Since the HTS is pressurized when the main pumps are in operation, the final state of the HTS under shutdown cooling is cold and pressurized.

Loss of the main HT pumps during a cooldown will result in inadequate heat removal via the preheaters. Thermosyphoning * will be required to remove the heat that was being removed in the preheater until maintenance cooling is put into service.

* Thermosyphoning will be discussed later in this module.

Maintenance Cooling System

As noted earlier, indirect shutdown cooling systems are only suitable to bring the HTS to a cold pressurized state.

Obj. 8.4 b) ⇔

The maintenance cooling system is used to take the HTS down to a cold depressurized state.

Obj. 8.5 ⇔

If maintenance requires the HTS to be depressurized and/or partially drained to header levels, or maintenance is required on the feedwater system, some **alternative form of cooling** must be provided. The maintenance cooling system will meet this requirement. It's simplified layout is shown in Figure 8.4. Note that only a single loop is used. This loop is physically located at a low level to allow partial draining of the HT system to header level. The system is also capable of cooling the HTS **__after__ BPC cooldown under emergency situations** (ie. if shutdown cooling is unavailable).

During normal system operation, the maintenance cooling system is isolated from the HTS.

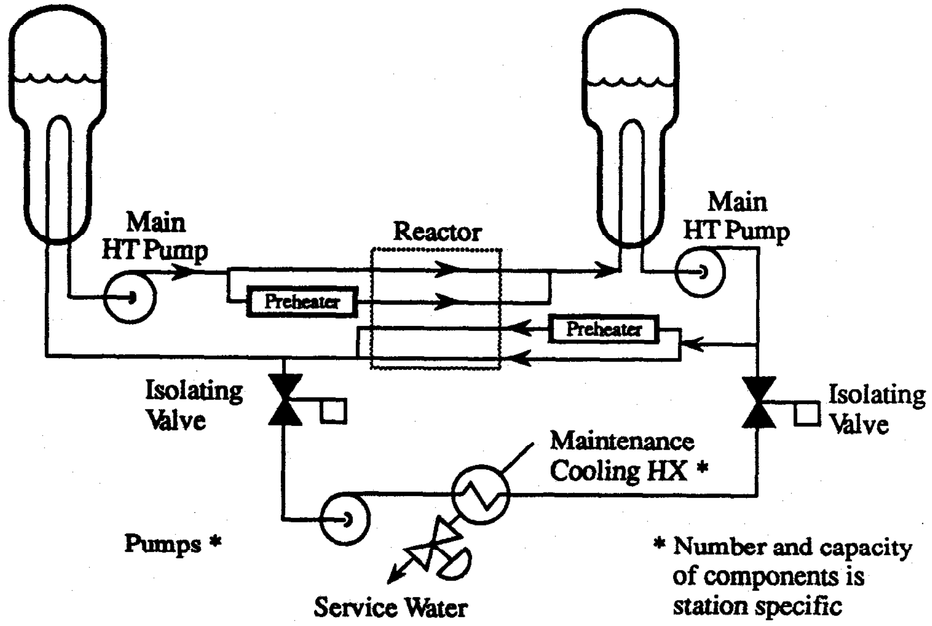


Figure 8.4: Typical Maintenance Cooling System

SUMMARY OF THE KEY CONCEPTS

- The HTS must be available at all times to remove decay heat from the fuel due to fission product decay. Power supplies to systems that cool the reactor when shut down are from Class III power, to ensure a reliable power supply.
- Direct cooling systems cool the HTS D_2O to provide cooling while shut down. Indirect cooling systems cool the feedwater, which indirectly cools the HTS D_2O in the preheater.
- The shutdown cooling system must remove decay heat to reduce HT temperature from ~165°C to ~60°C. The final state on shutdown cooling is cold and pressurized. Heat removal requirements are ~1-3% of reactor full power for a controlled cooldown. For direct cooling systems, the unit can be depressurized to allow maintenance on the system.
- The maintenance cooling system must remove decay heat to reduce HT temperature from ~60°C to ~30°C. The final state on maintenance cooling is cold and depressurized (and possibly drained to header levels). Heat removal requirement is ~1% of reactor full power.
- The maintenance cooling system is capable of cooling the HT system after steam reject cooldown.

THERMOSYPHONING

At full power operation, Class IV power is required for the main HTS circulating pumps and boiler feed pumps to ensure heat transfer and removal. If Class IV is lost, full power heat transfer capability is also lost and the reactor will trip either on low HT flow or high HT pressure (due to coolant swell, as average HT D_2O temperature increases).

⇔ Obj. 8.6 c)

After a loss of Class IV and the resultant reactor trip, some HTS **circulation** will be maintained by the **inertia** stored in the HTS pump motors/flywheels for a 2 to 3 minute period. This circulation, although reduced, continues to transport heat from the fuel to the boilers. During this period, the total heat input (fission, decay, and residual pump heat) is reduced to about 3% of full power values. The **final heat sink** is usually **steam discharge to atmosphere** via the SRVs or ASDVs (depending on the station).

Following motor/flywheel rundown, heat can still be transported to the boilers by a process of natural convection known as **thermosyphoning**.

⇔ Obj. 8.7 a)

The layout of a CANDU unit ensures that the **boilers** are at a **higher elevation** than the reactor. The **cooling action in the boiler** will increase the density of the D_2O coolant **causing it to fall back to the**

reactor. This will force the **hot, lower density, D_2O to rise** from the reactors to the boilers. A continuous flow pattern is thus established.

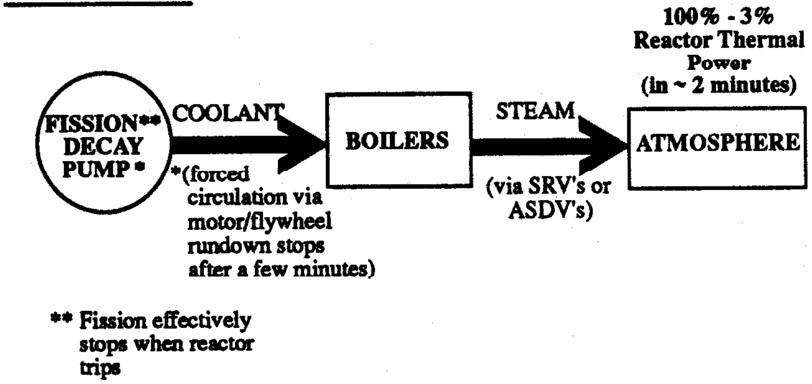
Obj. 8.7 b) ⇔

Cooling can be maintained indefinitely by this process providing the following criteria are maintained:

1. Reactor power is **limited to ~3% FP** or less (ie. decay heat levels).
2. **Boiler Pressure Control is functional** to maintain the ΔT between HT D_2O and boiler water. This will ensure that the HT D_2O density differences are maintained to "drive" the thermosyphoning flows.
3. **A boiler heat sink is available**, ie, SRVs or ASDVs plus a guaranteed supply of boiler feedwater (supplied by Class III power).
4. **HTS pressure and inventory control is operational.** If HTS pressure cannot be maintained, boiling may occur in the reactor outlet headers. If excessive boiling were allowed, flow may not be maintainable under two-phase (liquid and vapour) conditions.

The heat transfer paths following loss of Class IV power and under thermosyphoning conditions are shown in Figure 8.5.

(a) Pump Rundown



(b) Thermosyphoning

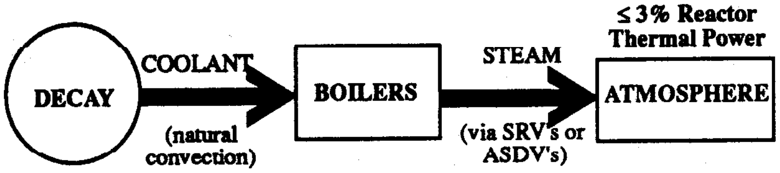


Figure 8.5: Heat Transfer Following Loss of Class IV Power

Crash Cooldown

⇔ Obj. 8.6 d)

Crash Cooldown is a procedure which quickly reduces heat transport system temperature following a system upset.

Boiler pressure (hence, boiler temperature) is **rapidly reduced** by **discharging steam to atmosphere** using either steam reject valves or instrumented safety valves. The rapid reduction in boiler temperature will cause a **corresponding increase in heat transfer rate from the HTS, thus rapidly lowering its temperature.**

It should be remembered that this procedure will, as already indicated for emergency cooling using shutdown coolers, **subject system components to extreme thermal stresses.** A full crash cool, ie. all available steam rejected to atmosphere, would normally **only be effected if a LOCA occurs.** For other unit upsets, which may require rapid cooling of the HTS, a sufficiently fast cooldown will usually be achievable with less than the full complement of steam discharge valves in use.

The heat transfer path for crash cooldown is shown in Figure 8.6.

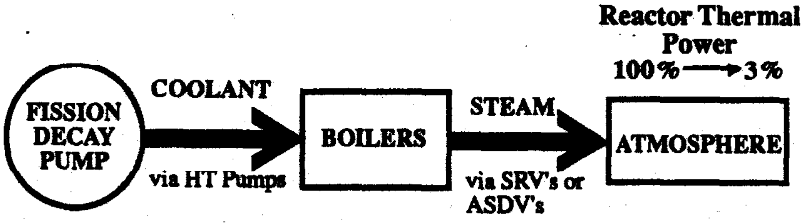


Figure 8.6: Crash Cooldown Heat Transfer Path

Emergency Cooling Using Shutdown Cooling

⇔ Obj. 8.8

If normal cooldown using BPC is not available, **emergency cooldown** of the HTS (immediately following a trip) can be achieved using only the **shutdown coolers by valving in the system without a prior warmup.**

⇔ Obj. 8.9 a), b)

The system is **designed to withstand the thermal shock** which will accompany this procedure, but for a **limited number of times only.** Extensive **repairs, inspections** or equipment **replacement** will be required if this limit is reached.

Following an emergency cooldown, a thorough **inspection** of the shutdown coolers must be carried out and tube sheet integrity assured.

Obj. 8.8 ⇔

The normal maximum capacity requirement for the shutdown coolers during an emergency cooldown is ~ **6-7% of full reactor thermal power.**

SUMMARY OF THE KEY CONCEPTS

- Thermosyphoning is achieved by natural convection between the reactor and the boilers. In the boilers the D_2O is cooled by the boiler water and then falls back to the reactor due the increased density of the D_2O. Hot D_2O is forced up into the boilers where additional heat can be removed. This method of heat removal is capable of removing ~3% reactor full power. Four conditions required to maintain thermosyphoning are:
  - Reactor power ≤ 3% FP (ie. decay heat),
  - BPC is functional to maintain ΔT between HT D_2O and boiler water in the boilers,
  - SRV's or ASDV's are available with a feedwater supply for heat rejection,
  - HTS pressure and inventory control system available to prevent HTS boiling.
- Emergency cooldowns are possible by placing the shutdown cooling system in service at elevated temperatures. Placing this system in service for emergency cooldown subjects the system to high thermal stresses. Inspections of components would be required following an emergency cooldown. The number of times that this system is capable of emergency cooldown is limited. The system capacity required is ~7% reactor full power.
- Crash cooldown is a rapid reduction in HTS temperature caused by discharging large amounts of boiler steam to atmosphere.

Page 13 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. The HTS must be available when the unit is shut down because ____

2. The shutdown cooling system is supplied by Class _____ power. The reason for this choice is____

3. The operation of direct and indirect types of shutdown cooling systems is as follows:

   a) Direct - ____

   b) Indirect - ____

4. The function of the:

   a) Shutdown cooling system is ____

   b) Maintenance cooling system is ____

5. A maintenance cooling system is provided when the method of shutdown cooling is indirect because ______________________

____

____

____

6. For each of the operating states listed below, label the appropriate block diagram (major pathway only) that shows the role of the HTS in transferring heat energy from the heat source to the heat sink.

   a) Zero power hot, pressurized when using a direct shutdown cooling system,

   b) Zero power hot, pressurized when using an indirect shutdown cooling system,

   c) Zero power cold, depressurized when using maintenance cooling,

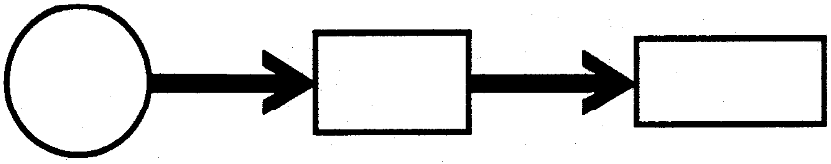
   d) Thermosyphoning,

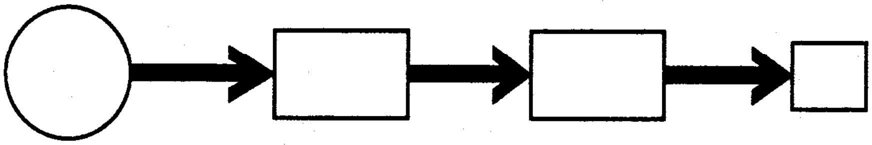
   e) Crash cooldown,

   The diagram must show:

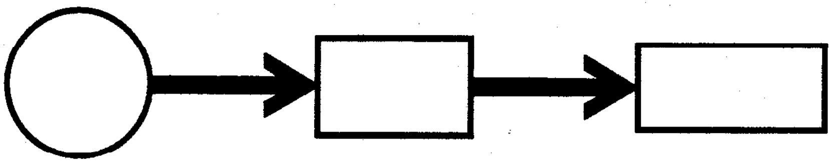
   i) Major heat sources,
   ii) Heat carriers,
   iii) Required pumps,
   iv) Heat energy transfer points,
   v) Heat Sinks,
   vi) Normal capacity of the system in terms of percent (approximate) reactor full power.

Shutdown Cooling
-Direct

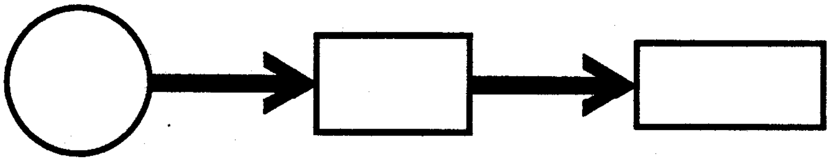




Shutdown Cooling
-Indirect



Thermosyphoning



Crash Cooldown

7. Thermosyphoning is a valid method of heat removal from a CANDU reactor.

a) Thermosyphoning is achieved by: ______________________

____

____

____

____

____

____

b) What four criteria must be met / maintained to ensure the viability of thermosyphoning?

i) ________________________

ii) ________________________

iii) ________________________

iv) ________________________

8. Explain how an emergency cooldown may be achieved without using the boiler system. ________________________

9. Explain the constraints and consequences of the following:

a) Valving in shutdown cooling at high temperatures,

____

b) Too frequent usage of the shutdown cooling system for emergency cooldowns. ________________________

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

Prepared by: D. Tennant, N. Ritter, WNTD
Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 9

HTS HEAVY WATER

OBJECTIVES:

After completing this module you will be able to:

9.1 a) Explain the two reasons why the heat transport system heavy water has a minimum isotopic limit. ⇔ *Pages 2-3*

b) Explain the reason why there is an upper isotopic limit for the heat transport system heavy water. ⇔ *Page 3*

9.2 a) State the four major causes of HTS downgrading. ⇔ *Page 4*

b) State the immediate and long term effects of HT system downgrading for the following conditions: ⇔ *Page 4*

i) Sudden downgrading to the minimum isotopic limit specified in station Operating Policies and Principles,

ii) Sudden downgrading to below the minimum isotopic limit specified in station Operating Policies and Principles,

9.3 a) Identify four potential radiological hazards of heat transport D_2O when the reactor is shut down. ⇔ *Pages 5-6*

b) Identify two additional potential radiological hazards of heat transport D_2O when the reactor is operating. ⇔ *Page 5*

9.4 Explain the major purpose(s) of each of the following systems or components (number of purposes indicated in brackets):

a) Heat transport D_2O collection system (1), ⇔ *Pages 7, 8*

b) Miscellaneous D_2O collection system (1), ⇔ *Page 8*

c) Vapour recovery system (4), ⇔ *Pages 8-9*

d) Liquid D_2O recovery system (1). ⇔ *Pages 9-10*

9.5 State three reasons why there are limits on isotopic and purity of D_2O for return to the heat transport system. ⇔ *Page 8*

9.6 For each of the following abnormal conditions, state the possible significant consequence(s) (number of consequences indicated in brackets):

Pages 10-11 ⇔ a) An abnormally high D_2O recovery/collection rate (over a period of time) (3),

Page 11 ⇔ b) A pressure tube leak (1),

Page 11 ⇔ c) A boiler tube leak (2).

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

A primary distinguishing feature of the CANDU reactor is the use of heavy water (D_2O) both as a moderator and coolant. This section covers the HTS coolant and its requirements with respect to D_2O quality and standards. Radiological hazards of the HTS coolant will also be discussed.

ISOTOPIC LIMITS

Remember that D_2O quality is usually expressed in terms of the percentage of D_2O by mass in a given sample of D_2O and H_2O, ie. **isotopic content**.

Obj. 9.1 a) ⇔ For day-to-day operation of a CANDU unit, a **lower limit is placed on D_2O coolant isotopic**. This lower limit is set for two basic reasons: economy and safety.

1. **Economy**

   Although the coolant plays a very minor role in terms of thermalizing fast neutrons, H_2O in the coolant will directly affect the **amount of neutrons absorbed** and, therefore, removed from the neutron cycle. For example, it is probable that with an HTS isotopic of 90% (ie. 10% H_2O), the Reactor Regulating System (RRS) could still maintain criticality. However, this would be done at the expense of a **higher fuel usage**. This fuel penalty must be traded off against the higher production and upgrading costs.

2. Safety

From a safety point of view, isotopic requirements are related to the potential for voiding in the HTS and the accompanying reactivity effects, particularly as a result of a LOCA.

The presence of H_2O in the coolant **increases neutron absorbtion.** Maintaining criticality requires the **addition of reactivity worth** (ie. lowered zone levels, etc.).

At the onset of a **LOCA**, pressure in the fuel channels is reduced resulting in boiling and the formation of **voids.** The neutrons which were **previously** being **absorbed** are now **available** for **fission.** Positive **reactivity worth** will **increase** rapidly * . Thus, the coolant isotopic must be maintained at a level such that the **excess neutrons** available through voiding are **controllable**, either by RRS or the Special Safety Systems. The normal minimum isotopic value is set by OP&P's at ~97.5%.

For example, it has been calculated that a typical CANDU reactor (600 MW) operating with equilibrium fuel and moderator and HTS isotopic of ~99.7% would experience an increase in reactivity up to 10 mk depending upon the degree of voiding**.

In most stations, an **upper limit** for heat transport system isotopic also exists for **safety reasons** ++. An upper limit on HTS isotopic limits the rate and magnitude of positive reactivity inserted during an in-core LOCA.

Say, for example, that a unit is operating and a LOCA with high isotopic D_2O occurs into the moderator. Any neutron poisons (eg. boron) present in the moderator will be displaced or diluted. This would result in an increase in reactivity, since the neutrons that were previously being absorbed by the poisons are now available for fission. The limits specified in your station will depend on maximum boron (or equivalent poison) loads allowed (eg. excess reactivity, for fuelling ahead), reactor design, moderator isotopic and shutdown system depth (to protect against in core LOCAs while shutdown and not in the GSS).

* This is discussed in more detail in the Nuclear Theory - 227 notes.

** Recall that because of the high isotopic, most of this increase is due to changes in the fast fission factor and the resonance escape probability). This is discussed in more detail in the Nuclear Theory - 227 notes.

⇔ Obj. 9.1 b)

++ This limit may be expressed as a difference between HTS and moderator isotopic.

Downgrading of HTS D_2O

Obj. 9.2 a) ⇔

The following are mechanisms which **downgrade** HTS D_2O during normal operations. All are attributable to H_2O ingress or formation.

1) Accidental additions of **downgraded makeup or collection returns.**
2) Use of **improperly deuterized IX resins** in the HTS purification circuit.
3) **Hydrogen addition** to the HTS (to be discussed later).
4) H_2O from **air in-leakage** to HT D_2O collection system and storage tank (particularly if the systems are opened for maintenance).

The first two sources can potentially be large sources of downgrading. The last two sources will produce small but continuous sources of downgrading.

Obj. 9.2 b) ⇔

Table 9.1 gives some of the expected short and long term operating effects which result from changes in D_2O isotopic.

Table 9.1
Effects of Isotopic Changes on Operation

Change in HT Isotopic From Operating Value of Between 97% - 100%	Immediate Effect on Reactor at Full Power Operation	Long Term Effect on Reactor at Full Power Operation
1 Isotopic slowly increasing due to virgin or upgrader D_2O additions for makeup (typical max ~ 0.05%/month).	No observable effect, isotopic change too small.	Fuelling rate (bundles/week) reduced slightly. Higher average fuel burnup.
2 Sudden downgrading by ≤ 3% to the lowest isotopic allowed by Operating Policies and Principles.	Operation continues with a drop in average liquid zone level (adjuster(s) possibly out).	Increased fuelling rate needed to return (and maintain) zone levels/ adjusters to normal operating positions. Lower average fuel burnup.
3 Sudden downgrading to below the limit in (2).	As above, unless drop in Δk is large enough to make reactor subcritical.	Reactor should be shutdown until minimum HT isotopic is available.

Radiological Hazards

The management and control of HTS coolant inventory must also take into account the radiological hazards which are present under different operating conditions.

During normal power operation, the coolant will contain:

1) **Coolant activation products** - Tritium, Nitrogen-16 (N^{16}), Oxygen-19 (O^{19}).
2) **Fission products** - principal source is failed fuel
   a) Halogen fission products, mainly Iodine-131 (I^{131}).
   b) Other gaseous fission products - mainly noble gases.
3) **Activated corrosion products** - mostly metallic isotopes created by a combination of activation and corrosion of HTS components.

⇔ *Obj. 9.3 a)*

The **activated corrosion products** will be distributed around the system and will tend to "**plate out**" on components. The γ will be capable of penetrating the pipework, causing an **external dose hazard** while operating and when shutdown. Some of the corrosion products will also emit β particles. This will pose an **external β hazard** if the HT D_2O leaks from the system, allowing these materials to leave the system. However, these hazards are greatly increased when carrying out maintenance on system components (eg. close proximity to components or the system is opened).

Most of the gaseous fission products (noble gasses) are short lived and will decay to very low levels in 1 day or less, hence are a major hazard while operating. These contribute to the external dose hazard as mentioned above. In addition to the above, some noble gasses, in high concentrations, can result in **external** β hazards (due to a β-γ decay).

Iodine-131 has a half life of ~8 days. Other radioiodine isotopes will decay in 1 day or less. The **source** of the **radioiodine** is **failed fuel.** The ion exchange columns in the HT purification system will remove the iodine from the system, but some iodine may still be present. Any leakage of coolant from the HT system releases the I^{131} which can result in an uptake *.

* Recall from your radiation protection training that the critical organ for Iodine uptake is the thyroid.

⇔ *Obj. 9.3 b)*

Under **normal conditions** (with the coolant contained within the system) the significance of the above radiological hazards is reduced somewhat due to the shielding provided by the system itself. But, N^{16} and O^{19} are produced in the core and are high energy gamma emitters, which presents an **external γ radiation** dose hazard. There is also a **neutron hazard** as a result of the decay of N^{16} (which emits high energy γ, which reacts with deuterium, resulting in a photoneutron emission). These hazards are somewhat controlled since the majority of the HTS is inaccessible when at-power (ie. within containment or access controlled). Following a shutdown, the formation of activation products will cease and N^{16} and O^{19} will quickly decay (in minutes) to negligible levels.

Any **leakage of coolant** from the HT system presents a major radiological hazard. The external γ hazard still exists (due to D_2O in the HTS and due to halogen fission products leaking from the HTS, N^{16} and O^{19}), but now is accompanied by a **tritium** hazard (internal β) and, possibly I^{131}, as previously mentioned. Note that this will be in addition to the "conventional" hazards posed by hot, pressurized liquids.

SUMMARY OF THE KEY CONCEPTS

- The HTS has minimum isotopic limits for fuel economy and reactor safety (voiding effects).
- The HTS has maximum isotopic limits for reactor safety (protection against in-core LOCAs).
- The four major sources of HTS downgrading are accidental additions of downgraded D_2O, improperly deuterized IX resins, formation of H_2O from H_2 addition and air ingress.
- The addition of downgraded D_2O to the HTS is a major concern because of the economic consequence of downgrading.
- Radiological hazards of HTS D_2O exist while at power and when shutdown. The sources of this hazard are coolant activation products, halogen fission products, gaseous fission products and activated corrosion products.
- While shutdown, the four major radiological hazards are from external γ, external β, tritium and I^{131}.
- While at power, the two major additional radiological hazards are from high energy γ from N^{16} and O^{19} and photoneutrons as a result of the decay of N^{16}.

HEAT TRANSPORT SYSTEM D_2O COLLECTION SYSTEMS

D_2O is very expensive. Chronic, unrecovered losses can impose an **economic penalty** on unit operation. In addition, it also poses a personnel **radiation hazard.**

Since the majority of the HTS operates at **high pressure**, the **likelihood of leakage is increased.** In fact, some equipment will leak small amounts of D_2O during the course of normal operation (eg. pump seals).

HTS D_2O Collection System

⇔ *Obj. 9.4 a)*

This system is provided to **collect the normal, expected leakage** from the HTS. It consists of a closed piping system connected to the various equipment collection points.

Typical collection points are:

- Main circulation pumps seals.
- Bleed cooler drain/vent lines.
- HTS vents.
- HTS valve glands.

The leakage will drain by gravity to a collection tank. The rate at which this tank fills will give an early indication of any high leakage rates.

A representative HT D_2O recovery system is shown in Figure 9.1.

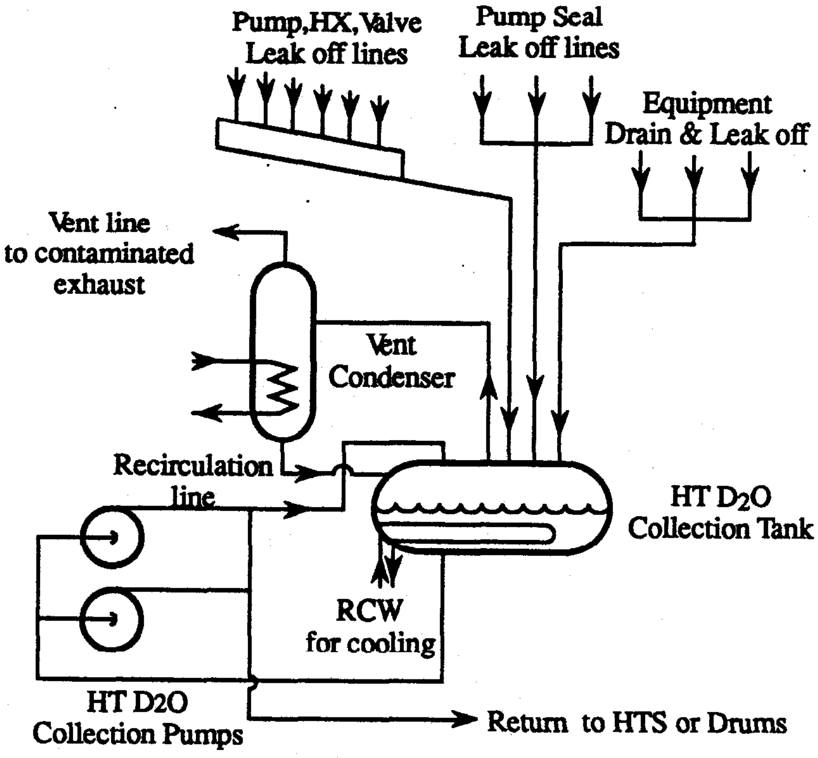


Figure 9.1
D2O Collection System

As much of the D_2O collected is hot, a **cooling system** is sometimes provided in the collection tank. Cooling water is passed through tubing immersed in the collection tank. This is a potential source of D_2O **downgrading** if tube leaks occur.

Any hot D_2O vapour is condensed in a **vent condenser** and the condensate returned to the collection tank. The vent condenser is also a possible source of D_2O **downgrading.**

The collection tank is provided with a high level alarm. When this comes in, the tank contents are recirculated by a pump to ensure thorough mixing of the contents (2 x 100% pumps are usually provided), and are then sampled. Normally, the contents meet specification and the D_2O in the tank can be returned directly to the HTS.

Obj. 9.4 a) ⇔

Leakage to this tank **should not be downgraded.** However, before returning it to the heat transport system, its isotopic should be checked to ensure it meets the minimum requirement (~97.5%) for the same **economic** and **safety** reasons mentioned at the beginning of the module. This D_2O must also be free of contaminants. If this D_2O is contaminated, **activation** of the contaminants or corrosion of the HTS may occur (this will be discussed in the Chemistry 224 course).

Obj. 9.5 ⇔

Miscellaneous D_2O Collection System

Obj. 9.4 b) ⇔

There are likely to be sources of D_2O from leakage points (throughout the reactor system) which **do not meet specifications for return to the system.** These collection points are routed to the miscellaneous D_2O collection system. Possible sources are the HTS collection system if D_2O collection tank contents are outside specification, the feed pump bearings and the contaminated exhaust.

For this system, the collected D_2O is fed to the upgrader or to drums.

Vapour Recovery System

D_2O leakage into the reactor vault atmosphere will form D_2O **vapour**, particularly when the air temperature is above normal ambient temperature. Note that reactor area vapour will not be exclusively D_2O, but will contain H_2O and other components.

Vapour will be routed to a **vapour recovery system** by extraction blowers. This system usually consists of **desiccants** which will **absorb the vapours.** Saturated desiccant is **regenerated** by heating the desiccant and releasing the now concentrated **vapour to a condenser.** The recovered liquid must then be returned to upgrading since it will be downgraded by the H_2O, etc, in the liquid. This system provides four advantages:

Obj. 9.4 c) ⇔

1) It **recovers expensive D_2O.**

2) It allows the **detection** of small chronic leaks.

3) It **reduces** the **atmospheric radiation levels** due to tritium.

4) The extraction action (through the purge driers) **reduces containment pressure** to slightly subatmospheric, thus inhibiting out-leakage to the station and the environment *.

* This is discussed in more detail in Module 13 (Containment).

A typical NGS may have more than one vapour recovery system which might serve areas such as the reactor vault, fuelling machine duct, and fueling areas.

Liquid D_2O Recovery System

⇔ *Obj. 9.4 d)*

The Liquid D_2O Recovery System, installed in most stations, **allows the reactor to be shut down in a controlled manner in the event of a small piping rupture.** The system will **return sufficient D_2O** to the HTS to **maintain cooling** in the fuel channels until the HTS can be cooled and depressurized. "Small" rupture indicates that HTS pressure can be maintained, ie. coolant input capability to the HTS is greater than the losses which are occurring.

Thus, this system **avoids the use of ECIS** with the **major downgrading** of coolant as a result of light water injection (and force the shutdown of the other units at multi-unit stations). This system also avoids the thermal stresses created by crash cooling and ECIS.

The basic system is shown in Figure 9.2.

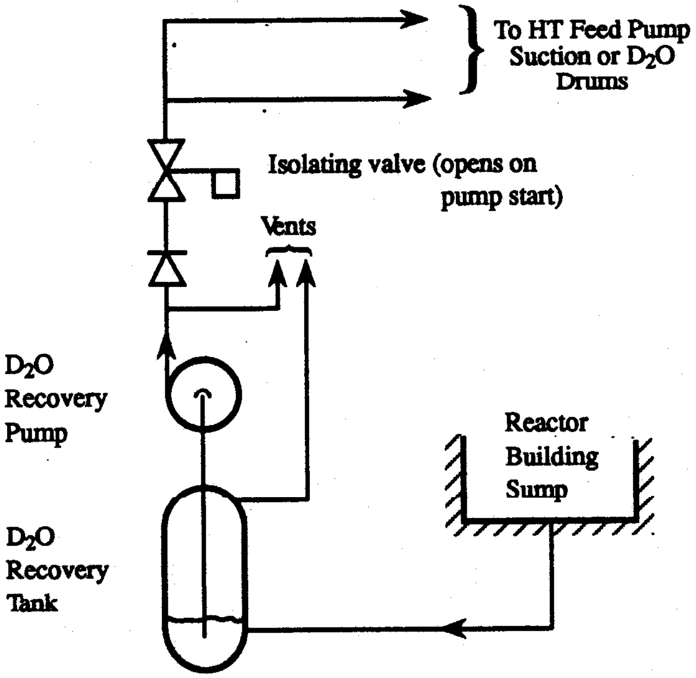


Figure 9.2
D_2O Recovery System

D_2O from the leak gravitates to a **sump and then to a recovery tank**, located at a low level in the reactor building. D_2O from this storage tank can be **pumped either to HTS** feed pump suction **or**, if the leak rate is small enough, **to drums** for subsequent chemical clean up and upgrading. In this latter case, any makeup D_2O required would be supplied from the unit's D_2O storage tank supplemented, if necessary, by additional supplies via the interunit tie (in multi-unit stations).

Note, that for the magnitude of leaks for which this system is designed, it is unlikely that the escaping D_2O, as it flashes to steam in the reactor building, is capable of initiating containment operation. The pressure rise in the reactor building should not exceed the containment PRV operating setpoint (for negative pressure containment systems).

SUMMARY OF THE KEY CONCEPTS

- HT D_2O collection collects leakage from leakage points in the HTS system where the collected water will likely meet specifications for return to the system. This D_2O must be checked for isotopic for the same safety and economic reasons mentioned earlier in the module. Chemical purity must also be checked to ensure corrosion in the HTS and activation of any contaminants are minimized.
- Miscellaneous D_2O collection collects leakage from other places in the HTS system where the collected water will not likely meet specifications for return to the system. This water is drummed or sent directly to upgrading.
- The vapour recovery system recovers D_2O vapours from various locations in the station, allows detection of small chronic leaks, reduces atmospheric levels of tritium and keeps containment pressure sub-atmospheric.
- The liquid recovery system returns sufficient D_2O to the HTS to maintain adequate system inventory to ensure fuel cooling in the event of a small pipe break. This water is recovered from sumps inside containment.

D_2O Leaks In The HTS

The various D_2O collection and recovery systems described can be used as a good indicator of HTS leakage and leak rates, as well as D_2O storage tank level.

Obj. 9.6 a) ⇔

Chronically **high leak rates** have several potentially severe consequences. They are:

1) **Release** of radioactivity (mainly tritium) to the plant and possibly the environment.

2) Potential **loss of HT pressure control** with subsequent fuel cooling problems.
3) **Economic burden** in the form of increased replenishment and upgrading costs.

Other Leakage Indications

Other potential leak points may require additional indications other than those related to D_2O recovery rates. Two such examples are:

1) **Pressure Tubes**

   An early indication of a pressure tube leak can be provided by constantly monitoring the dew point of the **annulus gas**. This reading will only indicate that a pressure tube is leaking - identification of the particular pressure tube will require the use of other identification methods. Thus, a leaking pressure tube may be a **pre-warning of a LOCA**, with its adverse effects.

   ⇔ *Obj. 9.6 b)*

2) **Boiler Tube Leakage**

   A leak in a **boiler tube(s)** will cause high pressure D_2O to enter the secondary system. The consequences will vary depending upon the magnitude of the leak. For example, several leaking (broken) boiler tubes can cause HT pressure to drop and level in the affected boiler to increase due to the inventory transfer from the HTS to the boiler feedwater (this is a LOCA). On the other hand, a small boiler tube leak will not cause such drastic control problems.

   A common consequence for all sizes of boiler tube leaks is the release of radioactivity, principally tritium, into the steam system. This causes the following consequences:

   ⇔ *Obj. 9.6 c)*

   a) **Containment has been breached. Radioactivity can be released** into the environment by **unmonitored** routes, eg. Boiler Blowdown and Condenser Air Extraction, Atmospheric Steam Discharge Valves (ASDV) or Steam Reject Valves (SRV).
   b) The **D_2O is unrecoverable**, constituting an economic penalty.

The subject of boiler tube leaks is covered in more depth in the Turbines and Auxiliaries 234 course.

SUMMARY OF THE KEY CONCEPTS

- An abnormally high leakage collection rate could result in:
    - Release of radioactivity,
    - Potential loss of HT pressure control and fuel cooling,
    - Economic penalty.
- Pressure tube leaks must be corrected since they could result in a LOCA from a failure of the pressure tube.
- Boiler tube leaks result in:
    - Unmonitored releases of radioactivity,
    - Unrecoverable D_2O,

Page 13 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. The two reasons the HTS has a minimum isotopic are:

a) ______________________________. This is a concern because ____________________________

____

____

______________________________________.

b) ______________________________. This is a concern because ____________________________

____

____

______________________________________.

2. The reason that there is an upper limit on HT D_2O isotopic is ____

____

____

3. The four major causes of HT system downgrading are:

a) ______________________________________

____

b) ______________________________________

____

c) ______________________________________

____

d) ______________________________________

____

4. On the following table, indicate the effect of HT system downgrading:

	Short Term Effects	Long Term Effects
HTS Downgrading To The Limits Specified in OP&Ps		
HTS Downgrading To Below The Limits Specified in OP&Ps		

5. a) The four major radiological hazards associated with the HTS D_2O, when shutdown are:

i) ______________________________

ii) ______________________________

iii) ______________________________

iv) ______________________________

b) The two additional major radiological hazards associated with the HTS D_2O, when operating are:

i) ______________________________

ii) ______________________________

6. a) The purpose of the HT D_2O collection system is:

____

______________________________.

b) The purpose of the miscellaneous D_2O collection system is to

____

______________________________.

c) The reason that these two collection systems are kept separated is ________________________________

____

7. The purposes of the vapour recovery system are:

   a) ____

   ______________________________________.

   b) ____

   ______________________________________.

   c) ____

   ______________________________________.

8. The purpose of the liquid D_2O recovery system is ____________

   ______________________________________.

9. A high D_2O collection rate would have the following adverse consequences:

   a) ____

   ______________________________________.

   b) ____

   ______________________________________.

   c) ____

   ______________________________________.

10. The danger associated with a pressure tube leak is ____________

    ____

    ______________________________________.

11. The consequences associated with boiler tube leaks are:

    a) ____
    ____.

    b) ____
    ____.

    c) ____
    ____.

12. The reason that there are limits set on HT D_2O isotopic for D_2O that is to be returned to the HTS is ______________________ and ________________. The reason that there are limits set on HT D_2O purity for D_2O that is to be returned to the HTS is to minimize ____________________________ and ____.

