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*

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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).

<u>Table 1.1</u>

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.

NOTES & REFERENCES

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.

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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:

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.

Obj. 1.5 a) ⇔

Obj. 1.5 b) ⇔

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.

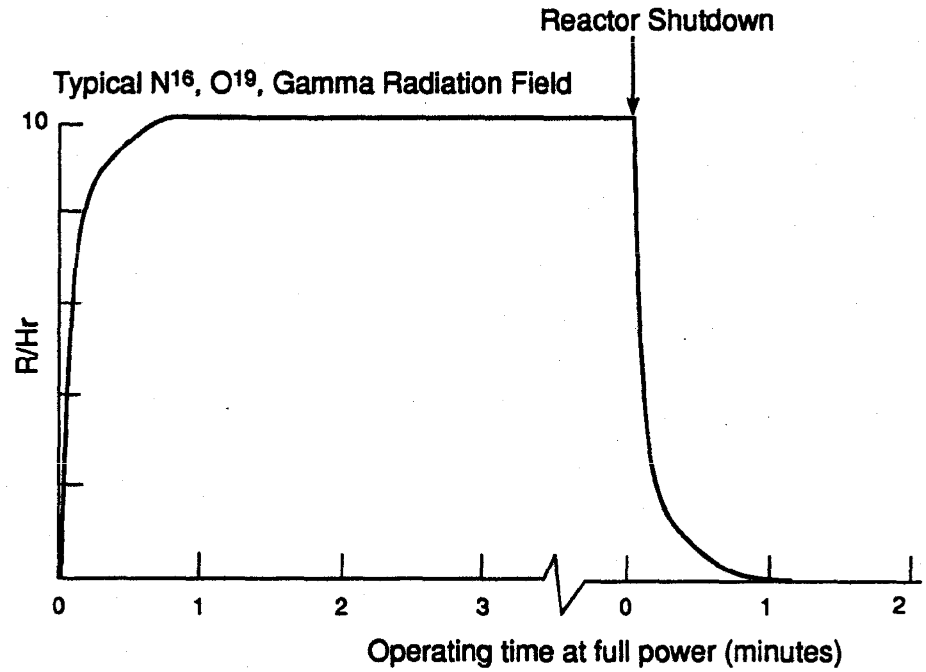

Figure 1.1

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).

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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}.

NOTES & REFERENCES

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.

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

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.

** 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.

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

ASSIGNMENT

1. Explain the term isotopic.

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

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

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

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

   a) ≤0.3%_______________________________________

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   b) >0.3%_______________________________________

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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.

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