Reactor, Boiler & Auxiliaries - Course 233

FUEL - PERFORMANCE AND OPERATING FEATURES

Before looking at the performance of CANDU fuel we shall define the parameters in common use to specify the various power rating associated with CANDU fuel.

I. LINEAR ELEMENT POWER RATING q

As a result of the low thermal conductivity of UO_2, the fuel has a very high centre temperature T_c with respect to its surface temperature T_s when operating in a reactor power, see Figure 2, section 70-1. This central temperature is the limiting factor on fuel bundle operation to prevent fuel centre-line (middle) melting. To specify an operating limit on fuel T_c itself is not used however, as it is not measurable in practice, but a quantity related to T_c is used instead. This quantity is q, the linear element power (and is approximately proportional to the fuel centre temperature T_c). It is physically the maximum design thermal power per unit length at which an element should be operated. Typical values are listed in Table I, section 70-1, for the various fuel bundles in use. For instance, at Pickering NGS-A, the maximum element rating is 52.8 kW/m. For an element length of 49.5 cm this then gives a maximum element power of 26.2 kW.

Not all fuel elements operate at the same power rating however and the maximum rated elements are the ones forming the outer ring of elements in a bundle. These elements experience the largest thermal neutron flux of all elements, as a result of the thermal neutron flux depression in the neighbourhood of the inner elements of the bundle. This is because as the thermal flux enters the fuel the UO_2 acts as an absorber and produces fast neutrons. As there is little moderation in the fuel or in the HT D_2O, not many thermal neutrons get through to, and are absorbed in, the inner fuel elements. The resulting flux depression in the fuel is illustrated in Figure 1, which shows the relative thermal neutron flux radially through a fuel bundle.

II. BUNDLE POWER LICENSE LIMIT

Knowledge of the above maximum element power rating q is actually of little value for reactor operation, because there is no way of measuring it directly in the reactor, to check how close to the limit an element may be operating.