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

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Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 10

HEAT TRANSPORT SYSTEM AUXILIARIES

OBJECTIVES:

After completing this module you will be able to:

10.1 a) For the heat transport purification system inlet temperature, explain three reasons why it is important and describe how it is maintained for: *⇔ Page 4*

- i) Purification systems operating at reduced pressures,
- ii) Purification systems operating at full HTS pressure.

b) For the heat transport purification system flow, explain two reasons why it is important and describe how it is maintained for: *⇔ Pages 4-6*

- i) Purification systems operating at reduced pressures,
- ii) Purification systems operating at full HTS pressure.

c) For the heat transport purification system ΔP across the IX column, explain the reason why it is important and describe how it is maintained. *⇔ Page 6*

d) For the heat transport purification system inlet pressure, explain three reasons why it is important and describe two methods how high pressures are controlled. *⇔ Page 7*

10.2 a) Give two examples of heat transport system conditions that require an increase in the rate of removal of heat transport impurities. *⇔ Page 8*

b) Describe how this increased removal rate is achieved. *⇔ Page 8*

10.3 Explain the purpose of hydrogen addition to the heat transport system and identify when it is required. *⇔ Page 9, 10*

10.4 Explain the major concern associated with each of the following conditions:

Page 9 ⇔ a) Unavailability of the hydrogen gas addition system.

Page 9 ⇔ b) A high rate of hydrogen addition.

Page 10 ⇔ c) H_2, D_2, and O_2 coming out of solution in:

- i) The D_2O storage tank,
- ii) The bleed condenser.

Page 11 ⇔ 10.5 a) State the reason why the gland seal supply system should be available at all times (HT pumps ON or OFF) and,

Page 12 ⇔ b) State the two major purposes of the gland seal supply system.

10.6 Explain why D_2O supplied for gland sealing must be:

Page 12 ⇔ a) Filtered,

Page 12 ⇔ b) Pressurized,

Page 13 ⇔ c) Cooled.

Page 13 ⇔ 10.7 a) State where the back up gland sealing supply comes from and explain how this supply is initiated.

Page 13 ⇔ b) Explain why additional cooling and purification is required for this supply.

Page 13 ⇔ 10.8 State four parameters that are monitored to verify seal problems.

Page 14 ⇔ 10.9 Explain the purpose of the gland return bottle-up valve.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

This module deals with a number of auxiliary systems essential for ensuring the reliable and prolonged operation of the Heat Transport System (HTS).

The systems described are:

1) HTS Purification,
2) HTS Hydrogen Addition,
3) HTS Main Pump Gland Seal Supply.

HEAT TRANSPORT PURIFICATION SYSTEM

Your previous R&A courses have already described the equipment, ie. filters, strainers, and ion exchange columns, required to effect purification of the HTS coolant.

Basically, the purification process has two main purposes:

a) To maintain HTS chemical parameters at specified levels.

b) To remove impurities (crud) from the HTS.

The method of providing the flow to the purification system is site specific. In most stations, purification occurs at a reduced pressure (300-1000 KPa). In other stations, purification occurs at full HTS pressure (9-10MPa). However, some general common parameters exist. A typical purification system arrangement is shown in Figure 10.1.

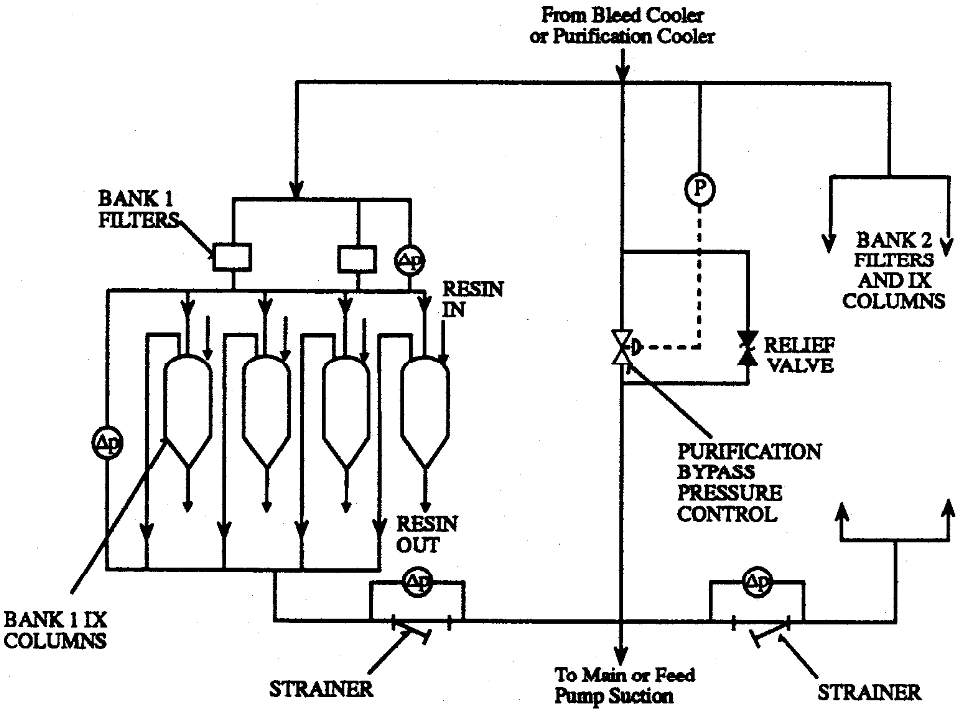

Figure 10.1: Typical HT Purification System

To ensure proper operation of this system, the following parameters must be maintained within limits:

a) Inlet temperature,

b) Flow,

c) ΔP across the system,

d) Inlet pressure.

Each of these parameters is discussed in detail below.

Inlet Temperature

Obj. 10.1 a) ⇔

The temperature of the D_2O coolant feed to the IX columns is **limited to about 65°C** to protect the IX resins from damage. A high temperature in D_2O feed to the IX columns can have the following possible consequences:

a) **Reduction in** ion exchange **efficiency** (particularly anion).

b) Risk of IX bead **melting** and subsequent **migration** into the HTS.

c) **Release** of any residual **chemicals** (eg. chlorides, fluorides) that may exist in the resin. This increases the risk of stress corrosion problems with zircaloy and stainless steel components.

To prevent these consequences, the HTS purification flow must be cooled from reactor operating temperature (~250°C) when the unit is at power. At most stations, a combination of a **bleed condenser and bleed cooler** provide the necessary temperature (and pressure) reduction. At the other stations, where purification occurs at full HTS pressure, the cooling is achieved by **two interchangers and a cooler**. In both cases, the D_2O is partially cooled by D_2O being returned to the HTS, and partially cooled by cooling water. Figure 10.2 shows the purification system arrangement for systems operating at reduced pressure. Figure 10.3 shows the purification system arrangement for systems operating at full HTS pressure.

Flow

Obj. 10.1 b) ⇔

In stations where the purification is performed at a reduced pressure, the flow rate is **adjusted** by varying the **bias on the bleed valves**. A typical maximum attainable flow is 40 kg/s. Assuming IX column performance is normal, this will result in a cleanup half-life of about 60 minutes. (This is the time taken to reduce impurity levels to one half of the original value, assuming no further impurity addition.)

Under normal operating conditions the flow rate will be close to 10 kg/s. Increased flow rates can be selected, for example, to reduce levels of I^{131} in the HTS or to reduce the effects of crud releases*.

* causes of crud releases will be discussed later in this module.

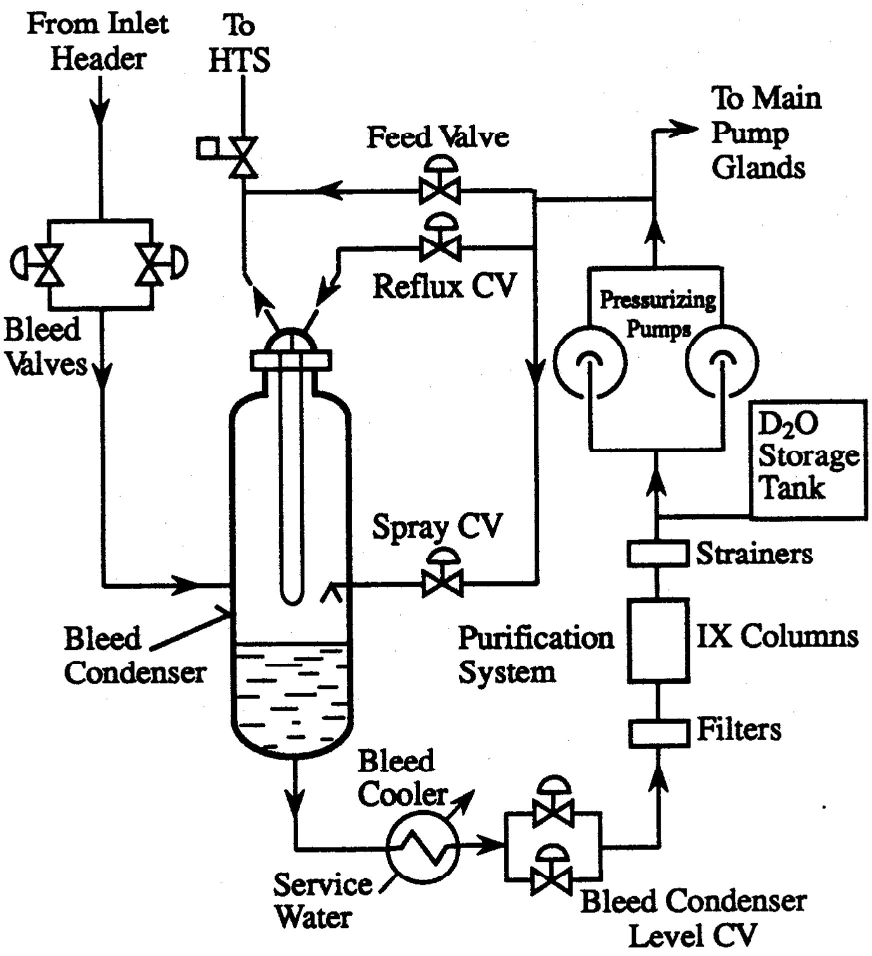

Figure 10.2
Purification System Requiring Pressure Reduction

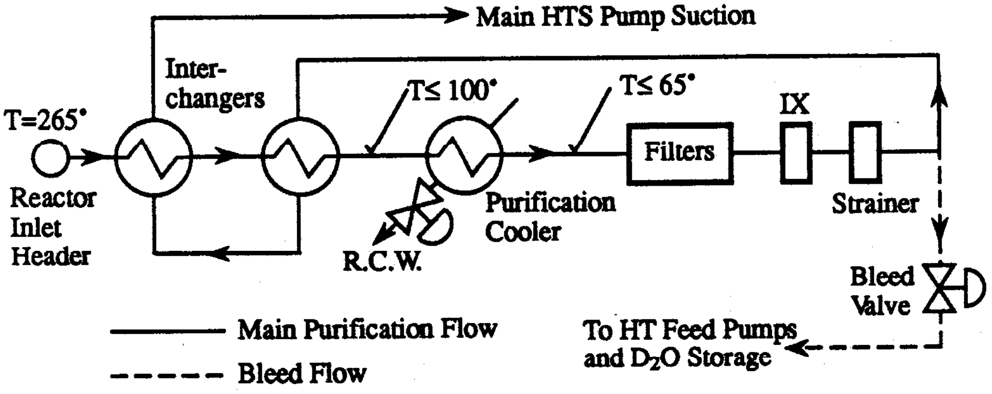

Figure 10.3
Purification System Using Full System Pressure

If this circulating **crud is not removed** from the HTS, subsequent neutron **activation and re-deposition** will create radiological problems in the HTS (increased man-rem). An increased purification flow will remove much or all of these products. But, the removal of these materials in the purification circuit will result in high radiation fields around the filters, strainers and IX columns.

However, purification flows that are **too high** will **reduce IX column efficiency** (ie. coolant does not have enough time in the column to effectively exchange ions).

For stations where the purification operates at full HTS pressure, the purification circuit flow rate is independent of the bleed valve. Purification is achieved via a bypass flow around the main HTS circulating pumps (refer back to Figure 10.3). The operator **manually controls the flow rate** through the purification system by means of a flow control valve. Flow is controlled at an upper limit of ~25 kg/s, equivalent to a purification half life of ~60 minutes.

Note that for the stations where the purification system operates at full HTS pressure, ΔP across the purification system is fixed by the HT system and circulating pump characteristics. Maximum flows are determined by pipe sizes and orifice plates, and are monitored by ΔP transmitters.

The purification flow control can be overriden by any high temperature situation, which may cause resin damage. This was discussed in the last section of Module 7.

ΔP Across Purification

Obj. 10.1 c) ⇔

The filters, IX columns, and strainers are each provided with a differential pressure indicator (as shown in Figure 10.1). Any **increase in ΔP** across the components will result in a **reduction of purification flow**. This could impair the effectiveness of the purification system. For this reason it is important that any increase in ΔP **above specification be corrected.**

For the filters, ΔP indicates the degree of crud accumulation and the need for filter replacement.

A high ΔP across the IX columns indicates an accumulation of solid impurities in the column or compaction of resin fines such that resin replacement may be required.

The strainers which are downstream of the IX columns will collect any IX resin which escapes. A high ΔP across the strainers indicates that strainer cleaning is required.

Pressure At Inlet

⇔ *Obj. 10.1 d)*

Design flow through the purification circuit is achieved by setting a predetermined inlet pressure to cover all expected pressure drops in the system. Inlet pressure that is **too high** will result in **increased** purification **flow** through the IX column with a probable **reduction in IX column efficiency**. In addition, **component overpressure** may result (for systems operating at reduced pressures). This situation may be corrected by either:

a) **Bypassing the purification system** and flowing directly to D_2O storage, or,

b) **Pressure relief valves** on the individual components. These will relieve to D_2O storage.

An inlet pressure that is **too low will reduce purification flow**. Again, this poses a risk of insufficient quantity of HTS D_2O being cleaned.

SUMMARY OF THE KEY CONCEPTS

- The HTS Purification System is designed to maintain HTS chemical parameters within specification and remove impurities from the HTS.
- Purification system temperatures are maintained ≤ 65°C to:
  - Ensure IX column resins do not release chemicals that could cause stress corrosion cracking of reactor components,
  - Prevent resin bead melting and migration into the HTS,
  - Prevent a reduction in IX resin efficiency.
- The purification temperature is controlled by proper cooling of the bleed flow. In the typical purification system, pressure and temperature reduction occurs in the bleed condenser and the bleed cooler. For the stations where the purification system operates at full HTS pressure, the cooling is performed by two interchangers and a purification cooler.
- Purification flow must be maintained at an optimum rate to ensure crud and fission products (I^{131}) are removed. Without purification, this crud could be activated and could re-deposit within the HTS.
- The flow through purification is controlled by the bleed bias. In stations where the purification system operates at full HTS pressure, the flow is manually controlled.
- High ΔP in the purification components would indicate that:
  - Filters are plugged and require replacement or,
  - Strainers are plugged and require cleaning or,
  - Resins are compacted or contaminated with impurities and will possibly require replacement.

- The pressure at the inlet is set to overcome all expected loses in the purification system. An inlet pressure that is too high will result in an excess purification flow and a corresponding decrease in resin efficiency. An inlet pressure that is too low will result in an insufficient purification flow for HTS cleanup.
- The purification inlet pressure is controlled by bypassing purification flow and ultimately by pressure relief valves on individual components.

ABNORMAL OPERATING CONDITIONS

Obj. 10.2 a) ⇔

We have already mentioned in passing that some situations require an **increased purification flow**, ie. reducing radioiodines and reducing effects of crud releases. They will now be explained.

Removal Of Radioiodines

The station licence sets limits for the quantity of radioiodine which may be present in the HTS with the unit at power. The reason for the limit is to protect the public and our employees from exceeding regulatory dose limits, should a release from the HTS occur. The presence of radioiodines in the HTS indicates fuel has failed in the reactor. Purification flow is increased to remove the radioiodine. If the levels exceed those stated in the licence, the unit must be shutdown. Even in the shutdown state, the purification flow will be maintained at a high level to facilitate the removal process. Note that the release of radioiodines from failed fuel may continue even after shutdown, depending on the severity of the fuel failure.

Removal Of Crud

Crud releases ("crud-bursts") can occur during certain reactor operating conditions resulting in thermal or chemical transients, such as HTS warmup and cooldown, reactor power manoeuvering or during normal reactor operation when chemical parameters stray from specification.

Obj. 10.2 b) ⇔

In these instances, primary removal will be by filters and increased purification flow. The **increase in purification** will usually be achieved by either or a combination of:

i) **Increased purification flow**, but recall that there are limits to this,

ii) Place **more purification equipment in-service**. This would increase the time spent in the IX columns by the coolant (ie. for a given flow, the flow would move slower through a larger number of flow paths).

HEAT TRANSPORT HYDROGEN ADDITION SYSTEM

Radiolysis of the HTS coolant while in the reactor core occurs with the resultant formation of D_2 and O_2 gases. These gases will remain in solution under normal HTS operating temperatures and pressures.

The radiolysis reaction is, fortunately, reversible and recombination can be promoted by the addition of H_2 or D_2 gas. D_2 and H_2 will behave identically as far as the reaction is concerned. Either could be used to scavenge the oxygen; the only difference being the end product: D_2O or H_2O.

The choice of gas is mainly economic. In terms of product (gas) cost, hydrogen is much cheaper than deuterium. However, the additional expense of D_2O downgrading must be considered since the addition of H_2 forms H_2O. At the moment hydrogen is used exclusively.

⇔ *Obj. 10.3*

Hydrogen is added to the HTS to **maintain the deuterium/hydrogen concentration**; and hence the **oxygen concentration**, within station **specified limits.**

The hydrogen concentration is monitored (as opposed to oxygen) because of the ease of measuring H_2. This ensures that an optimum amount of H_2 is injected into the system.

Inappropriate addition of hydrogen can result in the following adverse consequences:

⇔ *Obj. 10.4 a)*

a) Insufficient addition of hydrogen will result in the presence of an excess of O_2. Excess O_2 will promote **corrosion** with subsequent component wastage and activated crud (corrosion product) formation.

⇔ *Obj. 10.4 b)*

b) **Excessive addition of hydrogen** is also undesirable since it **promotes embrittlement of the pressure tubes***. Note also that any corrosion would result in some excess of D_2 (H_2) **.

* This is discussed in the Materials 228 course.

** This is discussed in the Chemistry 224 course.

Recall from Module 7 that there is a danger of H_2 coming out of solution at reduced HTS pressure, termed degassing.

Under normal operating conditions, degassing will be generally confined to two areas:

- The D_2O Storage Tank,
- The Bleed Condenser (or Degasser Condenser, depending on the station).

Both have D_2O liquid in thermal equilibrium with the D_2O vapour above.

NOTES & REFERENCES

Obj. 10.4 c) i) ⇔

In the **D_2O storage tank** the cover gas is helium. But H_2/D_2 gas will also be present due to degassing of the radiolysis gases. A concentration of more than about 4% H_2/D_2 gas will require purging to reduce the possibility of an **H_2/D_2 explosion.**

Obj. 10.4 c) ii) ⇔

In the **bleed condenser** the cover gas is saturated D_2O vapour with some O_2, D_2/H_2 and fission product gases (such as Xe and Kr). These gases come out of solution from the HT D_2O when it flashes to steam upon entering the bleed condenser. Being non-condensible at the bleed condenser temperature, these gases accumulate gradually in the bleed condenser atmosphere. They concentrate mainly in the vicinity of the reflux cooling coils because that's where the vapour condenses and leaves the gases behind (a process referred to as tube blanketing). This collection of gases **inhibits reflux cooling** in the bleed condenser.

Compared with areas of the bleed condenser that are more remote from the cooling coils, the partial pressure of vapour around the coils is decreased. Therefore, the condensed liquid that is formed on the cooling coils is cooler than the vapour at the D_2O inlet to the bleed condenser * (where gas concentration is lower). Thus, the ΔT between the vapour at the condenser top and the liquid at the bottom is indicative of accumulation of gases. If the ΔT becomes excessive, the gases are removed through the off gas system. This degassing will remove fission product gases as well as any D_2 and O_2 produced by radiolysis.

* You may recall from 225 and 234 courses that similar apparent subcooling occurs in the turbine condenser if non-condensibles accumulate there.

In units without bleed condensers, degassing is performed in the degasser condenser. A degassing flow is established to the degasser condenser from the HTS or by pressurizer steam bleed flow. The vapour/gas mixture is directed to a vent condenser, then to vapour recovery. Hence, the problem of reflux cooling capacity reduction is eliminated (Note also that only spray cooling is performed in the degasser condenser).

Reactor Shutdown

Obj. 10.3 ⇔

Radiolysis under **shutdown** conditions, is very much reduced and **hydrogen addition is discontinued.** This also reduces the risk of H_2 buildup in the HTS, especially during maintenance, when H_2 could create an explosion hazard.

Hydrogen Supplies

The hydrogen injection supply is from standard hydrogen cylinders. In most stations, the hydrogen addition is located at the HT feed pump suction. Cylinders are declared "spent" when their pressure falls to suction pressure at the feed pumps. Since pumps can become gas locked, the hydrogen supplies must be isolated when the pumps are shut down.

Note also that conventional hazards exist due to handling of pressurized gas cylinders and because H_2 can create an explosive mixture in air.

SUMMARY OF THE KEY CONCEPTS

- HTS warmup/cooldown, reactor power manoeuvres and normal operation with chemical excursions can cause crud bursts. Increased purification is required and will be performed by increased purification flows or valving more purification equipment into service.
- The addition of hydrogen to the HTS through the hydrogen addition system reverses the radiolysis reaction and recombines O_2 (to form H_2O) thus reducing risk of corrosion in the HT system. This system is not required during shutdowns, when radiolysis is much less.
- Increased amounts of non condensible gases (mainly O_2, D_2 or H_2 and noble gases) in the bleed cooler cause reduced efficiency of reflux cooling. Increased concentrations of O_2 with D_2 or H_2 in the D_2O storage tank could result in an explosion hazard.
- Excess hydrogen addition to the HTS increases the risk of hydrogen embrittlement of pressure tubes.

HEAT TRANSPORT GLAND SEAL SUPPLY SYSTEM

⇔ *Obj. 10.5 a)*

The main HTS pumps circulate **hot** (300°C), pressurized (~8-10 MPa) D_2O continuously, while the reactor is at power. Remember this D_2O contains **radioactive materials.** It is important that this **D_2O be contained within the pump** body and gland (which are part of the HTS boundary) **at all times.** To achieve this containment, the pump is sealed along its shaft through a gland.

This gland incorporates a number of mechanical seals (two or three depending on station). This seal arrangement allows a gradual pressure drop (from HTS pressure to atmospheric) in steps across the seals, hence reducing the pressure drop across individual seals. By allowing a gradual pressure drop across the seals (ie. causing some fluid to pass through each seal), a cooling and lubricating D_2O supply is available for the seal. It must also be noted that each of the seals is capable of holding full HTS pressure, but if one fails, redundancy has been lost.

For efficient operation these seals must be continuously supplied with cool, pure, high pressure D_2O. This is accomplished by the gland seal supply system.

This supply system has two main purposes:

Obj. 10.5 b) ⇔

a) To provide a flow of **cool** (~40°C), **filtered D_2O** to the gland for **cooling and lubrication** of the mechanical seals.

b) To provide **high pressure** (~12 MPa) D_2O to the seal cavities, and **thus prevent hot, unfiltered HT D_2O from entering the gland.**

A representative gland seal and supply system is shown in Figure 10.4 (at the end of the module, which can be unfolded and kept in sight for your reference).

The **normal supply** of D_2O for the gland seal supply system is the D_2O storage tank. This D_2O has already passed through the HTS purification system. It is **fed by the HTS feed pumps**, via a filter system, to a gland supply header.

Obj. 10.6 a) ⇔

This bank of filters, under normal conditions, is a precautionary measure. It further reduces the possibility of abrasive particulates entering the gland. Note that the seal faces (carbon and tungsten carbide) are lapped to a high degree of flatness (thousandths of a millimetre) and even the most minute **particles are capable of inflicting damage** and, therefore, causing additional leakage through the seal faces.

A minimal amount of D_2O passes through each seal itself providing lubrication. This **lubrication flow reduces** any **heat** generated by **friction.** This flow will typically be a few cc/minute.

About 10% of the total gland supply D_2O flows between the various seal cavities via seal throttles (or breakdown cells) arranged in parallel with the seal faces. This results in a progressive lowering of D_2O pressure in successive seal cavities. The flow of this cool D_2O from cavity to cavity, via the breakdown cells, will also remove heat from the seal.

Obj. 10.6 b) ⇔

The remainder of the flow is handled in one of two ways, depending on the seal design. In some seals, all of the remaining flow (~90% of total flow) will enter the HTS through the restriction (throttle) bushing. **This flow is the major factor preventing hot D_2O** from the HTS entering the gland and also represents a **constant addition** of D_2O to the HTS **inventory** (ie. bleed valve opening required). In other seal designs, only ~10% of the flow enters the HTS via the restriction bushing (serving the same purpose as mentioned above) and the rest of the flow goes into the recirculation flow in the seal. Note that a majority of this recirculation flow will bypass the seal through ports in the seal housing (not shown in Figure 10.4).

Gland return flow is taken from the final seal cavity. Any leakage across the final seal will be contained by the backup seal and will be directed to D_2O collection.

As previously mentioned, the gland seal requires a supply of cool pressurized D_2O at all times when the HTS is at pressure. The **loss of this supply** would cause rapid **overheating** of the seal because of:

⇔ *Obj. 10.6 c)*

a) The loss of cool D_2O flowing through the seals.

b) The entry of hot D_2O from HTS through the restriction bushing.

This overheating can fail seals in a very short time period, typically minutes (if the gland seal return valve is not closed *). To guard against this, a **backup** gland seal **supply** is provided. It is taken from the main **HTS pump discharge (or RIH) and/or the fuelling machine D_2O supply pumps** ** (only in some stations). This will usually be at a **high temperature** (>250°C) and a some cooling must be provided to cool the D_2O to ~40°C. This cooling is accomplished by the either the recirculation cooler or by the backup gland cooler, depending on the seal design. This D_2O also has a higher level of **impurities**. The in-line **gland filters** are used to clean up the D_2O.

⇔ *Obj. 10.7 a)*

* This will be discussed later in the module.

⇔ *Obj. 10.7 b)*

** Due to limited capacity of these pumps, fuelling cannot continue when this feed is required.

Note that the provision of **check valves** ensures that the backup supply **becomes available immediately** on loss of normal supply. The cooling water to the backup coolers or recirculation coolers (depending on the station) is always in-service. The check valves also prevent interaction between the backup and normal supply under normal conditions.

⇔ *Obj. 10.7 a)*

Since a total loss of seal supply can cause seals to fail in a very short time, it is important to provide control room staff with indications of gland supply problems. These indications include:

⇔ *Obj. 10.8*

a) Individual pump gland **seal flow**.

b) Gland **return temperature**.

c) Gland **interseal temperatures (and recirculation temperature,** where used).

d) Gland **interseal pressures.**

Note that gland filter differential pressure can also be monitored, which may indicate impending flow problems due to filter blockage. This could prevent potential seal damage.

No reactor or HT pump trips are directly initiated from these parameters. Manual intervention by the operator is required to trip the pump or adjust parameter values on alarms which require action.

Gland Return

The return lines from each gland return the D_2O to the feed pump suction. Seal cavity pressure can often be adjusted by manual operation of a valve in the return line.

Obj. 10.9 ⇔

The motorized "**bottle up**" valve can be closed automatically on low gland supply flow. This may be necessary if, for example, feed pumps are lost and backup supplies are not available. This prevents the **much hotter and impure HTS D_2O from entering the gland through the throttle bushing.**

When bottled-up, cooling of gland seal water is now limited to that provided by the recirculation cooler (where installed) or by the cooling water jacket which surrounds the gland (not shown on diagram). Normal gland flow must be restored as soon as possible to avoid seal damage.

SUMMARY OF THE KEY CONCEPTS

- The HTS Gland Seal Supply System must be available at all times to keep the potentially contaminated HTS D_2O within the main pumps (hence within the HTS boundary).
- The HTS Gland Seal Supply System provides clean, cool, high pressure D_2O to the HTS pump glands. This provides cooling and lubrication for the mechanical seals and prevents leakage of the hot, impure HTS D_2O from the main HTS pump bodies from entering the gland. Filtering is required to ensure seal faces are not damaged by foreign particles.
- The backup gland seal supply is supplied from the discharge of the HTS circulating pumps (or RIH) and/or the fuelling machine D_2O supply pumps. This water is hot and impure, hence it requires cooling and filtering before it is supplied to the gland.
- The seal flows, return temperatures, interseal temperatures (and also recirculation temperature) and interseal pressures can be monitored to determine seal condition.
- The bottle-up valve automatically closes on loss of seal flow. This prevents the hotter and impure HTS D_2O from entering the seal.

Page 15 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. a) The temperature of the purification flow must be controlled because:

   i) ______________________________

   ____

   ii) ______________________________

   ____

   iii) ______________________________

   ____

   b) For stations using purification systems at reduced pressure, cooling is provided by the ________________ and the ________________. For stations using purification systems at full HTS pressure, cooling is provided by ______________________ and ________________ ______________________.

2. a) Purification flow is controlled by ________________ in systems operating at reduced pressures. For stations using purification systems at full HTS pressure, purification flow is controlled by ______________________.

   b) High purification flow rates are a problem because ________

   ____

   ______________________________.

   c) Low purification flow rates are a problem because ________

   ____

   ______________________________.

3. ΔP in the purification components is monitored because ________

   ______________________________.

   ΔP is controlled by ______________________________

   ______________________________.

4. a) The pressure at the purification inlet is set to:
    - i) ______________________________________
    ____
    - ii) ______________________________________
    ____
    - iii) ______________________________________
    ____

   b) High pressures in the purification system are controlled by:
    - i) ______________________________________
    ____
    - ii) ______________________________________
    ____

5. Two examples of heat transport system conditions that require an increase in the rate of removal of heat transport impurities are:

   a) ______________________________________.

   b) ______________________________________.

6. Two methods of increasing the rate of impurity removal are:

   a) ______________________________________.

   b) ______________________________________.

7. The purpose of hydrogen addition system ____________________

   ______________________________________. It

   is required (at all times / never / intermittently) when the reactor is

   operating because ______________________________

   ______________________________.

8. a) The major concern associated with the unavailability of the hydrogen gas addition system is ________________________.

   b) An excess of hydrogen in the HTS could cause _____________

   ________________________________.

   c) H_2, D_2, and O_2 coming out of solution in the bleed condenser will cause ____.

   d) H_2, D_2, and O_2 coming out of solution in the D_2O storage tank could cause _______________________________________.

9. a) The two major purposes of the gland sealing supply system are:

   i) ____

   ____

   ii) ____

   ____

   b) The gland sealing supply system should be available at all times because

   ____

   ____.

10. a) The D_2O used for gland sealing must be cooled because

    ____

    ____.

    b) The D_2O used for gland sealing must be filtered because

    ____

    ____.

    c) The D_2O used for gland sealing must be pressurized because

    ____

    ____.

11. The back up gland sealing supply comes from either ____________ ______________________ or ______________________ ____________________, depending on the station. It is placed in service by opening of ______________________ ______________________________________. This supply requires additional ____________________ and ____________________ because damage to the seals could from ______________________ or ______________________.

12. Four parameters monitored to verify seal problems are:

a) ______________________________________

b) ______________________________________

c) ______________________________________

d) ______________________________________

13. The purpose of the gland bottle-up valve is to ______________ ______________________________________ ______________________________________.

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

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Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 11

SHUTDOWN SYSTEMS

OBJECTIVES:

After completing this module you will be able to:

11.1 State the two general abnormal conditions which the shutdown systems are designed to protect against. ⇔ ***Page 2***

11.2 Explain the requirement for a shutdown system. ⇔ ***Page 3***

11.3 a) State two types of shutdown systems (excluding moderator dump) in a typical CANDU station and, ⇔ ***Pages 3-4***

- b) Explain the reason why two shutdown systems are installed. ⇔ ***Page 4***
- c) Explain the reason why each system must be independent of the other and of all other process systems. ⇔ ***Page 5***

11.4 List three features incorporated in a typical shutdown system to increase its reliability. ⇔ ***Page 5***

11.5 State when the shutdown systems must be available. ⇔ ***Page 6***

11.6 Identify the preferred state of the shutdown systems during a unit shutdown. ⇔ ***Page 6***

11.7 Explain the reason why a shutdown system should be a fail-safe system. ⇔ ***Page 7***

11.8 Explain the reason why additional safety interlocks are tied into the shutdown systems. ⇔ ***Page 8***

11.9 a) Explain the difference between an absolute and conditional trip. ⇔ ***Page 8***

- b) For a conditional and an absolute trip: ⇔ ***Pages 8-9***
  - i) State one example of a parameter that will cause a reactor trip.
  - ii) Explain why each of the parameters you have used as an example has been selected.

11.10 For the following situations:

Page 10 ⇔ a) Slow loss of reactor regulation,

Page 10 ⇔ b) Fast loss of reactor regulation,

Pages 10, 11 ⇔ c) Loss of primary heat sink effectiveness.

i) State the common absolute trip parameter (excluding manual) provided to protect against the event.

ii) State the reason why the parameters in (i) were chosen.

Page 12 ⇔ 11.11 Explain the importance of redundant parameters for shutdown system actuation.

Page 13 ⇔ 11.12 State two reasons why SDS No. 1 and/or SDS No. 2 can be actuated manually.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The purpose of the shutdown systems (SDS) is to quickly shut down the reactor by a rapid insertion of large amounts of negative reactivity into the core. This may be required during major process system failures that cannot be safely handled by the Reactor Regulating System (RRS), stepback or setback functions, or other safety related systems.

Obj. 11.1 ⇔ The shutdown systems protect the unit against **two major types of process system failures**:

a) Loss of reactor control.
b) Loss of reactor heat sink effectiveness.

Some of the possible causes of loss of reactor control can be:

a) Removal of negative reactivity from the core (driving adjusters out, draining liquid zones, etc).

b) Failure of the reactor regulating control program.

Some of the possible causes of loss of heat sink can be:

a) Loss of coolant accident (LOCA).
b) Loss of Class IV power (loss of main HTS circulation pumps).
c) Loss of secondary heat sink (loss of boiler feedwater).

Effectiveness of Shutdown Systems

The shutdown systems must be capable of responding to the **worst unit failure or combination of failures** and safely shutdown the reactor to a level which will maintain cooling capability to the fuel. For example, a large LOCA will cause a large increase in reactivity due to voiding of fuel channels. This will produce a large increase in reactor power. It will also reduce heat sink effectiveness by reducing HTS system pressure. A Loss Of Regulation Accident (LORA) can cause a fast increase in reactivity, and consequently a fast rise in reactor power. The shutdown systems must be capable of responding both **quickly** enough and with **enough negative reactivity** depth to **prevent failure of the coolant system boundary** following a process system failure.

⇔ Obj. 11.2

The trip setpoints chosen reflect parameters to prevent fuel melting and subsequent failure. Since we don't have operational experience with fuel centerline melting, we cannot say, with any confidence, that pressure tube failure will not occur if centerline melting occurs. Hence, fuel centerline melting dictates the choice of setpoints for the trip parameters. The only way we can be reasonably sure that centerline melting will not occur is to prevent 'dryout'.

Let us consider another problem. If there is a mismatch between heat production and heat removal, ie. heat production > heat removal, should the reactor be tripped or should the power be brought down through a setback in order to restore the balance between heat production and heat removal? The key to answering this question is time. Typically, a reactor trip will bring the reactor power down to ~6-7% FP in a few seconds while a setback at a typical rate of 0.5%/sec will do the same thing in ~3.5 minutes. It is clear that we cannot afford a serious imbalance in heat production versus heat removal for ~3.5 minutes. Therefore, the reactor must be tripped.

Basically the shutdown systems must insert a larger amount of negative reactivity faster than the positive reactivity buildup created by the unit failure.

Note that both SDS1 and SDS2 are typically actuated in less than one second and that in less than two seconds enough negative reactivity is inserted to terminate any unit failures.

Types of Shutdown Systems

In most CANDU reactors the two types of shutdown systems used are:

⇔ Obj. 11.3 a)

a) Shut-Off Rods (SORs)

This shutdown system uses **shut-off rods** which are stainless steel encased, hollow cadmium (a strong neutron absorber) rods which drop, under gravity, into the core. Vertical guide tubes are located within the calandria to guide the rods while they fall into the core. These rods are normally held above the core by electrically energized clutches, located on the reactivity mechanism desk. When this shutdown system is actuated, the clutches holding the rods above the core de-energize (channelized electrical contacts), allowing the rods to fall into the core (the initial acceleration is assisted by springs, which are compressed by the retracted rods). This makes the reactor deeply subcritical, and thus, reactor power drops quickly to a low level.

b) Liquid Poison Injection

The liquid injection shutdown system operates by **injection of gadolinium nitrate**, under pressure, through horizontal dispersion lines into the moderator. Gadolinium, like cadmium, is a strong neutron absorber. This system consists of several gadolinium nitrate (poison) tanks, which can have their contents driven into the core by pressurized helium. When this shutdown system is actuated, helium pressure is applied to the poison tanks through channelized valves. The poison is then displaced and distributed into the moderator, causing the same effect as the SORs, a rapid drop in power to a low level.

It is possible to quickly reset the shutoff rod trip (if the cause of the trip is known and corrected), thus avoiding a poison outage. Recovery immediately after a liquid poison injection trip is impossible, due to the length of time required for the moderator purification system to remove the poison. This is why the SOR trip (SDS1) is the preferred SDS and is actuated first.

Other Shutdown Systems

A few early CANDU units use moderator dump to provide a shutdown. This is accomplished by dumping the moderator into a separate "dump" tank below the calandria. With the moderator out of the calandria, the fast fission neutrons are not slowed or thermalized, hence, reactor power drops to a safe, low level.

Because of its relatively slow action time, moderator dump is not a primary method of achieving a shutdown . It will only be used if the shut-off rods do not reduce reactor power quickly enough.

Safety Design Principles

Obj. 11.3 b) ⇔

For additional **safety, two** shutdown **systems** are provided. SDS1 must be capable of safely shutting down the reactor in the absence of SDS2, and likewise, SDS2 must be capable of safely shutting down the reactor in the absence of SDS1.

In order to prevent faults in one safety system from affecting another system, the shutdown systems are **functionally independent** from:

⇔ *Obj. 11.3 c)*

- Each other,
- The reactor regulating system,
- Any process system, for example, SDS1 uses power to cause the contacts to open, SDS2 uses air actuated valves to cause the poison injection,
- The other safety related systems, ie. ECIS, containment.

Each SDS is independent from the other in two aspects:

1. Functional independence is achieved by designing the two shutdown systems on two different principles: mechanical insertion of a strong neutron absorber and chemical poisoning of the moderator by a neutron absorber.
2. Geometric independence is achieved by the vertical insertion of shut-off rods while the liquid poison is injected through horizontal tubes into the core.

