NOTES & REFERENCES

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)

* * *

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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.

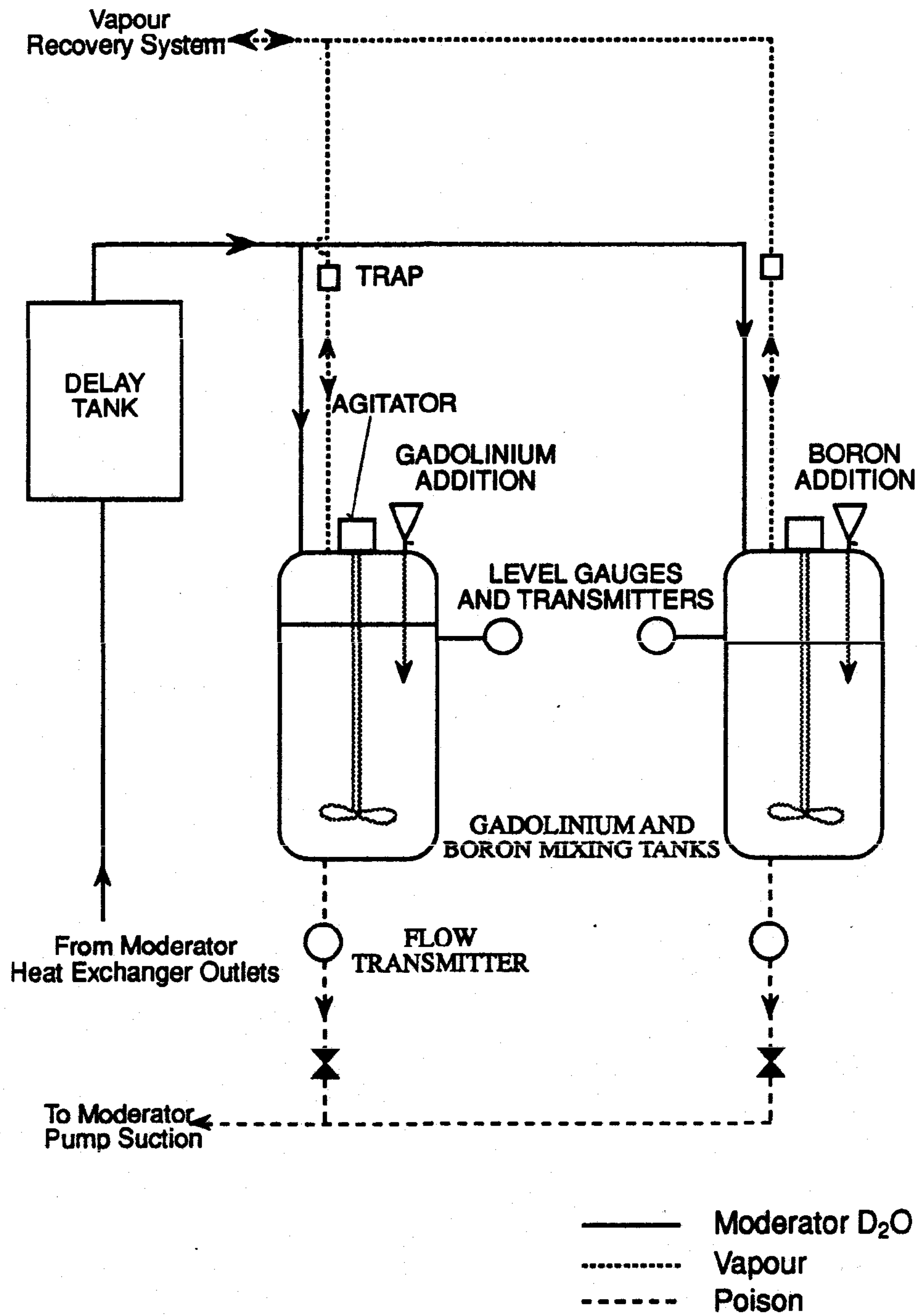

Figure 4.1 Typical Moderator Liquid Poison Addition System

NOTES & REFERENCES

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.

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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.