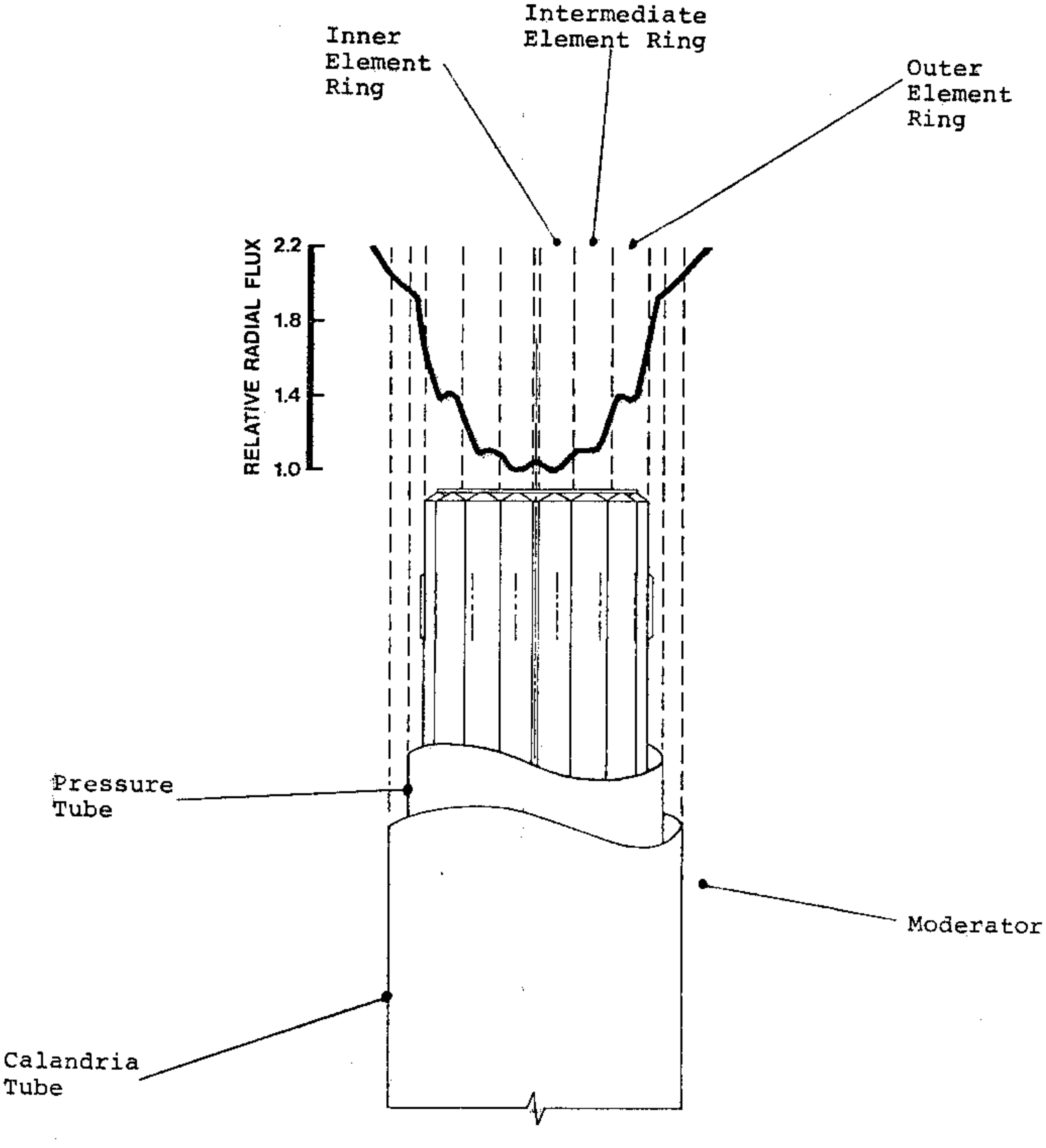


Figure 1: Thermal Neutron Flux Depression in a Fuel Bundle

What is of relevance for reactor operation is the bundle power license limit. This is defined in Station Operating Policies as a power that should never be exceeded, the fuel not being designed to be operated above this limit. Above this limit the probability of fuel defects increases rapidly. For Pickering NGS-A 28-element fuel, for example, this limit is 705 kW/bundle.

III. NOMINAL MAXIMUM BUNDLE POWER

The above license limit sets an absolute specific limit on bundle power and is related to another bundle power rating - the nominal maximum which is typically ∿10% below the license limit, for example, 636 kW at Pickering NGS-A. This rating defines the bundle power which should not be exceeded during normal operation but may be exceeded during 'abnormal' events such as adjuster rod withdrawals or booster insertions. What this rating does therefore is to give a ∿10% operating margin, for events such as adjuster movement, so that a reactor derating may not necessarily be required when bundle power exceeds 636 kW. If a derating is specified by the Operating Manual, say for the withdrawal of a certain number of adjusters, then this means that the localized power increases are larger than this operating margin allows for at full power.

The increase in nominal maximum bundle power that has been made available over the years is illustrated in Figure 2. Values range from ∿220 kW at NPD to ∿900 kW at Bruce.