To increase its reliability, the following three features are incorporated in a typical SDS:

⇔ *Obj. 11.4*

1. The means of measuring the unit variables and actuating the two shutdown systems are separated and duplicated (**independent**). For example, the detectors for each channel are separated and independent with their power, air and water supplies from different sources. The individual instrumentation channels for each shutdown system also follow a physically separate route through the station. This approach reduces the probability that any credible event will simultaneously affect both safety systems on more than one channel.
2. Each shutdown system is configured in a **triplicated** channel format (also called "2 out of 3 logic") (**redundant**). Shutdown action is initiated when the setpoint of any two of the three shutdown (trip) channels are exceeded by any unit variable or combination of variables. This triplication has the following advantages:
   - **On-line testing** and maintenance of individual channels is possible.
   - The unit is not shut down due to a single spurious trip signal.
   - One channel can fail without disabling the system.

   If a component fails unsafe (ie. channel, or parameter, does not trip), there are still two channels which will cause a trip. If the component fails in a safe state (ie. channel (or parameter) trips), the reactor does not trip, because 1 additional channel is required to trip. (Note that the probability of failure is small, which makes two simultaneous failures highly improbable). The safe failure will be annunciated because it trips the channel or parameter. The unsafe failure may only be discovered by testing. The test frequency has been chosen to demonstrate that the required reliability targets are met (ie. minimize unavailability).

3. The selection of **quality** components for the shutdown system also increases the probability that the system will function as designed.

Availability

Obj. 11.5 ⇔

Because the SDSs are so essential for reactor safety, the reactor must not be operated if either shutdown system is not functional. Sufficient shutdown capability has to be **available at all times** to safely terminate any unit failure or combination of failures.

The reactor must be placed in the guaranteed shutdown state (GSS)* if a SDS is to be removed from service. Note that only one SDS would normally be removed from service at any given time.

Obj. 11.6 ⇔

During unit **shutdowns**, it is **preferred** to keep the shutdown systems **poised**. This ensures that the shutdown systems are ready to trip the reactor, should the need arise (eg. to stop a LORA from low power).

* The guaranteed shutdown state places the reactor in a condition where the reactor cannot go critical due to worst credible process failures. The specific details will be provided in your station specific training.

SUMMARY OF THE KEY CONCEPTS

- The shutdown systems protect against loss of reactor control and loss of heat sink effectiveness.
- The shutdown system must insert enough reactivity depth quickly enough to counteract any unit failure or combination of failures to prevent coolant system boundary failures.
- Two shutdown systems are provided for additional safety. The two systems use shut off rods and liquid poison injection. The shutdown systems are independent of each other, all process systems and all other special safety systems to prevent faults in one system from affecting another.
- Three features incorporated to increase shutdown system reliability are:
  - Independence of components,
  - Use of triplicated channel format, allowing for on-power testing,
  - Selection of high quality components for use in the shutdown system.
- The shutdown systems must be available at all levels of reactor operation. During shutdowns the shutdown system protects against unexpected power increases.

Fail Safe Feature

⇔ *Obj. 11.7*

We have to ensure that the shutdown systems are fail-safe. This means that, in the **event of equipment, power or other failures** of the shutdown systems, **they will shut down the reactor** (even though it may not be the result of an actual trip). This assures that reactor power will be reduced if the shutdown system fails. Fail safe, in this case, means that failure of a component or channel should cause the device(s) to go to the position that they would go to if the system was tripped.

For example, in the case of SDS1, the SORs are held above the core by energized clutches. If a power failure to the clutches occurs, the clutches are de-energized and the SORs drop into the core, shutting down the reactor.

In the case of SDS2, helium under pressure is isolated from the poison storage tanks by pneumatically actuated air-to-close valves. If an instrument air failure occurs, and the valve actuator loses pressure, the valves will open. The pressurized helium will then drive the poison from the storage tanks into the core, shutting down the reactor. (Note that in practice, these valves are provided with air reservoirs (connected to the actuator) which fill under normal operating conditions to instrument air system pressure via a non return valve . The non return valve prevents the air in the reservoir from re-entering the failed air system. A loss of air supply will not then automatically cause a trip, since the stored air will keep the valve in its closed position. Also note that a genuine trip will dump the air in a normal manner).

This fail safe feature cannot accommodate all failures. Examples of failures that cannot be guarded against are helium injection valves sticking closed or SOR being stuck out of the core. This type of failure would be detected by the safety system tests, and is one reason why we perform tests on these passive systems (ie. this type of failure is not annunciated).

Interlocks

When a shutdown system trips the reactor, the reactor regulating system is signalled and will not attempt to raise power levels. It will also take the following additional safety steps to augment the trip:

- Fill the liquid zones,
- Drop control absorbers (CA) into the core,
- Lower the reactor power setpoint.

The main purpose of these additional safety steps is to ensure that the reactor regulating system is supporting the actions of the shutdown system (note also that CA insertion prevents the reactor from going critical on withdrawal of the SORs when the trip is reset).

While the reactor is tripped, interlocks prevent the removal of moderator poison and the driving out of control absorbers and adjuster rods and prevents insertion of boosters (depending on the station). **This prevents an inadvertent reactivity increase.**

Obj. 11.8 ⇔

The interlock restrictions remain in force until the shutdown systems are functional again (poised).

Absolute and Conditional Trips

Reactor trips are of two types:

- Absolute and,
- Conditional.

Obj. 11.9 a) ⇔

An **absolute trip** is **a trip that is functional at all states of reactor power.**

Obj. 11.9 b) ⇔

Rate Log is an absolute trip. Its trip value for SDS1 is set at 10% Present Power (PP)/second at any power. If the reactor power increase is too fast to be safely handled by the reactor regulating system, the shutdown systems will trip the reactor.

Further examples of absolute trips are:

- High Neutron Power, which will provide protection against fuel overrating at all times.
- Heat Transport High Pressure, which will provide protection against HT overpressure and damage resulting in a LOCA.

Obj. 11.9 a) ⇔

A **conditional trip** is valid **only above a certain power limit.** Conditional trips allow the unit to be shutdown without tripping the reactor, keeping the shutdown system poised for use. Depending on the parameter, these trips can be conditioned out at different levels.

The conditional trips also protect against reactor power increases from low power by being reactivated at the conditioning level. As reactor power increases, the trip conditioning parameter will be met at the appropriate power level and will trip the reactor preventing any further power increase.

Obj. 11.9 b) ⇔

For example, low HT pressure is a conditional trip. This low HT pressure trip protects against dryout at high power conditions (ie. prevent film boiling/dryout *). During a reactor shutdown and cooldown, HT pressure can be lowered. As reactor power is lowered to below the conditioning level, the low HT pressure trip is conditioned out. This prevents an unwanted reactor trip. At low power levels, the fuel will be "cold", and dryout is less likely to occur. At the lower HT pressure, reactor safety is not compromised because heat removal capability from the fuel is not impaired. But say that the reactor power increases

* Dryout is discussed in Module 16.

unexpectedly from the low power state with low HT pressure. At powers above the conditioning level, boiling and dryout may occur in the HT system as the fuel temperature increases. The power increase would cause the reactor to trip when power reached the trip conditioning level, preventing dryout.

Another example of a conditional trip is heat transport gross coolant low flow. For example, the trip setpoint for this variable is typically set between 75% and 90% nominal flow, provided the reactor power is greater than ~1% FP. If reactor power is below ~1% FP, then this trip is conditioned out. Full coolant circulation is not required to remove this heat, ie. alternate heat sinks have this capacity. Even with the reduced circulation, dryout will not occur, since the fuel is "cold". This conditioning trip allows the main HT pumps to be shut down during a unit shutdown. An increase in reactor power above the conditioning level without adequate coolant circulation would cause the reactor to trip, preventing dryout.

Further examples of conditional trips are:

- Boiler Low Level,
- Pressurizer Low Level.

SUMMARY OF THE KEY CONCEPTS

- The shutdown system must be a fail-safe system to trip the reactor should any component or energy supply for the system fail.
- The purpose of interlocks with shutdown systems is to prevent inadvertant reactivity increases.
- An absolute trip parameter is a trip parameter that is valid at all levels of reactor operation. A conditional trip parameter is only valid above a certain reactor power level. This allows the shutdown system to remain poised (its desired state) during a shutdown.

Trip Protection

Key neutronic and process system variables are monitored at all times. These unit variables have "trip" setpoints. When the key unit variables exceed the trip setpoints on two of three channels, the shutdown system is actuated and will trip the reactor.

Note that the shutdown system trip setpoints for SDS1 and SDS2 are staggered to allow SDS1 to trip first, thus making a trip recovery possible. This is discussed further in the Staggering of Trip Setpoints section on page 13.

The most common key variables are listed on the next few pages.

1. **High Neutron Power**

   Obj. 11.10 a) ⇔

   The trip value is set below the level at which the fuel bundle power ratings (critical channel power) would be exceeded. This prevents excessive power increases resulting from a large LOCA (where channel voiding has taken place) or during a **LORA** (where the rate is low enough to not trip on neutronic rate and not increase HTS pressure beyond the pressure and inventory control capabilities).

2. **Neutronic Rate (Log or Linear)**

   Obj. 11.10 b) ⇔

   Its trip value is set to a level which prevents the reactor power from increasing too fast, ie. rate that RRS cannot effectively limit the peak power reached (loss of reactor control). This could occur during a large LOCA as mentioned above or during a fast **LORA**.

3. **Heat Transport Pressure High**

   Obj. 11.10 a & c) ⇔

   This trip is used to protect against excessive overpressurization of HT system due to the **loss of heat sink effectiveness.** This also protects against accidents like a slow (or "moderate") **LORA** (ie. pressure and inventory control system cannot accommodate swell), loss of feedwater and loss of Class IV power.

4. **Heat Transport Pressure Low**

   It trips mainly to cope with the effects of LOCAs and steamline breaks (ie. causing a rapid collapse of HTS pressure). This prevents the critical channel power from decreasing due to a decrease in HT pressure. This will prevent dryout and the resultant fuel overheating and failure.

5. **Heat Transport Gross Coolant Low Flow**

   It is used as a trip variable to cope with the effects of LOCAs and loss of Class IV power (ie. reduced HTS circulation due to pump trip). This prevents the critical channel power* from decreasing due to a decrease in HT coolant flow. This will prevent dryout and the resultant fuel overheating and failure.

   * More about critical channel power can be found in the 225 Thermodynamics course and in Module 16.

6. **Pressurizer Low Level**

   It trips to deal with the effects of accidents causing a shortage of HT D_2O inventory, like LOCAs or steamline breaks (causing coolant shrinkage and pressure reduction, see also HT Low Pressure trip).

7. **Boiler Low Level**

   It is used as a trip variable to deal with the effects of failures in the steam and feedwater system, ie. steamline breaks and feedwater breaks. This parameter trips the reactor if the boilers are lost (or anticipated to be lost) as a heat sink.

8. **Boiler Feedwater Low Pressure**

   It trips to cope with the effects of failures in the feedwater system, ie. feedline breaks, pump failures, etc. This parameter trips the reactor if the boilers are lost (or anticipated to be lost) as a heat sink.

9. **Moderator Temperature High**

   It trips to deal with the effects of the loss of heat sink to the moderator *. In stations using boosters, high booster coolant (moderator) temperature will trip the reactor to prevent booster damage.

* Note that the moderator also will serve as an ultimate heat sink to the HTS in a major accident (where fuel channels overheat and sag until they contact the calandria tube). It also prevents excessive thermal stresses between the end shield and the calandria.

10. **Reactor Building High Pressure**

    This trip deals with the effects of a LOCA or feedwater/steamline breaks inside containment.

11. **Heat Transport High Temperature**

    It is used to cope with the effects of fuel overheating and HTS overpressure protection (ie. as a back-up) for a **loss of heat sink effectiveness**. (Non-boiling reactors only).

⇔ Obj. 11.10 c)

SUMMARY OF THE KEY CONCEPTS

- A fast LORA will cause the reactor to trip on NEUTRONIC RATE. Rate parameter was chosen because the rapid power increase will be detected and will trip the reactor.
- A slow LORA will trip the reactor on HIGH NEUTRON POWER and/or HIGH HEAT TRANSPORT PRESSURE (depending on the rate of power increase). If reactor power increases cause a large HTS swell as heat input is increased, the HTS pressure will increase, hence, this is the reason for this choice of parameters. If the reactor power increase is slow enough to keep the pressure increase within the capacity of the pressure and inventory control system, the reactor power will rise to the high neutron power trip setpoint, hence, this is the reason for this choice of parameters.
- A loss of heat sink effectiveness will trip the reactor on HIGH HEAT TRANSPORT PRESSURE OR HIGH HT TEMPERATURE. These parameter have been chosen because the reduction in heat sink effectiveness will cause the HTS temperature to increase, causing an immediate swell in the HTS. The boiler low level trips and boiler feedwater low pressure will also protect against the reduction of heat sink capability (as backup trip parameters).

Redundant Parameters

The unit has many combinations of possible trip parameters:

For excessive heat production (beyond the capacity of heat sinks),

- Neutronic Rate,
- High Neutron Power.

For **mismatch between heat production and heat removal,**

- Heat Transport Pressure High,
- Heat Transport Temperature High

Impending mismatches are protected by

- Boiler Low Level,
- Boiler Feedline Low Pressure,
- Moderator Temperature High ensures that heat balance is maintained in the moderator.

For **loss or impending loss of HT system,**

- Heat Transport Gross Coolant Low Flow,
- Boiler Room Pressure High,
- HT Low Pressure,
- Pressurizer Low Level.

Obj. 11.11 ⇔

The point to make here is that, for the same unit failure, the unit has a **combination of trip protections**. Should one or more trip protections fail, others will shut down the reactor. These **redundant parameters are an important design feature which contribute considerably to the safety of CANDU** reactors.

As an example, a combination of effects/trip protections **for a LOCA** could be:

a) Voiding in the pressure tubes. This causes a steep rise in reactor power due to positive void reactivity coefficient. **Neutronic rate** and **high neutron power** trips provide protection.

b) Depressurization of HT system due to loss of D_2O coolant. **Heat transport pressure low** trip provides protection.

c) Increasing boiler room pressure. The HT system D_2O, escaping at high pressure and temperature flashes into steam causing an increase in pressure. **Boiler room high pressure** trip is available.

d) Decrease in the coolant flow if an inlet header should rupture. D_2O designated for channel flow would be lost from the break. **Heat transport gross coolant low flow** trip is available.

e) Decreasing level in the pressurizer through the loss of HT system D_2O. **Pressurizer level low** trip is available.

Staggering of Trip Setpoints

Note also that the trip setpoints are staggered for SDS1 and SDS2 to avoid actuation of both shutdown systems in the same time. This keeps the SDS2 poised and ready to fire, should SDS1 fail to lower reactor power. Also, a recovery from a trip is possible with SDS1 if the cause of the trip can be identified and corrected quickly. With SDS2 we do not have this option because poison removal from the moderator takes too long. Therefore, once SDS2 has fired, a poison outage cannot be avoided.

For an example of the above, typically the RATE LOG trip value is set at 10% PP/second for SDS1 and 15% PP/second for SDS2 .

Manual Trips

If the operator has reason to believe that a serious unit failure has occurred or an automatic trip has failed, the **reactor must be tripped manually** even if an automatic trip has not occurred (yet). This is an extra safety feature added to CANDU reactors.

⇔ Obj. 11.12

SUMMARY OF THE KEY CONCEPTS

- Redundant parameters ensure that the reactor trips even if a trip parameter should fail. This is an additional safety feature for the shutdown system design.
- For enhanced reactor safety, the reactor is to be tripped manually if the operator believes that a serious unit failure has occurred, even if the reactor has not tripped on its own.

You can now **work on the assignment questions.**

⇔ Page 15

ASSIGNMENT

1. The two situations that the shutdown systems are designed to protect against are:

   a) ______________________________

   b) ______________________________

2. a) The requirement for a shutdown system is:

   ____

   ____

   b) These requirements are put in place in order to ______________

   ____

   ______________________________.

3. a) Two typical types of shutdown systems are:

   i) ______________________________

   ii) ______________________________

   b) Two shutdown systems are provided because ______________

   ______________________________.

4. A shutdown system must be completely independent of:

   a) ______________________________.

   b) ______________________________.

   c) ______________________________.

   d) ______________________________.

   This is because ______________________________

   ____

   ______________________________.This

   independence is achieved by ______________________

   ____

   ____

   ____

   ______________________________.

5. Three features incorporated to increase the reliability of the shutdown systems are:

   a) ______________________________

   b) ______________________________

   c) ______________________________

6. The shutdown system must be available ______________________________. During periods of reactor shutdown, the shutdown systems must be ______________________________ to prevent ______________________________.

7. a) The shutdown systems must be fail-safe systems because ______________________________

   ____

   ____

   ______________________________.

   b) The system has additional interlocks in order to ______________________________

   ____

   ______________________________.

8. An absolute trip parameter is valid for ______________levels of reactor power operation. A conditional trip parameter is valid ______________________________.

   Conditional trips are required because required because ________

   ____

   ______________________________.

9. A fast loss or reactor power regulation will trip the reactor on ______________________________. This parameter was chosen because ______________________________

   ____

   ____

   ______________________________.

10. A slow loss or reactor power regulation will trip the reactor on

    ______________________ or ___________________________.

    These parameters were chosen because ____________________

    ____

    ____

    ____.

11. A loss of primary heat sink effectiveness will trip the reactor on

    __________________ or ____________________________.

    This parameter was chosen because _______________________

    ____

    ____

    ____.

12. Redundant parameters are important because ________________

    ____

    ____

    ____.

13. The reactor should be tripped manually when

    a) ____

    b) ____

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

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Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 12

EMERGENCY COOLANT INJECTION

OBJECTIVES:

After completing this module you will be able to:

12.1 State the purpose of the Emergency Coolant Injection System (ECIS). ⇔ ***Page 2***

12.2 State what is meant by a Loss of Coolant Accident (LOCA). ⇔ ***Page 3***

12.3 a) State the key parameter that will cause a reactor trip for: ⇔ ***Page 3***

i) A large LOCA,

ii) A small LOCA.

b) State the parameters that must be satisfied before ECI will be initiated. ⇔ ***Page 4***

12.4 State the other safety system (beside SDSs or ECIS) which may be activated following a LOCA. ⇔ ***Page 4***

12.5 State, in the order in which they occur, the three operational phases of the ECIS and explain their purpose. ⇔ ***Pages 5-7***

12.6 Explain three reasons why ECIS initiates a crash cooldown. ⇔ ***Page 5***

12.7 Explain two reasons for continued HT pump operation for as long as possible following a LOCA. ⇔ ***Pages 5-6***

12.8 Describe the sequence of operation of the following major components and their function in the operation of ECIS: ⇔ ***Pages 8-9***

a) ECI water storage tank,

b) Accumulator tank or injection pump(s),

c) Injection valves,

d) Recovery sump,

e) Recovery pumps,

f) Recovery heat exchangers.

NOTES & REFERENCES

Page 10 ⇔ 12.9 List three features incorporated in a typical ECIS to increase its reliability.

12.10 State what is meant by the terms:

Page 10 ⇔ a) Poised,

Page 10 ⇔ b) Blocked,

Page 11 ⇔ c) Recallable.

Page 10⇔ 12.11 State the two major consequences or concerns associated with a failure to block ECIS before depressurization of the heat transport system.

Page 11 ⇔ 12.12 List the required reactor state when the ECIS is blocked.

Page 11 ⇔ 12.13 State two reasons why ECI can be initiated manually.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

This module will cover the purpose of the ECIS system, its initiation and operation. A typical system is shown in Figure 12.1, which is at the end of the module. This figure can be unfolded and kept in sight for your reference.

PURPOSE OF THE ECIS

The Emergency Coolant Injection System (ECIS) is an integral part of the "Defence in Depth" philosophy which governs the operation of CANDU reactors. Recall that this philosophy considers the presence of five separate barriers designed to minimize the release of fission products to the environment. These are:

- Ceramic Fuel,
- Fuel Sheath,
- Pressure Tube,
- Containment,
- Exclusion Zone.

Obj. 12.1 ⇔ The ECI system is poised with the unit in a normal operational state. It will automatically operate to cool the heat transport system in the event of a loss of coolant accident. A flow of light water is injected to refill the HT system; re-wet the fuel and **provide a heat sink** for any residual and decay heat.

Note for large breaks, the coolant discharged from the break will be sufficient to carry heat from the fuel (although the boilers are still the primary heat sink). In the case of smaller breaks, where the discharge of coolant is not sufficient to cool the fuel, alternate methods of heat removal must be used (eg. in the boilers by maintaining coolant circulation as long as possible *).

* This is discussed in more detail on page 5 of this module.

The amount of fission products released from the fuel after a LOCA will depend on the size of the LOCA and how well ECIS has performed. When ECIS is fully functional and copes with a LOCA, a large number of fuel failures is not expected *.

* This assumes that the SDSs quickly reduce reactor power to decay levels.

If for any reason the automatic operation of ECIS fails, the operator can intervene at any point in the sequence of operations and manually initiate ECI.

LOSS OF COOLANT ACCIDENT (LOCA)

⇔ *Obj. 12.2*

A **LOCA** is defined as a leak of D_2O from the HT system causing sustained low HT pressure. This would mean that normal HT pressure cannot be maintained or pressure recovery to normal levels is not anticipated within a defined time, usually five to ten minutes.

Examples of a loss of coolant (LOCA) from the HT system could be:

- A header break.
- A pressure tube or feeder break.
- Failure of an ice plug while the system is open for maintenance during a shutdown.

The operator can detect a LOCA during a shutdown by a loss of HT inventory.

Support System Requirements

⇔ *Obj. 12.3 a)*

Effective operation of the ECIS must follow operation of either or both Shutdown Systems (SDSs). On **large LOCAs**, the leak will cause the HT pressure to fall, which will cause the coolant in the HTS to flash to steam (voiding). The void coefficient results in a large positive reactivity increase and a rapid rise in reactor power. The reactor regulating system tries to control this power increase, but is not designed to handle such rapid insertions of positive reactivity. Consequently, there will be an automatic shutdown of the reactor by SDS1 and/or SDS2 initiated by a log rate and/or high neutron power trip.

For **smaller LOCAs**, eg. rupture of a small feeder or instrument line, the loss of HT inventory will be slow enough that the regulating system can cope with the resultant power increases.

Under these conditions, the reactor trip will be initiated by non-neutronic trips, such as low HT pressure or low pressurizer level.

Obj. 12.4 ⇔

For the larger LOCAs, the resultant rise in reactor vault pressure due to the escaping coolant flashing to steam will almost certainly cause features of the **containment system** to come into operation. This action further reduces the risk of large quantities of radioactive fission products being released to the environment. This issue will be discussed further in the module on containment.

ECI System Initiation

Obj. 12.3 b) ⇔

The ECI system will automatically operate when a majority vote (2 out of 3, or 3 out of 4 channels, depending on the station) is received on the **primary and at least one conditioning parameter** (which are also channelized). For all CANDU stations, the primary parameter is **low HT system pressure**. The pressure, (typically ~5 MPa), is well below the HT pressure that would cause a reactor trip (typically 7 to 8 MPa).

The conditioning parameter distinguishes the event as a LOCA, as opposed to a process failure. For example, low HT pressure can be caused by a loss of HT feed, but low HT pressure in conjunction with rising vault pressure could indicate that a loss of coolant is occuring to the vault.

The conditioning parameters in use vary with the station, but may include high vault temperature or high vault/boiler room pressure, high moderator level (for LOCA into the moderator), sustained low HT pressure and low HT flow.

SUMMARY OF THE KEY CONCEPTS

- The purpose of the ECI system is to provide a heat sink to the fuel in the event of a LOCA to protect the first two barriers to fission product release.
- A loss of coolant accident (LOCA) is defined as a leak of D_2O from the HTS causing sustained low pressure.
- SDS trip parameters for large LOCA's are neutronic trips. SDS trip parameters for small LOCA's are low HT pressure or low pressurizer level.
- Containment system actions will be required for a LOCAs into containment.
- The major ECI initiating parameter for a LOCA will be low HTS pressure combined with at least one conditioning parameter. Typical conditioning parameters are high reactor vault temperatures and pressures, boiler room high pressure, high moderator level, low HT flow and sustained low HT pressure.

ECI SYSTEM PHASES

There are three principal operational phases: ⇔ *Obj. 12.5*

a) **Blowdown,**
b) **Injection,**
c) **Recovery.**

Blowdown

Once the reactor has tripped, the primary requirement is to provide an alternate source of cooling water to the fuel (now approaching decay heat levels) as quickly as possible. ECIS injection can only commence when the HT system pressure has fallen to the ECIS injection setpoint. This **depressurizing period** is typically referred to as **blowdown.** Initially, a HT pressure reduction occurs due to the leak and due to the shrinkage of D_2O after a reactor trip. The rate of depressurization will then slow down as the pressure in the HTS reaches the saturation pressure associated with the HTS temperature. At this pressure, the coolant flashes to steam to prevent total collapse of HTS pressure. The time taken for this to occur is largely dependent upon the size of the LOCA, hence, blowdown times can vary greatly.

⇔ *Obj. 12.6*

Once the HTS reaches ECIS initiation pressure, a crash cooldown of the boilers is initiated. All boiler safety valves (or large steam reject valves, in some stations) are opened to reduce boiler pressure (hence boiler temperature) causing HTS shrinkage. This **further lowering of HTS pressure** will allow the colder ECI **water to enter the reactor** and will also **reduce** the **leakage rate** of inventory from the HT system. This effectively **removes the boilers as a heat source,** which could maintain HT pressure and temperature, hence slowing the depressurization. (Once the cold ECI water is injected into the HTS, its main purpose is to cool the fuel. If cold water is injected without crash cooling, the hot feedwater in the boilers will transfer heat to the injected water and the HTS). This is especially useful for small LOCAs, when the depressurization of the HTS can be slow. This allows cold ECIS water to be injected sooner.

⇔ *Obj. 12.7*

Circulation through the HT system is maintained by the **main HT pumps** for as long as possible. A higher flow rate of coolant from the core to the boilers is achieved with these pumps running. This results in a **higher rate of heat removal** from the heat transport system and hence, a faster depressurization to injection pressure. Forced circulation also **mixes liquid and vapour** (retarding vapour pocket formation) which aids in keeping the fuel wet, thus minimizing fuel failures. The pumping of two phase flow and/or pump cavitation due to low suction pressure will cause severe vibrations in the HT circulation pumps. To prevent further loss of inventory due to pump seal damage, the pumps may have to be tripped (in some stations the failure of pump seals will cause a breach of containment). As mentioned for thermosyphoning, the inertia of the main HTS pump motors or flywheels will continue circulating the coolant for some time after the pumps are tripped (but may be opposed by ECIS injection).

In some stations, low speed drives are installed on main HT pumps, which continue circulation of the coolant to maintain fuel cooling (these low speed drives will allow the pump to operate without cavitation). This is especially useful for small breaks, where the discharge of the coolant from the break is not sufficient to carry heat from the fuel (as mentioned earlier in this module).

Injection

At the ECIS injection pressure, **injection of water** into the system commences to restore coolant inventory. This is referred to as the **injection phase**. Light water injection from one or more storage tank (s) continues until the inventory from the tank(s) has been depleted. The injection phase can vary in duration, depending on the break size and the water inventory available.

High pressure injection is accomplished by one of two methods. Some stations use high pressure pumps to inject the light water coolant to the core. The other stations use a pressurized gas (N_2) to drive the injection water into the core.

At some stations, a grade elevation water tank and/or an elevated emergency water storage tank (part of the dousing tank reserved for injection) exists to supplement the inventory of water available for injection. Once the high pressure injection phase is over, **low pressure pumped injection** begins from these tanks. This extra water is particularly useful in bridging the period between the high pressure injection and the recovery phase.

Typical high pressure ECIS injection pressures range between 4.2 and 5.5 MPa depending on the station and delivery method used.

This range of injection pressures is chosen for three main reasons:

a) The extra system cost needed to provide equivalent flow at higher pressure (particularly for a pump system) is not warranted.

b) To reduce the amount of time and number of occasions that the ECIS must be blocked when operating at reduced HT pressures.

c) To reduce water hammer effects.

Point (b) is important since one of the logic decisions required for injection is to determine if the HT pressure is less than ECIS injection pressure.

The system size and injection pressure is optimized to provide adequate injection flow and pressure before the HT inventory has been depleted. This prevents fuel failures that may occur during blowdown.

Recovery

The light and heavy water mixture which has discharged from the break as a result of the HT system blowdown and ECIS injection is **collected in the ECI recovery sumps** in the containment floor. It is then **cooled** in heat exchangers and **re-injected** into the HT system by recovery pumps (or in some stations, to the suction of the HP injection pumps). This is referred to as the **recovery phase** (or post accident water cooling, in some stations). In most stations this is accomplished by a dedicated recovery system. This maintains adequate cooling in the HT system and provides a long-term heat sink for the reactor to prevent fuel failures (due to overheating from decay heat).

The heat removal mechanism from decay heat levels is shown in Figure 12.2.

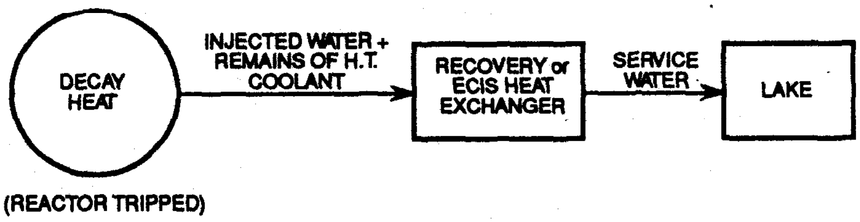

Figure 12.2 : ECIS Heat Removal Chain

The quantity of water injected during the HP and LP injection phases must be sufficient to accommodate water lost due to holdup in the recovery flow path. It must also provide sufficient recovery pump suction head to prevent cavitation and possible vapour locking of the recovery pumps. Water recovered from the recovery sumps must be screened and filtered to prevent debris from blocking the pump inlets and thereby impairing the recovery phase. For this reason, housekeeping inside the reactor vaults is very important.

The recovery pumps do not require the higher pressure (and flow) delivery capability of the injection phase since the HT system is operating at reduced pressure. Also, the decay heat produced by the reactor is substantially reduced in the long term. The recovery system is therefore sized accordingly, for long-term performance with reduced flow and pressure requirements.

The duration of the recovery phase can be up to three months. For this reason, it is important that there is a secure electrical supply to the recovery pumps, ie. hence Class III power is used.

SUMMARY OF THE KEY CONCEPTS

- The blowdown phase of ECI is the phase that allows the HTS to depressurize to ECI injection pressure.
- The injection phase is the period where injection of stored water takes place.
- The recovery phase is the period that the water recovered from the LOCA is cooled and re-injected (via pumps) into the reactor to maintain long term fuel cooling.
- ECI initiates a crash cooldown to remove the boilers as a heat source. This could prevent depressurization of the HTS.
- The crash cooldown lowers the HTS pressure by causing HTS shrinkage. This reduces the leakage rate from the HTS. This also ensures pressure reduces to allow injection of cold water into the HTS for fuel cooling.
- HTS coolant circulation is maintained as long as possible to maximize coolant circulation for fuel cooling. This results in a higher rate of heat transfer to the boilers and ensures that depressurization to ECI injection pressure will occur as fast as possible. The flow of coolant also mixes liquids and vapours to prevent vapour pocket formation, hence keeping fuel wet.

ECIS System Operation

Obj. 12.8 ⇔

Note that the ECI system in your station may vary from the system(s) desccribed below. The intent is to generically describe the actions of a typical ECI system. Any differences will be discussed in your station specific training.

Once the ECI initiation pressure is reached and at least one conditioning parameter is satisfied, the following major actions occur simultaneously:

- Crash cooldown, which was discussed earlier in the module,
- Preparation for HP injection (and LP pumped injection),
- Preparation for the recovery phase of system operation.

For systems using gas accumulators, fast acting valves open to allow the pressurized gas in the accumulators to pressurize the water held in the accumulator water storage tanks. The unit H_2O and D_2O injection valves will open (in the affected unit only, in a multi-unit station) to allow injection flow to commence. ECIS valve sequence and operation are designed to minimize the effects of water hammer, which could be caused by the rapid injection of the water (ie. valves open slowly, system is vented to remove air gaps, etc). Injection will continue until a low level in the accumulator water storage tank is reached. The isolation valves will then close to prevent gas ingress into the HT system. The recovery pumps are also started when ECI is initiated, in preparation for the recovery flow.

For systems using high pressure water pumps, water in the ECI storage tank(s) feed the suction of these pumps. These pumps are started when ECI is initiated (or when conditioning parameter is satisfied, depending on the station), in preparation for the injection flow. The recovery pumps are also started and will recirculate injection water (depending on the station, they may feed the high pressure injection pumps, this arrangement is not shown in Figure 12.1). The unit H_2O and D_2O injection valves will open (in the affected unit only, in a multi-unit station) to allow injection flow to commence (water hammer preventive measures are as mentioned above). Injection will continue until a low level in the water storage tank is reached (or in some stations, a preset time limit is exceeded). The isolation valves close to prevent air ingress into the pumps and ECI system.

In some stations, after the initial high pressure injection is completed, additional water is provided by a grade level storage tank or an emergency water storage tank. The valves from the tank will open and this water is then pumped by the recovery pumps into the reactor core. This continues until a preset low level in the tank is reached or a preset high level in the recovery sump is reached (which ensures adequate water is available for the recovery phase). The storage tank isolation valves will then close.

Once the above injections are completed, the recovery phase (post-accident water cooling) begins. Water that has spilled from the reactor has been collected in the recovery sump. The recovery sump isolation valves will then open and the recovery flow will start. Water will be pumped from the recovery sump to the recovery heat exchangers. Then the water is returned to the reactor core for fuel cooling. In the recovery heat exchangers, the reactor decay heat is transferred to cooling water.

SUMMARY OF THE KEY CONCEPTS

- For systems using gas accumulators, fast acting valves open to allow the pressurized gas in the accumulators to pressurize the water held in the accumulator water storage tanks. For systems using high pressure water pumps, valves open to allow the water in the ECI storage tank(s) to feed the suction of these pumps. The pumps are started in preparation for the injection flow.
- The unit H_2O and D_2O injection valves will open (in the affected unit only, in a multi-unit station) to allow injection flow to commence.
- In some stations, after the initial high pressure injection is completed, additional water is provided by other storage tanks. This water is pumped by the recovery pumps into the reactor core.
- Once the above injections are completed, the recovery phase (post accident water cooling) begins. Water that has spilled from the reactor has been collected in the recovery sump. The recovery sump isolation valves will open and the recovery flow will start . Water will be taken from the recovery sump, pumped to the recovery heat exchangers and then the water is returned to the reactor core for fuel cooling. The recovery heat exchangers will remove the decay heat from the coolant.

Emergency Coolant Injection System Reliability

Obj. 12.9 ⇔

Like the two shutdown systems, high reliability is maintained independence, redundance and selection of high quality components for construction and maintenance of the system *.

* More details were provided in Module 11.

Emergency Coolant Injection System States

Let us consider the following states of "readiness" in which the ECIS can exist:

Obj. 12.10 a) ⇔

a) **Poised**

While poised, the system is available to operate automatically when the initiating parameter setpoints are reached on the correct number of channels. No operator action is required.

Obj. 12.10 b) ⇔

b) **Blocked**

Obj. 12.11 ⇔

When blocked, the system will not operate automatically. When the heat transport main system is being depressurized, automatic injection is prevented by a blocking handswitch, which overrides the automatic opening of the injection control valve(s). This prevents an initiation when heat transport pressure drops below ECI injection pressure. The result of injection would be addition of H_2O and **down-**

grading of the HT heavy water which would result in a considerable **economic penalty**.

However, blocking of ECIS is only **permissible** once heat transport temperature is below a specified value (typically <90°C) or when HT pressure is at or below injection pressure (this must be performed before ECI conditioning parameters are satisfied). A blocked system needs only simple control room action to return it to the poised state.

⇔ ***Obj. 12.12***

When the heat transport system is depressurized for maintenance and ECI is blocked, ECI can be **manually initiated** in the event of a LOCA. Recall also from page 3 that if for any reason the automatic operation of ECIS fails, the operator can manually initiate ECI.

⇔ ***Obj. 12.13***

c) **Recallable**

⇔ ***Obj. 12.10 c)***

The system will not operate automatically or manually.

The ECI system can only be made recallable with the unit(s) in a specified shutdown and cooldown state. It must always be possible to restore it to service within a predefined time which depends upon the status of the unit, and is specified in your station operating manual.

SUMMARY OF THE KEY CONCEPTS

- The reliability of the ECI system is increased by the use of:
  - Redundant components,
  - Quality components,
  - Independence.
- The term "poised" refers to the state when ECI is ready to operate automatically, in the event of a LOCA.
- The term "blocked" refers to the prevention of the system from operating automatically as designed. In this state the system can be returned to service (ie. poised) by simple control room action.
- The ECI system can also be fired manually in case:
  - A LOCA occurs while depressurized for maintenance (ie. while blocked).
  - Automatic actions do not occur as designed (ie. while poised).
- The term "recallable" refers to a state when the system cannot be activated manually or automatically. While in this state, the system must be able to be returned to service within a predetermined time limit.

- The HTS must be below a certain temperature (typically 90°C) before the ECI system can be blocked.
- If the HTS is depressurized before the ECI system is blocked, ECI will operate as designed when conditioning parameters are met. This would downgrade the HTS, resulting in a severe economic penalty.

Page 13 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. The purpose of the Emergency Coolant Injection System is to___
____
____
____
____

2. A Loss of Coolant Accident (LOCA) is defined as __________
____
____
____

3. The typical shutdown system trip parameters which occur prior to ECI:

   a) For a large LOCA are ________________________,
   ____
   ____

   b) For a small LOCA are ________________________,
   ____
   ____

4. The primary ECI initiating parameter for a LOCA is __________
____________________________. Three examples of conditioning parameters are:

   a) ____________________________________
   b) ____________________________________
   c) ____________________________________

5. The other special safety system (besides SDS1, SDS2 and ECIS) that may be activated following a large LOCA is ____________
____.

6. The three operational phases of ECIS are:

   a) ______________. The purpose of this phase is ______________________________

   b) ______________. The purpose of this phase is ______________________________

   c) ______________. The purpose of this phase is ______________________________

7. Two reasons that the HT pumped circulation is maintained as long as possible are:

   a) ______________________________

   b) ______________________________

8. Three reasons why ECIS initiates a crash cooldown are:

   a) ______________________________

   b) ______________________________

   c) ______________________________

9. a) Describe the functions of the following major components:

   i) ECI water storage tank, ______________________________

   ____

   ____

   ii) Accumulator tank or injection pump(s), ________________

   ____

   ____

   iii) Injection valves, ____________________________________

   ____

   ____

   iv) Recovery sump, ____________________________________

   ____

   ____

   v) Recovery pumps, ____________________________________

   ____

   ____

   vi) Recovery heat exchangers, __________________________

   ____

   ____

   b) Describe the sequence of operation of the following major components:

   i) ECI water storage tank,
   ii) Accumulator tank or injection pump(s),
   iii) Injection valves,
   iv) Recovery sump,
   v) Recovery pumps,
   vi) Recovery heat exchangers.