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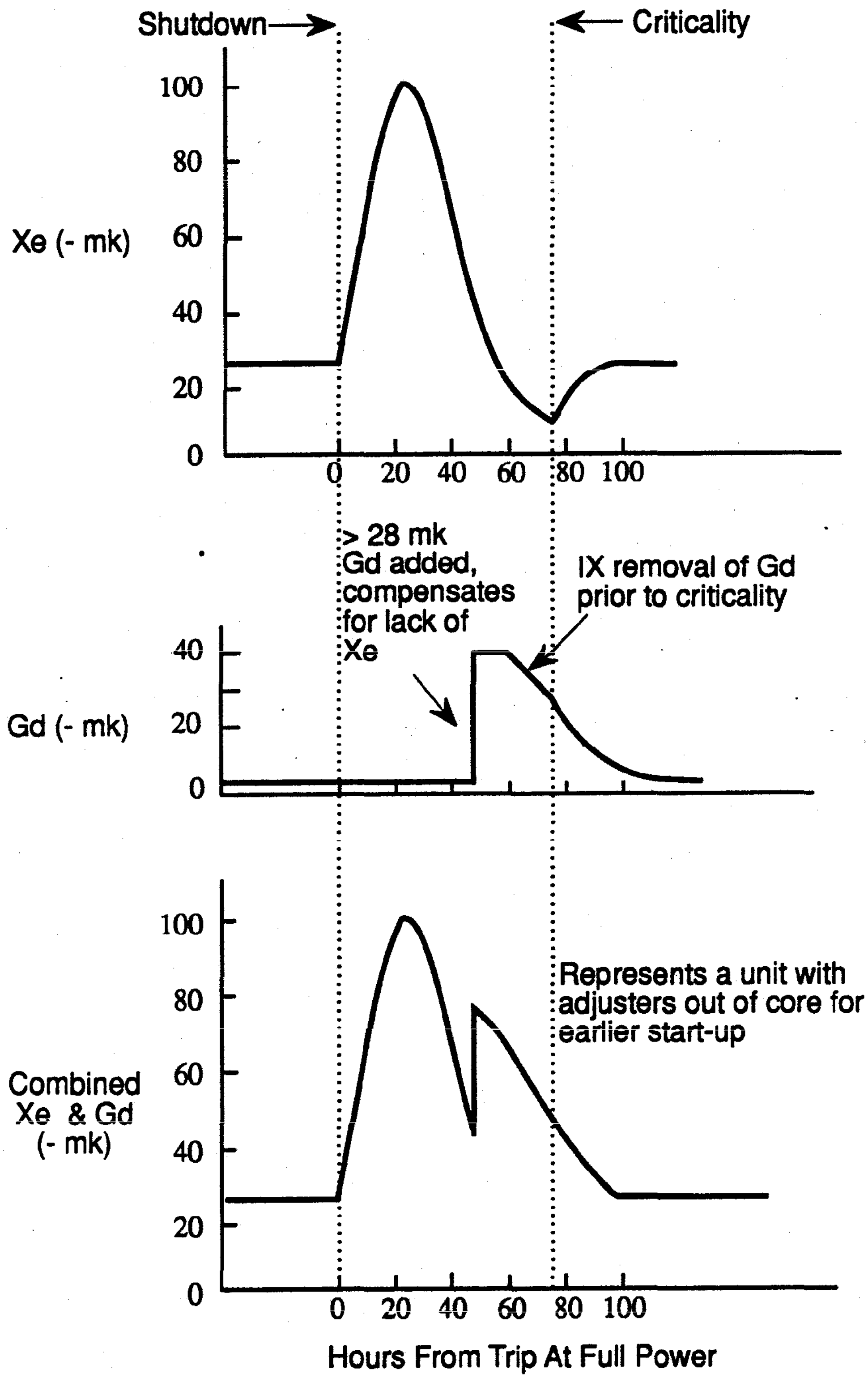