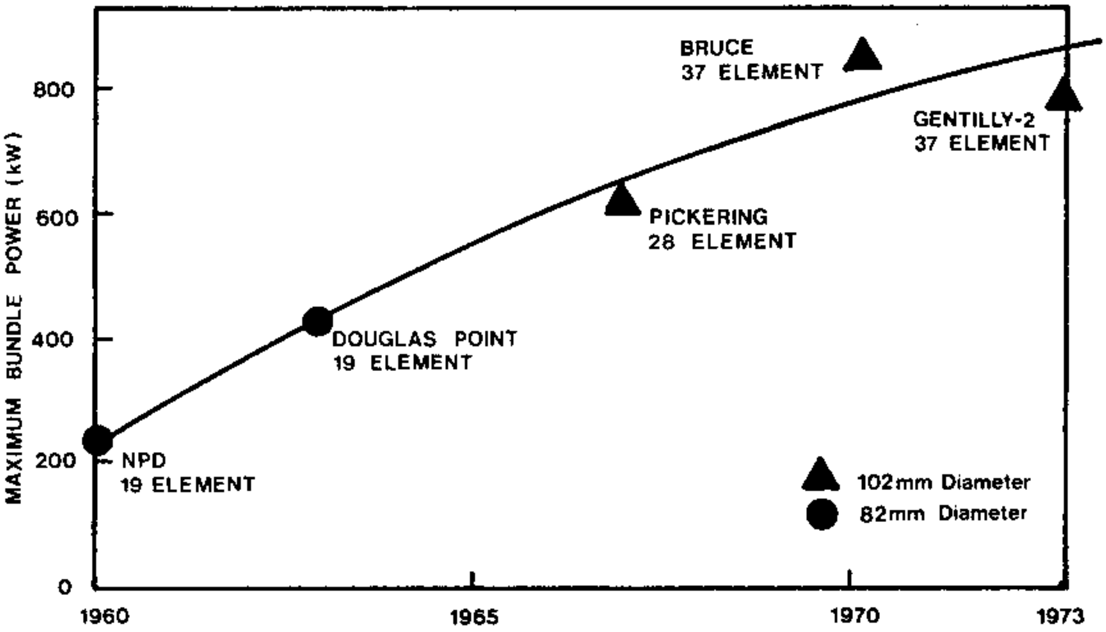


Figure 2: Bundle Power Versus Year of Design

The nominal maximum bundle power can be related to the maximum element power rating discussed above. From the maximum element power q and knowledge of the thermal neutron flux shape through the bundle the nominal maximum power can be calculated by the fuel designer. (Note that the maximum bundle power is not simply the maximum element rating times the number of elements, as the inner elements operate at lower ratings due to the flux depression.)

The fuel scheduling program (see below) is designed so that this nominal maximum bundle power rating is not normally exceeded.

IV. RELATIONSHIP BETWEEN BUNDLE POWER, CHANNEL POWER AND CHANNEL ΔT

In the previous section we have discussed the fact that fuel bundles have a power rating in kW, but have not mentioned how this can be measured or monitored in practice. First it should be realized that in fact there are no direct measurements that indicate to the control room operator the power produced by individual bundles. We will explain however how bundle power can be indirectly monitored by measuring fuel channel ΔT.

Channel Power and Channel ΔT

Channel power can be defined as the sum of the thermal powers produced by all individual bundles in a channel. It can also be alternatively defined and measured by use of the following relation:

$$\text{Channel Power} = \text{Channel } \Delta T \times \text{Channel Flow} \times \text{Specific Heat of HT } D_2O \qquad (1)$$

(Note that this is true only if the HT D_2O is subcooled (not boiling). If it is boiling and the channel power is increasing then the measured channel ΔT will remain constant giving a misleading value, in the unsafe direction. For boiling conditions equation (1) has to include a correction for steam quality to be accurate.)

Along a fuel channel the channel power distribution is proportional to the average thermal neutron flux distribution along a channel and this is shown typically in Figure 3. The shape of the channel power distribution is generally similar for all channels, although there will be some minor variations in the Figure 3 distribution due to the following effects:

- location of channel relative to adjuster rods and other reactivity mechanisms rods
- fuelling direction
- local Xe concentration
- proximity to recently refuelled channels.