____

____

____

10. Three features typically incorporated to enhance ECIS availability are:

    i) ______

    ii) ______

    iii) ______

11. The availability the ECIS must have when the unit is in the "at power" state is ______.

12. a) When ECI is poised it means ______

b) When ECI is blocked it means ________________________

____

____

c) When ECI is recallable it means ______________________

____

____

13. The ECIS can be blocked only when the HT system is__________

____.

14. The heat transport system is about to be depressurized. The action required before the HTS reaches ECI initiation pressure is

____.

Failure to do this will result in ______________________

____

____.

15. The ECI system can be actuated manually to protect against:

a) ____

____

b) ____

____

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

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Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 13

CONTAINMENT

OBJECTIVES:

After completing this module you will be able to:

13.1 State the two types of containment systems in use with CANDU reactors and identify the poised system common to both types. ***⇔ Page 5***

13.2 State how pressure is normally maintained subatmospheric for a Pressure Suppression Containment system. ***⇔ Page 6***

13.3 State two functions that the total water inventory in containment must provide in the event of a LOCA. ***⇔ Pages 6, 11***

13.4 For a pressure suppression containment (PSC) system, describe the functions of the dousing system and how dousing is initiated. ***⇔ Page 6***

13.5 For a PSC system, describe the function of the vault coolers (normal operation and during a LOCA). ***⇔ Pages 6, 7***

13.6 For a PSC system, describe what containment box-up/button-up is, and how it occurs. ***⇔ Page 7***

13.7 Describe the operation of a PSC system during:

- a) A small LOCA, ***⇔ Page 7***
- b) A large LOCA. ***⇔ Page 7***

13.8 For a negative pressure containment (NPC) system describe the function of:

- a) Pressure relief duct, ***⇔ Page 9***
- b) Upper vacuum chamber, ***⇔ Page 11***
- c) Main vacuum chamber, ***⇔ Page 12***
- d) Dousing, ***⇔ Page 12***
- e) Main and upper chamber vacuum pumps, ***⇔ Page 11***
- f) Pressure relief valves, ***⇔ Page 12***
  - Small or instrumented
  - Large
- g) Vacuum duct (2 functions), ***⇔ Page 13***
- h) Vault coolers. ***⇔ Page 14***

13.9 For an NPC system, describe:

Pages 11-12 ⇔ a) How vacuum is maintained in the main and upper chamber,
Page 12 ⇔ b) Conditions which cause the PRVs to operate,
Page 14 ⇔ c) What containment box-up / button-up is and how it occurs,
Page 15 ⇔ d) How dousing is initiated.

13.10 Describe the operation of an NPC system during:

Page 15 ⇔ a) A large LOCA,
Page 16 ⇔ b) A small LOCA.

Page 16 ⇔ 13.11 State the purpose of airlocks for both types of containment systems.

Page 17 ⇔ 13.12 Explain the purpose of the Filtered Air Discharge System (FADS).

Page 18 ⇔ 13.13 Explain the purpose of the hydrogen igniters.

Page 19 ⇔ 13.14 State how pressure is normally maintained subatmospheric for a Negative Pressure Containment system.

Page 19 ⇔ 13.15 Explain why a containment system should be available at all times when a unit is at power. List the required unit state if the containment system is to be made unavailable.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The containment system protects the public, station personnel and equipment against the adverse conditions following an increase in reactor building pressure, usually as a result of a LOCA. This module will discuss the types of containment systems, the types of containment structures, the function and operation of containment components.

The containment system is designed to contain:

a) The energy released as heat and pressure.
b) The activity released, eg, tritium and fission products to within limits.

The LOCA, which usually triggers the use of the containment system, may have been caused by such events as:

a) Mechanical failure of the HTS, for example, as a result of long term poor chemical control or a system transient.

b) Loss of Regulation Accident (LORA) with failure to shut down the reactor quickly enough with subsequent pressure tube failure.

c) Loss of Class IV power with failure to shut down the unit, again, followed by pressure tube failure.

For events such as (b) and (c), failure of both shutdown systems must occur (such a combination of failures highly unlikely). Due to failure to shutdown the reactor, the amount of energy released to containment under these two circumstances would be much higher than that from a LOCA in which reactor power is terminated by shutdown system action.

Let us recall, from Module 12, the events following a LOCA into containment at full power. The Heat Transport System (HTS) D_2O at high pressure and temperature, will be released, and a portion of it will flash to steam. The reactor building temperature and pressure will increase. (Pressure may be above atmospheric for a few minutes, whereas temperature may rise to as high as 95°C for several hours.)

The containment structure must provide the initial heat sink under these conditions until alternate long term heat sinks can be made available (eg. ECIS Recovery Heat Exchangers) following ECIS operation to rewet and cool the fuel.

The amount of fission products released will depend on how rapidly the power pulse was terminated, how the fuel was operating prior to the LOCA and how well the ECIS has performed. When the ECIS is fully functional and copes with the LOCA, a large number of fuel failures is unlikely, and the quantity of fission products released will be small. (Remember, the primary function of ECIS is to maintain fuel cooling, which will prevent/minimize fuel failures following a LOCA.) However, a LOCA can cause tritium releases in the reactor building in the order of tens of thousands of times the Maximum Permissible Concentration in air *(MPCa).

* **Recall, from radiation protection training, that working in 1 MPCa tritium concentration for 40 hrs/wk for 1 year will give the maximum permissible annual dose for whole body exposure.**

If for any reason ECIS is unable to fully cope with the LOCA, a large number of fuel failures are almost certain and a large release of fission products is to be expected. Higher than normal radiation fields will occur inside containment.

Containment is basically a structural envelope which contains the reactor and high pressure components of the HTS. At various locations interfacing with other systems will occur, eg. boilers. The interfacing depends on how much equipment is located within containment.

In earlier CANDU stations and at 600 MW units, all boilers and HTS circulating pumps are totally within containment. This naturally increases the size of the reactor buildings required to house these components.

In the case of the older CANDU units, a larger containment structure is required to accommodate the larger volume of the reactor vaults.

At newer stations, the decision was made, following a detailed safety study, to relocate various equipment items and thereby reduce the size of containment required. For example, only the main HT pump bowls and boiler bases are within containment. Figure 13.1 below shows the extension of the HTS beyond the containment boundary.

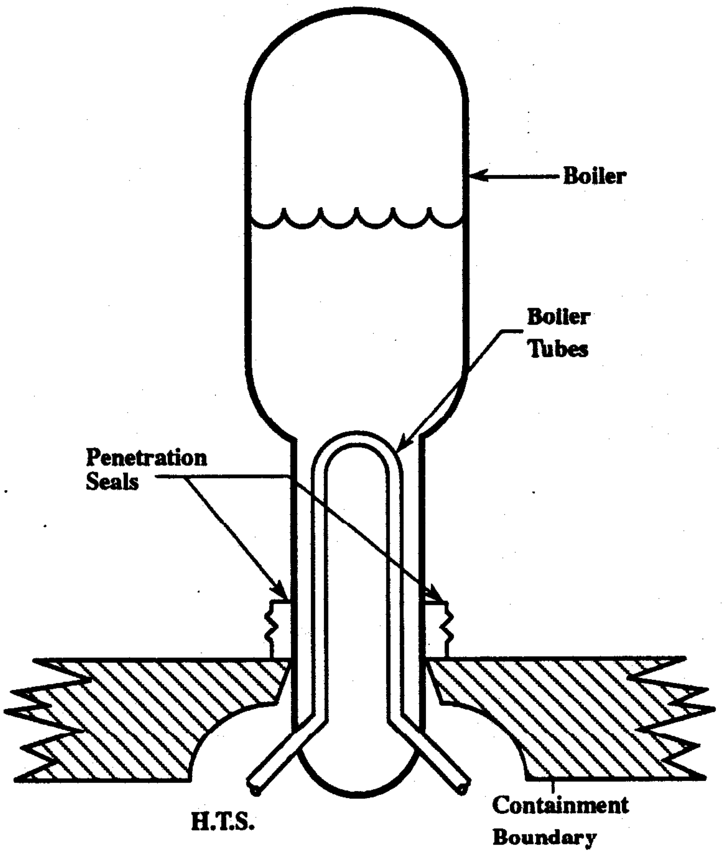


Figure 13.1
Typical Boiler Configuration

The larger containment structure of older stations has areas that have some accessibility on power (with and without using access control, depending on the area). This feature is not present at the newer stations.

Containment effectiveness is determined by the leak rate from the structure during an accident situation. The basic principle is, therefore, to eliminate or minimize leaks and, if leakage occurs, it must be in a controlled manner and monitored. This is one reason why containment is maintained subatmospheric. Any leakage is inward. An exhaust flow is maintained to keep the pressure subatmospheric. This exhaust is filtered and monitored.

Note that all containment penetrations (piping, cables, airlocks, transfer chambers, etc.) have seals to prevent leakage. A periodic pressure test is also performed to verify containment integrity.

Outleakage will occur if containment pressure is above atmospheric. If pressure exceeds design limits, containment structural damage can occur.

TYPES OF CONTAINMENT

⇔ *Obj. 13.1*

Two types of containment systems are currently employed in CANDU reactors:

1) **Pressure suppression** - used in CANDU 600 MW single unit stations.
2) **Negative pressure** - used at all Ontario Hydro multi-unit stations.

The effectiveness of both types of containment is dependent upon having a **poised ECI system** available to limit the longer term energy input in the event of a LOCA.

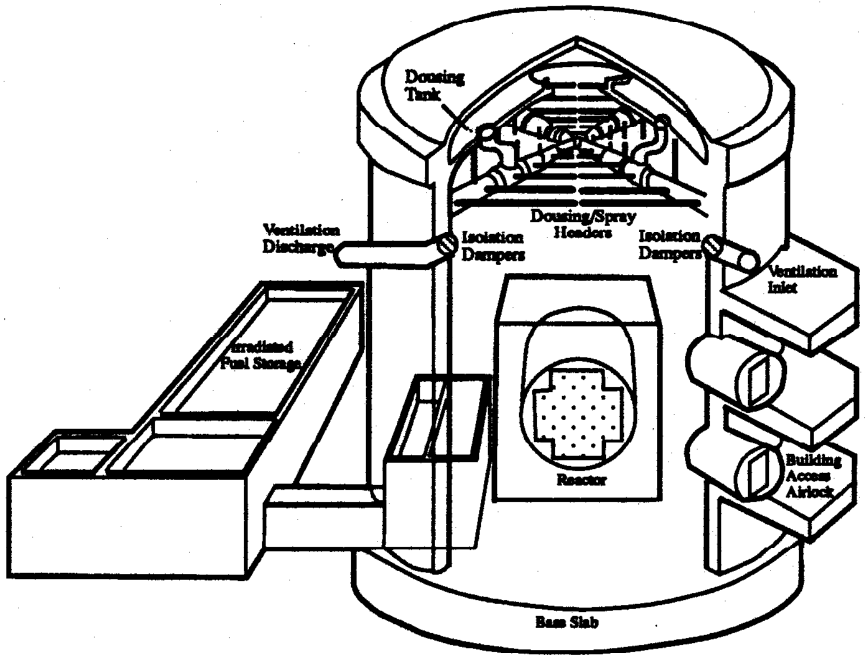


Figure 13.2
Typical Pressure Suppression Containment System

PRESSURE SUPPRESSION CONTAINMENT (PSC)

A general schematic of a pressure suppression system is shown in Figure 13.2 at the bottom of the previous page.

Containment consists of a prestressed concrete structure with a domed roof, a dousing system, airlocks and a closure system. The concrete walls are over 1 metre thick.

All internal surfaces of the containment structure, eg, the upper dome, outer walls, and base slab, the outer surfaces of the irradiated fuel discharge bay and airlocks normally form part of the containment boundary (during fuel transfers, the boundary extends to the surfaces of the irradiated fuel storage bay).

Obj. 13.2 ⇔

During normal operation, the **pressure** within containment is maintained **slightly subatmospheric** by **ventilation system** operation.

When, for any reason, the containment pressure increases above atmospheric, and especially during a LOCA, the leakage from containment must be limited. The release of tritium and fission products to the environment is kept below the maximum permissible level by not exceeding a specified leak rate. For any size of LOCA, the overpressure should not exceed the limit of ~120 kPa(g).

Obj. 13.3 ⇔

Obj. 13.4 ⇔

* Recall from Module 12 that a portion of the dousing water is reserved for ECI injection.

A dousing tank is located in the dome of the containment building. It holds light water for both **dousing** (~2000 m^3) and medium pressure **emergency coolant injection** (~500 m^3)*. Dousing is **accomplished by the opening of the dousing valves.** With these valves open, water flows by gravity from the storage tank to the spray headers to cause dousing. (These valves are channelized and require a majority vote to initiate dousing). **Dousing** condenses the released steam and thus:

1) **Absorbs the heat energy in the steam;**
2) **Reduces the magnitude and duration of the containment overpressure** pulse;
3) **Dissolves soluble fission products** (eg, I^{131}), and **entrains insoluble fission products**, minimizing the airborne spread of contamination.

Note that noble gas fission products, like Krypton 88, will be unaffected by dousing.

Obj. 13.5 ⇔

The containment structure is normally **cooled and dehumidified by vault coolers**. This is necessary due to sources of heat (HTS piping, boilers, etc.) and humidity (small leaks of D_2O, H_2O) within containment.

PSC Button-up/Box-up

⇔ *Obj. 13.6*

During a LOCA, the containment structure can be isolated from the environment by **closing the isolation points**. The isolation points are **dampers** at the ventilation penetrations and **valves** on the piping penetrations. This is termed "button-up" or "box-up". This is done to prevent leakage above permissible levels (as discussed in the previous section).

Button-Up (Box-Up) is typically initiated by any of the following signals:

- High containment radioactivity,
- High containment pressure,
- High exhaust and stack radioactivity or loss of stack monitoring.

Operation of PSC During a Small LOCA

⇔ *Obj. 13.7 a)*

⇔ *Obj. 13.5*

In the case of a small LOCA, the energy release will be smaller but will likely occur over a longer period. Containment pressure will slowly increase, and **box-up** will occur on one or more of the initiating parameters. The **vault coolers** may condense the resulting steam (and limit containment pressure) such that pressure to initiate dousing is not reached.

If pressure continues to rise to the dousing setpoint (~14 kPa(g)), some **intermittent dousing** action will occur as the dousing valves open and close on staggered setpoints, as shown in Figure 13.3.

Under these conditions after the initial period of dousing, which will cease when pressure falls to the dousing "OFF" setpoint (~7 kPa(g)), pressure will probably again increase and further dousing cycles may be required until pressure remains below the "OFF" setpoint. As energy input from the LOCA falls (due to depressurization of the HTS), condensation on walls, and vault coolers becomes a major factor in keeping containment pressure low.

Operation of PSC During a Large LOCA

⇔ *Obj. 13.7 b)*

For a large LOCA containment pressure and temperature increase rapidly. Containment **button-up** (and a reactor trip) occurs at a containment pressure of about 3.5 kPa(g) and **dousing commences** at an overpressure of approximately 14 kPa(g).

For a large LOCA, there will be a period of continuous dousing which will quickly reduce containment pressure towards atmospheric. Further reduction in containment pressure will be effected by the **vault cooling** system and further periods of dousing as required. This response is also shown in Figure 13.3.

Once pressure has returned to near atmospheric, efforts can be made to clean up the containment atmosphere.

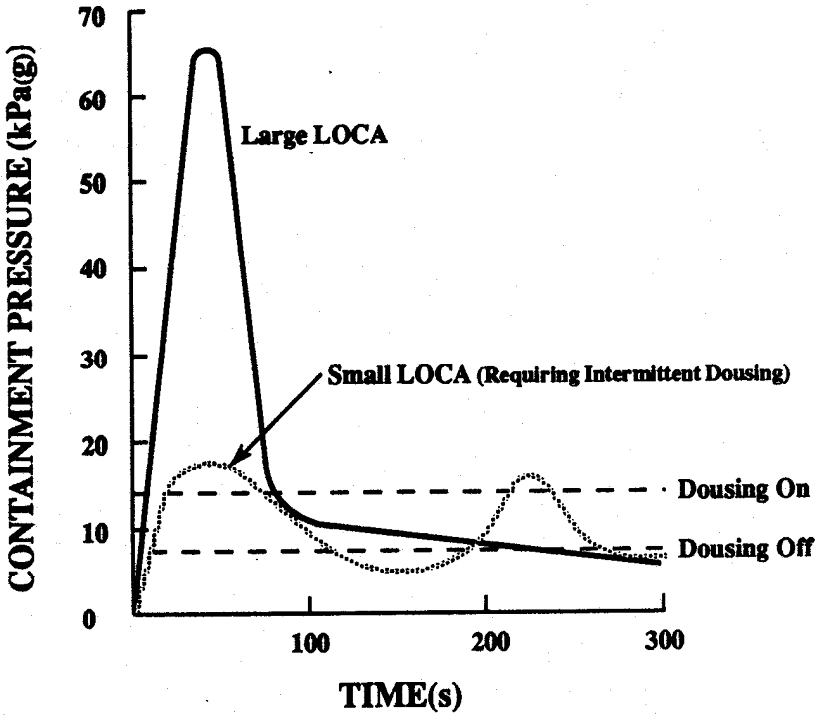


Figure 13.3
Typical Response of Pressure Suppression Containment To Large and Small LOCAs

SUMMARY OF THE KEY CONCEPTS

- Two types of containment are pressure suppression containment and negative pressure containment. A poised system common to both is the ECI system.
- PSC pressure is normally maintained subatmospheric by the ventilation system.
- The dousing system limits containment pressure by condensing steam released as a result of a LOCA. Also, soluble and insoluble fission products will be dissolved/entrained in the water.

- Dousing, for a PSC system, will be initiated by high vault pressure and occurs via the opening of dousing valves, which are located in the distribution lines below the dousing tank.
- Box-up (button-up) is a means of isolating the containment structure from the enviroment. Ventilation and piping penetrations are closed to prevent leakage above permissible levels.
- Following a large LOCA, for a PSC system, containment pressure quickly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. The dousing valves will open to initiate dousing to cope with the large pressure increase. As containment pressure reduces, dousing stops, but will restart as required to maintain pressure low.
- Following a small LOCA, for a PSC system, containment pressure slowly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. The vault coolers will act to condense the steam and will cool the vault atmosphere. This may limit the containment pressure increase to the point where no dousing action is required. If containment pressure continues to rise, dousing will start and stop intermittently to keep containment pressure low.
- Vault coolers normally act to cool and dehumidify the containment atmosphere.
- The water in the dousing tank is for both dousing and ECI injection.

NEGATIVE PRESSURE CONTAINMENT

This form of containment is used for all multi-unit CANDU stations, with some site variations.

⇔ Obj. 13.8 a)

The system is characterized by a vacuum building which, as its name suggests, is normally held at a pressure well below atmospheric, typically 7-14 kPa(a). The reactors themselves are housed in separate reinforced concrete buildings. The two structures are connected by a **pressure relief duct**, which allows any steam/air mixture in the event of a LOCA to travel to the vacuum building. The vacuum building (see Figure 13.4) is normally isolated from the relief duct (more specifically, the pressure relief valve manifold) by a number of pressure relief valves. The reactor buildings (and pressure relief duct) are normally maintained at a slightly subatmospheric pressure to minimize outleakage of potentially contaminated air during normal reactor operation (by purge driers, or ventilation systems *, depending on the station).

* More information is provided on page 19.

At older stations the reactor containments are larger than those of other sites. This dictates that the vacuum building must have a larger volume.

The vacuum building concept is unique to multi-unit CANDU stations for which it offers an economical advantage over individual unit containment systems.

One disadvantage of a Negative Pressure Containment System (NPC) is that following a LOCA on a single unit, the vacuum building becomes unavailable to the other units, and shutdown of these unaffected units is required. Note also that the ECIS is no longer available for injection to the other units, hence a shutdown would be required anyway.

Following a LOCA, the subsequent rise in pressure in the pressure relief duct will cause the pressure relief valves, to open. The air and steam/contaminants produced by the LOCA are then drawn from the reactor vaults into the vacuum building. This means that the affected unit is purged of its contaminated atmosphere in a relatively short period (30-60 seconds). Containment pressure in the affected unit can return to subatmospheric once again. This minimizes both the contamination of equipment within the reactor building and any uncontrolled releases.

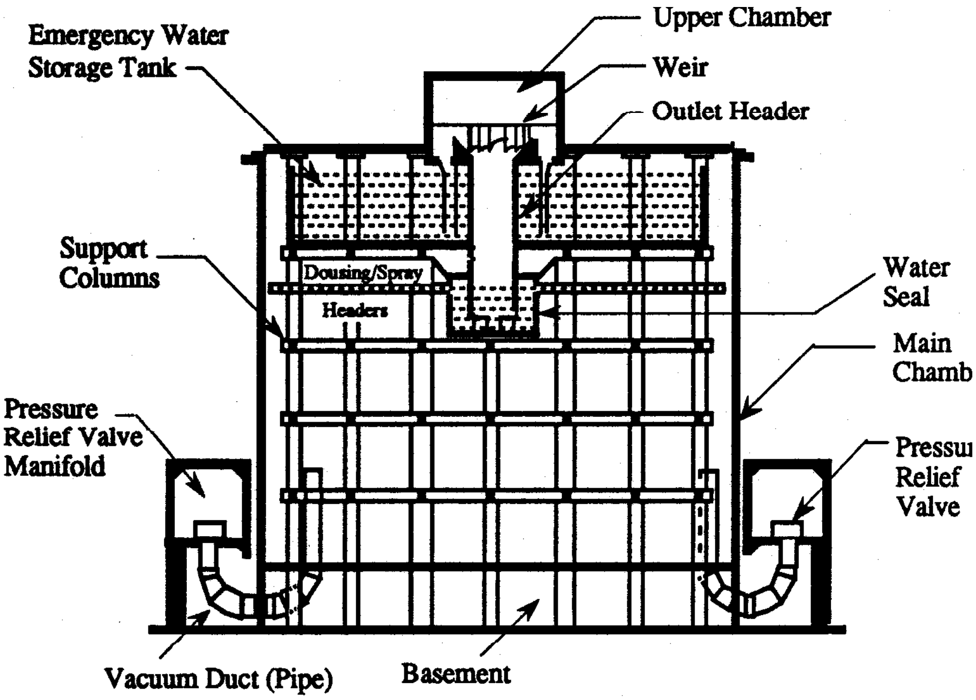


Figure 13.4 : Typical Vacuum Building

One additional note to make here is that the requirement to remove the steam/air mixture from the reactor vaults requires a clear passage to the vacuum building. This is why the fuelling machines should not be parked side by side in the fuelling machine duct (part of the pressure relief path to the vacuum building). Improper parking of the fuelling machines with a LOCA in progress could restrict steam/air movement, which would allow pressure on the LOCA side of the fuelling machines to build up. This could cause damage to the reactor vault due to overpressurization.

Note that this containment structure will leak at a higher rate during the short overpressure during a LOCA. But, this is only short term (ie. NPC has a higher leak rate for short term versus PSC which has a lower leak rate, but for a longer time).

Vacuum building

The vacuum building greatly reduces the chance of leaks from the containment area, by limiting containment overpressure during a LOCA. Without it, even the short duration overpressure transient (30-60 seconds) in the containment area following a LOCA would result in unacceptable leakages to the environment.

The building is a reinforced concrete structure of sufficient volume to accommodate all of the air and steam drawn in from the reactor building and pressure relief duct in the event of an accident.

Note that the upper portion of the vacuum building contains an emergency water storage tank (see Figure 13.4), which contains water for both dousing and the ECIS (in some stations). This water also provides the necessary vacuum isolation between the upper and main chambers plus the water seal in the spray (or dousing) header. *⇔ Obj. 13.3*

The vacuum building is divided into:

a) Upper Vacuum Chamber

This chamber is **isolated by watersealing** and held at a low subatmospheric pressure, typically ~7 kPa(a), by means of **vacuum pumps** located in the vacuum building basement. Its main **purpose is to provide a ΔP to automatically initiate dousing** action following a LOCA. *⇔ Obj. 13.8 e) & 13.9 a)* *⇔ Obj. 13.8 b)*

b) Main Chamber

This has a much larger volume than the upper chamber (typically 60-70 times larger), and again, is maintained at a pressure of approximately ~7 kPa(a). This **pressure is maintained by vacuum** *⇔ Obj. 13.8 e)*

Obj. 13.9 a) ⇔

pumps, similar to those used for the upper chamber, which are also located in the vacuum building basement. **Isolation from the upper chamber** is by a **water seal**, and **isolation from the containment** structure is by the **pressure relief valves.**

Obj. 13.8 c) ⇔

Obj. 13.8 d) ⇔

The **main vacuum chamber** accommodates the steam-air mixture from a LOCA (or steam line break into containment). It is in this chamber that the dousing will occur. As noted for a PSC system, **dousing** condenses the steam, limits vacuum building pressure increases and dissolves and entrains fission products (except for noble gases).

Pressure relief valves

Obj. 13.8 f) ⇔

The pressure relief valves form the **isolation between the pressure relief duct and the vacuum building**. They are designed to **open automatically** when the pressure in the relief duct rises to just above atmospheric (typically at ~3.5–7 kPa(g)).

Obj. 13.9 b) ⇔

There are, typically, 12 to 20 such valves depending on the station. The majority are termed Pressure Relief Valves (PRV), and three or four, depending on the station, are **Instrumented Pressure Relief Valves (IPRV)**. As the pressure rises in the pressure relief valve manifold (directly connected to the relief duct) to the required setpoint, the pressure acts directly on the PRVs and IPRVs, causing the valves to open (see Figure 13.5 on the next page). This will allow the high pressure air-steam mixture to enter the vacuum building from containment.

When the pressure falls (typically to +3.5 kPa(g)), all PRVs will close while the IPRVs remain open until pressure falls to a subatmospheric level (~ -2 kPa(g)). The IPRVs will then modulate between an open and closed position as pressure varies in a range from -1 kPa(g) to -2 kPa(g).

The **IPRVs can be manually controlled** because the "top" of the valve can be subjected to a vacuum from the vacuum building, causing the valve to open.

At some stations, in addition to PRV's and IPRV's, there are Auxiliary Pressure Relief Valves (APRV) which are physically smaller, and are capable of handling the pressures generated by small LOCA's. Their operating setpoints are lower than those of the larger PRV's. Typically, they open at +1.5 kPa(g) and will reclose as pressure falls to about -6.5 kPa(g). They then will modulate as pressure varies between the closed value and -3.5 kPa(g) when they will once again be fully open.

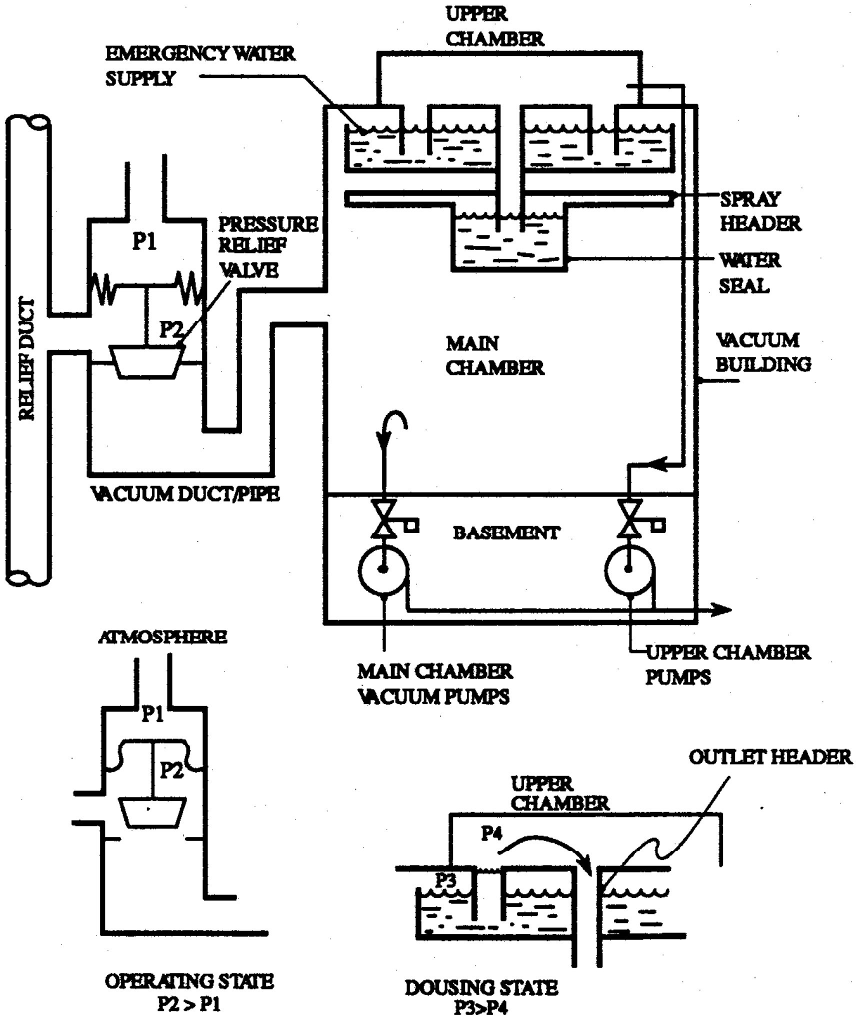


Figure 13.5
Schematic of Typical Negative Pressure Containment System

Note that in the case of a large LOCA, *all* PRVs, IPRVs, and *any* APRVs will open.

Vacuum duct

The vacuum duct (or vacuum pipe) is the **passage from the PRVs into the main vacuum chamber**, allowing the air/steam mixtures following a LOCA to enter the vacuum building. From Figure 13.4 you will notice their shape, and hence the reason for their other name, "J-Tubes".

⇔ Obj. 13.8 g)

Their shape serves another **purpose:**

> The duct allows isolation of a PRV from the vacuum building by filling the vacuum duct with water. The filling of the duct forms a water seal between containment and the vacuum building, allowing for maintenance/manual opening of the valve.

Note that the ducts opening is well above, or extends well above, the main chamber floor. This prevents water on the floor (after a douse) from flooding these tubes and forming a water seal. Flooding of these tubes would make the vacuum building unavailable to keep containment pressure subatmospheric.

NPC Button-up/Box-up

Obj. 13.9 c) ⇔

The button-up/box-up method is similar to that previously mentioned for PSC systems, ie. dampers and valves on penetrations close. But for a NPC system, this **will also automatically turn off all vacuum pumps** for both upper and main vacuum chambers (to prevent discharge of contaminated air).

Vault cooling

Obj. 13.8 h) ⇔

As for a PSC system, the containment structure is **cooled and dehumidified** by vault coolers. This is necessary due to sources of heat (HTS piping, boilers, etc.) and humidity (small leaks of D_2O, H_2O) within containment. This system normally maintains containment between 35-40°C.

SUMMARY OF THE KEY CONCEPTS

- Vacuum pumps maintain the vacuum building upper and main chamber pressures at a very low level. This maintains the effectiveness of the vacuum building as an energy sink following a LOCA.
- The main chamber provides an area to which the reactor vault atmosphere is drawn following a LOCA. The steam will be condensed there by the dousing action as pressure increases.
- The upper chamber maintains a ΔP which allows an increase in main chamber pressure to automatically cause dousing.
- PRVs isolate the pressure relief duct from the vacuum building main vacuum chamber. These valves will open automatically to control containment pressure increases following a LOCA. Large and small PRVs actuate to cope with large LOCAs, by allowing a large

amount of air/steam mixture to enter the vacuum building. After the pressure has been reduced, the small PRVs will modulate to maintain containment pressure subatmospheric in the "longer term". Instrumented PRVs can be operated from the control room. This is accomplished by applying a vacuum to the top of the valve (from the vacuum building).

- The vacuum duct connects the pressure relief duct to the main vacuum chamber (isolated by the PRVs). This duct allows maintenance on a PRV, when the duct is filled with water, by forming a water seal.
- The pressure relief duct connects the reactor containment structures (vaults) to the pressure relief manifold.
- The upper chamber is isolated to maintain a ΔP from the lower chamber by a water seal. Vacuum is maintained by the vacuum pumps, which remove any air inleakage.
- The PRVs operate when containment pressure exceeds a design limit. Increasing pressure acting directly on the valve will cause the valve to lift off of its seat.
- Box-up or button-up will be initiated by containment high pressure, containment high radioactivity or stack monitoring high radioactivity/out of service. This action closes all potential leakage points out of the containment structure by closing valves, dampers, etc.
- Vault coolers normally provide cooling and dehumidification to containment.

NPC operation during a large LOCA

⇔ Obj. 13.10 a)

A large LOCA will generate large volumes of high temperature steam (~100°C) as the HTS coolant escapes from the break. Pressure and temperature within containment will quickly increase and initiate **containment box-up (button-up).**

As relief duct pressure increases to the design pressure of the **PRVs** (APRVs first, where installed, followed by the IPRVs and main PRVs), they will **open**, and the high pressure, high temperature air/steam mixture will be drawn into the vacuum building through the vacuum ducts.

⇔ Obj. 13.9 d)

The **increase in vacuum building pressure acts on the water** in the emergency storage tank and **water is forced into the upper vacuum chamber** (refer back to Figure 13.5). Note that the water seal prevents the main chamber atmosphere from entering the upper chamber (through the outlet header) as main chamber pressure increases. The filling of the upper chamber with water allows flow over a weir into the outlet and spray headers, thus **initiating dousing** into the main chamber. The spray of cold H_2O into the steam/air mixture (in the main chamber) will condense the steam. This will reduce pressure as the volume of the steam decreases.

Note that, in most stations, the weir design in the upper chamber (as shown in Fig. 13.4 on page 10) prevents the formation of syphon, by preventing the air in the upper chamber from being carried into the outlet header. If the air in the upper chamber is lost, a syphon will form. If a syphon forms during dousing, it will not stop until the tank is empty.

As a result of the pressure decrease during dousing, **PRV closure will occur**. PRVs initially, then followed by APRVs and IPRVs. Containment pressure will then be maintained subatmospheric by the IPRVs or APRVs and vault coolers, as described earlier. A typical pressure transient for a large LOCA is shown in Figure 13.6 on the next page.

* This is discussed on page 18.

In the long term, to retain the containment pressure subatmospheric, the Filtered Air Discharge System * is initiated by the operator.

Obj. 13.10 b) ⇔

NPC operation during a small LOCA

In this instance, the pressure rise within containment will be smaller, and it is likely that the opening pressure of the large PRVs will not be reached.

The overpressure in containment in this instance will be **handled by the IPRVs or APRVs**, depending on the station. When containment pressure is reduced, the APRVs will close, but will modulate to maintain containment pressure negative. If the LOCA is small enough, the opening pressure of any relief valve may not be achieved, and the increase in pressure and the return to subatmospheric conditions will be handled by the **vault coolers** (provided enough steam is condensed).

Dousing during a small LOCA will be dependent upon the pressure rise in the vacuum building, and, **if dousing occurs, it will cycle** following the modulation of the IPRVs or APRVs.

AIRLOCKS

Obj. 13.11 ⇔

Airlocks are penetrations in the containment boundary that are provided to allow the **passage of personnel and equipment, without breaching the containment boundary**. This is accomplished by the use of a double set of doors for each airlock. By having only one door open at any time, the containment boundary is not breached. Each of the airlock doors are sealed by using an inflatable seal. Operating procedures and built in interlocks are used to ensure that the containment boundary is not breached when airlocks are used.

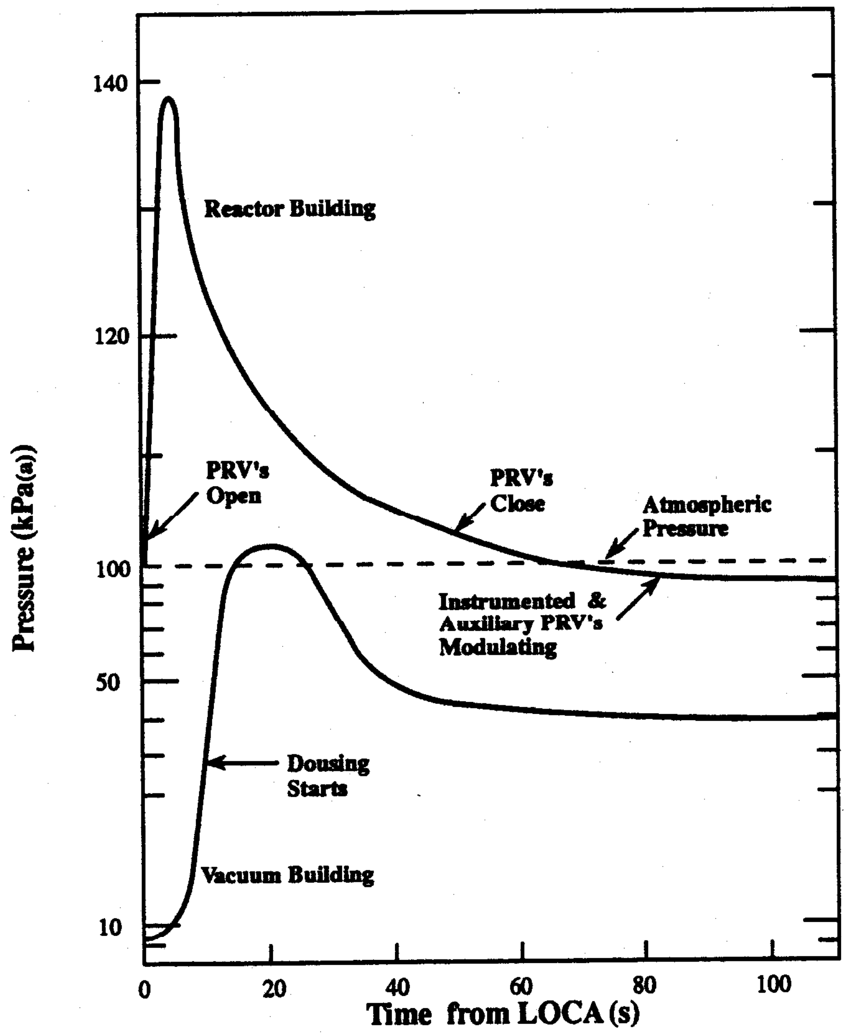


Figure 13.6
Typical Pressure Transients in Reactor and Vacuum Buildings following a LOCA, (50% HT D_2O loss)

Larger penetrations, for the transfer of very large pieces of equipment, are called transfer chambers. They are similar to an airlock, but are constructed of concrete, rather than steel. Their operation is also the same as an airlock, with a very few being sealed by bolted connections.

FILTERED AIR DISCHARGE SYSTEM

Following a LOCA event, containment will gradually repressurize due to air inleakage (small holes in containment seals, air system leakage, etc.). Filtered air discharge is initiated to keep containment or the vacuum building subatmospheric. Containment air is evacuated via the FAD (Filtered Air Discharge) system instead of via the normal operation filter (through the contaminated exhaust system). FAD consists of demisters (which remove entrained water droplets), heavy

⇔ *Obj. 13.12*

duty High Efficiency Particulate in Air (HEPA) filters to remove particulates and charcoal adsorbers to remove radioiodines. Once the air discharge is established through FAD, the containment atmosphere can be maintained in a subatmospheric state (note that these FAD units are not 100% efficient, and will release small amounts of particulates and radioiodines, tritium and all the noble gas activity).