Figure 4.2 Gd Concentration in Moderator After a Shutdown of about Three Days

NOTES & REFERENCES

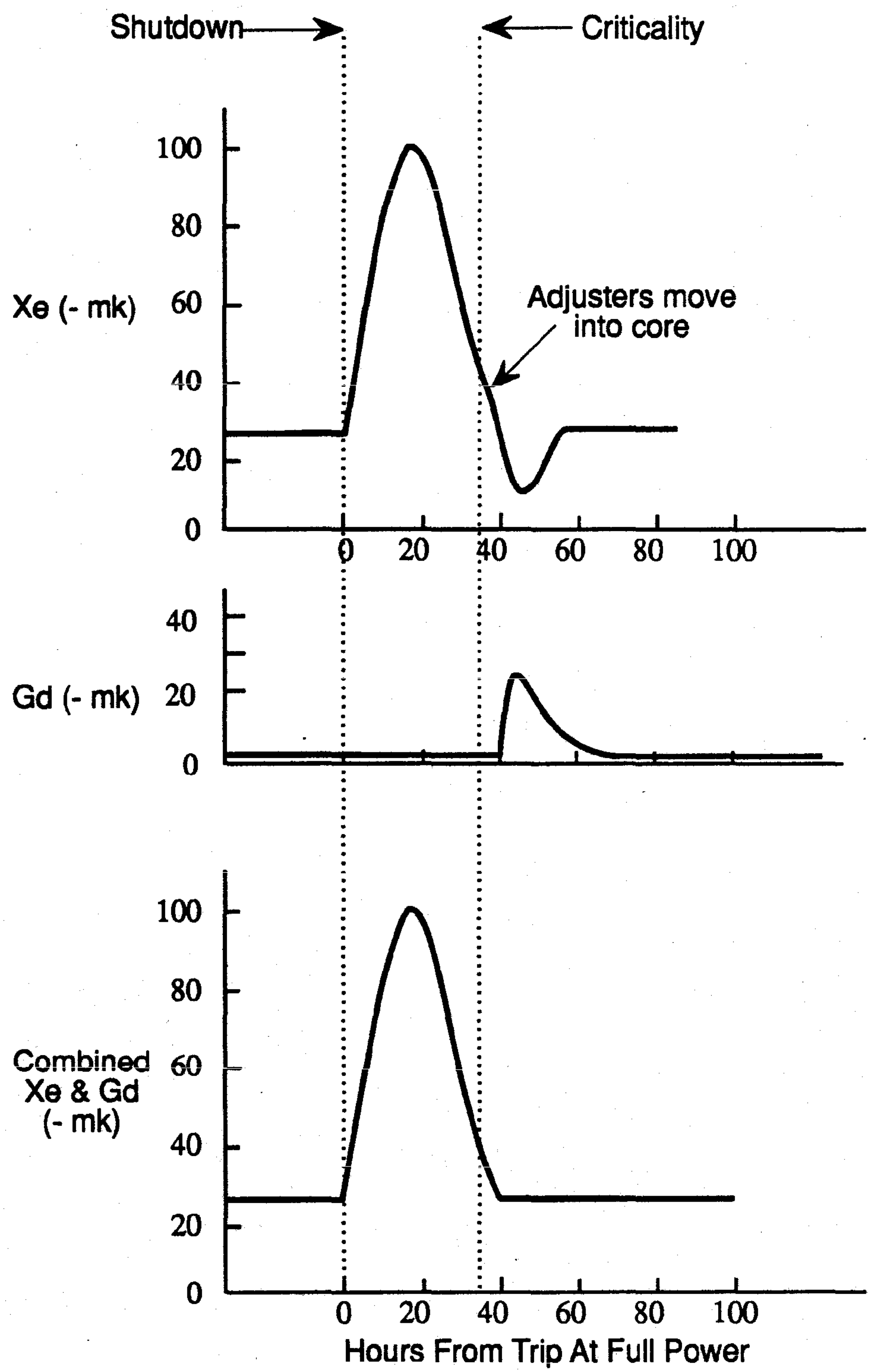

Figure 4.3 Gd Concentration In Moderator For a Start-Up 1.5 - 3 Days After A Shutdown

NOTES & REFERENCES

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.