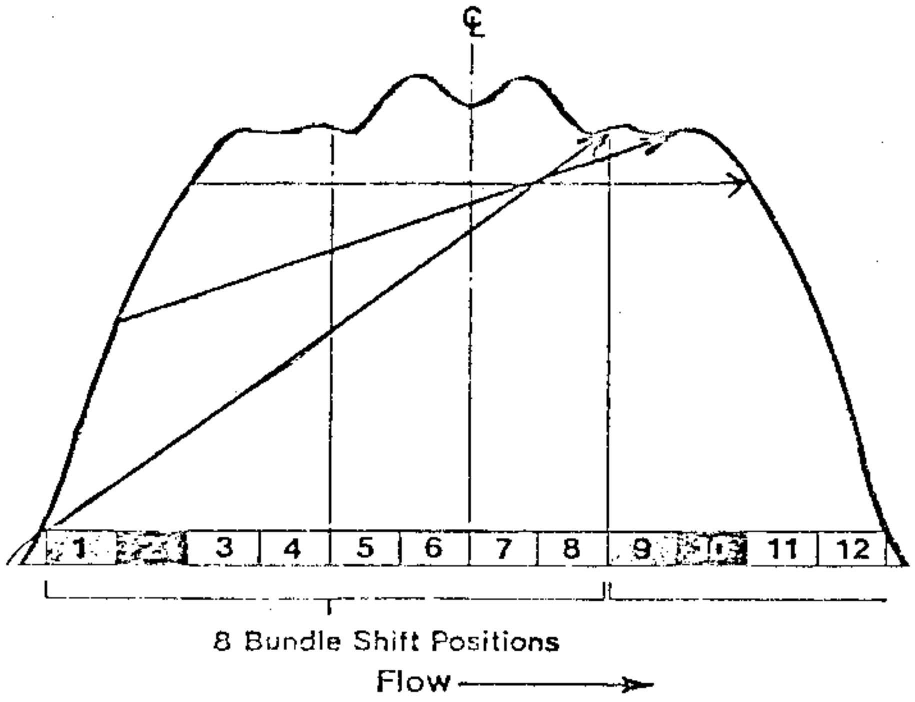


Figure 3: Pickering Axial Thermal Flux or Power Distribution Along a Fuel Channel

To prevent us from exceeding bundle power limits within a fuel channel then, ideally we would like to be able to measure the localized power (or neutron flux) along each channel to ensure that the effects above do not cause localized bundle over-rating. This could be done by having large numbers of in-core flux detectors monitoring the flux (and hence thermal power) of all the fuel bundles. Alternatively we could measure the ΔT of each individual bundle in the channels. Neither of these methods is practical because of the requirements for large numbers of incore instruments. In practice, maximum bundle power is estimated indirectly.

From relationship (1) as the channel flow rate is fixed (by design), and the specific heat is also approximately constant, then the channel ΔT is proportional to the total channel power. Hence the channel ΔT is a measurement of the sum of the individual bundle power in a channel. From the design flux shape along a channel, the channel ΔT obtained when the highest-powered bundle reaches its maximum bundle power, can be determined. Hence a limit can be set on channel ΔT to prevent bundle overrating. The problem here is, however, we do not measure all the channel inlet temperatures in the stations to allow the ΔT's to be determined, because of the extra instrumentation required. Instead, the inlet header (or headers') temperature is measured and, for a given header, the temperature is the same for all individual inlets, so that individual inlet temperature measurement is not necessary. ΔT limits can then be set by setting limits on individual channel outlet temperatures which are indicated directly in the control room.

We have just discussed how the channel ΔT limits (or channel outlet temperature limits) protects against bundle power over-rating and this is the situation at Pickering, for example. At Bruce, however, the channel ΔT (or outlet temperature) limits are set by a different consideration. Here the limit is set by the maximum channel power allowable (rather than individual fuel bundle power), which is set from considering the possibility of dry-out occuring. This is when the heat transfer becomes less efficent as the film boiling mechanism for heat transfer is approached, and the fuel sheath temperature will rise rapidly. This phenomena sets the heat transfer limit of reactor channels. However, as with Pickering, the final objective of a channel outlet temperature limit is to prevent fuel damage, whether it is caused by power overrating or a result of a reduction in the heat transfer from the fuel.

Note that if boiling occurs in a channel the outlet temperature will not continue to rise after boiling starts because then the outlet water condition is saturated. This could lead to undesirable overheating of fuel due to steam blanketing as the % of the boiling increases. The only way to confirm that the channel outlet is boiling is to compare the outlet temperature and corresponding outlet header pressure measurements with those expected from values read from steam tables.

V. FUEL BUNDLE PERFORMANCE AND CRITERIA FOR DEFECTS

Some bundles become defective during operation and are discharged before their terminal burn-up has been reached. The percentage of fuel which suffers defects is, however, small. Table I summarizes CANDU fuel performance to date.

Some basic defect criteria have been established from operating experience in stations and have been found to depend on the following parameters:

(a) fuel burn-up.
(b) final bundle power P after a power increase in a bundle.
(c) magnitude of a bundle power increase, ΔP.
(d) bundle dwell time at a higher power than its final power, eg, during refuelling.
(e) manufacturing defects, such as faulty end plug welds.
(f) handling damaged bundles.
(g) fretting by debris circulating in the HT system.
(h) flow induced fretting when a bundle is parked in cross flow in the end fitting when the F/M malfunctions.