HYDROGEN IGNITERS

In the event of a LOCA with a coincident failure of ECIS, high fuel sheath temperatures will result. If the fuel temperature exceeds ~1100°C, steam/zirconium oxidation will cause the formation of D_2/H_2 by the following reaction:

$$Zr + 2D_2O \longrightarrow ZrO_2 + 2D_2$$

Obj. 13.13 ⇔

To prevent high D_2/H_2 and O_2 concentrations from forming, and igniting, within containment, a **hydrogen ignition** system is used.

The principle behind its use is to deliberately ignite the D_2/H_2 and O_2 mixture in **low** concentrations in a steam environment. The ignition of D_2/H_2 at low concentrations prevents severe pressure/temperature transients that could cause damage to the containment envelope (which could occur if high concentrations of D_2/H_2 were allowed to build up to explosive levels and ignite).

The hydrogen igniters are heating coils, similar to a heating coil on a stove, which will heat to ≥750°C to cause the ignition of the D_2/H_2. In the Bruce and Darlington units, these igniters are located at several different elevations within the reactor vault* and, in the Pickering units, they are in the fueling machine vaults and service rooms.

* At Darlington there are also igniters located in several SDC rooms.

SUMMARY OF THE KEY CONCEPTS

- Dousing occurs when increased pressure in the vacuum building main chamber forces water into the upper chamber, causing water to spill into the dousing headers.
- Following a large LOCA, for a NPC system, containment pressure quickly starts to rise. Box-up (or button-up) is initiated on one or more of the initiating parameters. All the PRVs (APRVs followed by main PRVs and IPRVs) will open to cope with the large pressure increase. Vacuum building main chamber pressure will increase. This will cause dousing to occur to reduce main chamber pressure. As containment pressure reduces, the large PRVs will close, followed by the IPRVs and APRVs. The IPRVs, and/or APRVs, depending on the station, will modulate to maintain pressure subatmospheric.

- Following a small LOCA, for a NPC system, containment pressure slowly starts to rise. Box up (or button up) is initiated on one or more of the initiating parameters. The vault coolers will act to condense the steam and will cool the vault atmosphere. This may limit the containment pressure increase to the point where no PRV action is required. If containment pressure continues to rise, the APRVs or IPRVs will open to reduce containment pressure. Once containment pressure is reduced, the APRVs will close, but will modulate to keep containment pressure below atmospheric.
- Airlocks allow for the passage of personnel and equipment into/out of containment without opening containment to atmosphere.
- The filtered air discharge system (FADS) will allow the contaminated air in the containment or vacuum structure to be discharged to atmosphere (at a controlled rate) after it is filtered to remove contaminants. This can maintain containment pressure subatmospheric.
- The hydrogen ignition system will ignite low concentrations of D_2/H_2 formed during a LOCA, thus preventing severe containment damage.

VAULT ATMOSPHERE

Purge driers

Recall from Module 9 that the purposes of the vapour recovery system are:

a) Collection and recovery of D_2O vapour present in containment as a result of normal HTS coolant leakage.

b) Removal of airborne tritium within containment.

c) Maintaining containment pressure slightly subatmospheric.

⇔ *Obj. 13.14*

Point c) is our concern here. After the vapour recovery stage in the vapour recovery system, air is either returned to containment or discharged to atmosphere through the **purge driers*** and the station stacks where it is further filtered and monitored by the contaminated exhaust system. **This air flow through the purge driers normally keeps containment pressure subatmospheric** (ie. removes the air that has leaked into containment).

* The purge driers are considered part of the vapour recovery system.

For a PSC system and older stations, a similar purge system to that mentioned above, maintains the containment D_2O areas at a slight negative pressure, relative to other accessible areas.

Availability

Obj. 13.15 ⇔

Containment (and all its associated subsystems, ie. vacuum building, dousing water inventory, etc) must be **available at all unit states** (except when the unit is in the guaranteed shutdown state) to **preserve the fourth barrier to radioactive releases to the environment.**

The containment system is considered to be available if it is capable of limiting radiation doses to the public to within legal limits.

To minimize the containment unavailability, the following measures have to be taken:

- The containment system shall not intentionally be removed from service unless HT system(s) are at or below 90°C and the reactor(s) are in a guaranteed shutdown state.
- At least one door of each airlock shall be kept closed at all times.
- The system has to be tested according to a testing schedule to demonstrate that it meets the unavailability targets.
- The necessary maintenance shall be performed in a timely manner.

Reliability

Containment (and all its associated subsystems), like the SDSs and ECIS, must be very reliable. High reliability is achieved by independence, redundance and selection of high quality components, as discussed in the previous two modules.

SUMMARY OF THE KEY CONCEPTS

- NPC pressure is maintained subatmospheric by the purge driers.
- Containment must be available at all times while the unit(s) operate to ensure that releases are minimized in the event of a LOCA.
- The reactor(s) must be shut down and cooled if the containment system is made unavailable.
- The shift supervisor must approve testing and maintenance of the containment systems.
- The reactors will be operating for normal testing of containment system components. But, in some cases, ie. leak tests, the unit(s) must be shut down for testing.

Page 21 ⇔

You can now work on the assignment questions.

ASSIGNMENT

1. a) Two types of containment systems used in CANDU stations are:

   i) ______________________________

   ii) ______________________________

   b) The poised __________ system is available to limit the long term energy input into containment in the event of a LOCA.

2. The function of an airlock is to provide ____________________

   ____

   ____

3. Box-up or Button-up occurs by ____________________

   ____

   ______________________________. For a NPC system this also shuts down the ____________________ and the ____________________. These actions occur to ____________________

   ____

   ______________________________.

4. Vault coolers act to:

   a) Normally-______________________________.

   b) During a LOCA-______________________________.

5. Dousing systems act as follows:

   a) ______________________________.

   b) ______________________________.

   c) ______________________________.

6. For a NPC system,

   a) The upper vacuum chamber maintains a ________ such that ________________ will occur automatically when main vacuum chamber pressure increases.

b) The pressure in the vacuum building main chamber is maintained by the ______________________________.

c) The main vacuum chamber is where ______________ will occur.

d) PRVs normally ________________ containment from the vacuum building. During a LOCA, ____________________ in containment causes these valves to open.

e) The vacuum duct connects ________________________ to the ____________________________. This duct allows maintenance on the PRVs by __________________________________ ____.

f) The pressure relief duct connects the ____________________ to the ______________________________.

g) The vacuum in the upper chamber is maintained by the ______ _______________ seal. Any air inleakage is accommodated by the ______________________________.

7. For a NPC system, the dousing mechanism is:

____

____

____

____

____

8. For a PSC system, the dousing mechanism is:

____

____

____

____

____

9. The purpose of the Filtered Air Discharge System is: ____________________

10. The purpose of the Hydrogen Igniters is: ____________________

11. a) For a PSC system, a small LOCA will cause containment to: ____________________

11. b) For a PSC system, a large LOCA will cause containment to: ____________________

12. a) For a NPC system, a small LOCA will cause containment to: ____________________

b) Following a large LOCA, for a NPC system, containment ____
____
____
____
____
____

13. The containment system must be available with the unit at power because ____
____
______________________________. If the containment system is to be made unavailable, the units must be ______________
____
____.

14. Dousing or emergency storage tank water is for ______________ and ______________________.

15. PSC pressure is normally maintained subatmospheric by the ______________________________. NPC pressure is normally maintained subatmospheric by the ______________________.

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

Prepared by:	N. Ritter, WNTD
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

NOTES & REFERENCES

Module 14

ANNULUS GAS SYSTEM

OBJECTIVES:

After completing this module you will be able to:

14.1 State three important benefits obtained by using CO_2 as the annulus gas. ⇔ ***Page 3***

14.2 State the reason why the annulus gas system must be circulating in order to fulfill its purposes. ⇔ ***Pages 3-4***

14.3 For each of the following parameters: ⇔ ***Page 4***

a) Pressure;
b) Dew point;

State why it is monitored and give a typical range of values encountered in normal operation.

14.4 State six reasons why purging of the annulus gas system may be required. ⇔ ***Page 5***

14.5 For each of the following abnormal conditions, state the indicated number of major operating concerns: ⇔ ***Pages 6-7***

a) High annulus gas pressure (2),
b) Low annulus gas pressure (2),
c) Leakage of the annulus gas (2),
d) Air in the annulus gas (3),
e) High or increasing moisture levels (2).

14.6 State when the annulus gas system may be stagnant. ⇔ ***Pages 7-8***

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

A general review of the annulus gas system includes:

- System purposes;
- Gas selection;
- System operation.

Following the introduction, a discussion of topics includes:

- Dew point;
- Annulus gas pressure;
- Abnormal unit conditions.

A very basic layout of an annulus gas system is shown in Figure 14.2 on fold-out page 13. This page is available for reference as you work through the module.

System Purposes

To understand the function of the annulus gas system, we should first review the location of the annuli in the calandria. Figure 14.1 indicates the location of the annulus gas as a boundary between the moderator and heat transport system.

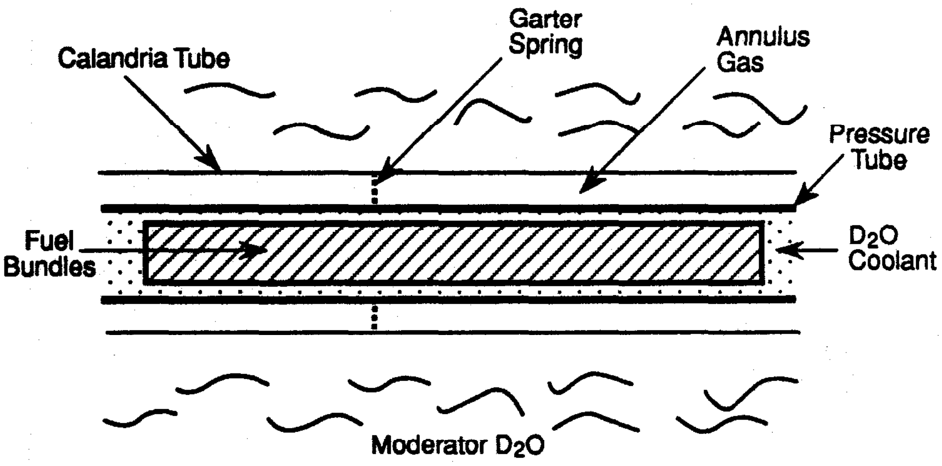


Figure 14.1 Sketch of Annulus Gas Position

Serving as a separating medium, the two main purposes of the system include:

- To provide a method to **detect** and **locate** leakage from a pressure or calandria tube.
- To provide **thermal insulation** between the hot pressure tubes and the relatively cool calandria tubes. This minimizes heat losses from the heat transport system coolant to the moderator coolant, thereby increasing the efficiency of the unit.

Secondary purposes of the annulus gas system include:

- Providing a dry gas atmosphere in the fuel channel annuli to **prevent corrosion** of fuel channel components;
- Providing a means to **drain leakage** from the heat transport, and moderator systems.

Gas Selection

To fulfill the functions required of an annulus gas, the following properties are necessary:

- **Low thermal conductivity** (good thermal insulator);
- **Low** tendency to promote **corrosion**;
- **Low radiation fields** (limited activation products).

Of the proposed annulus gases for CANDU stations, CO_2 has proven most suitable because of its good insulating properties. In the presence of water, carbonic acid (H_2CO_3) is formed. This acid is only mildly corrosive and is not a problem in the small amounts experienced. CO_2 can also form radioactive C^{14} from the neutron activation of C^{13}. Since C^{13} has a natural abundance of 1% and has a very small neutron absorption cross section, the quantity of C^{14} produced is very small. ⇔ *Obj. 14.1*

System Operation

Annulus gas flows through the fuel channel annuli, to an outlet header and then to the compressors. The compressors provide the motive force to circulate the annulus gas to the inlet header and back through the system. Circulation of the annulus gas is important for early leak detection since it ensures the **dew point readings** and **gas sampling represents all of the annuli.** Without circulation, it may take a long time (days) for a small D_2O leak to be detected. Because continuous circulation is so important, the system is designed to allow for gas flow through the channels even when the compressors are unavailable. This is achieved by supplying fresh gas from the bulk supply via the pressure ⇔ *Obj. 14.2* regulating valve and venting to atmosphere via the purge line through contamination monitors. When a leak exists, most stations can also vent to containment for vapour recovery. This mode of circulation without the compressors is referred to as the **continuous purge** mode. The gas addition bottles through a pressure regulating valve are the normal supply to the annulus gas system.

Dew point analysers in the main outlet header determine the system dew point. These readings as well as temperature and pressure are trended in the main control room for comparison purposes. There are also sample stations, usually in the main outlet headers, which allow for manual sampling of the gas.

The system piping is arranged such that any liquid in the system drains by gravity to the drain header. A moisture beetle in this header will indicate the presence of liquid.

Some stations have an oxygen addition system connected to the header downstream of the compressors. Small amounts of oxygen gas are added to the annulus gas to promote a harder oxide layer on the outside of the pressure tubes. Most stations will be retrofitted with this system for this reason. Oxygen can also be used to purge any solid C^{14} deposits by converting them to CO_2 (this is used for decontamination purposes prior to outages, eg. O_2 concentrations used will be higher than normal operating values).

Annulus Gas Pressure

Obj. 14.3 a) ⇔

The annulus gas system should be pressurized even when the unit is shut down. Positive pressure is maintained **to prevent the ingress of air**. As air ingresses, argon activation in air can lead to high gamma fields.

With the HT system cold, the annulus gas pressure is set to a low value, typically 14 kPa(g). As reactor power increases, the annulus gas pressure increases, typically, in the range **25 to 100 kPa(g)**. When the pressure drops below setpoint, the operator can restore pressure via the pressure regulating valve.

Dew Point

Obj. 14.3 b) ⇔

A dew point analyser(s) measures the **moisture content of the annulus gas**. The signals are sent to the control room where they are trended for comparison purposes so that a **leak trend** can be established. The rate of rise of dew point can also be established as a requirement for purging.

The allowable moisture levels in the annulus gas are usually expressed as a dew point and vary from station to station. A typical dew point operating range is **- 40°C to - 10°C** with - 30°C as a normal operating value.

System Purging

⇔ *Obj. 14.4*

Whenever the moisture content of the gas approaches the dew point upper limit, the gas should be purged. Fresh dry gas is used to replace the impure gas for the following reasons:

a) To **remove accumulated moisture** which would otherwise contribute to high corrosion rates and mask small leaks. The reasons for purging include preventing build-up of corrosion products and preventing blockage of the interconnecting tubing for the channel annuli.

b) To **remove corrosive impurities**, the most critical being nitric acid formed from N_2 and O_2 via air ingress.

c) To **remove air** in the system, typically following maintenance to the system.

d) To **reduce gamma fields** in accessible areas, when Ar^{41} has formed as a result of air ingress.

e) To **lower the dew point** prior to startup of the reactor from a cold shutdown. As the reactor heats up, the temperature and pressure will increase in the annulus gas system. The partial pressure of any water vapour in the system will also increase, raising the dew point. To counter this effect, the dew point is lowered prior to heatup by a purge with dry gas.

f) To maintain **leak detection** capability by maintaining gas flow through the system when the compressors are unavailable.

SUMMARY OF THE KEY CONCEPTS

- CO_2 has the beneficial properties of:
  - – low thermal conductivity;
  - – low corrosion;
  - – limited activation products.
- Annulus gas must be circulated or purged to ensure dew point measurements and gas sampling are representative of all of the annuli.
- System pressure should be kept above atmospheric pressure to prevent air ingress. A typical range is 25 to 100 kPa(g).
- Dew point is monitored to detect moisture from leaks. A leak tight system should have a dew point range of - 40°C to - 10°C.

- Purging may be necessary to:
  - remove accumulated moisture;
  - remove corrosive impurities such as nitric acid;
  - remove air from the system;
  - reduce gamma fields;
  - maintain leak detection capability when the compressors are unavailable;
  - lower the dew point before a cold startup.

ABNORMAL UNIT CONDITIONS

1. High Annulus Gas Pressure

Obj. 14.5 a) ⇔

Annulus gas pressure can increase due to the following causes:

- Pressure tube rupture;
- Thermal effects due to increases in reactor power;
- Pressure regulating failure.

Annulus gas overpressure can cause strain, **fatigue** or even **rupture** of the **calandria tubes** or secondly, **fatigue** or **rupture** to the **bellows seals** joining the annulus gas system to the pressure tube end fitting.

Overpressure protection is provided by pressure relief valves. Some stations use rupture discs on the compressor outlet in combination with the pressure relief valves.

2. Low Annulus Gas Pressure

Obj. 14.5 b) ⇔

Annulus gas pressure can decrease due to the following causes:

- System leakage;
- Loss of bulk gas supply;
- System shrinkage on reactor cooldown.

It is possible to draw vacuum on the system if it is isolated and cooled. **Pressure below atmospheric** in the annulus gas system **could cause the collapse of calandria tubes.** Where possible, the system should be repressured via the bulk storage and any leaks repaired. **Air in-leakage is** also **a concern** at low annulus gas pressures because of the resulting increase in radioactivity.

3. Annulus Gas Leakage

Obj. 14.5 c) ⇔

Annulus gas can escape through piping leaks or channel bellows leaks. This can present a **radiation hazard** as well as **reduce** the or the moderator. A **stagnant mode of operation** is then used to **locate the leaking annulus.** The compressors are shut down and isolated with the purge valves closed to:

- Maximize condensation of D_2O in defective channels and;
- Reduce the spread of moisture throughout the annulus gas system.

A leak search also includes checks of channel outlet temperatures. The leaking fuel channel transfers heat from the pressure tube to the calandria tube via the leaking D_2O. If the gas space surrounding the leaking pressure tube fills with D_2O the heat transfer rate increases to effectively lower the channel outlet temperature. However, the channel outlet temperature data may not indicate the leaking pressure tube until sufficient fluid condenses and accumulates. It should be kept in mind that low channel outlet temperatures can also result from other reasons such as the pressure tube touching the calandria tube.

Note that a beetle alarm may take a long time to come in, depending upon the leak location and size. Sight glasses may also be available in some stations to detect liquid flow from individual annuli.

SUMMARY OF THE KEY CONCEPTS

- For the following conditions the operating concerns are given:

Conditions	Operating Concern(s)
High gas pressure	Failure or rupture of calandria tubes, failure or rupture of bellow seals if overpressure protection fails.
Low gas pressure	Air in-leakage, collapse of calandria tubes.
Gas leakage	Radioactive hazard, reduced ability to check P trends.
Air in system	Radioactive hazard primarily, Ar^{41}, production of corrosive nitric acid, moisture masking leaks.
High or increasing dew point	High pressure and temperature hazards with potential for a LOCA, radiological concerns.

ability to check P (pressure) trends. The escaping annulus gas from any leakage points may contain radioactivity in the form of:

- C^{14}, an activation product, as CO_2 gas or as a particulate;
- Entrained fission products and loose contamination from fission products;
- Tritium from D_2O leakage.

Annulus gas leakage can also cause low annulus gas pressure which, as mentioned in item 2 above, may lead to air in-leakage.

4. Air in the Annulus Gas

⇔ *Obj. 14.5 d)*

Maintenance work or leaks in the system cause air ingress into the annulus gas.

The presence of air leads to radioactive hazards and the production of **corrosive nitric acid** (from N_2). The predominant **radiation hazard** is Ar^{41}, an activation product. Other radiation hazards include C^{14} produced from N^{14}, and N^{16} and O^{19} from O^{16} and O^{18}. **Moisture from air** in the system **may mask leaks.**

5. High or Increasing Moisture Content

⇔ *Obj. 14.5 e)*

An increase in dew point indicates an increase in moisture content of the annulus gas.

Possible causes of high or increasing dew point may be:

- Pressure tube leak;
- Calandria tube leak;
- Air in-leakage;
- Impure annulus gas supply.

For a persistently high dew point after purging, the most probable cause is a pressure tube leak, because of HT system high pressure and temperature. Two **operational concerns** exist with increasing dew point. Firstly, that a contaminated system is leaking with **radiological concerns** and the **potential for a subsequent LOCA** with possible fuel and calandria tube damage. The leak will eventually increase over time when power changes produce temperature changes in the leaking system. Secondly, a **high temperature and pressure hazard** exist in the case of a HT system leak.

6. Leak Location

⇔ *Obj. 14.6*

To locate the leak source, a sample of condensed fluid is obtained by passing a stream of moist annulus gas through a cold finger*. The sample is then analysed to determine if the source is the HT system

* A cold finger is a trap in dry ice which freezes the moisture.

NOTES & REFERENCES

- The system may be stagnant to determine the location of a confirmed leaking annulus by maximizing condensation of D_2O in the defective channels and reducing the spread of moisture throughout the annulus gas system.

You can now **work on the assignment questions.**

⇔ ***Page 11***

ASSIGNMENT

1. State three desirable properties of CO_2 as an annulus gas:

   a) ______________________________

   b) ______________________________

   c) ______________________________

2. The annulus gas system is normally circulating even when the unit is shut down. Why is this desirable?

   ____

   ____

3. a) Dew point is one of the most important operating parameters for the annulus gas system. Why is this the case?

   ____

   ____

   b) Why is annulus gas pressure monitored?

   ____

   ____

   c) State typical operating ranges for the following parameters.

   Dew point ______________________________

   Pressure ______________________________

4. Occasionally conditions warrant purging of the annulus gas system. State six reasons why purging would be required:

   a) ______________________________

   b) ______________________________

   c) ______________________________

   d) ______________________________

   e) ______________________________

   f) ______________________________

5. Under what operating condition would the annulus gas compressors be shut down and isolated?

   ____

   ____

6. Complete the following chart:

Conditions	Operating Concerns
High or increasing dew point	____________________ ____________________
______________	Radioactive hazard Ar ^{41}, ____________________ ____________________
Gas leakage	____________________ ____________________
Low pressure	____________________ ____________________
High pressure	____________________ ____________________

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

Prepared by:	D. Bieman
Revised by:	P. Bird, WNTD
Revision date:	June, 1992

Module 15

SHIELD COOLING SYSTEMS

OBJECTIVES:

After completing this module you will be able to:

15.1 a) State the reason why the end shield requires cooling. ⇔ ***Page 2***

b) Explain the consequence of the loss of end shield cooling: ⇔ ***Page 3***

c) State the approximate percentage of reactor thermal power removed by the end shield cooling system. ⇔ ***Page 3***

15.2 For the end shield cooling system, list:

a) Heat sources at power (2), ⇔ ***Page 3***

b) Heat transfer path, ⇔ ***Pages 4-6***

c) Heat sinks (1). ⇔ ***Page 6***

15.3 Explain the reason why the end shield cooling system purification loop is required. ⇔ ***Pages 4-5***

15.4 a) State three parameters, other than the controlled variable (temperature), which must be monitored to ensure that end shield cooling system performance is adequate. ⇔ ***Page 6***

b) Explain why each of the parameters given in a) are useful in monitoring end shield cooling system performance. ⇔ ***Page 6***

15.5 State three required actions when end shield cooling has been lost. ⇔ ***Pages 6-7***

15.6 a) State three conditions which must be satisfied to allow the end shield cooling system to be taken out of service. ⇔ ***Page 7***

b) State the main heat source in the end shield when the reactor is shutdown and cooled down. ⇔ ***Page 7***

c) Explain the reason why the end shield cooling system can be taken out of service at that time. ⇔ ***Page 7***

d) Explain the three special precautions required if the end shield is to be drained. ⇔ ***Page 7***

NOTES & REFERENCES

Page 8 ⇔ 15.7 a) State the reason why the biological/thermal shield requires cooling.

Page 8 ⇔ b) Explain the consequences of the loss of biological/thermal shield cooling flow.

Page 9 ⇔ c) State the approximate percentage of reactor thermal power removed by the biological shield cooling system.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

Recall from the previous levels of the Reactors, Boilers and Auxiliaries course that there are three types of shield used in CANDU reactors to protect personnel and equipment. These shields are as follows:

a) Calandria End Shields – Used to protect personnel against γ in the reactor vault during unit shutdowns only.

b) Biological Shield – Used to protect personnel against radiation, mainly γ and fast neutrons during unit operation.

c) Thermal Shield – Protects equipment and structures against heat generated by the absorption of nuclear and thermal radiation emitted by the reactor.

Note that in most stations that the thermal and biological shields are combined*.

* This is discussed on page 8.

This module covers the normal and shutdown cooling requirements of the shield cooling systems and the adverse consequences of the loss of system cooling. The draining of the end shield cooling system will also be discussed.

CALANDRIA END SHIELDS

Cooling Requirements

Obj. 15.1 a) ⇔

During normal operation, heat is generated in the end shield components by both radiation absorption (neutron plus γ) and by heat conduction. This heat cannot be allowed to build up, since it could result in **reactor component damage** due to excessive thermal stress. This heat must be removed by the end shield cooling system.

⇔ Obj. 15.1 b)

Upper and lower temperature operating limits are set for the end shield to prevent excessive **thermal stresses** from developing between the end shield and the calandria. The calandria shell and the end shield components are welded together and contain many rolled joints. An excessive ΔT in either direction will cause increasing **differential expansion**, which is severely constrained because of the design. Structural damage such as **fractured welds, failed rolled joints** and **displaced** shielding **slabs** (where installed) may occur. A very important parameter then, is the temperature difference (ΔT) between the moderator and the end shields. (Typical values of end shield temperatures are ~60°C at the inlet and 65°C-70°C at the outlet. Recall from the moderator circulation system module (2), typical moderator inlet/outlet temperatures are 40°C/60°C).

⇔ Obj. 15.1 c)

At full power, the heat produced in the end shields will typically be less than **1 %** of total reactor thermal power. The heat sources are divided as follows:

⇔ Obj. 15.2 a)

a) About 30% is due to **absorption of neutrons and γ from fission and fission products** (ie. decay γ).

b) The rest is due to **heat conducted** from the hot **end fittings** and the **moderator.**

Design Types

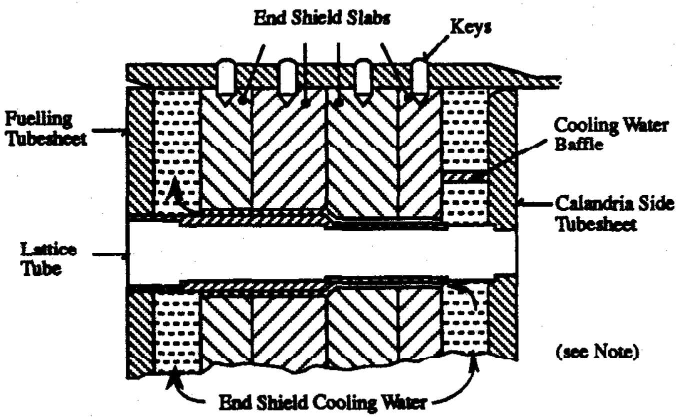
All CANDU reactor end shields are water cooled and are of two basic design types .

The first design uses carbon steel slabs, cooled with light water (Fig. 15.1 (a) on the next page). The carbon steel slabs are keyed together to make up a single thick section centered in the end shield. This thick section, combined with the channel shield plugs, provides the shutdown shielding for the end of the reactor *. Cooling is provided between this steel shield and each of the tubesheets. Cooling flow is directed from the bottom to the top of each shield and through the space provided by the lattice tubes (for end fittings of the fuel channels).

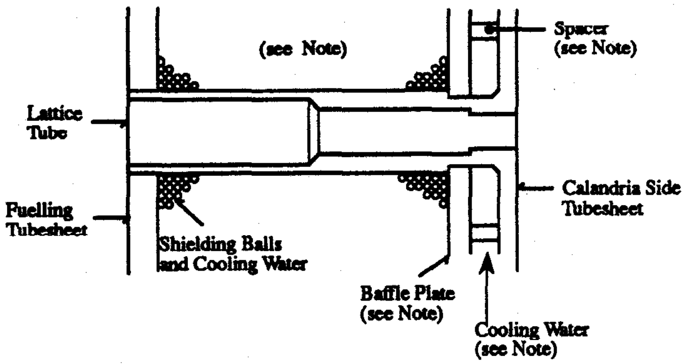
* Recall from previous R&A courses that shutdown shielding at the face of the reactor would be inadequate without shield plugs in the channels.

The second design uses carbon steel balls for the shielding media, and is also cooled with light water (Fig 15.1 (b)). This design features better heat transfer for improved cooling and a lower construction cost than the slab design. This design is also more tolerant of high ΔTs, in terms of thermal stressing of the end shield and calandria components. All of the newer stations use this design.

15.1 a) Slab Design



15.1 b) Shielding Ball Design



Note : Designs vary slightly from station to station

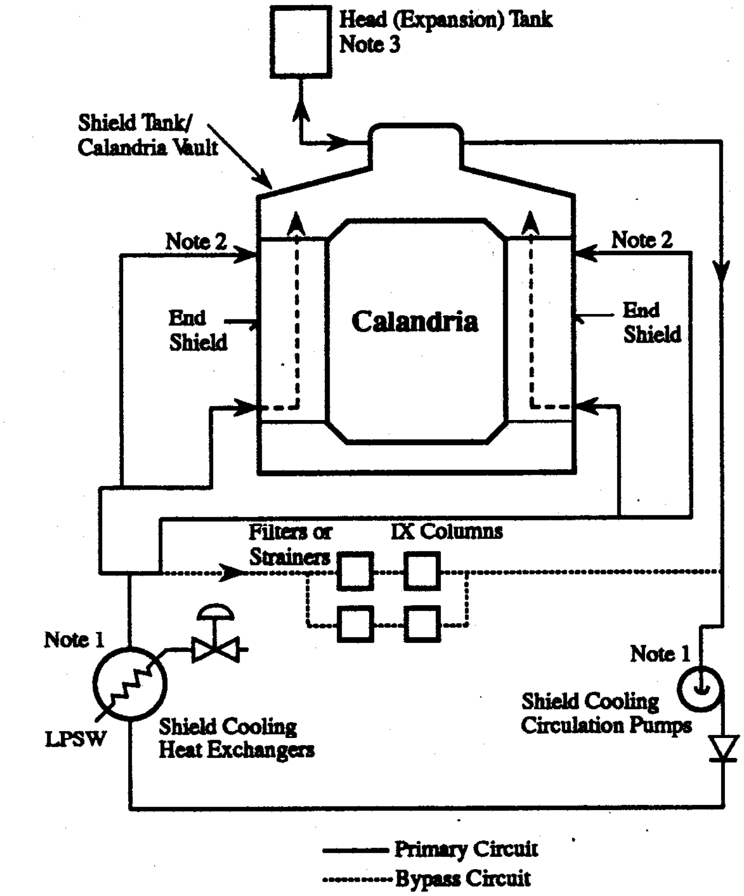
Figure 15.1 : Basic End Shield Designs

End Shield Cooling

Obj. 15.2 b) ⇔ A typical shield cooling design is shown in Figure 15.2. The shield cooling system consists of pumps, heat exchangers, a bypass purification circuit and a head (expansion) tank.

The system recirculates demineralized light water through the end shields to pick up the heat from the shielding slabs or balls. The water is cooled, cleaned and used for shielding elsewhere in the system (ie. in the shield tank, if installed).

Obj. 15.3 ⇔ The circulated water is purified by filters (or strainers) and IX columns to minimize and **remove corrosion products**. These corrosion products occur because carbon steel is used in the end shields (steel balls or slabs, shield tank). These products must be removed to minimize contamination spread by the **transport** of activated corrosion



Note : 1. Number and capacity of components varies from station to station.
2. To baffle area or distribution pipes in tank.
3. Connected directly to pump suction in some stations.

Figure 15.2 : Simplified Flow Diagram for End Shield/Shield Tank Cooling Systems

products. To minimize corrosion, the pH of the shield cooling system is controlled to between 9.8 and 10.7 by the use of LiOH resin in the IX columns.

The head (expansion) tank is connected to the shield tank extension at the top of the reactivity mechanism deck, or directly to the pump suction in some stations. Its function is to accommodate shrinkage and swell of the coolant (ie. ensure proper level maintained), and to provide a positive suction head to the circulating pumps to prevent cavitation. Because of the γ and neutron fluxes, radiolysis can occur in the end shields, causing a hydrogen hazard in the head tank. To minimize this hazard, the head tank is open to contaminated exhaust to vent off the hydrogen, and in some stations may also be purged with nitrogen.

The pumps circulate the coolant through the end shield (and shield tank), the heat exchangers and the purification loop. The pumps are supplied by Class III power to ensure circulation is restored rapidly following a loss of Class IV power. This is because of the potential damage due to thermal overstressing of the end shield/calandria (due to loss of cooling flow).

The heat exchangers transfer heat **from the coolant** circulated through the end shield **to service water**. Temperature control is achieved by regulation of the control valves on the service water side of the heat exchangers. The temperature is controlled at approximately moderator temperature, hence avoiding large ΔT's and the resultant thermal stresses between the end shield and calandria. This service water then transfers heat **to the environment**.

Obj. 15.2 c) ⇔

Obj. 15.4 a) & b) ⇔

Parameters, other than end shield and heat exchanger inlet/outlet temperatures, available for monitoring cooling are:

- **Shield tank/head tank levels**, to ensure that adequate coolant is available for cooling ie. no "dry" spots exist, and to ensure the circulating pumps do not cavitate. These levels will also indicate temperature changes by indicating shrinkage and swell of the coolant. This may mean there are leaks from the system,
- Gross **flow** of the coolant, to ensure coolant is flowing and will also automatically initiate additional pumping capacity as required,
- **Pressure** measurement at pump's suction, discharge, HX discharge and ΔP across the HX. These pressures will indicate flow problems, eg. break locations, flow blockages, etc.

Loss Of End Shield Cooling

Obj. 15.5 ⇔

The temperature of the end shields will immediately increase if there is a loss of cooling. This could cause a large ΔT between the end shield and calandria. Prompt actions are required which would include the following (note that, typically, only a few minutes are available before the second step in the following list would be required):

1) **Check for, and correct** cooling system **deficiencies**. Possible causes are:
    - Service water and temperature control valves operation,
    - Pump operation, eg. pumps cavitating (and coolant not circulating), etc.
    - Shield tank and head tank level low,
    - Large leaks (low pressures, low head tank level),
    - Moderator cooling system malfunctioning, causing increased heat transfer to the end shields.
2) If the above checks/actions are unsuccessful, **reactor power must be reduced *** until heat removal capability of the shield cooling system matches heat production. In some stations, this occurs automatically via a reactor setback on loss of ESC flow.

* The rate of power reduction required will be listed in your station's operating procedures.

3) If the above actions are not successful, a **cooldown of the HTS** (or crash cooldown in some stations) will be required.

End Shield Cooling System Requirements

The end shield cooling system must be functional at all power levels of reactor operation. The shield cooling system **may be shut down** if the following conditions are met:

⇔ ***Obj. 15.6 a)***

- The **reactor** has been **shut down** for a specified time period (4–24 hrs*),
- The main **moderator temperature** is less than a specified limit (~38 to 40°C*) and,
- The **HTS** is **"cold"** (≤ ~55°C*).

* Values vary from station to station.

These conditions ensure that the heat input into the end shield will not result in damage due to overstressing. With the reactor shutdown, and the HTS and moderator cooled, the **heat source** is mainly decay γ, which will be at extremely low levels, as compared to operating heat sources. This **heat will be taken away** by natural convection by the reactor vault atmosphere, moderator and HTS systems (all still being cooled).

⇔ ***Obj. 15.6 b)***

⇔ ***Obj. 15.6 c)***

Special precautions must be taken if the end shield is to be drained. Without water in the end shields, the natural convective cooling of the water within the end shield (mentioned above) would be lost, resulting in possible thermal stresses and damage. Without the shielding effect of the water, radiation fields may reach thousands of R/Hr at the reactor face. The corrosion protection provided by the water will also be lost, resulting in corrosion (due to air access to wetted surfaces) and eventual activation and activity transport. Draining of the system would require:

⇔ ***Obj. 15.6 d)***

1) Detailed stress analysis to ensure stresses due to thermal effects do not exceed design limits,
2) Measures to control corrosion are implemented and,
3) Access to reactor areas is restricted or additional shielding is provided to compensate for the loss of shielding from the water.

Note that AECB approval may also be required (depending on the station), as increased exposure risks to station personnel will exist .

THERMAL SHIELD

The thermal shields used in CANDU reactors are also of two basic designs.

Obj. 15.7 a) ⇔

The first design uses shield plates internal to the calandria. Thick stainless steel liner plates are supported inside the calandria shell. These plates are **heated by γ radiation, fast neutrons** (due to leakage) **and thermal heat** from the core. Cooling of the thermal shield is performed by the moderator D_2O, through the moderator cooling circuit. Unfortunately, in this design, sufficient heat escapes the reactor to make it necessary for a cooling system in the surrounding concrete shielding. This will be discussed next, when considering prevention of damage to the biological shield. This system does reduce the required capacity for the biological shield cooling system.

The second approach uses a water filled shield tank which surrounds the calandria (Note: some stations use a steel tank, others use a steel lined concrete structure). This tank encloses and supports the reactor core and **absorbs the γ, fast neutrons and heat** from the reactor core. This water shield provides biological shielding at the top of the reactor (called the reactivity mechanism deck) and provides shutdown access shielding elsewhere. This design is used in the newer stations. Because no separate biological shield cooling is necessary, the advantages of this design are reduced construction costs and time compared to the previous design (which requires extensive runs of cooling pipes embedded in the biological shield). The cooling of this thermal shield is via the end shield cooling system as previously shown in Fig. 15.2.

In both cases of thermal shield design, the cooling of the thermal shield is performed as a function of another system, ie. moderator or shield cooling system. Thus the percentage of heat removed in these cooling systems also includes the heat generated in the thermal shields.

BIOLOGICAL SHIELDS

The design of the biological shields reflect the effectiveness of the thermal shield.

Obj. 15.7 a) ⇔

Obj. 15.7 b) ⇔

For the thermal shield internal to the calandria, additional shielding surrounding the calandria is required. This shield, known as the biological shield, is made of heavy concrete and is comprised of the calandria vault walls, roof, floor, and hatches. This shield is heated due to the **absorption of neutron and γ radiation** from the core as well as **thermal heat convected and radiated from the core.** Cooling of this shield is required to limit the concrete temperature to ~60°C. At higher temperatures, water is driven out of the concrete, resulting in the following adverse consequences:

a) Thermal stresses may cause **spalling** and **cracking** in the concrete, hence its **physical strength** will be reduced.

b) With less water in the concrete, it is **less effective** as a **neutron shield**.

Cooling of the concrete of the biological shield is provided by water flow through pipes embedded within the concrete. The cooling water is circulated by an independent system, similar to the end shield cooling system, consisting of pumps, heat exchangers, head tank and a bypass filter system. The typical heat removed by this system is **<0.1%** of reactor full power.

