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).

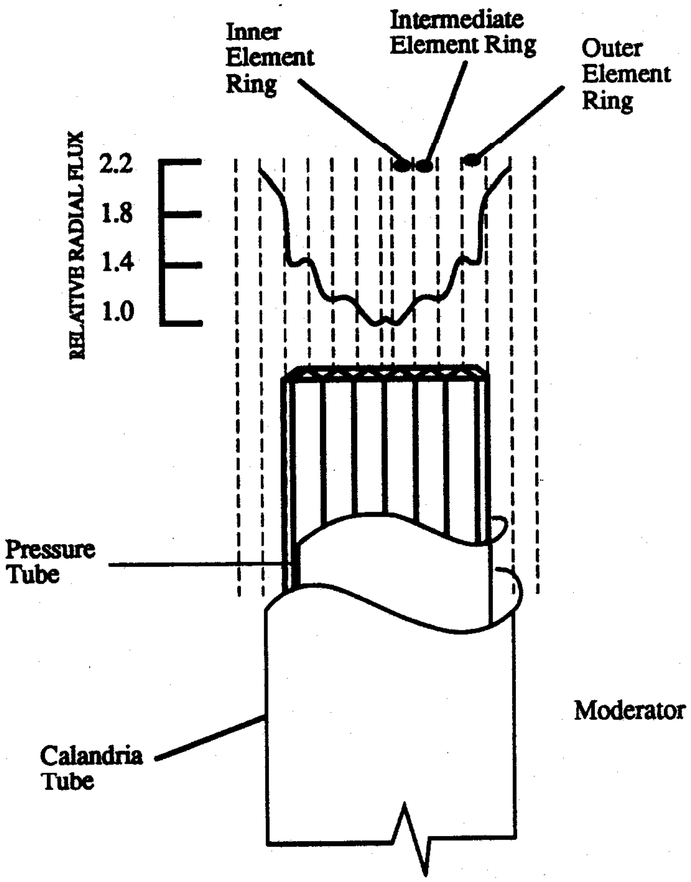
Similar effects can be shown using a non-standard or "skewed" flux profile. For this example, assume that the flux profile is skewed toward the channel outlet, ie. the high flux, hence higher power production, is at the channel outlet. As the coolant flows through the channel, it gets hotter as it picks 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.

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