Parameters (a) to (d) above can lead to what is usually called power ramp (ie, increase) defects.

TABLE I

CANDU Fuel Performance Data

(to December 1979)

UNIT	BUNDLES IN CORE	IRRADIATED	DISCHARGED	DEFECTIVE	% DEFECTIVE
PNGS-A					
Unit 1	4680	34680	30000	100	0.29
Unit 2	4680	32680	28000	1	0.003
Unit 3	4680	26780	22100	6	0.02
Unit 4	4680	24080	19400	4	0.02
BNGS-A					
Unit 1	6240	18740	12500	23	0.12
Unit 2	6240	19040	12800	41	0.22
Unit 3	6240	15440	9200	27	0.18
Unit 4	6240	10240	4000	4	0.04

Power reductions, shutdowns, HT depressurizations and constant power operation do not contribute significantly to fuel failures. Sufficient operating experience is now available so that it is possible to specify the parameters (a) to (d) above so that the probability of fuel defects can be reasonably well predicted, as a result of refuelling or movement of a reactivity mechanism rod.

Analysis of operating experience has shown that:

- New fuel may be taken up to its nominal maximum bundle power as soon as it is in core without defecting.
- When bundle power is increased, the larger the power increase, ΔP, then the more likely is the bundle to defect.
- The longer the bundle dwell time is in regions of higher power than the final power, during a refuelling shuffle, then the more likely is the bundle to defect, eg, 10 minutes is riskier than 5 minutes.

The second of the three results just mentioned is illustrated in Figure 4.