⇔ Obj. 15.7 c)

For the water filled shield tank or vault design of thermal shield, cooling of the surrounding concrete biological shielding structures is not required. The effectiveness of the thermal shield is sufficient to eliminate the need for embedded cooling pipes in the containment/shielding structures.

SUMMARY OF THE KEY CONCEPTS

- The end shield and biological/thermal shields require cooling to remove heat derived from the absorption of γ radiation, neutrons and thermal heat from the reactor core. Cooling is required while operating at any reactor power level, and for some time after shutdown.
- The end shield temperatures must be limited to prevent thermal stresses from occurring between the end shield and the calandria shell. Damage could result from high stresses.
- The heat removal from the end shield at power will be 0.2 to 0.6 % reactor full power. When shut down with the HTS and moderator cooled, heat production will be mainly due to decay γ. This will be a small heat source and convective cooling will be adequate.
- Heat removal from the end shield occurs via heat transfer from the steel slabs or balls to the circulated coolant, then in the heat exchangers from the coolant to the service water, which is rejected to the environment.
- Special precautions must be taken if the end shield is to be drained. Stresses resulting from the loss of cooling must be determined, measures to protect against system corrosion and increased radiation fields must be taken.

- The end shield cooling system purification loop is required to remove activated corrosion products from the system. These corrosion products are removed to ensure that activity transport in this system is minimized.
- Other parameters which are monitored to ensure adequate end shield cooling are system flow, shield/head tank levels, and system pressures.
- The required actions on the loss of end shield cooling are to restore cooling, reduce reactor power and a cool down the HTS as required to maintain ΔT's.
- Loss of cooling to the thermal/biological shields will result in overheating of concrete structures, which will result in the concrete drying out, leading to damage and reduced shielding against neutrons.
- The heat removal from the biological shield (where cooling systems are installed) will be $< 0.1\%$ reactor full power.

Page 11 ⇔

You can now **work on the assignment questions.**

ASSIGNMENT

1. The end shields must be cooled because they are heated by:

a) ____

____

b) ____

____

2. The consequence of the loss of end shield cooling are:

____

____

____

____

____

3. The approximate reactor thermal power removed by the end shield cooling system is ________. The two major sources of heat at full power are:

a) ____

____

b) ____

____

4. The heat transfer path for the end shield cooling system is:

____

____

____

____. The

ultimate heat sink for this system is ____________________

____________________________________.

5. The end shield cooling system requires a purification system because:

____

____

____

____

____

6. Three parameters (other than temperature) that are monitored to ensure adequate end shield cooling system performance are:

a) ____________________________________,

which is useful in monitoring performance because ________

____

____

____

____

b) ____________________________________,

which is useful in monitoring performance because ________

____

____

____

____

c) ____________________________________,

which is useful in monitoring performance because ________

____

____

____

____

7. When the end shield cooling has been lost the following major actions are required:

   a) ____

   ____

   b) ____

   ____

   c) ____

   ____

8. The end shield cooling system can be shutdown when the following conditions are satisfied :

   a) ____.

   b) ____.

   c) ____.

   The end shield cooling system can be taken out of service at that time because ____

   ______________________________________. The major

   sources of heat at this time will be ________________.

9. Three precautions required before draining the end shield are:

   a) ____

   ____

   ____

   b) ____

   ____

   ____

   c) ____

   ____

   ____

10. a) The biological/thermal shield must be cooled because they are heated by ______________________________

____

b) If this heat is not removed, damage may occur to the ______

______________________________, leading to the following adverse consequences:

i) ______________________________

____

____

ii) ______________________________

____

____

11. The approximate reactor thermal power removed by the biological shield cooling system is ______%.

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

Prepared by: N. Ritter, WNTD
Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 16

FUEL PERFORMANCE

OBJECTIVES:

After completing this module you will be able to:

16.1 a) List the seven factors which currently contribute to fuel failures during reactor operation. ⇔ *Pages 2-3*

b) List the methods that can be used to minimize each of the factors listed above. ⇔ *Page 3*

16.2 Explain two factors that can cause high fuel temperatures. ⇔ *Pages 3-6*

16.3 Explain the reason for a limit on the amount of power to be extracted from a bundle or channel and the consequence of exceeding this limit. ⇔ *Page 6*

16.4 State the information typically available to the operator to ensure that the bundle power limit is not exceeded by any bundle for:

a) A non-boiling channel (1 method). ⇔ *Page 8*

b) A channel in boiling (2 methods). ⇔ *Pages 8-9*

16.5 State three reasons for detecting, locating, and removing failed fuel from the reactor. ⇔ *Page 10*

16.6 Explain the indicated number of general techniques used for: ⇔ *Pages 10-12*

a) Detection of failed fuel in the reactor (1),

b) Locating failed fuel in the reactor (2).

16.7 State three methods that can be used to reduce iodine concentrations in the coolant (assuming the concentration is rising from just below the action limits to shutdown levels). ⇔ *Page 13*

16.8 State the reason why high iodine concentrations may occur on a shutdown even though the shutdown process itself did not cause fuel to fail. ⇔ *Page 13*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The performance of CANDU fuel is assessed in four main areas:

a) Maximized power production per bundle and per channel.

b) Maximized power production over a period of time (burnup).

c) Minimum number of failures.

d) Performance under major upset conditions.

Points a), b) and d) are largely decided by the design of the fuel and the method of operation of the particular unit. It can be stated that the first two conditions will generally be achieved making fuel failure our critical factor.

It must also be remembered that the fuel operates in a hostile environment. The HTS operates at high pressures, a temperature of about 300°C and at a pH of about 11 in high radiation fields. Fuel bundles can spend up to eighteen months in the reactor.

In practice, operation of CANDU reactors over the years has not highlighted fuel failures as a significant problem. The introduction of CANLUB* fuel and changes in operating strategies have reduced fuel failures to less than 0.1%. It should be noted that only one element usually is found to be defective in a bundle. Thus the defect statistics based on defective elements for CANLUB fuel drops to 0.002%. This low figure does not mean that the problem is solved. Efforts must continue to at least maintain and, if possible, improve these figures.

* Recall from previous R&A courses that CANLUB fuel has a layer of graphite between the pellet and the sheath. This graphite layer will reduce pellet/sheath friction, reducing strains due to pellet movement. This graphite layer also provides a physical barrier to corrosive fission products for the sheathing. (It also improves the thermal contact between the pellet and the sheath).

It must also be recalled that the fuel provides the first two barriers to the release of fission products (ie. the ceramic fuel itself and the fuel sheath). Fuel failure inevitably results in the release of fission products into the Heat Transport System.

This module will discuss potential causes for fuel failures, mechanisms to prevent fuel failure(s) and methods to detect and remove failed fuel from the reactor during normal operation. This module will also discuss methods available to the operator to ensure fuel bundle power limits are not exceeded.

Obj. 16.1 a) ⇔

Failure mechanisms

The seven main **observed failure mechanisms** for CANDU fuel during reactor operation are:

1) Manufacturing faults - particularly in terms of metal and welding quality.

2) Fretting and erosion due to debris in the HTS (particulary for the initial core load).
3) Cracking due to hydride cracking around the endcap welds, or stress corrosion cracking of the Zircaloy sheathing.
4) Careless handling of fuel, leading to mechanical stresses on the sheath (ie. due to chipped ceramic, etc.).
5) Fuel overrating, ie. producing too much power from a bundle.
6) "Ramp" failures or bundle overpowering, ie. large, rapid changes in reactor power from one steady state condition to another. This is especially important for bundles that have been in the core for a long time.
7) Loss of cooling of a bundle.

⇔ Obj. 16.1 b)

Methods that can be used to **minimize the fuel failure** mechanisms listed above are:

1) Careful inspection of all fuel bundles before loading into the reactor to eliminate those which have obvious flaws.
2) Good housekeeping to ensure that debris is not introduced into the HTS.
3) Ensure that all HTS chemical parameters are strictly enforced.
4) Careful handling of all fuel bundles, which includes manual handling of new bundles and handling of new and spent fuel by the fuelling machines.
5) Proper fuel and physics calculations and proper fuelling operation. This will prevent placing too many new bundles in high reactivity zones of the core, etc.
6) Minimize large, rapid changes in reactor power from one steady state condition to another.
7) While fuelling, both flow and temperature in the channel are monitored since this is the most likely time a flow blockage will occur, causing a loss of bundle cooling. Under normal operation, flow measurement is limited to fully instrumented channels only. All channel outlet temperatures are monitored but, if a channel is boiling, outlet temperature alone will give no indication of flow blockage.

These procedures will do much to ensure that fuel failures are minimized.

The potential failure mechanisms dealing with loss of cooling and bundle overrating are discussed below.

Fuel Overheating

Obj. 16.2 ⇔

Centerline melting of the fuel will cause pellet expansion, leading to stressing and failure of the fuel sheath. The **fuel element** centre line **temperature**, our principal concern, is dependent upon **two factors**:

1) The amount of heat produced in the fuel.

2) The ability to remove heat from the fuel.

The above can result in excessively large differential temperatures being required (between the fuel elements and the coolant), in order to transfer the heat being generated. This can lead to overheating of the fuel and/or fuel sheath.

Recall that our fuel material, UO_2 , has very low thermal conductivity and that even under normal operating conditions with the fuel sheath temperature at about 300°C the centre line temperature of high power bundles will approach 2000°C. The approximate melting temperature of UO_2 is ~2750°C. Our normal operating practices must ensure that fuel temperatures which could cause fuel failures are avoided.

The **quality of heat removal** can be verified by:

1) Flow measurement- fully instrumented channels (FINCH) and adequate number of HTS pumps in service (also ΔP monitoring during fuelling).

2) Temperature measurements where temperatures are useful (ie. at channel inlet at all times and at channel outlets when the channel is non-boiling (low power)).

3) Pressure measurements in the HTS.

4) Thermal power measurements, either by the fully instrumented channels (FINCHs) or secondary side measurements. Reactor thermal power can be calculated by using FINCH flows and temperatures (as representative of the core). By using various flows and temperatures on the secondary side, reactor thermal power can be calculated.

In a forced convection mode, as the coolant changes from subcooled to full film boiling conditions, heat transfer conditions will change considerably*.

* The fuel cooling process is described in detail in the Heat and Thermodynamics Course 225.

Consider a channel as reactor power (hence fuel temperature) increases. There will be an initial increase in heat transfer as initial (nucleate) boiling begins. As boiling becomes more pronounced, progressive steam blanketing (film boiling or dryout) will occur and heat transfer reduces. This reduction begins when Critical Heat Flux (CHF) conditions are exceeded (even slightly). Recall from the 225 course, that the maximum heat flux that can be removed by nucleate boiling is termed the critical heat flux (CHF). The power in a channel at which critical heat flux conditions are met is termed the Critical Channel Power (CCP). Note that CHF conditions can be established even below the previously defined CCP (for a normal flux shape) if the flux shape deviates from normal *. Changes in thermohydraulic conditions and/or flux shape will result in a new critical channel power for that channel.

* More information about this will be discussed later in the module.

We operate reactors such that the Critical Heat Flux will not be reached under normal operating conditions. If full steam blanketing (film boiling) occurs, heat transfer will be mostly by conduction and radiation across the film and fuel temperatures will increase drastically (by 100's of degrees.) Fuel failure is highly probable. Recall also that channel voiding increases reactivity and would add to the problem.

Overrating will almost certainly produce excessive element centre line temperatures. This would eventually lead to centre line melting and pellet expansion, with a high probability of sheath failure. Gross overrating could cause pressure tube damage due to fuel bundle disassembly (deformation).

As mentioned previously, the fuel overheating can be caused by a **combination of power produced and coolant conditions.**

With a "standard" full power neutron flux profile, but with a reduced coolant mass flow through the channel, boiling will occur or will be reached at a point closer to the inlet (for a channel that is already in boiling). The bundles at the exit end of the channel will likely be subjected to dry out conditions and overheating of the final bundles is possible. Note, however, that the bundles subject to overheating were not those subjected to the maximum neutron flux conditions.

A similar result would have been achieved by increasing the neutron flux levels with the coolant flow unchanged (overheating following overrating).

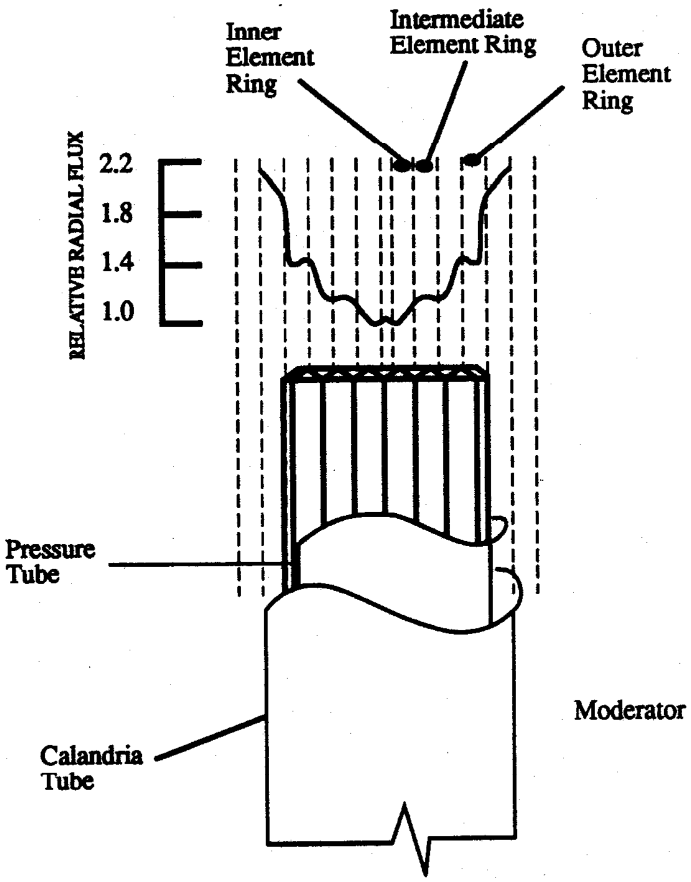
Similar effects can be shown using a non-standard or "skewed" flux profile. For this example, assume that the flux profile is skewed toward the channel outlet, ie. the high flux, hence higher power production, is at the channel outlet. As the coolant flows through the channel, it gets hotter as it picks up heat from the fuel bundles, and the margin to boiling decreases. As this coolant (with a low margin to boiling) passes over the high power bundles at the channel outlet, film boiling will occur due to high bundle temperatures (these bundles will be much hotter than a normal bundle due to the flux shape). This will lead to fuel bundle overheating, with a higher probability of fuel failures.

Since flow in adjacent channels is in opposite directions, the skewed flux shape described above would produce a higher flux at the inlet end of these channels. Note that assuming all other channel conditions are similar to the channel mentioned in the paragraph above, the same amount of heat is being produced in these two channels. But, in this second case, the coolant is passing over the high power (hot) bundles with a much larger margin to boiling, since they are at the channel inlet. These bundles will be cooled without any boiling occurring. The bundles at the channel outlet, being cooler (these bundles will be cooler than a normal bundle due to the depressed flux at the channel outlet), will be adequately cooled without dryout occurring in the channel.

Power Limits

Fuel centerline temperatures must be limited, but it is not a parameter that we can measure in our reactors. This is further complicated by the fact that neutron flux in the reactor will vary axially and radially. Even within the fuel bundle itself, there is a variation in the thermal neutron flux (shown in Figure 16.1). Recall from the 227 course that this flux depression is caused by the outer fuel elements absorbing thermal

Figure 16.1
Thermal Neutron Flux Depression in a Fuel Bundle



neutrons from the surrounding moderator. Thus, progressively fewer neutrons are available for the intermediate and inner fuel elements.

Taking these facts into account, at the design stage, the upper limit at which fuel failure is still unlikely must be established. The maximum bundle power limit must be below the power required to cause fuel failures.

The Station Licence contains the limiting values for fuel bundle, fuel channel and reactor power and coolant flow. Operating procedures and policies must ensure that these figures are not normally exceeded so that fuel failures and subsequent release of fission products are limited.

⇔ *Obj. 16.3*

In most stations, **bundle and channel power limits** are specified to ensure that bundles are not overrated under normal operating conditions or during transients.

Limiting the channel power alone is not sufficient to ensure that no fuel bundle is overrated. This is because flux can deviate from its normal shape.

For example, a bundle power during normal operating conditions may be limited by the channel power limit (ie. taking channel power, number of bundles and a "normal" flux distribution into account, the bundle will be producing powers below the licence limit to ensure the channel power is not exceeded).

Now let's say that a flux tilt develops due to a Xe transient. This may result in the majority of the power being produced at the inlet end of a channel. Now, it is possible that a particular bundle at the "high power" end of the channel is producing power in excess of the licence power limit, while the channel power limit is not being exceeded.

One note to make here is that as the bundle burnup increases, the maximum power that it can be subjected to before failures occur reduces. This is caused by the increasing sheath embrittlement together with mechanical stresses, mainly due to the buildup of fission product gases. We operate our reactors so as not to subject high burn-up bundles to high power, hence reducing this type of fuel failure.

Bundle power monitoring

Individual fuel element and bundle powers are not measured. To ensure that the bundles are operating within their power limits (and therefore well below centre line temperature limits) at all bundle locations, we must monitor a parameter that is measurable - Channel Power. This is the sum of the thermal powers produced by all individual fuel bundles in a channel.

The **actual measurement technique used to determine channel power varies** as to whether or not boiling is allowed in the channels.

Obj. 16.4 a) ⇔

For a non-boiling channel

Channel power = Channel ΔT x Channel flow x Specific heat capacity of HTS D_2O

A sufficiently flat flux profile must also be ensured to prevent bundle power limits from being exceeded.

Obj. 16.4 b) ⇔

For a boiling channel

ΔT is no longer valid once boiling has commenced (because it will stay constant as long as there is some liquid in the channel). For this situation it is necessary to take account of the steam contribution at the channel outlet by either:

a) Inlet and outlet flow measurements, of a limited number of channels (FINCHs), is measured. A comparison of inlet and outlet volumetric flow rates determining the proportion of steam, and hence the enthalpy content at the outlet * (ie. the outlet flow volume will be larger than the inlet flow volume because the steam will occupy more space than water alone). A sufficiently flat flux profile must also be ensured to prevent bundle power from being exceeded. Note, once that flux shape is known, predictions of channel power and the outlet coolant quality in channels other than FINCHs can be made (with the aid of computer software).

* Note that the saturation temperature or pressure must also be known.

b) i) At High Power

By measuring bulk thermal power and ensuring a sufficiently flat flux profile. The power of individual channels and bundles can be determined (again with the aid of computer software). Thus it can be ensured that channel and bundle power limits will not be exceeded.

ii) At Low Power (Non Boiling Situation)

By the use of ΔT measurements across the reactor and, again, ensuring a sufficiently flat flux profile.

In all the cases above, the flux shape is assumed to be a normal ("flat") shape. Generally, the liquid zone control system controls the flux shape within allowable limits, provided the liquid zones do not go out of their control range (individual zone control is phased out at extreme zone levels to ensure good bulk power control *).

* This is discussed in the I & C 236 course.

In some reactors, additional flux shape information is available from a number of in-core vanadium detectors (Flux Mapping system). Off line computer simulations are used when necessary to determine accurate flux shapes and ensure that licence limits are not exceeded.

Our general concern therefore is to prevent the critical channel power, hence fuel channel dryout, from being reached.

We can meet our criterion in a non-boiling reactor by ensuring that under all analyzed neutron flux shapes, mass flow rates and HTS pressures, the outlet temperatures remain below saturation at all times. Protection can be ensured by initiating a reactor power reduction should any outlet temperature approach the saturation temperature. Separate neutronic safety system trips will ensure that flux shape distortions will not cause any bundle overrating.

To prevent dryout in the boiling reactor, we ensure that flux shapes are known and channel power is monitored using channel flows (in a representative number of channels) and bulk power measurements.

Short term local flux excursions will be indicated and corrected by RRS mechanisms (zones, adjusters, etc.). The operator is prevented, by a combination of design and procedures (defence in depth philosophy) from introducing sudden and drastic changes in neutron flux profiles.

SUMMARY OF THE KEY CONCEPTS

- The seven factors that contribute to the majority of fuel failures are manufacturing defects, fretting and erosion, stress corrosion cracking and hydride cracking, careless handling of fuel, overpowering, overrating and loss of cooling.
- These fuel failure mechanisms can be minimized by careful fuel bundle inspection before use, good housekeeping throughout the HTS, enforcement of all HTS chemical parameters, careful handling of fresh and spent fuel bundles, proper fuelling operations, moderate reactor power changes and monitoring of flows and temperatures while fuelling.
- There are limits on power to be extracted from a bundle or channel to prevent fuel overrating, hence preventing fuel failures due to the resultant overheating. These two limits are required to prevent overrating/overheating during operation with normal and abnormal flux shapes.
- High fuel temperatures can be caused by fuel overrating or inadequate cooling.
- Information available to the operator to ensure any bundle is not overrated is:
  - For a non-boiling reactor, by using channel outlet temperatures to measure channel power and ensuring a reasonably flat flux profile,
  - For a boiling reactor at high power, by using channel flows in a representative number of channels, using bulk power measurements and ensuring a reasonably flat flux profile.
  - For a boiling reactor at low power (non boiling operation), by using channel outlet temperatures to measure channel power and ensuring a reasonably flat flux profile.

DETECTION AND LOCATION OF FAILED FUEL

Failed fuel will inevitably release fission products (FP's) into the Heat Transport System. The first two barriers in the prevention of fission product release have been breached.

Obj. 16.5 ⇔

It is important that any failed fuel be detected, located and removed from the reactor as soon as possible for the following reasons:

a) Failed fuel will, especially under power manoeuvres, release large quantities of FP's into the coolant. This will **increase radiation levels** to plant personnel and ultimately to the general public in the event of releases. This will also make the detection and location of future fuel failures more difficult due to the masking effect created.

b) Note that for the above reason, there is a **shutdown limit** for I^{131} in the HTS *. The shutdown of the unit will result in lost power production.

* This will be discussed in more detail on page 12 of this module.

c) In addition, leaving failed fuel in the reactor could worsen the situation. **Channel blockage** and damage to the pressure tube during defuelling could eventually result from distorted/disassembled fuel bundles. Debris in the HTS may contribute to future fuel failures.

Continuous and individual monitoring of all fuel bundles to determine and locate failures would be an almost impossible task and certainly not economically justified. Even continuous monitoring of individual fuel channels is not presently done at any CANDU location.

The usual method consists of first detecting the presence of a failed fuel element somewhere in the reactor and then locating it.

Various methods have been tried, over the years, to detect failed fuel. Some methods have proven to be more viable than others. All methods employed to date, however, have one feature in common, ie. they all measure gammas or neutrons emitted by a Fission Product (FP).

These detection and location methods vary from station to station, but the **basic methods** are:

Obj. 16.6 a) ⇔

Detection of Failed Fuel

Sample analysis of D_2O from HTS using high resolution γ detectors.

- This will detect gross activity as well as specific γ energies from various isotopes (this is explained in more detail below). This can be accomplished by on-line Gaseous Fission Product (GFP) monitoring, which detects radioactive gases released from the fuel.

This method will detect the presence of failed fuel only. This can also be accomplished by grab samples with lab analysis in the event that the GFP system is not available.

Location of Failed Fuel

⇔ ***Obj. 16.6 b)***

Various methods have been used to locate failed fuel, but only two remain in general use.

a) Scanning of outlet headers/feeders.

- Fission product solids, also known as Depositing Fission Products (DFPs), will be released from the failed fuel. In general the DFPs have limited circulation and tend to be deposited on sheaths, feeders, headers, etc. downstream of the location of the failure. Gamma detectors placed within the feeder cabinets can scan the outlet feeders for individual channels. High activity on a given outlet feeder of a channel would indicate failed fuel in that channel. Thus, this method can be used to locate the channels containing the failed fuel.

b) Detection of delayed neutrons.

- When the presence of failed fuel is indicated by the failed fuel detection system, sample lines from the outlet of individual channels can be scanned for the presence of delayed neutrons. These sample lines are long enough to allow the decay of γ and photoneutrons to reduce the background levels seen by the neutron detectors. Thus, the presence of fission product decay neutrons in a sample line indicates that there is failed fuel in the channel.

Detection and location are further complicated by the fact that the HTS always contains some fission products due to FPs deposited from previously failed fuel, and perhaps, the presence of trace quantities of uranium on the external surfaces of the elements (deposited during fuel fabrication). In addition, there may be an inventory of Activated Corrosion Products formed by the passage of 'crud' through the reactor.

From the hundreds of fission products produced in the fuel, which radionuclides should be chosen to best complement the available detection instrumentation?

For failed fuel detection, radionuclides chosen for detection should have the greatest decay yield (production) possible and should be sufficiently volatile to escape easily from the failed fuel (such as noble gases). Because gases are not removed by the purification system, this gives extra sensitivity to a monitoring system based on noble gases. Half lives should be such that an equilibrium value (4-5 half lives) can be achieved in the HTS over a reasonable period of time (days). This permits detectable quantities to build up, even from a small leak.

Also, in practice, this biases the system heavily towards the detection of gammas rather than neutrons (since neutrons have a smaller decay yield).

For location using delayed neutrons, volatile delayed neutron emitters are observed. A half life of slightly longer than the delay times used for the sample lines (for the decay of N^{16} and O^{19}) is desired. The short half life ensures that the signal from the channel with the failed fuel will be higher than the signals from other channels, since the isotopes will decay before they have dispersed throughout the core.

For location using depositing fission products, the DFP must readily deposit itself on the feeder before dispersing throughout the HTS. Longer half lives will allow for the buildup of activity on the outlet feeders. The chief disadvantage of this system is that DFPs do not easily escape from the fuel.

This leads to a **general conclusion:**

Short half lives (< 1 min) are most suitable for failed fuel location.

Longer half lives (hours-days) are most suitable for failed fuel detection.

The most recent CANDU generating stations use systems which monitor:

1) Specific γ energies from isotopes, typically Kr^{88}, Xe^{133}, Xe^{135}, I^{131} and total γ for failed fuel detection *.
2) Delayed neutrons from Br^{87} or I^{137} for failed fuel location *.

* These isotopes are discussed in the Nuclear Theory 227 course.

HT System Iodine Concentrations

The Station Licence imposes a limit on the quantities of fission products, usually referenced to I^{131} levels, which can be tolerated with the reactor in an at power condition. It is worth pointing out that with no failed fuel present, the level of I^{131} in the HTS is normally quite low. The continued presence of one failed fuel element under steady state reactor operation can increase this "normal" levels by a factor of about four. Power transients however will increase the level of I^{131} in the coolant by a further factor of 10 to 50 times, ie. up to 200 Ci per failed element due to stressing of the defect.

For example, a typical action limit is 500 Curies I^{131} in the HT D_2O and a shutdown limit of 1000 Curies I^{131}. These iodine limits are set primarily because of potential environmental releases, the in-plant consequences of high HT iodine concentrations are also important. In this case, iodine uptake by plant personnel due to HT D_2O leaks and subsequent iodine vapour release is the reason.

As a precaution against further increases of I^{131} at the action limit, **reactor power should not be changed** as this could make the defect(s) worse. HT **purification flow should be maximized** to remove the I^{131} as rapidly as possible from the HT D_2O. **At the shutdown limit, the reactor should be shut down,** the HT system cooled down and the HT purification flow rate maximized, until the iodine concentration is reduced. As mentioned earlier for any fuel defect, the defect must be located and removed from the reactor.

⇔ Obj. 16.7

Should the reactor be shutdown due to high levels of I^{131} in the HTS, the observed **iodine will often increase** (by up to a factor of 20 or so) following the shutdown.

⇔ Obj. 16.8

This does not mean that more defects have been produced. What has happened is that more iodine has been released into the HTS coolant by the **additional stressing of existing defects** (due to temperature and pressure changes in the fuel pellets/sheaths on shutdown).

SUMMARY OF THE KEY CONCEPTS

- Failed fuel is removed from the reactor to reduce radiation levels in the HTS for plant personnel protection and protection of the public (in the event of a LOCA), prevent fission products from entering the HTS, prevent channel blockage or pressure tube damage during defuelling and prevent a plant shutdown once shutdown limits of I^{131} in the HTS are reached.
- Three general techniques for detecting and locating failed fuel are: sample analysis of D_2O from the HTS system, scanning of outlet headers/feeders and the use of high resolution gamma or neutron detectors.
- The methods for detection of failed fuel use the detection of longer lived fission products γs (either gross activity or specific γ energies). Shorter lived γs or delayed neutrons are used for failed fuel location.
- To reduce I^{131} levels in the HTS, power should be maintained steady to prevent making the defect worse, purification flow maximized and the defective fuel located and removed.
- I^{131} concentration may increase because shutdowns could make the defect worse from thermal and mechanical stressing.

You can now **work on the assignment questions.**

⇔ Page 15

ASSIGNMENT

1. The seven factors that currently contribute to the majority of fuel defects are:

   a) ______________________________

   b) ______________________________

   c) ______________________________

   d) ______________________________

   e) ______________________________

   f) ______________________________

   g) ______________________________

2. The methods that can be used to reduce the chances of the above fuel failures are:

   a) ______________________________

   ____

   b) ______________________________

   ____

   c) ______________________________

   ____

   d) ______________________________

   ____

   e) ______________________________

   ____

   f) ______________________________

   ____

   g) ______________________________

   ____

3. The reason for limits placed on individual bundle and channel power is to prevent ____________________. In most stations, these two limits are specified to protect against ________

____

____

4. High fuel temperatures can be caused by :

   a) ____________________________________

   ____

5. The information available to the operator that a fuel bundle is not overpowered in any channel is:

   a) For a boiling channel ______________________

   ____

   ____

   b) For a boiling channel ______________________

   ____

   ____

   c) For a non-boiling channel ____________________

   ____

   ____

6. Failed fuel is removed from the reactor because:

   a) ____________________________________

   ____

   b) ____________________________________

   ____

   c) ____________________________________

   ____

7. a) Failed fuel is detected by ____________________.

This principle behind this method is ________________

____

____

b) Failed fuel can be located by ____________________.

This principle behind this method is ________________

____

____

c) Failed fuel can be located by ____________________.

This principle behind this method is ________________

____

____

8. a) Three methods to reduce the I^{131} concentration in the HTS (when concentration reaches the action limit) are:

i) ____________________________

____

ii) ____________________________

____

iii) ____________________________

____

b) The additional required action when the I^{131} concentration in the HTS reaches the shutdown limit is to________________

____

9. Iodine concentrations may increase on a shutdown even though the shutdown did not cause the fuel failures because ______________

____

____

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

Prepared by: D. Tennant, N. Ritter, WNTD
Revised by: P. Bird, WNTD
Revision date: June, 1992

Module 17

FUEL HANDLING

OBJECTIVES:

After completing this module you will be able to:

17.1 Explain the reason why each of the following is a factor that is used to determine if a channel can be fuelled.

- a) Channel burn-up, *⇔ Page 3*
- b) Power distribution, *⇔ Page 3*
- c) Reactivity gain, *⇔ Page 3*
- d) Channel abnormal conditions, *⇔ Page 3*
- e) Defective fuel in the core, *⇔ Page 3*
- f) Proximity to recently fuelled channels, *⇔ Page 3*
- g) Abnormal operating conditions, *⇔ Page 4*
- h) Liquid zone levels. *⇔ Page 4*

17.2

- a) State the preferred reactor state during refuelling. *⇔ Page 4*
- b) Explain three reasons why the state given in (a) is preferred. *⇔ Page 4*
- c) State the required approval authority for fuelling while in a state other than the preferred state. *⇔ Page 5*

17.3 Explain three methods that are used in CANDU reactors to detect flow blockages while fuelling. *⇔ Pages 6-7*

17.4

- a) Explain the three concerns when handling irradiated fuel. *⇔ Pages 7-8*
- b) Explain the additional precaution taken when handling failed fuel. *⇔ Page 8*

17.5

- a) State the four parameters monitored for the Irradiated Fuel Bay water and explain the reason why they are monitored. *⇔ Pages 9-10*
- b) State the parameter monitored for the Irradiated Fuel Bay atmosphere and explain why it is monitored. *⇔ Page 10*

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

The operating life of a CANDU reactor can be divided into three distinct periods from the point of view of fuel management:

1) The period from first criticality when the reactor is loaded only with fresh fuel to the onset of fuelling.
2) The period from the onset of fuelling, necessary to maintain the reactor critical, to the final or equilibrium core state.
3) The equilibrium period, which is characterized by a relatively stable distribution of the overall core power and burn-up. This equilibrium period covers most of the reactor life.

It is this last period that we are interested in with regards to fuelling criteria:

This module will discuss fuelling considerations, channel blockage detection while fuelling and handling and storage of irradiated fuel.

Fuelling Considerations

The Fuelling Engineer provides a fuelling list specifying the channels to be fuelled. This list is produced by running the computer program SORO or RFSP (Simulation Of Reactor Operation/Reactor Fuelling and Simulation Program), depending on the station. The channels to be fuelled are determined on the basis of such factors as power distribution, zone levels, fuel burnup, Channel Power Peaking Factor (CPPF – the ratio of actual channel power to a reference channel power, also referred to as 'ripple'), position of reactivity mechanisms, number and types of fuel bundles last inserted in the core, etc.

Only channels which appear in the fuelling list may be fuelled.

While in general the information provided by SORO/RFSP is valid, changes in the core conditions may have occurred since the simulation was performed. These changes would require that SORO/RFSP be run again to provide updated information. Depending on the station, these programs are run a minimum of three times per week, and more often when core conditions are changing, ie. adjusters driving etc.

The following are considerations used for the selection of channels to be fuelled:

1) Higher **burnup channels** shall be fuelled first. The reason is that in these channels the fuel is depleted and reactivity is low. Higher burn-up channels are underpowered, and should be fuelled preferentially. ⇔ ***Obj. 17.1 a)***

2) **Reactor power distribution** shall be kept symmetrical. Asymmetry in power distribution increases the load on the Reactor Regulating System (RRS) which has to maintain a zone reactivity balance. This increases the probability of a reactor trip (Neutron Over Power/Regional Over Power Trips will occur if a zone power is too high). To achieve axial flux symmetry, equal numbers of channels shall be fuelled from each end of the reactor. To achieve radial (and azimuthal) symmetry, proportional numbers of channels shall be fuelled in each zone controller region. ⇔ ***Obj. 17.1 b)***

3) The channels with the largest **reactivity gain** on fuelling may be selected if the overall core reactivity is low. ⇔ ***Obj. 17.1 c)***

   The core reactivity is maintained by compensating the reactivity loss due to fuel burn-up with the reactivity gain due to fuelling rate. When the fuelling rate cannot be maintained, it is necessary to fuel channels with high reactivity gain on fuelling, ie, high burnup channels in the innermost part of the core.

   If margin to trip * is low for such a high reactivity gain channel, two actions may be taken:

   - Derate (or be prepared to derate) the reactor,
   - Prior to fuelling, calibrate the NOP/ROP (Neutron OverPower/Region OverPower) detectors to restore the appropriate margin to trip.

   * Margin to trip is covered in more detail in your Reactor Safety course.

4) The channels to be fuelled should not have known **abnormal conditions** that will hinder fuelling, such as closure plug or seal face problems. This means the fuelling machine may have problems attaching to the channel, sealing against the channel, reseating the channel closure, etc. These conditions could cause a unit to be shut down for repairs. ⇔ ***Obj. 17.1 d)***

5) **Defective fuel** bundles shall be removed as soon as possible. Fission product releases to the HTS must be prevented, as was discussed in Module 16. ⇔ ***Obj. 17.1 e)***

6) Avoid fuelling channels **close to recently refuelled channels.** ⇔ ***Obj. 17.1 f)***

   Excessive fuelling in one region of the core may lead to high fuel bundle powers (due to high neutron flux), leading to overheating and fuel failures.

Obj. 17.1 g) ⇔

7) There shall be no fuelling with control absorbers (CAs) in the core. CAs drop in the core only during **abnormal operating conditions** (such as reactor trips, stepbacks, etc). Fuelling operations are to be performed only during normal operating conditions, ie. reactor operating at a steady power level.

   During fuelling operations, reactivity changes should be avoided, ie. poison removal/addition, moving adjusters, etc. Adjuster position imposes no restriction on fuelling.

   Fuelling operations shall not take place during reactor power increases.

   During the transients mentioned above, Xenon transients will occur. This can result in the formation of flux tilts. As discussed in the preceding module, flux tilts can cause bundle overheating and/or bundle overpowering. With the addition of the positive reactivity of a new fuel bundle, the previously mentioned problems are compounded, and hence, must be avoided.

Obj. 17.1 h) ⇔

8) All factors being equal, in practice the channels with low **zone levels** should be fuelled first. Fuelling zones with high levels can possibly cause flooded zones, and therefore, ineffective flux tilt control. Liquid zone levels must be kept within their correct operating range.

The fuelling list provides for more channels to be fuelled than scheduled. Hence, the operator is allowed some choice in the selection of the fuel channels for items 4 through 8 on the list above (with the approval of their Shift Supervisor).

Preferred Operating State During Refuelling

Obj. 17.2 a) ⇔

The preferred state during refuelling operations is with the **reactor critical and operating**. The reasons are that:

Obj. 17.2 b) ⇔

a) **RRS is functional** with the reactor critical. It can **detect, and immediately compensate for changes in reactivity** to limit possible overpower transients. When the reactor is subcritical, the reactivity insertions are not observable. This could cause the reactor to go critical earlier than expected, when a reactor restart is initiated.

b) Additionally, if fuelling is performed while the unit is shut down, there may be **no indications of flow blockage.**

c) Zirconium under irradiation becomes brittle, and is even more **brittle when cold.** This increases the chances of fuel damage due to handling.

However, we should remember that performing on-power fuelling does present some operational concerns such as:

1) Opening the HT system pressure boundary (potential for a LOCA).
2) Insertion of a foreign object in the channel (possible flow blockage causing fuel overheating).
3) Local flux distortions (place demands on RRS).

The **Station Manager** must approve fuelling of the reactor in any state other than the preferred state.

⇔ ***Obj. 17.2 c)***

SUMMARY OF THE KEY CONCEPTS

- Considerations used to select channels for fuelling are:
  - Channel abnormal conditions, to ensure that the fuelling process can safely take place;
  - Defective fuel in the core must be removed to prevent releases to the HTS;
  - Proximity to recently fuelled channels, to ensure that bundle overpowering and overheating does not occur;
  - Abnormal operating conditions, to ensure that bundle overpowering and overheating does not occur due to the influence of Xe transients;
  - Channel burn-up, to ensure channels are not underpowered;
  - Power distribution, to ensure that zone reactivity balance is maintained;
  - Reactivity gain, to ensure the reactor can remain critical
  - Liquid zone levels, to ensure that liquid zones remain within their control range.
- The preferred state for fuelling the reactor is with the reactor critical and the unit operating. This allows RRS to detect and compensate for changes in reactivity. While shut down, flow blockage detection may also be unavailable. Also, zirconium is brittle when cold, which makes fuel damage due to handling more likely.
- The Station Manager must authorize fuelling in any other state than the preferred state.