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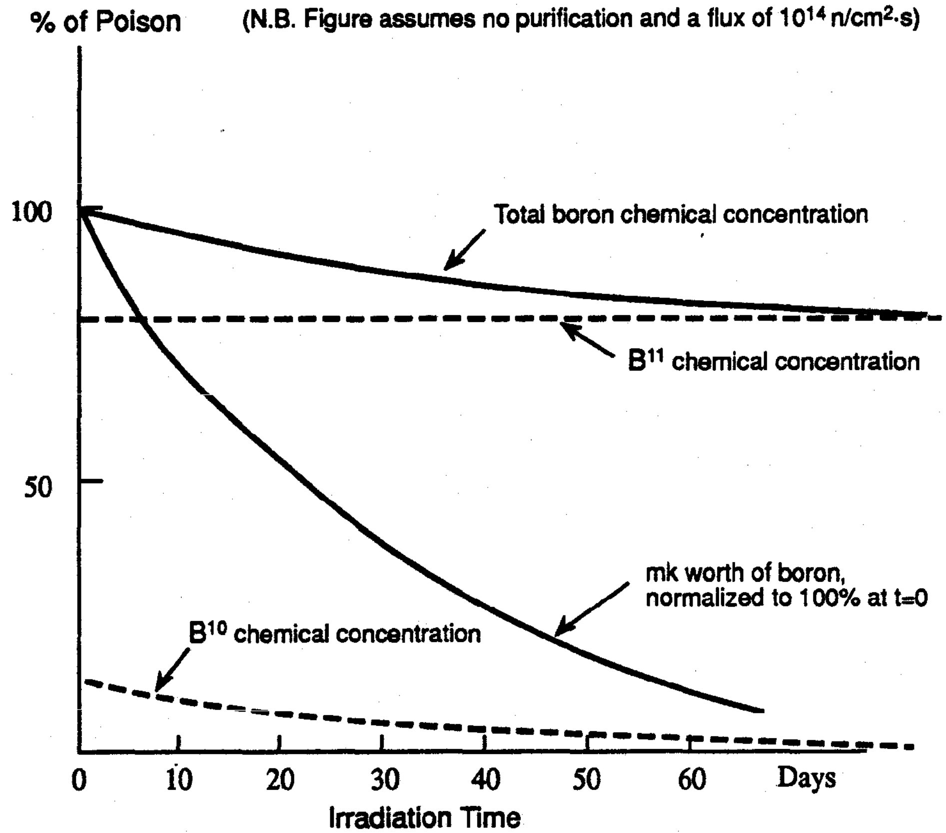

Figure 4.4 Variation of Boron mk Worth and Boron Chemical Concentration with Irradiation Time

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.

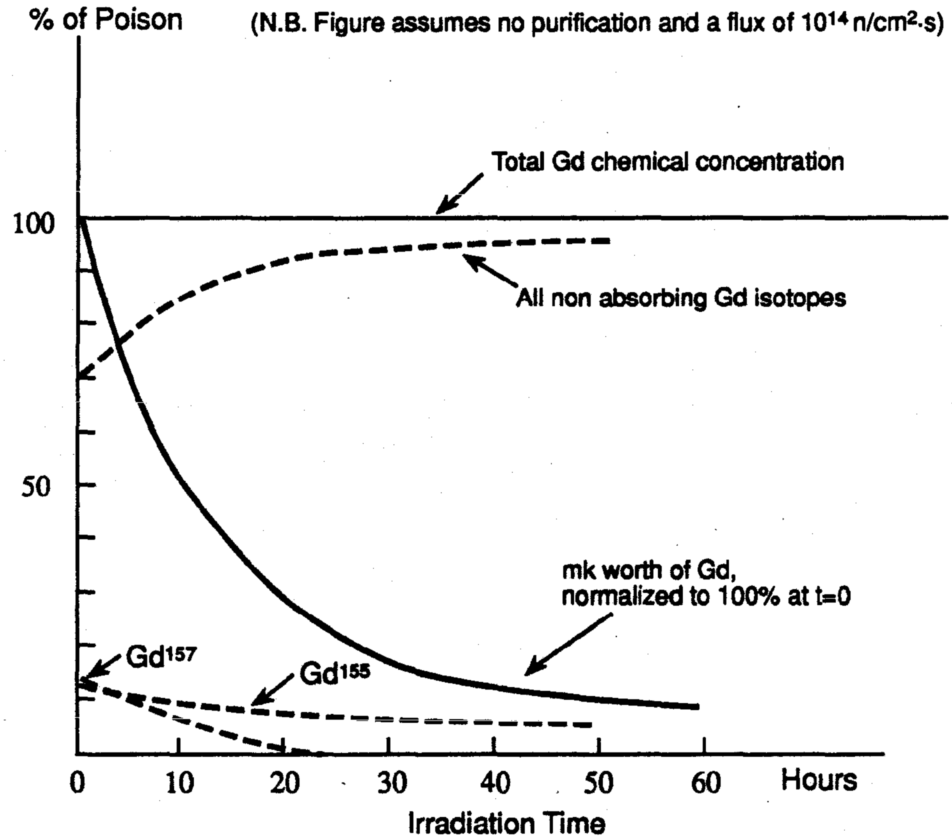

Figure 4.5 Variation of Gadolinium mk Worth and Chemical Concentration with Irradiation Time

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;

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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.

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- 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) ______________________________

NOTES & REFERENCES

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.

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Revised by: P. Bird, WNTD

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