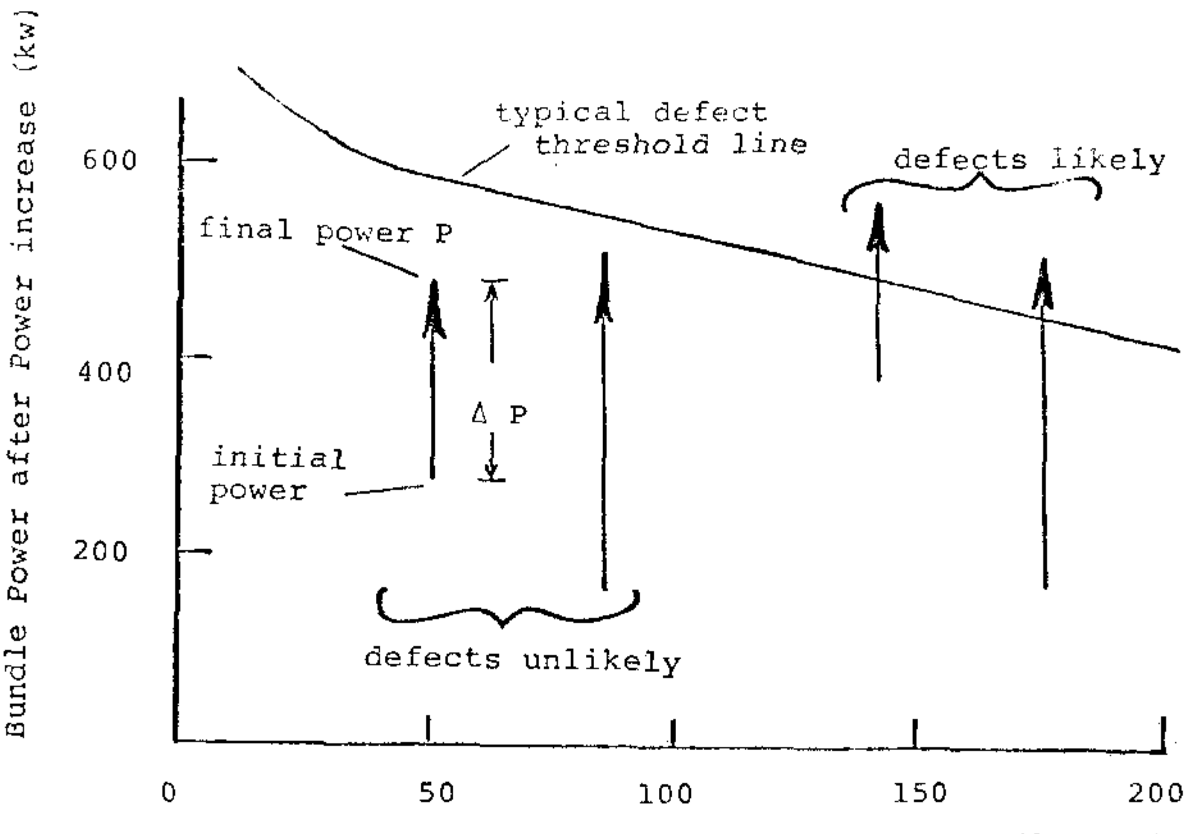


Figure 4: Fuel Defect Criteria

Each of the arrows represents a power increase seen by bundles of various burnups during a reactor power increase or a refuelling operation. The power change ΔP is represented by the length of the arrow and the final power P corresponds to the top of the arrow. The probability of fuel defecting increases, the farther P is above the defect threshold line. This so-called defect line indicates a certain probability of fuel defecting if the final power P goes above this line. The farther P is above this line, the more likely is a defect to occur.

A specific example of the use of Figure 4 is shown in Figure 5 which gives a typical bundle power history versus burnup obtained from a fuel management computer program. The defect threshold line is shown dashed and the bundle power crosses this line at 130 MW hr/kg U burn up. This bundle was removed at a burnup of 210 MW hr/kg U after about 20 months in core and was found to have a small defect in it.

The following two actions taken at Pickering NGS-A illustrate practical use of this analysis to improve operating procedures.

1. The withdrawal sequencing of adjusters at Pickering NGS-A and the allowable power during and after the transient was changed so that the defect threshold line of Figure 4 was not crossed by any bundle.

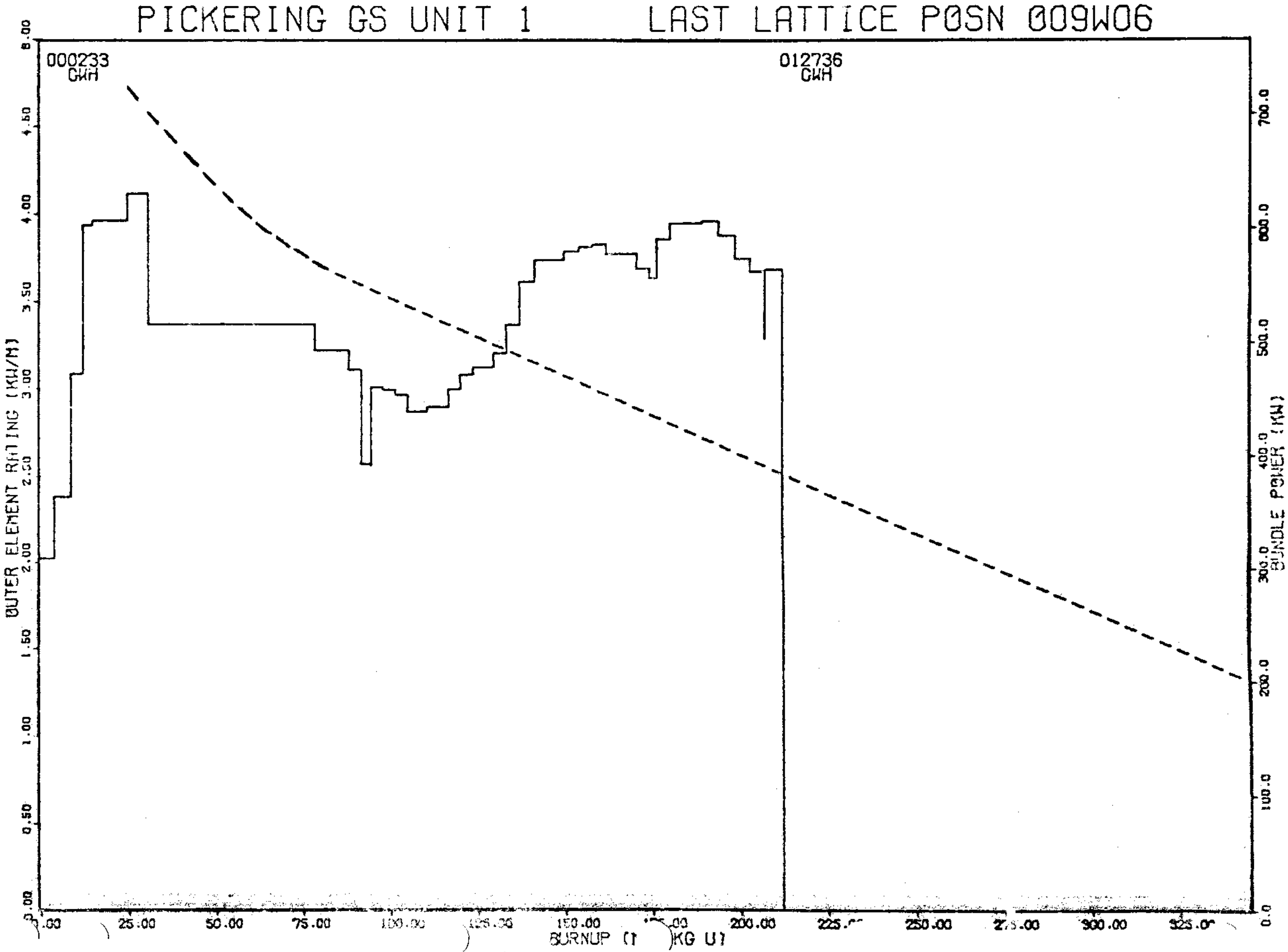
2. A change from 8 to 10 bundles shifting was made at Pickering NGS-A in the high power channels. The original fuel shifting scheme for Pickering NGS-A is shown in Figure 3. illustrating the power distribution along a typical channel (axial power). For an 8 bundle shift at Pickering NGS-A, the largest ΔP increases were in bundles #9 and #10, and indeed, most defects were observed in these bundles.