Channel Blockages

One of the concerns while fuelling is channel blockage. The chances of a channel blockage during refuelling are increased due to the insertion of fuel, rams etc. into the channel. If a blockage occurs, coolant circulation is reduced, with the potential for fuel overheating. This could result in fuel damage and release of fission products to the HTS.

Obj. 17.3 ⇔

A flow blockage in a channel can be determined in a number of ways:

1) If the channel being fuelled is a **fully instrumented channel, direct flow indication** is available. A flow blockage would be directly seen as a reduction of flow. As very few channels are fully instrumented, (no fully instrumented channels are installed in some CANDU units) other methods of flow blockage detection are required for the other channels.

2) The **channel outlet temperature** is measured for each outlet feeder pipe. This is performed with RTDs (Resistance Temperature Detectors). During fuelling, many changes in channel flow and temperature will occur. Some of these changes occur due to shield plug removal, fuel carrier and ram insertion into the channel and fuelling machine cooling effects and flows. If channel outlet temperature rises more than expected * (as compared to a routine fuelling operation), it is likely that a coolant flow reduction has occurred.

   * This may also be indicated by various temperature alarms, which will be covered in your station specific training.

   Of course, this method is only valid for non boiling channels, since channel outlet temperature will not increase above saturation temperature corresponding to HTS pressure. (One note to make here is that for some CANDU units with boiling channels, cool D_2O is injected by the fuelling machine to take a boiling channel out of boiling while being fuelled. This allows the channel ΔT to be used for flow blockage detection during fuelling.)

3) For channels in boiling, a method of determining if a flow blockage has occurred is by monitoring **ΔP across the channel** (measured on the fuelling machines). The measurement of coolant ΔP across the channel will correspond to a certain coolant flow. If the ΔP changes dramatically, a flow blockage has likely occurred. The change in ΔP will indicate the location of the blockage.

   - For example, if the ΔP across the channel **decreases** dramatically, a flow **blockage** has likely occurred in the inlet or outlet **feeder**. Say there is a 95% flow blockage in the channel inlet feeder. The reduced flow will reduce frictional losses in the channel and feeders. The pressure at the channel outlet will be very close to the outlet header pressure. The pressure at the channel inlet will not be as influenced by the inlet header due to the blockage, hence channel inlet pressure will also approach the pressure at the channel outlet. As you can see, the ΔP across the channel has decreased (ie. ΔP will approach zero as flow reduces (caused by a feeder blockage)). Similarly, a channel outlet feeder blockage will cause pressures to approach the channel inlet pressures, and have a similar decrease in channel ΔP.

- For example, if the ΔP across the channel **increases** dramatically, a flow **blockage** has likely occurred **in the channel.** Say there is a 95% flow blockage in the channel. The reduced flow will reduce frictional losses in the channel and feeders. The pressure at the channel outlet will be very close to the outlet header pressure. The pressure at the channel inlet will be very close to the pressure of the inlet header. As you can see, the ΔP across the channel has increased (ie. ΔP will approach the inlet to outlet header ΔP as flow reduces (caused by a channel blockage)).

Detection of a flow blockage on each channel during operation is not practical, since blockages during operations, other than fuelling, are unlikely. Detection is especially difficult if the channel is a boiling channel, in which a blockage would not increase the channel's outlet temperature. In this situation a blockage would be detected by a flow verification procedure. In this procedure, the reactor output is periodically reduced, reducing the channel outlet temperatures below the saturation temperature. At that point of the procedure, the channel outlet temperatures will be checked that they are reading correctly and that they respond to the changes in reactor power. If no changes are occurring, or the temperature remains at saturation temperature, a flow blockage may be suspected. Corrective actions will be required (eg. verify channel conditions with fuelling machines, attempt to clear a blockage, reduce power further, shutdown, etc.).

Handling Irradiated Fuel

Irradiated fuel discharged from the reactor continues to produce significant amounts of heat. A fuel bundle produces a few kW **decay heat** for several hours following discharge. For example, a typical irradiated fuel bundle produces about 10 kW of heat 1 hour after discharge. Natural air cooling can remove only 1 kW of this heat*. If the decay heat is not removed, the sheath will deteriorate due to high temperature oxidation.

* without causing bundle overheating.

An irradiated fuel bundle is **extremely radioactive**. For example, the dose rate 1 metre from a typical bundle in air is ~100 000 rem/hr after 1 day following discharge. A 20 second exposure at 1 metre would result in a dose of 600 rem, which is for all practical purposes, lethal. Obviously, protection against such high doses is also necessary.

⇔ *Obj. 17.4 a)*

For these two reasons, the irradiated fuel shall be **adequately cooled and shielded at all times**. Therefore, adequate cooling and shielding are provided during the residence time of the fuel bundles, both within the fuelling machine (F/M) and during the transfer process to the irradiated fuel bay.

At some point in the fuel handling process, while transferring the fuel from the fuelling machine to the irradiated fuel bay, the fuel bundle may be exposed to air. However, this happens for a short while only (minutes at the most) and will not result in a fuel failure if cooling is resumed.

As mentioned earlier, another concern about irradiated fuel is that the sheath **becomes brittle** with irradiation and is particularly brittle when cold. **Special care** should be exercised in handling irradiated fuel throughout the fuelling process.

Handling Failed Fuel

Obj. 17.4 b) ⇔

Particular problems are encountered when handling failed fuel bundles due to the potential for **spread of contamination**.

Fuel bundles can fail while in the core, or during the fuel handling process. The detection and location of failed fuel has been described in the Module 16.

As mentioned above, at some point in the irradiated fuel handling process, the fuel bundles may be exposed to air. At this point, airborne particulates and iodine samples are taken to determine the presence of failed fuel. When airborne sample fields increase a couple of times over their normal values, failed fuel is suspected. (Note, this can be used to identify a failed bundle or at least narrow the failures down to a pair of bundles. Monitoring during the defuelling process could also be used to attempt to identify the failed fuel bundle(s).)

In most stations, the failed fuel is processed normally and sent to the Irradiated Fuel Bay (IFB). In some stations the defective fuel is left in the fuelling machine while it still clamped onto the reactor. This allows the HTS purification circuit to remove a large portion of the escaping fission products.

In the IFB, the failed bundle will be identified/examined and can be **stored in specially designed failed fuel cans**, or, for small defects, can be stored with the rest of the irradiated fuel.

Monitoring the Irradiated Fuel Bay

The irradiated fuel is extremely radioactive and hot. Both the radioactivity and heat are caused mostly by the decay of fission products.

The **radioactivity** of irradiated fuel bundles is mainly γ. There is a lot of α activity (from the products of the U_{238} decay) and β activity (from the decay of fission products) in the bundles, but both particles are short range and absorbed within the bundles. As mentioned previously the γ from a fuel bundle after 1 day will be ~100,000 rem/hr at 1 metre. Even after longer periods, these γ fields can be very high (1,000 rem/hr @ 1 metre after 1 month, 10 rem/hr @ 1 metre after 1 year).

The decay heat is also quite significant. Remember that a typical fuel bundle produces about 10 kW of **decay heat** 1 hour after discharge. Even after 2 weeks, the decay heat production will be approximately 1 kW. This heat input for the IFB could be very high when the reactor has to be completely defuelled as in the case of an accident. (Note that long term cooling requirements are not as demanding, as decay heat from a bundle after 1 year will be ~1Watt.)

It is clear then that the IFB should provide **adequate shielding and cooling at all times**. The IFB is filled with demineralized water because demineralized water does not contain suspended or dissolved impurities. This minimizes corrosion of the fuel and IFB systems and keeps the IFB clear to allow for the inspection and handling of the fuel. The demineralized water in the IFB provides the following:

- Shielding against radiation
- Cooling medium to remove decay heat;
- Purification circulation.

Shielding against gamma radiation is best provided by heavy elements like lead. However, the same amount of shielding can be provided by sufficient thickness of lighter elements. Therefore, a few meters of water act as a very efficient shield*.

The IFB cooling system should be able to remove all the decay heat from all the fuel bundles stored. This IFB cooling circuit is composed of circulation pumps, HXs, inlet and outlet headers. Sufficient redundancy is provided for reliability purposes.

* Equivalent shielding is provided by 8mm of lead or 98mm of water for a γ energy of 1Mev. These thicknesses will reduce fields in half.

The following parameters are monitored for the IFB water:

⇔ ***Obj. 17.5 a)***

a) To maintain water **purity**, a small portion of the total inventory is passed through the purification circuit. The role of the purification circuit is to remove suspended solids, to reduce dissolved solids, and to remove corrosion products (including contaminants brought into the IFB on the transferred bundles). These substances can foul the components of the circuit. The purification circuit also serves to remove the excess water in the IFB and route it to the active liquid waste system. The circuit consists of skimmers, pump(s), filters, and IXs.

   The conductivity and turbidity * in the IFB are monitored to ensure that the concentration of impurities are acceptably low. When these parameters exceed their upper limits, filters and IX resins shall be replaced.

* These parameters are discussed in more detail in the Chemistry 224 course.

b) The **temperature** of the IFB shall be monitored and maintained within limits, typically around 30°C. If the IFB water exceeds the limits, the IFB walls can be damaged (in some stations an epoxy liner is used, which can be damaged by high temperature and rate of temperature change). The temperature control is automatically performed by throttling the LPSW valves on the secondary side of IFB HXs.

c) The water in the IFB shall be maintained at a **level** high enough to provide adequate shielding. If the water level is too low, the shielding will not be sufficient. If the water level is too high, it causes diversion (at the IX column outlet) of cleaned water to the active liquid waste system. Therefore, the water level should be monitored and controlled. Level control is achieved with an upper and lower level switch. If the level is too low, the make-up demineralized water valves open more. If the level is too high, the IX effluent valves open more.

d) The **flow** of IFB water through the cooling and purification circuits is monitored and controlled to ensure that cooling and purification requirements can be met.

Obj. 17.5 b) ⇔

The IFB room is provided with a ventilation and filtration system to remove radioactive particulates and exhaust the gases. The failed fuel in the IFB will release fission products which can contaminate the IFB. Gas bubbles rising to the surface of the water indicate the release of gaseous fission products, and therefore, the **presence of radioactive gases in the IFB is monitored** (the IFB has area γ monitors, as well as monitoring the exhaust for gross activity). Hydrazine can be added to suppress the release of gaseous fission products from the IFB water surface. This gives the IFB purification system more time to remove them since hydrazine will combine with radioiodines and form chemical products which are less volatile and more soluble in IFB water.

SUMMARY OF THE KEY CONCEPTS

- Flow blockages can be detected by fully instrumented channel flow indications, channel outlet temperatures for non-boiling channels and ΔP measurements for boiling channels.
- Irradiated fuel requires shielding and cooling at all times. Care must be given to physical handling of the fuel because the sheath has become brittle.
- In most cases, defect fuel will be placed in specially designed canisters for storage to minimize the spread of contamination.
- IFB water is monitored for temperature, flow, level and purity.

- The IFB atmosphere is monitored for radioactive gases. These gases indicate the presence of failed fuel.

You can now **work on the assignment questions.**

⇔ ***Page 13***

ASSIGNMENT

1. Explain why the following factors are used to determine if a pre-selected channel can be fuelled.

   a) Channel abnormal conditions, ______________________

   b) Defective fuel in core, ______________________

   c) Proximity to recently refuelled channels, ______________________

   d) Abnormal operating conditions, ______________________

   e) Channel burn-up, ______________________

f) Power distribution, ______________________________

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____

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____

g) Reactivity Gain, ______________________________

____

____

____

____

h) Liquid zone levels, ______________________________

____

____

____

____

2. a) The preferred state for refuelling is ____________________. This state is chosen because:

   i) ______________________________

   ____

   ii) ______________________________

   ____

   b) The ____________________ must approve fuelling in any other state.

3. Explain how flow blockages during fuelling can be detected by the following methods:

   a) Channel ΔT: ______________________________

   ____

   ____

   b) In fully instrumented channels in the reactor: ____________

   ____

   ____

c) Channel ΔP: ______________________________

____

____

4. a) Irradiated fuel must be ____________________ and ____________________ at all times. Also, care must be taken when physically handling irradiated fuel (via fuel handling equipment) because ____________________

______________________________.

b) Failed fuel must be placed in ______________ to minimize the spread of ____________________.

5. Four parameters monitored for IFB water are:

a) ______________. This parameter is monitored because

____

____

____

b) ______________. This parameter is monitored because

____

____

____

c) ______________. This parameter is monitored because

____

____

____

d) ______________. This parameter is monitored because

____

____

____

6. The IFB atmosphere is monitored for ________________________.

   This parameter is monitored because ________________________

   ____

   ____

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

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Revised by: P. Bird, WNTD
Revision date: June, 1992

NOTES & REFERENCES

Module 18

UNIT UPSETS

OBJECTIVES:

After completing this module you will be able to:

18.1 For each of the following:

a) Reactor trip, ⇔ *Pages 2-5*
b) Reactor stepback, ⇔ *Pages 6-7*
c) Reactor setback, ⇔ *Pages 8-9*

Explain:

i) The consequences to unit operation,

ii) Other major operational concerns,

iii) The key control room indications which would confirm the event,

iv) Under what condition it is to be performed manually.

18.2 For each of the following upsets:

a) Large and small LOCA's, ⇔ *Pages 10-13*
b) Loss of reactor regulation, ⇔ *Pages 14-15*
c) Loss of feedwater, ⇔ *Pages 16-18*
d) Main steam line break, ⇔ *Pages 19-21*
e) Loss of turbine load, ⇔ *Pages 22-24*
f) Loss of Class IV, ⇔ *Pages 24-26*
g) Loss of Class III, ⇔ *Pages 27-28*
h) Loss of Class III with Class IV unavailable, ⇔ *Pages 28-29*

Explain:

i) The consequences to unit operation,

ii) Other major operational concerns,

iii) The general indications alerting the control room operator to the upset (including automatic actions in response to the upset),

Areas to be considered include general turbine generator operation; boiler pressure and level; HTS pressure, temperature and inventory; reactor power levels; special safety systems.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

This module will cover transient and upset conditions, which will not normally be encountered during steady state operation. These conditions include reactor trips, stepbacks, setbacks, LOCAs, LORAs, loss of load, steam/feedwater system upsets and loss of power.

Due to numerous station specific differences, the names and existence of various systems may differ somewhat from those in your station.

In the series of events described for objective 18.2, setbacks and stepbacks * have been purposely omitted due to the station specific differences. Although the setbacks and stepbacks will occur, the trips as indicated, will not likely be avoided.

* These setbacks and stepbacks will be dealt with in your station specific training.

REACTOR POWER REDUCTIONS

In the following section, three methods of reactor power reductions will be discussed:

- Reactor trips,
- Reactor stepbacks,
- Reactor setbacks.

As you recall from Module 11, a reactor trip is a rapid shutdown of the reactor, when a critical plant operating limit is exceeded. A reactor trip is initiated by one of the shutdown systems mentioned in Module 11. This protects against a loss of reactor power regulation and/or loss of heat sink effectiveness. Recall also that the equipment used to detect the parameters is completely separate from the regulating system and all other process systems.

Reactor stepbacks and setbacks are regulating system responses, and reduce reactor power when a unit abnormality occurs. The rate at which they reduce power varies, depending on the urgency of the event. This will be discussed in more detail in the following sections.

REACTOR TRIP

Consequences To Unit Operation

Obj. 18.1 a) i) ⇔

The major **source of heat** (fission heat) will immediately drop to a very low level. This will cause the heat input to the HTS to drop to decay heat levels.

NOTES & REFERENCES

HT temperature will drop due to the reduced heat input, which will cause a coolant shrinkage and a **pressure** decrease.

Boiler pressure and temperature will also reduce due to the reduced heat input. Boiler **level** will be dropping due to shrinkage of boiler inventory and the programmed ramping down of boiler level as the reactor power is decreased.

In an attempt to maintain boiler pressure, the **turbine** will be **unloaded** (runback) and will eventually be followed by motoring *. This prevents excessive reduction of HTS pressure.

* Recall from the 234 course that a runback is an automatic reduction in turbine governor valve opening based on a parameter, such as steam pressure or poor condenser vacuum. Motoring occurs when the turbine is fully unloaded (GVs closed), but the generator is still synchronized.

If the reactor was in the reactor lagging mode of operation, **control reverts** to the **reactor leading** mode of operation.

Major Operational Concerns

⇔ *Obj. 18.1 a) ii)*

High power operation cannot continue without the risk of equipment and/or fuel damage. **Reactor power must be lowered** to avoid damage to the fuel and reactor components.

The reactor must be within the capacity of the available **heat sink** to ensure fuel cooling.

The **HTS pressure and inventory control** must be **restored** by the action of the feed system and pressurizer (where installed), to ensure fuel cooling can be maintained (ie. maintain subcooled conditions to prevent dryout).

The **operator** must **ensure** that all **automatic actions** are occurring to bring the reactor to the **shutdown** state and to **stabilize the** unit * (reactor power decreasing, HT pressure recovering, T-G runback, etc.). This ensures that equipment damage and/or wear does not occur.

* Appropriate manual actions will be taken if auto actions fail to occur.

The **condition** that caused the trip must be **identified and corrected** before authorization to reset the trip will be given by the shift supervisor.

If the condition has not been identified or the problem cannot be corrected within 10 to 35 minutes, depending on the station, a **unit poison outage** will occur (unavoidable if poison injection occurred).

Indications

⇔ *Obj. 18.1 a) iii)*

Many indications are available to the control room operator that a reactor trip has occurred. **Panel indications** and **alarms** will indicate the **parameter** which initiated the trip. Indications will show that the **shutdown system(s)** has/have been **activated** (ie. SOR drop, poison injection, moderator dump, depending on the station).

A rapid **power decrease** will be observed due to the addition of a large amount of negative reactivity to the core.

Heat transport system **pressure and temperature** will indicate that they are **dropping** due to lost heat input, hence shrinkage occurs. Indications of shrinkage are D_2O storage tank and pressurizer level drop (where installed), and feed system action. Pressure and inventory control action will restore HTS pressure. Temperature will stabilize with only decay and pump heat producing a ΔT across the reactor.

A reactor **stepback** (depending on the station) will also occur to add negative reactivity to the core. Note that the stepback (control absorber insertion) occurs to prevent the reactor from going critical when shut-off rods are withdrawn (ie. on trip reset). Indications will show that control absorbers are in core. The **liquid zones** will also indicate that they are **filling** to aid in the negative reactivity addition.

To ensure the reactor remains shut down, positive **reactivity insertion** is **prevented**, ie. adjuster position, booster position, moderator level setpoint is captured by actual level, depending on the station. Annunciations will be given to indicate these conditions.

If the reactor was in the reactor lagging mode of operation, **annunciations** will show that control has reverted to the **reactor leading** mode of operation. Reactor power is held at decay levels.

Indications will show that **boiler pressure** is dropping during the transient and boiler **level** is reducing. Turbine steam valve indications will show that the valves are closing as the turbine unloads.

Use Of a Manual Trip

Obj. 18.1 a) iv) ⇔

The triplicated trip logic makes the reactor trip very reliable. **Manual reactor trips** would be required if an **automatic** reactor trip **did not occur** when it was supposed to, or the operator recognizes an abnormal condition and trips the reactor before any trip set point is reached.

Note that, by design, reactor safety is not dependent on operator action. The requirement for a manual trip would depend on the unlikely failure of both shutdown systems to detect the upset.

Also certain situations as **dictated by your station specific operating documents**, may require a reactor trip, ie. Loss of Class III power. This trip is not to protect against any immediate safety concern, but rather to avoid upcoming problems or actual trip conditions if a rapid power reduction did not occur at that time. For example, it is better to reduce reactor power prior to letting conditions reach the trip setpoint (ie. less potential for equipment damage).

The manual trip is performed by **depressing** the shutdown system trip **button** (this ganged button depresses the contacts for all three trip channels simultaneously). Each shutdown system has its own manual trip button.

SUMMARY OF THE KEY CONCEPTS

- The indications of a reactor trip available to the control room operator are:
  - Annunciation of the parameter initiating the trip;
  - Indications that the shutdown system has activated, ie. SOR's in core, liquid poison injected, moderator dumped;
  - Reactor power rapidly reducing to decay levels;
  - Liquid zones filling and control absorbers fall into core;
  - HTS temperature drops due to reduced heat input, which will also cause a pressure drop due to shrinkage, pressure then recovers;
  - Boiler level, pressure and temperature drop during the transient;
  - Turbine unloads to maintain boiler pressure, followed by motoring;
  - Control will revert to the reactor leading mode of operation, and reactor power is held at decay levels;
  - Annunciations will show that reactivity devices are frozen.
- High power operation cannot continue without the risk of equipment or fuel damage.
- The reactor must have an adequate heat sink to ensure that fuel cooling is not in jeopardy (HT pressure adequate, boiler levels maintained at setpoint, etc.).
- The problem must be identified and corrected before any power increase is attempted. If reactor power is not raised within 10 to 35 minutes, a poison outage will occur.
- The operator must ensure all auto actions occur to stabilize unit operation in the low power state.
  - Reactor power decreasing, HT pressure and inventory control restored;
  - Boiler level controlled and boiler pressure controlled via turbine unloading.
- Manual trips must be performed if an automatic trip fails or as station specific documentation or conditions dictate.

NOTES & REFERENCES

REACTOR STEPBACK

Consequences To Unit Operation

Obj. 18.1 b) i) ⇔

A reactor stepback is a rapid reactor power reduction if certain plant parameter(s) operating limits are exceeded. A stepback is accomplished by dropping the control absorbers (a neutron absorber) into the core. For each control absorber, the clutch coil contacts, which hold the absorber in place, are de-energized, allowing the **control absorber to drop**. This will result in a very rapid reactor power reduction (very much like a reactor trip, but it is much quicker to recover from a stepback than from a trip). The stepback will be terminated when the reactor power reaches the preset endpoint, or when the stepback condition clears, whichever occurs first (note that the endpoint may vary, depending on the initiating event).

The major **source of heat** (fission heat) will immediately be reduced. This will cause the heat input to the HTS to drop.

Reactor control, HT temperature and pressure, boiler pressure, temperature and level will be similar to that described for a reactor trip.

Similar to a reactor trip, the **turbine** will be **unloaded** in an attempt to maintain boiler pressure, and may be followed by motoring if the power drop is large enough.

Major Operational Concerns

Obj. 18.1 b) ii) ⇔

The **operator** must **confirm** that reactor **power** is **reduced** to the new "safe" level and **automatic actions** are restoring stable unit operation. If no stepback was initiated, the condition could lead to a reactor trip (larger upset with less of a chance for recovery).

The reactor must be within the capacity of the available **heat sink** to ensure fuel cooling.

The **HTS pressure and inventory control** must be **restored** by the action of the feed system and pressurizer (where installed), to ensure fuel cooling can be maintained (ie. maintain subcooled conditions to prevent dryout).

The **condition** that caused the stepback must be **identified and corrected** before normal high power operation will be approved by the shift supervisor.

A **poison out** may occur, depending on duration and how much reactor power has been reduced.

NOTES & REFERENCES

Indications

⇔ ***Obj. 18.1 b) iii)***

Upon detection of the stepback parameter, the condition is **annunciated** in the control room.

The **reactor power** will be observed to **rapidly fall** as the control absorbers drop into the core. The reactor power setpoint is also lowered quickly. The control absorber drop will be stopped when either the **endpoint** of the stepback is reached, **or** the stepback **condition clears.**

Unit control, liquid zone*, HTS pressure and temperature, boiler pressure, temperature and level as well as turbine-generator indications will be similar to those of a reactor trip (but may be less drastic for stepbacks that do not go down to zero power).

* Zones begin to fill but action may occur too quickly to be observed, levels then settle to stabilize power at new setpoint.

Use Of Manual Stepbacks

⇔ ***Obj. 18.1 b) iv)***

Manual operation of the **stepback** function would only be performed as station procedures dictate. Since the control absorbers drop into the core very quickly, the endpoint of the stepback would be difficult to control without some computer input. Manually, only a full control absorber drop could be assured with any certainty.

No single dedicated pushbutton or handswitch exists for a manual stepback. A manual stepback would be accomplished by turning off the stepback program in both control computers.

SUMMARY OF THE KEY CONCEPTS

- The indications of a reactor stepback available to the control room operator are:
  - Annunciation of the parameter that caused the stepback;
  - Reactor power rapidly drops to a specified endpoint or until the stepback condition clears;
  - Control absorbers drop into core;
  - Liquid zones filling;
  - HTS pressure drops(due to shrinkage), then recovers;
  - If the reactor was in the reactor lagging mode of operation, control reverts to the reactor leading mode of control;
  - Boiler level, pressure and temperature all drop;
  - Turbine unloads to maintain boiler pressure.
- Operation at the previous power level cannot continue without the risk of more drastic action such as a reactor trip.
- The reactor must be within the capability of the available heat sinks.
- The problem must be identified and corrected before any power increase is attempted.

NOTES & REFERENCES

- The operator must ensure all auto actions occur to stabilize unit operation at the new "safe" power level (HTS pressure control, boiler level and pressure, etc.).
- Manual stepbacks are performed only as station procedures dictate.
- The risk of a poison outage may exist, depending on the magnitude and duration of the power reduction.

REACTOR SETBACKS

Consequences To Unit Operation

Obj. 18.1 c) i) ⇔

A reactor setback is a slow, controlled power reduction if certain plant parameters exceed operating limits. A setback is accomplished by adding water (a neutron absorber) to the liquid zone control units in the core (control absorbers, where available, may also lower into the core to aid in power reduction if power error exceeds a preset limit). This will result in a slow reactor power reduction. The setback will be terminated when the reactor power reaches the preset endpoint, or when the setback condition clears.

If a **setback was not initiated** under these circumstances, the condition could lead to a **much faster power reduction** by a reactor **stepback** (where available) or reactor **trip** (ie. the next lines of defence).

The major **source of heat** (fission heat) will immediately be reduced. This will cause the heat input to the HTS to drop, and HTS temperature will drop.

Note that, due to the reduced rate of shrinkage (as compared to a reactor trip or stepback), the **HTS pressure** drop will be minimized, since the pressure and inventory control system will be able to accommodate the shrinkage more closely.

Reactor control, turbine-generator response, boiler pressure, temperature and level will be similar to that described for a reactor stepback.

Major Operational Concerns

Obj. 18.1 c) ii) ⇔

The **operator** must **confirm** that reactor **power is reduced** to the new "safe" level and **automatic actions** are restoring stable unit operation.

The reactor must be within the capacity of the available **heat sink** to ensure fuel cooling.

The **HTS pressure and inventory control** must be **restored** by the action of the feed system and pressurizer (where installed), to ensure fuel cooling can be maintained.

The **condition** that caused the setback must be **identified and corrected** before normal high power operation will be approved by the shift supervisor.

A **poison out** may occur, depending on how much reactor power has been reduced.

Indications

⇔ *Obj. 18.1 c) iii)*

Upon detection of a setback parameter, the **condition** is **annunciated** in the control room.

The **reactor power setpoint** (and reactor power following) will be **ramped down** at a pre-determined rate (in some stations this rate is fixed, in others the rate is determined by the initiating condition).

The power reduction stops when the **setback endpoint** is reached (ie. the new "safe" power level, depending on the condition) or until the setback **condition clears**.

Unit control, liquid zone (and possibly control absorber), HTS pressure and temperature, boiler pressure and temperature and level and turbine-generator indications will be similar to those of a reactor stepback (but changes will be less drastic than for stepbacks).

Use Of The Manual Setback

⇔ *Obj. 18.1 c) iii)*

As previously mentioned for reactor trips, a **manual setback** may be required if **an automatic** setback did not occur, or the operator has identified that a reactor power reduction in a controlled manner is required due to a unit abnormality.

Certain situations, as **listed** in station specific **operating documents**, may also require a setback for power reduction to avoid upcoming automatic protective action (reactor trip). For example, a manual setback is required on detection of falling instrument air pressure, ie. air pressure cannot be maintained (this reduces reactor power before control is lost).

The operation of the setback **handswitch** on the control panel initiates a manual setback.

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- The indications of a reactor setback available to the control room operator are:
  - Annunciation of the cause of the setback;
  - Reactor power following setpoint down to a specified endpoint, or where condition clears, at a given rate;
  - Liquid zones filling;
  - HTS pressure lowers slightly due to shrinkage, then recovers;
  - Boiler level, pressure and temperature are decreasing;
  - Turbine unloads to maintain boiler pressure;
  - If the reactor was in the reactor lagging mode of control, control reverts to the reactor leading mode.
- Operation at the previous power level cannot continue without the risk of a much faster power reduction by a stepback or trip. The reactor must be within the capability of the available heat sink.
- The problem must be identified and corrected before any power increase is attempted.
- The operator must ensure all auto actions occur to stabilize unit operation at the new "safe" power level (boiler pressure and level, HTS pressure, etc.).
- The risk of a poison outage may exist, depending on the magnitude and duration of the power reduction.
- Manual setbacks must be performed if an automatic setback does not occur or as station specific documentation or conditions dictate.

Pages 31-37 ⇔

You can now **work on assignment questions 1-3.**

LOSS OF COOLANT ACCIDENT (LARGE AND SMALL)

Obj. 18.2 a) i) ⇔

Consequences To Unit Operation

As defined earlier in this course, a LOCA is a loss of D_2O from the HT system causing sustained low HT pressure. This would mean that normal HT pressure cannot be maintained or pressure recovery to normal levels is not anticipated within a defined time period.

The **HT D_2O** required for fuel cooling is **being lost** from the HTS (ie. loss of fuel's heat sink).

The location of the source of HT coolant loss is also very important, ie. in-core or out-of-core (say into the boilers via ruptured boiler tubes). This presents varying concerns listed in the next section.

For a **small LOCA,** the shutdown systems will **trip** the reactor on **HT low pressure** and/or **low pressurizer level**. These trips occur simply due to the loss of coolant inventory beyond the capacity of the pressure and inventory control system. (Note: other trips, where installed, will also occur, eg. containment high pressure).

For a **large LOCA,** the reactor behaves differently. During a large LOCA the HTS depressurizes very rapidly. The rapid depressurization will cause coolant **voiding** in the core. This voiding causes a large insertion of positive reactivity into the core (due to the positive void coefficient). The reactor power quickly increases because the regulating system cannot respond to such quick changes in reactivity (or reactor power). The shutdown systems will **trip** the reactor on **high neutron power** and/or on a **neutronic rate power increase**. (Note: other trips may also occur on HT low pressure, low pressurizer level and/or containment high pressure, where installed).

After the reactor trip, heat input from the fuel will be reduced to decay heat levels and **HTS temperature** will be reduced. This will cause HT coolant shrinkage and a pressure drop.

A **rapid ("crash") cooldown** * will occur by the opening of the boiler safety valves (or large steam reject valves, depending on the station) to ensure the reactor fuel is adequately cooled. The purposes of crash cooling for both small and large LOCAs, although common, vary slightly in relative importance, and are explained below.

* The operation of crash cooldown and ECI were discussed in Module 12.

For a **small LOCA,** the depressurization of the HTS is slow (ie. coolant lost through the break is not sufficient to rapidly depressurize the HTS). Crash cooling reduces the HTS pressure to allow for a more rapid ECI injection to re-wet the fuel. For a small break, the boilers are still the main heat sink, and the boiler pressure/temperature reduction will provide cooling to the HTS (maintains the heat sink). And, since the leak rate is small in the first place, the reduction in leak rate due to depressurization will not be as dramatic as compared to a large LOCA.

For a **large LOCA,** the depressurization of the HTS is very rapid, and the boilers (still pressurized and hot) become a heat source to the HTS (note that the coolant discharged from the break is removing heat from the fuel, but rapid ECI injection is still required to re-wet the fuel). Crash cooling will reduce the boiler pressure/temperature to remove the boiler as a heat source. Since the HTS depressurization is so rapid, crash cooling's effect to reduce HTS pressure to injection pressure may not be noticeable. The overall pressure reduction will result in a reduced leak rate from the HTS.

The **turbine and CSDV's will trip** (on the ECI initiation signal, but not all stations) to prevent turbine/condenser damage from two-phase flow that may result from the boiler swell when the boiler safety or steam reject valves open to depressurize the boilers.

NOTES & REFERENCES

Emergency coolant injection will inject water to replace the lost coolant when HTS pressure drops to 5.5 to 4.2 MPa, depending on the station, followed by low pressure pumped injection (if installed) and low pressure recovered injection.

Depending on the location of the break, **containment** * may **box-up** (button-up) on high containment pressure or activity to prevent releases. Also, depending on the location of the break, indications may show that **dousing** has occurred. This limits the vacuum building/containment (reactor building, for the CANDU 600 design) pressure increase. Longer term responses of the emergency coolant injection system and the containment system are covered in the appropriate sections of this course.

* The operation of containment was discussed in Module 13.

Other Major Concerns

Obj. 18.2 a) ii) ⇔

Reactor power levels, hence fuel temperatures, **must be lowered** to ensure pressure tube/calandria tube integrity is maintained, and allow fuel cooling to be maintained.

Also, with decreasing pressure in the HTS, fuel cooling will be impaired due to excessive localized boiling and voiding, leading to possible dryout conditions. Rapid cooling will be required by ECIS and crash cooling. ECIS maintains HTS pressure as high as possible to minimize the boiling and voiding, ie. prevent pressure tube damage and fuel dryout by maintaining subcooled conditions within the reactor.

A **feedwater** source must be available to maintain a heat sink (for crash cooling). (Note that there should be sufficient boiler inventory to reduce HTS pressure to the point of ECI injection, but your heat sink should be monitored/ensured.)

For an in-core LOCA, when the moderator (with its soluble poison) is being displaced from the calandria by the leaking HT coolant, the reactor must remain **subcritical**. Hence, additional poison will be required to ensure that the reactor does not go critical when HT D_2O displaces the poisoned moderator D_2O.

Releases must be **monitored** to ensure appropriate actions are taken so as not to exceed regulatory release limits. The operator must also evaluate possible radiological hazards around plant equipment, because equipment that is not normally radioactive can be highly contaminated (eg. ECI equipment, etc.). Containment integrity must be ensured to prevent any unmonitored releases (also prevents exceeding regulatory release limits). Other unmonitored releases, via boiler steam or boiler blowdown (if a boiler tube rupture occurs), must be avoided.

NOTES & REFERENCES

Indications

Obj. 18.2
⇔ a) iii)

Indications available to the control room operator of a LOCA include **falling HTS pressure**, the rate depending on the size of the break. A HTS **inventory loss** will be detected by decreasing D_2O storage tank level, decreasing pressurizer level (where installed)* and feed system action.

* assuming that the leak is not from the top of the pressurizer, which would cause the pressurizer level to increase.

The **location** of the HTS breach **may also be detected** (ie. out of core or in core). These indications may include beetle alarms in containment or collection sumps, rising containment pressure and temperature due to the flashing coolant, rising moderator for an in-core LOCA and high D_2O in boiler H_2O alarms for boiler tube ruptures *.

* These are only a list of some of the possible paths for the D_2O, others may exist.

Indications of a **reactor trip** and parameters causing the trip will be annunciated. These were discussed at the beginning of this module.

Indications will show that **crash cooling** is occurring (ie. boiler safety valves open, boiler pressure is low, etc.). Indications will show that the turbine and CSDVs have been tripped to prevent damage from two phase flow.

Indications will show that high pressure **emergency coolant injection**, followed by low pressure pumped injection (where installed) and low pressure recovered injection (pumps running, valve operation, flow indication).

Panel indications will show that **containment** is buttoned-up (boxed-up) and, dousing valves open, pressure relief valves open, dousing is occurring, etc. (depending on type of containment).

SUMMARY OF THE KEY CONCEPTS

- During a LOCA, coolant is being lost a rate sufficient to exceed the capacity of the HTS pressure and inventory control systems.
- Adequate HT pressure must be maintained to prevent dryout, and thus sustain coolant capacity to remove heat.
- Reactor power must be shut down to decay heat levels (and maintained shutdown) to remain within the capacity of the degraded heat sink.
- Indications of a LOCA will be:
  - HT pressure will be decreasing at a rate depending on break size;
  - HT inventory will be reducing as seen by a dropping D_2O storage tank level and pressurizer level (where installed);
  - Location of the HTS breach may be noted, ie. out of core or in core;
  - For a large LOCA, the reactor will trip on high neutron power or high log rate neutron power increase;

NOTES & REFERENCES

- For a small LOCA, the reactor will trip on low HT pressure or low pressurizer level;
- Crash cooldown will begin with the opening of the boiler safety valves (or large steam reject valves) to quickly cool the reactor;
- The turbine and CSDV's will trip, depending on the station, to protect the turbine/condenser from damage due to two phase flow;
- ECI will operate to inject coolant for the reactor as seen by injection valves opening, pumps starting and injection flows starting;
- Containment may box-up on high containment pressure or high activity;
- Dousing may occur to minimize the pressure increase in the vacuum/containment/reactor buildings.

LOSS OF REGULATION

Consequences To Unit Operation

Obj. 18.2
b) i) ⇔

* This section will concentrate on a LORA with a reactor power increase. Although LORAs with power decreases are still a concern, increasing power LORAs have the potential for damage and are discussed in this module.

Let us first define Loss of Regulation Accident (LORA) as "operation of reactivity control mechanisms which leads to unintended or uncontrolled increases (or decrease*) in reactor power". If no actions were taken, this power increase could cause **pressure tube damage** and **fuel dryout** (which may lead to fuel failures). Note that extremely large rates of power increases may cause immediate fuel damage due to the creation of large thermal stresses within the fuel element and fuel sheath, and due to overstressing of the fuel sheath from expanding gases from within the fuel.

This loss of power regulation could also result in HTS **overpressure**, which could result in a **HTS failure causing a loss of coolant and radiological releases**. As we can see, reactor power must be reduced to the safe state, since reactor control has been lost.

Reactor power will be increasing at a rate determined by the nature of the LORA.

Heat transport system pressure and temperature will be **increasing** due to the increased heat input to the coolant from the fuel (D_2O storage tank and pressurizer level increase, where installed). **Boiler pressure** (and temperature) will increase, as heat input to the boilers is increased.

* Recall that these valves have a limited capacity for pressure relief (ie. mechanical overpressure only).

The **heat transport pressure control** system will attempt to control pressure (ie. bleed system or pressurizer action where installed). If this pressure control is not sufficient, the HTS relief valves will operate in an attempt to protect the HTS from damage *.

Boiler pressure will be controlled by steam rejection to atmosphere via steam reject valves or atmospheric steam discharge valves (or opening of GVs in the reactor leading mode of control). (We will assume that if the unit is in the reactor lagging mode of operation, the BPC action to reduce reactor power will be ignored due to the LORA).

The shutdown system(s) will **trip** the reactor on **high neutron power, neutronic rate or high HTS pressure** (or temperature) depending on the rate of the power increase. (Note that no credit will be given to the setback or stepback functions. This is because the reactor regulating system and possibly other components are malfunctioning or have run out of range, and hence, may not be able to reduce reactor power.) **Boiler levels will be ramped down with the decrease in reactor power.**

The effects of a reactor trip have been discussed earlier in the module.

Other Major Concerns

⇔ *Obj. 18.2 b) ii)*

The cause of the LORA must be identified and corrected before a reset of the reactor trip will be approved. If the problem cannot be identified and corrected immediately, the reactor must be placed in the Guaranteed Shutdown State (GSS), since the regulating system is assumed to be unavailable.

Indications

⇔ *Obj. 18.2 b) iii)*

Indications will show that reactor **power** is **rising** (unrequested). A **flux tilt** may also be observed if the power increase is limited to portions of the core only.

Indications available to the control room operator will show that one or more of the **reactivity devices** will be observed to be **inserting positive reactivity**. The liquid zones may be draining, control absorbers may be driving out of the core, the adjusters may be driving out of the core, boosters being inserted into the core, moderator level increasing, or moderator poison being removed. It is also possible that a lack of detection is the cause of the LOR, hence these indications may not be available.

HTS and boiler pressures and temperatures will be seen to increase (indications have been mentioned earlier in the module). Boiler pressure will be controlled by ASDVs/CSDVs before the reactor trip and by turbine runback after the reactor trip. HTS pressure will be restored after the reactor trip occurs. **Boiler levels** will show a decrease after the reactor trip.

Indications will show that the **reactor has tripped** on high neutron power, neutronic rate (log or linear), or high HT pressure (or temperature), depending on the rate of power increase.

After the actions listed above, normal HTS pressure control will be regained and reactor power will be reduced to a safe level.

SUMMARY OF THE KEY CONCEPTS

- An unterminated LORA could cause fuel overpowering, leading to dryout and hence, fuel failures. The power increase may also lead to HTS overpressurization, leading to HTS failures and hence, loss of coolant and radioactive releases.
- Indications of a LORA available to the control room operator are:
  - Reactor power will be increasing (unrequested);
  - HTS pressure and temperature increases (for LORA rates that cause HTS swell beyond the pressure and inventory control system);
  - Boiler pressure and temperature will increase due to the increased heat input, steam rejection to atmosphere may be required;
  - Reactivity devices may be observed to be adding positive reactivity to the core;
  - Possible flux tilt formation;
  - The reactor will trip on high neutron power, neutronic rate or high HTS pressure (or temperature), depending on the rate of power increase;
  - After the reactor trip, reactor power will be at a safe level and the unit will stabilize in the zero power hot state.

Pages 37-42 ⇔

You can now **work on assignment questions 4-17.**

LOSS OF FEEDWATER

Consequences To Unit Operation

Obj. 18.2 c) i) ⇔

The loss of feedwater represents a **loss of the major heat sink** for the reactor. This feedwater normally carries the heat away from the reactor via the boilers in the form of steam.

High power operation cannot continue without a continued feedwater supply, otherwise the boilers will be quickly depleted of remaining feedwater. Note that none of the backup heat sinks (eg. shutdown cooling) are capable of removing reactor full thermal power.

Boiler levels will be decreasing due to the large mismatch between steam flow and feedwater makeup.

The heat transfer in the boilers occurs in two stages. The first stage transfers heat to the feedwater (in the preheater) and the second stage

NOTES & REFERENCES

converts the feedwater to steam. The cooling effect of the feedwater in the preheaters (internal or external preheaters) is immediately lost, resulting in a **D_2O temperature** increase into the reactor. The **HTS pressure and inventory volume** increases due to the expanding coolant (swell).

Boiler pressure increases because of a lack of cold feedwater entering the boiler and also because of the increased average temperature of the HT D_2O in the boilers, (ie. with increased D_2O temperature there will be a higher ΔT across the boiler tubes, resulting in an increased heat transfer to the feedwater inventory in the boiler).

For the reactor leading mode of operation, the turbine steam valves will try to accommodate the boiler pressure increase. For the reactor lagging mode, the reactor power will be reduced in an attempt to reduce the boiler pressure. Since **boiler pressure control** via the governor valves is limited, the steam reject valves or atmospheric steam discharge valves, depending on the station, will open to control boiler pressure (indications will show that the valves are open and boiler pressure is returning to normal).

The reactor will trip on **high HTS pressure** (or temperature) **and/or boiler low level.** (Note that the reactor may also trip on low boiler feedwater pressure or high boiler room pressure, depending on the station and the cause of the feedwater loss, eg. feedwater line break inside containment).

Other Major Concerns

⇔ *Obj. 18.2 c) ii)*

The loss of feedwater can be the result of two basic events. The first being a break in the boiler feedline *, and the second, the stopping of flow due to valve closures, pump trips, etc.

With failure of the boiler feedline, a deadly personnel safety **hazard** exists due to the hot feedwater and the water flashing to steam. **Electrical problems** may occur as equipment gets hot and wet. This will jeopardize electrical supplies and create further operational problems.

* It is assumed that the break is upstream of the non-return valves in the boiler feedlines (due to their proximity to the boilers). This would prevent the boiler inventory from being discharged from the break.

This event represents a degradation of the heat removal capability and eventual complete loss of heat sink, unless corrective action is taken.

Indications

⇔ *Obj. 18.2 c) iii)*

The loss of feedwater will be noticed by a **decreasing boiler level.** This may affect some or all of the boilers, depending on the cause of the loss of feedwater.

HTS pressure (and temperature) will increase due to the reduced heat removal in the preheaters (and boilers). **HTS swell** will be indicated by high bleed flow accompanied with no feed flow, increasing D_2O storage tank level and increasing pressurizer level, where installed.

Boiler pressure and temperature will be seen to rise due to the increased temperature of the HTS. Panel indications will show that steam is being discharged to atmosphere (steam reject valves or atmospheric steam discharge valves).

Depending on the cause of the accident, feedwater **flow indications** may show that feedwater **flow has stopped** (in the case of pump trip or valve failure or error), **or** indications will show a **very high flow** (in the case of a feedline break). Along with high flows, electrical faults may also be evident due to the hot feedwater and flashing steam.

HTS pressure and inventory control will be restored by feed/bleed action, pressurizer actions and HTS liquid relief valve opening (if required).

SUMMARY OF THE KEY CONCEPTS

- The loss of feedwater represents the loss of the major full power heat sink for the reactor. Full power operation cannot continue since the boilers will eventually be depleted of all water, and no backup heat sink is capable of removing full reactor power.
- Indications of a loss of feedwater are:
  - Decreasing boiler level;
  - Increasing boiler pressure;
  - HTS pressure, temperature and inventory volume increase due to reduced cooling of D_2O in the preheaters and boilers;
  - The atmospheric steam reject valves will open to control boiler pressure;
  - HTS pressure will be regained by normal pressure and inventory control system action;
  - Feedwater flow indications will show that feedwater flow has stopped, or if a feedline break has occurred, feedwater flow indications will be high;
  - The reactor will trip on HTS high pressure or boiler low level.
- A deadly personnel safety hazard exists from hot feedwater/steam in the powerhouse. A search and rescue must be performed to assist injured personnel. Electrical faults may also be evident and cause further problems, and power must be maintained as feasible.

MAIN STEAMLINE BREAK

Consequences To Unit Operation

⇔ *Obj. 18.2 d) i)*

During a main steamline break, the **boiler inventory** required to cool the reactor is being **discharged to the powerhouse** (or into containment in some stations). This rapid depressurization of the boilers results in an uncontrolled cooldown (similar to crash cooling), causing a reduction of HTS pressure and temperature.

Once the feedwater inventory is depleted, the heat sink is lost and excessive HTS boiling will occur. This results in **impaired fuel cooling** capability and eventual fuel dryout could occur. The reactor power must be immediately lowered to reduce fuel temperatures and restore HTS pressure, preventing fuel failures.

After the steam line break occurs, the **boiler pressure** rapidly **decreases.** With a pressure decrease, the amount of boiling will increase. The presence of more steam bubbles will cause the boiler level to rise significantly, resulting in a steam-water mixture being discharged from the boiler outlet (the cyclone separator capacity will be exceeded).

The **HTS pressure and temperature drop** rapidly due to the uncontrolled heat removal in the boilers. **HTS inventory volume decreases** due to shrinkage as can be seen by D_2O storage tank levels and pressurizer levels (where installed). The ECI initiation setpoint may be reached.

For the reactor lagging mode of control (in some stations), reactor power will be increased to try to maintain boiler pressure until the upper power limit is reached, and when a preset boiler pressure error then exists, contro19Yçlverts to the reactor leading mode of control. For the reactor leading mode of control, the **turbine will be unloaded** by BPC to attempt to maintain boiler pressure. (Note in some stations, a low boiler pressure unloader exists in the turbine governing system to unload the turbine if BPC failed to do so. However, this action may be too slow to prevent turbine damage due to water induction. Protection can only be achieved by tripping the turbine.)

An indication of increased feedwater **flow** will be seen, due to the increased flow to the depressurized boiler(s)*. Note that boiler level control will also call for increased feedwater flow due to the apparent decrease in boiler level**.

The **turbine output** will be **reduced** because the turbine inlet pressure is dropping rapidly, and because the governor valves are closing in an attempt to maintain the boiler pressure setpoint. This reduces the work done by each kg of steam. Also, the total amount of steam flowing through the turbine is reduced due to the steamline break.

* Recall that the centrifugal pump flow increases with decreasing discharge pressure.

** Apparent decrease in boiler level results from a decrease in boiler content density. This is discussed further as part of Objective 18.2 d) iii) on the next page.

The reactor will **trip** on **low boiler level or HT low pressure**, depending on the break discharge rate and location. (Note in some stations the reactor may also trip on low boiler feedwater pressure or low pressurizer level, if installed). This will ensure fuel temperature is reduced to enable the HTS to cool the fuel. The tripping of the reactor will also reduce heat input to the boilers, resulting in less steam discharge to the powerhouse. In some stations, the break can be inside reactor building, causing the reactor to trip on high reactor building pressure.

The **BLC** program will attempt to control the **boiler level** on the level term only or may fail completely, since the steam flow term and boiler level terms have gone irrational (due to low boiler level and very high flow rates and/or steam flow backfeed via the balance header).

Condensate make up valves will open on low hotwell level to provide a condensate supply for the boilers. In some stations, the inter-unit feedwater tie will also be able to provide feedwater for the boiler inventory.

Other Major Concerns

Obj. 18.2 d) ii) ⇔

A steamline break into containment will appear similar to a LOCA. Falling HTS pressure and rising containment pressure can confuse this upset with a LOCA. The major difference is that a LOCA may be accompanied by high containment activity and neutronic trips, whereas a steamline break is not.

The discharge of steam will also create widespread **electrical problems** as equipment gets hot and wet. This would jeopardize electrical supplies in all the units, not just the incident unit. Steam in the powerhouse also presents a **deadly hazard** to the station personnel as temperatures increase and air is displaced.

Two-phase flow from the boilers results from the swell in the boilers, which may result in turbine damage. Note that for a large steamline break, the resulting discharge flow from the boilers may be several times the normal full power flow rate.

Feedwater inventories will be **decreasing** ie. deaerator and condenser hotwell levels will decrease, since the plant is operating on an "open cycle" ie. condensate is not being returned to the unit.

Indications

Obj. 18.2 d) iii) ⇔

The **boiler level** indications will show a **rapid level decrease** due to the lost inventory (Note again that boiler level has actually swelled causing two phase flow from the top of the boiler. The false low level indication is because the rapid depressurization causes a decrease in boiler content density, which makes the level instrumentation indicate, falsely, that the level has decreased). Deaerator and condenser hotwell levels will be decreasing.

HTS pressure and temperature will decrease, causing coolant shrinkage, as seen by decreasing D_2O storage tank and pressurizer levels, where installed.

Boiler pressure (and temperature) will decrease rapidly as the steam is discharged through the break. The **turbine generator output** will decrease rapidly.

Noise may be evident in the control room that a steam line break is occurring.

Various **alarms** may indicate that **electrical trips** and/or fault may be seen due to the steam in the powerhouse.

The **reactor** will **trip** on low boiler level and/or HT low pressure, (possibly on low boiler feedwater pressure or low pressurizer level, if installed).

SUMMARY OF THE KEY CONCEPTS

- During a main steamline break, the boiler inventory is being discharged to the powerhouse.
- The steam in the powerhouse is a deadly hazard to station personnel. Electrical faults may also be evident and cause further upsets, and power must be maintained as feasible.
- The rapid boiler depressurization causes an uncontrolled cooldown. When feedwater inventory is depleted, the full power heat sink for the reactor will be lost.
- Turbine damage due to water induction may also result from two-phase flow from the boilers.
- Indications of a main steamline break are:
    - Noise in the powerhouse;
    - Boiler pressure and level decreasing;
    - HTS pressure, temperature and inventory volume decreasing due to the uncontrolled cooldown, ECI initiation pressure may be reached;
    - Turbine generator output decreasing;
    - Reactor trip on HTS low pressure or boiler low level;
    - Boiler inventory will be maintained by the inter-unit feedwater tie, where available, and condensate make-up to the condensate system ;
    - Feedwater flow indications show increased feed to the depressurized boiler.

- The HTS pressure must be maintained by additional feed or the operation of the Emergency Coolant Injection system.

Pages 43-47 ⇔

You can now **work on assignment questions 18-29.**

LOSS OF LOAD

Consequences To Unit Operation

Obj. 18.2 e) i) ⇔

The loss of load (also referred to as a load rejection) is the inability of the grid to accept the power produced by the generator. A full loss of load represents a **loss of a heat sink pathway** of approximately **30%** of the reactor's total full power heat (ie. steam flow through the turbine has decreased to supply unit service loads only. Since the steam flow to the condenser then drops, the overall heat being rejected is quite low compared to normal operation.). For stations not using CSDVs, this will be a loss of approximately 100% of the heat sink. A reactor power reduction may be required to bring the reactor power within the **capacity of the available heat sink.**

During normal operation ~70% of the heat produced is rejected to the condenser. In stations using CSDVs, the condenser is now the reactor's full heat sink (excluding atmospheric discharge). Depending on the capacity of the condenser or CSDVs, a **reactor power reduction may be required** to prevent **thermal overloading** of the condenser (station CSDV and/or condenser capacities vary between ~65 to 100% FP).

For stations using SRVs, the available heat sink is now the atmosphere via steam discharge. Although SRVs are rated for 100% FP, power is reduced to minimize the amount of steam that is discharged, hence **conserving feedwater supply.**

In some stations, the power reduction will occur due to a **stepback** upon the detection of the loss of turbine load.

In other stations, the reactor/turbine power mismatch causes boiler pressure to rise. Since BPC cannot control boiler pressure via the turbine steam control valves (since the turbine governing system is trying to prevent overspeed), the pressure is controlled via steam reject valves and/or boiler safety valve action. A **setback** on steam reject valve action occurs, which would be terminated at a level preventing a poison outage, while minimizing feedwater wastage.

On the loss of line, the **turbine generator speed** will initially increase due to the large power mismatch*.

* This is discussed in the 235 Electrical Systems course.

HT pressure and temperature will increase due to the power mismatch between the reactor and the boilers, causing HTS inventory to swell.

After the above reactor power reductions, **boiler pressure** is controlled by the **steam reject valves** or the **condenser steam discharge (dump) valves** (depending on the station). Boiler level will be ramped down as reactor power is lowered.

Other Major Concerns

⇔ Obj. 18.2 e) ii)

Turbine **overspeed** must also be **limited to avoid possible catastrophic equipment damage or an overspeed trip**, both leading to a total **loss of turbine generator output**. An overspeed trip would increase the chances for a total loss of Class IV power, particularly in single unit stations.

To prevent a poison outage, reactor power will need to be maintained ~60% FP via steam discharge to the condenser or atmosphere. In the event of steam discharge to atmosphere, adequate feedwater reserves must be available to supply continued reactor cooling requirements.

Indications

⇔ Obj. 18.2 e) iii)

The panel indications will show that the turbine-generator has disconnected from the grid, and turbine speed in increasing.

The turbine governing system will quickly **stop steam flow** to the turbine to avoid a turbine overspeed trip and indications of turbine steam valves closing will be seen. This will be accompanied by a **fast runback** which limits the frequency changes (after the overspeed transient is over) in the power still being supplied by the generator to the unit.

A **boiler pressure increase** will be seen as the steam flow from the boilers is reduced. Boiler pressure will be controlled by steam rejection to the condenser or to the atmosphere, depending on the station.

HTS pressure and temperature increases will be observed.

A reactor **power reduction** will occur via a setback or stepback, depending on the station.

SUMMARY OF THE KEY CONCEPTS

- A loss of load represents a loss of approximately 30% of the high power heat sink. Reactor power must be brought within the capacity of the available heat sink.

- A turbine overspeed must be avoided to prevent possible equipment damage and an overspeed trip would result in a total loss of turbine generator output. An overspeed trip would also increase the possibility of a loss of Class IV power.
- Reactor power must be maintained high enough to avoid a poison outage. In stations using SRVs, final reactor power must be such that steam discharge to the atmosphere is minimized to ensure an adequate feedwater inventory. In stations using CSDVs, the final reactor power may have to be limited to avoid thermal overload of the condenser.
- Indications of a loss of load are:
  - The generator is disconnected from the grid and turbine speed is increasing;
  - Turbine governing system action quickly stops steam flow to the turbine to prevent an overspeed trip. Final turbine generator speed is near normal;
  - Reactor power reduces via setback or stepback to within the capability of the available heat sink, and kept high enough to minimize the chance of a poison out;
  - Boiler pressure is being maintained by the steam reject valves or the condenser discharge valves.

LOSS OF CLASS IV POWER

Consequences To Unit Operation

Obj. 18.2
f) i) ⇔

Upon the total loss of Class IV* power, all **Class IV loads** will be **lost.** Normal high power operation cannot continue without Class IV power, because of the impaired heat sink (explained below).

* An example of this may be on a loss of load followed by a turbine overspeed trip and failure to transfer to the station service transformer.

The **turbine** will **trip** on **high condenser pressure**, since condenser cooling water pumps have lost power (an annunciation will be received and the turbine steam valves will be seen to close). In some stations, the generator excitation system is supplied from Class IV power. Hence, upon the loss of power, the turbine generator trips on loss of excitation, which is much faster than the low condenser vacuum trip. Also in some stations, a turbine trip on loss of governing system hydraulic fluid pressure also occurs.

The **condenser steam discharge (dump) valves** (where installed) **also trip closed** to **prevent** condenser and LP turbine exhaust cover **overpressure**. This, combined with the turbine trip, results in rising boiler pressure.

The HTS coolant circulation is reduced due to the loss of power to the main coolant circulation pumps. The **HTS temperature** increases since the coolant must pick up more heat from the fuel (ie. for the same power level with reduced coolant flow, the coolant ΔT must increase to remove the same amount of heat). The **HTS system pressure will increase** due to the coolant swell. HTS **inventory volume increases** as the coolant expands (due to the increasing temperature and increased amount of boiling), which can be seen by increasing D_2O storage tank level and increasing pressurizer level (where installed) and bleed flow.

The shutdown system(s) will **trip** the reactor on **gross low HTS flow or high HTS pressure** to maintain fuel integrity and avoid overstressing the HTS. Reactivity devices will also operate to insert negative reactivity as described earlier in this module.

The **boiler pressure** will be controlled by the atmospheric steam reject valves. **Boiler levels** will decrease due to the loss of the main boiler feed pumps until makeup is restored from the Class III pumps.

The **emergency transfer system** will attempt to restore power to the dead Class III busses. The required Class III loads will automatically be picked-up. This will ensure that all critical loads will have their power supply to prevent damage as described in the next section. In single unit stations and depending on how widespread the power loss is in multi-unit stations, the standby generators and emergency power generators (if installed) will start to supply the Class III power.

Other Major Concerns

⇔ Obj. 18.2 f) ii)

The **Class III** system will also be **lost**, since it is normally supplied by the Class IV system. Class III power must be restored to the unit to ensure critical loads are restored, such as HT feed pumps, auxiliary feedwater supplies, instrument air, Class II power, service water, shutdown cooling, other Class III feeds, etc. It is also essential to ensure that lube oil, jacking oil, generator seal oil and turning gear are available to **safely shut down the turbine**. This ensures damage to turbine and generator bearings and seals does not occur.

Forced HTS **coolant circulation** has been lost, hence **thermosyphoning** will be required to remove the heat from the fuel.

HTS pressure and inventory must be maintained, since this is essential for thermosyphoning and prevention of voiding in the HTS. The pressurizer heaters (where installed) have lost their power supply.

Indications

⇔ Obj. 18.2 f) iii)

Many **electrical alarms** and indications (ie. dead busses) will be seen to indicate the widespread loss of Class IV and III power in the unit. The emergency transfer scheme will be operating to restore Class III power, standby generators and emergency power generators may also start to restore power, depending on the station.

NOTES & REFERENCES

The parameter that caused the **reactor trip** will be annunciated in the control room. The indications of the reactor trip have been previously discussed.

Heat transport pressure will increase initially, D_2O storage tank and pressurizer level (if installed) will rise due to HTS swell (until the reactor trip occurs).

Condenser pressure will be seen to increase, and will result in **turbine and CSDV trips.**

Boiler pressure will increase due to the HTS temperature increase and due to the reduced steam flow from the boilers due to the turbine trip. **Boiler levels** will drop due to the loss of the boiler feed pumps (and due to the boiler pressure increase caused by the turbine trip).

SUMMARY OF THE KEY CONCEPTS

- The effects of the loss of Class IV power are impaired fuel cooling due to the loss of power to the HT pumps. High reactor power operation cannot continue due to this impairment.
- The normal Class III power supply will also be lost since it is normally fed from the Class IV power system.
- Thermosyphoning will be required because forced coolant circulation over the fuel has stopped.
- Indication available in the control room that a loss of Class IV power has occurred are:
    - Many electrical alarms indicating the loss of Class III and Class IV power;
    - HTS pressure and temperature increase due to the increased heating of the slower moving coolant;
    - D_2O storage tank and/or pressurizer levels increase due to the expanding coolant;
    - The reactor will trip on high HTS pressure or HTS low flow;
    - The turbine and condenser steam reject valves trip (where installed) to protect the condenser and LP exhaust cover from overpressure.
    - Boiler pressure will be controlled by the steam reject valves, or atmospheric steam discharge (dump), depending on the station;
    - The emergency transfer system will attempt to restore power to the dead busses. Essential Class III loads will be re-energized to prevent fuel and equipment damage. The standby generators and the emergency power generators may start, depending on the station.

Pages 48-52 ⇔

You can now **work on assignment questions 30-39.**

UNAVAILABILITY OF CLASS III POWER

This section will deal with two cases,

- Loss of Class III Power with Class IV power available,
- Loss of Class III Power with Class IV power unavailable.

LOSS OF CLASS III POWER WITH CLASS IV POWER AVAILABLE

Consequences To Unit Operation

⇔ *Obj. 18.2 g) i)*

As you recall from previous electrical courses, Class III power supplies Class I power and Class II power (indirectly, through the Class I system). The total loss of Class III power * (ie. all Class III busses dead, and emergency transfer system ** failure after a loss of Class III power) leaves **Class I and Class II power on the battery supplies** (note that this occurs in spite of Class IV power still being available). A 40 ~ 45 minute reserve exists until the batteries will be depleted. After this, the Class I and Class II power supplies will be lost. **Unit control and control room indications will also be lost** with these power supplies. The reactor must immediately be placed in the **safe** (shutdown) state before the Class II and Class I power supplies are lost (i.e. reactor placed within the capacity of the available heat sink). (Note that in some stations, an automatic setback on loss of end shield cooling water pressure will occur to reduce reactor power.)

* Assume all attempts to restore power are unsuccessful.

** Recall that the emergency transfer system will attempt to restore Class III power to the dead busses by connecting to a "healthy" power supply, ie. other busses or standby generators.

Other Major Concerns

⇔ *Obj. 18.2 g) ii)*

If Class IV power is now lost, the full power heat sink would also be lost (this is discussed in the next section of this module).

Class III power must be restored as soon as possible to ensure that critical loads have a power supply such that the reactor has a heat sink (auxiliary feedwater supplies, instrument air, service water, Class II power, end shield cooling, etc.) and the turbine generator can be safely shut down, etc.

A low power **heat sink and a backup** must be established prior to loss of Class I and Class II power, to ensure the fuel will be adequately cooled. The reactor must be transferred to the available heat sink without causing undue thermal stresses (controlled cooldown).

The reactor trip causes a rapid HTS pressure drop due to shrinkage. The loss of Class III results in the loss of the feed pumps. Heat transport system **inventory** must be **maintained** during cooldown to ensure fuel cooling. Note that emergency coolant injection and a crash cool initiation setpoint will be reached.

NOTES & REFERENCES

Indications

Obj. 18.2 g) iii) ⇔

Electrical **alarms** and **indications** (ie. dead busses) will show that the Class III power system has been lost.
Annunciations will show that the **emergency transfer scheme** will be attempting to restore Class III power. Breaker operation will also be seen to attempt to restore the lost power.

SUMMARY OF THE KEY CONCEPTS

- The loss of Class III power will result in the loss of Class I and Class II power supplies. This loss will occur when battery supplies are depleted in about 40 ~ 45 minutes. The loss of these power supplies will result in the loss of unit control and control room indications. The reactor must be placed in the safe (shutdown) state and a low power heat sink placed in service prior to the loss of unit control.
- Inventory makeup will be lost, which may require ECI for makeup.
- The indications for loss of Class III power are:
  - alarms and indications of dead Class III busses;
  - Emergency transfer scheme operating to try to restore Class III power;
  - Eventual loss of unit control and control room indications.

LOSS OF CLASS III POWER WITH CLASS IV POWER UNAVAILABLE

Consequences To Unit Operation

Obj. 18.2 h) i) ⇔

With the additional total **loss of Class IV** power added to the total loss of Class III, further complications arise. The full power **primary heat sink has been impaired** due to the loss of HTS coolant circulation (heat transport pumps are supplied by Class IV power). Note that coolant circulation continues but decreases, due to the rundown characteristics of the HT pumps/motors/flywheels. The reactor must be **immediately tripped** to prevent fuel overheating. Sustained loss of all power would not provide for decay heat removal or allow the monitoring of critical safety parameters.

The effects on boiler pressure and level, HTS pressure and temperature, turbine and CSDV trips, and reactor trips have been discussed in the section covering the loss of Class IV power.

NOTES & REFERENCES

Other Major Concerns

Also, as discussed in the previous section, **Class I and Class II** power supplies (with unit control and control room indications) **will be lost** (after 40~45 minutes). The reactor must be placed in the safe state before these power supplies are lost (ie. reactor placed within capacity of available heat sink).

⇔ ***Obj. 18.2 h) ii)***

Forced HTS **coolant circulation** has been lost, hence thermosyphoning will be required to remove the heat from the fuel.

HTS pressure and inventory control must be restored since the pressurizer heaters (where installed) and feed pumps have lost their power supply (which is essential for thermosyphoning).

Note again that a crash cool will be initiated and emergency coolant injection may be required to maintain HTS pressure and inventory.

Indications

Refer to the INDICATIONS section on loss of Class IV power on page 25 and to the INDICATIONS section on loss of Class III power on page 28.

⇔ ***Obj. 18.2 h) iii)***

SUMMARY OF THE KEY CONCEPTS

- The loss of Class III power with the additional loss of Class IV power results in the impairment of the primary heat sink. This impairment is due to the loss of forced circulation of HTS coolant (due to the loss of power to the HTS Pumps).
- The loss of Class III power (since Class III is normally fed from Class IV power) will result in the loss of Class I and Class II power supplies. This loss will occur when battery supplies are depleted in about 40 ~ 45 minutes. The loss of these power supplies will result in the loss of unit control and control room indications, hence, the monitoring of critical safety parameters cannot continue. The reactor must be placed in the safe (shutdown) state and a low power heat sink placed in service prior to the loss of unit control.

You can now **work on assignment questions 40-44.**

⇔ ***Pages 53-55***

ASSIGNMENT

REACTOR TRIP

1. a) Explain the effect of a reactor trip on each of the following parameters:

   i) HT pressure and temperature ____________________

   ____

   ____

   ii) Boiler pressure and temperature ____________________

   ____

   ____

   iii) Boiler level ____________________

   ____

   ____

   iv) Turbine generator operation ____________________

   ____

   ____

   v) Mode of unit operation ____________________

   ____

   ____

   b) Reactor power must be lowered when a trip situation occurs because ____________________

   ____

   ____

   c) Final reactor power must be ____________________

   ____

d) HTS pressure and inventory control must be restored because ____

________________________________. Pressure control is regained by the actions of:

i) ____

ii) ____

e) The cause of a reactor trip must be ____________________ and ______________________ before the trip can be reset and the unit returned to power.

f) If the reactor power is not raised quickly enough after a trip the unit will ______________________________

g) Typical indications of a reactor trip are:

i) ____
____

ii) ____
____

iii) ____
____

iv) ____
____

v) ____
____

vi) ____
____

vii) ____
____

NOTES & REFERENCES

h) A manual reactor trip must be performed under the following situations.

i) ______________________________

____

ii) ______________________________

____

REACTOR STEPBACK

2. a) Explain the effect of a reactor stepback on each of the following parameters:

i) HT pressure and temperature ______________

____

____

ii) Boiler pressure and temperature ______________

____

____

iii) Boiler level ________________________

____

____

iv) Turbine generator operation ______________

____

____

v) Mode of unit operation __________________

____

____

b) Reactor power must be lowered when a stepback situation occurs to avoid ________________________

____

NOTES & REFERENCES

c) Final reactor power must be ______________________________

____

d) After the stepback, HTS pressure control is regained by the actions of:

   i) ____

   ii) ____

e) The cause of the stepback must be ________________ and ____________________ before the reactor trip can be reset.

f) If the reactor power is not raised quickly enough after a stepback to low power levels, the unit will ______________

____

g) The stepback stops when ______________________ or ____.

h) Typical indications of a reactor stepback are:

   i) ____

   ____

   ii) ____

   ____

   iii) ____

   ____

   iv) ____

   ____

   v) ____

   ____

   vi) ____

   ____

   vii) ____

   ____

i) A manual reactor stepback (is / is not) normally performed because ______

______

REACTOR SETBACK

3. a) Explain the effect of a reactor setback on each of the following parameters:

i) HT pressure and temperature ______

______

______

ii) Boiler pressure and temperature ______

______

______

iii) Boiler level ______

______

______

iv) Turbine generator operation ______

______

______

v) Mode of unit operation ______

______

______

b) Reactor power must be lowered when a setback situation occurs to avoid ______

______

______

c) Final reactor power must be ______

______

NOTES & REFERENCES

d) After the setback, HTS pressure control is regained by the actions of:

i) ______________________________

ii) ______________________________

e) The cause of the setback must be ______________ and ______________ before reactor power can be raised.

f) If the reactor power is not raised quickly enough after a setback to low power levels, the unit will ______________ ______________________________

g) The setback stops when ______________ or ______________.

h) Typical indications of a reactor setback are:

i) ______________________________

ii) ______________________________

iii) ______________________________

iv) ______________________________

v) ______________________________

vi) ______________________________

vii) ______________________________

i) Two situations when you would manually setback the reactor are:

i) ____

____

ii) ____

____

LOSS OF COOLANT ACCIDENT

4. Explain the effect of a loss of coolant accident on each of the following parameters:

a) HT pressure and temperature ______________________

____

____

____

____

b) HT inventory ______________________________

____

____

____

____

c) Reactor power ______________________________

____

____

____

____

d) Boiler pressure and temperature ____________________

____

____

____

____

e) Boiler level ______________________________

f) Turbine generator operation ______________________________

g) Containment ______________________________

h) Shutdown systems ______________________________

i) Emergency coolant injection system ______________________________

NOTES & REFERENCES

5. For an in core LOCA, an additional concern is ________________ ________________________ because ________________________ ____ ____

6. For a LOCA into the boilers, an additional concern is __________ ____ because ____ ____ ____

7. HTS pressure is maintained as high as possible by the operation of ________________________________. The purpose of this is to maintain _________________ conditions within the reactor.

8. __________________________ will occur by the opening of the large steam reject valves (or boiler safety valves, depending on the station). The turbine and CSDV's will trip to prevent ____________ ____ ____ ____.

9. The ___________ supply must be maintained to ensure crash cooling can be maintained.

10. Typical indications of a LOCA are:
    - a) ____ ____
    - b) ____ ____
    - c) ____ ____
    - d) ____ ____

e) ______________________________

f) ______________________________

g) ______________________________

LOSS OF REGULATION ACCIDENT

11. Explain the effect of a loss of regulation accident on each of the following parameters:

a) HT pressure and temperature ______________________________

b) HT inventory ______________________________

c) Reactor power ______________________________

d) Boiler pressure and temperature ______________________________

NOTES & REFERENCES

e) Boiler level (after reactor trip) ____________

f) Turbine generator operation ____________

g) Shutdown systems ____________

12. A loss of regulation will cause an ________ increase in reactor power. This could cause fuel dryout leading to ____________.

13. A loss of regulation is caused by reactivity devices (adding / removing) reactivity from the core. One or more of the following may be observed:

    a) Liquid zones (filling / draining).

    b) Control absorbers driving (into / out of the core).

    c) Adjusters are driving (into / out of) the core.

    d) Boosters are driving (into / out of) the core.

    e) Moderator level is (increasing / decreasing).

    f) Moderator poison is being (added / removed).

14. A flux tilt (will / will not / may) occur if ____________

15. Boiler pressure will be controlled by a ______________________

____.

16. The reactor will trip on ______________________,

______________________ or ______________________,

depending on the ________ of power increase.

17. Typical indications of a LORA are:

a) ____

____

b) ____

____

c) ____

____

d) ____

____

e) ____

____

f) ____

____

g) ____

____

LOSS OF FEEDWATER

18. Explain the effect of a loss of feedwater accident on each of the following parameters:

a) HT pressure and temperature ______________________

____

____

____

____

NOTES & REFERENCES

b) HT inventory ______________________________

c) Reactor power ______________________________

d) Boiler pressure and temperature ______________________________

e) Boiler level ______________________________

f) Turbine generator operation ______________________________

g) Shutdown systems ______________________________

19. Loss of feedwater results in the loss of the ____________________ ____, and normal high power operation (can / cannot) continue.

20. Feedwater flow indications will show that flow has______________ ________________ or that flow has ______________________ if a break has occurred. If a break has occurred a ________________ hazard exists due to hot feedwater and flashing steam.

21. Typical indications of a loss of feedwater accident are:

a) ____

____

b) ____

____

c) ____

____

d) ____

____

e) ____

____

f) ____

____

g) ____

____

22. ____________________ faults may be occurring due to a feedline break.

MAIN STEAMLINE BREAK

23. Explain the effect of a steamline break on each of the following parameters:

    a) HT pressure and temperature ______

    b) HT inventory ______

    c) Reactor power ______

    d) Boiler pressure and temperature ______

    e) Boiler level (actual) ______

f) Boiler level (indicated) ______________________________

____

____

____

____

g) Turbine generator operation __________________________

____

____

____

____

h) Shutdown systems ________________________________

____

____

____

____

24. a) Condensate make-up will be initiated by a ______________
__________________. In some stations, the ___________
________________________ is available to provide
feedwater to the boilers.

b) When the feedwater has been depleted, the fuel cooling
concern is ______________________________________

____

____

25. Feedwater flow indications will show that flow has___________
______________ because ______________________________
____
____.

NOTES & REFERENCES

26. The following two hazards exist in the powerhouse due to steam environment:

    a) ____

    ____

    b) ____

    ____

27. Typical indications of a steamline break are:

    a) ____

    ____

    b) ____

    ____

    c) ____

    ____

    d) ____

    ____

    e) ____

    ____

    f) ____

    ____

    g) ____

    ____

28. ____________________ faults may be occurring due to the steam in the powerhouse.

29. HTS pressure recovery may require additional feed or action from ____.

NOTES & REFERENCES

LOSS OF LOAD

30. Explain the effect of a loss of load on each of the following parameters:

 a) HT pressure and temperature ________________________

 b) HT inventory ________________________

 c) Reactor power ________________________

 d) Boiler pressure and temperature ________________________

 e) Boiler level ________________________

f) Turbine generator operation ____________________

____

____

____

____

g) Shutdown systems ____________________

____

____

____

____

31. Turbine overspeed must be avoided for the following two reasons:

a) ____________________

____

b) ____________________

____

32. Final reactor power must be high enough to avoid a __________ __________, but must also remain low enough to minimize steam __________ (ie. conserve __________ __________) or prevent __________ __________ of the condenser.

33. After the loss of load, boiler pressure will be controlled by __________ or __________.

34. Typical indications of a loss of load are:

a) ____________________

____

b) ____________________

____

c) ______________________________

d) ______________________________

e) ______________________________

f) ______________________________

g) ______________________________

LOSS OF CLASS IV POWER

35. Explain the effect of a loss of Class IV power on each of the following parameters:

a) HT pressure and temperature ______________________________

b) HT inventory ______________________________

c) Reactor power ______________________________

d) Boiler pressure and temperature ______________________

e) Boiler level ______________________

f) Turbine generator operation ______________________

g) Shutdown systems ______________________

h) Standby generators and emergency power generators ______

36. The loss of Class IV power also results in the loss of __________ power. This is indicated by ______________________.

NOTES & REFERENCES

37. Fuel cooling is impaired due to the ____________________ coolant circulation. ______________________ will be required to remove the decay heat from the fuel.

38. The _________________ or _________________________ start, synchronize and load to restore __________ power. Critical loads will be _______________ automatically. A few examples of these critical loads are _________________, ________________________ and ___________________________.

39. Typical indications of a loss of Class IV power are:

a) ____

____

b) ____

____

c) ____

____

d) ____

____

e) ____

____

f) ____

____

g) ____

____

LOSS OF CLASS III POWER

40. Explain the effect of a loss of Class III power on each of the following parameters:

    a) HT pressure and temperature ____________________

    ____

    ____

    b) HT inventory ____________________

    ____

    ____

    c) Reactor power ____________________

    ____

    ____

    d) Boiler pressure and temperature ____________________

    ____

    ____

    e) Boiler level ____________________

    ____

    ____

    f) Turbine generator operation ____________________

    ____

    ____

    g) Shutdown systems ____________________

    ____

    ____

    h) Standby generators and emergency power generators ______

    ____

    ____

h) Emergency coolant injection system ______________________

____

____

41. The loss of Class III power leaves Class I & II power on the ___________________________. This supply will last approximately _______________________. When Class I & II supplies are lost, unit __________________ and ________________ indications will also be lost. The reactor must be placed in the ______________________ before these power supplies are lost.

42. Typical indications of a loss of Class III power are:

a) ____

____

b) ____

____

c) ____

____

LOSS OF CLASS IV AND CLASS III POWER

43. The additional concern of losing Class IV power with Class III unavailable is that ____

____

____

____

____

____

NOTES & REFERENCES

44. The reactor must be ___________________ and an immediate ___________________ must be commenced. Critical cooling loads ____ ____________________________________.

Note that consequences to the unit and indications have been covered in the previous sections of this module

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

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