As a result of changing to 10 bundles shifting (in the higher power channels) and the change in adjuster rod sequencing, a significant drop in the defect rate was achieved. Table I illustrates this by comparison of Unit 1 with Units 2 to 4 where most of the defects in Unit 1 were incurred in the first year of operation.

VI. DETECTION OF AND IMPORTANCE OF FUEL DEFECTS

We have discussed the criteria for fuel defects to occur but have not yet asked what is measured to detect their occurrence nor why defects are important. Both of these are discussed in relation to HT iodine concentrations.

Figure 5: Power History of Bundle 98850C



(a) Detection of Failed Fuel

This is done by detecting fission products released by the fuel defects into the HT D_2O. Generally speaking, fuel defects are defined as fission products leaking from the fuel pellets through the fuel sheath into the HT D_2O.

The extent of a defect can vary widely, from a minor fission product leakage through small sheath cracks, to massive defects where fuel pellets are lost from the fuel element(s) through large holes/cracks in the fuel sheath (Figure 6). Fuel damage caused by mechanical problems, associated with channel fuelling operations, is not generally classified as defective fuel, as such.

Detection methods used in the stations are:

(i) iodine monitoring/sampling

(ii) gaseous fission product monitor.

We will mention only iodine sampling here as it is the principle method. [Do not, however, confuse the detection methods with location methods for failed fuel.] Location refers to the specific channel location of failed fuel. The system which provides location of defects is usually the delayed neutron-monitoring system. Failed fuel location methods can usually be operated also as detection methods but methods designed only for detection cannot be used for location.

A fuel defect(s) is expected to be present when the heat transport D_2O I-131 concentration increases above ∿20 μCi/kg D_2O (740 kBq/kg). For example, in the Pickering NGS-A chemical analysis, given in section 30-3, Table I, it is likely that Unit 2 has ∿1 defect bundle and Unit 3 perhaps 2 or 3 defect bundles.

Iodine is always detectable in the HT D_2O even if defects are not present, due to 'tramp' uranium on the fuel sheath due to contamination during the fuel bundle manufacture.

(b) Iodine Limits

I-131 concentration in the HT D_2O is used as a defect detection method primarily because I-131 is the most critical fission product that could be released to the environment in case of a loss of coolant and failure of containment. The critical exposure that could result from this is to the thyroid of young children. It is also convenient because it is easy to detect and is easily released into the coolant from fuel failures, being easily vaporized.

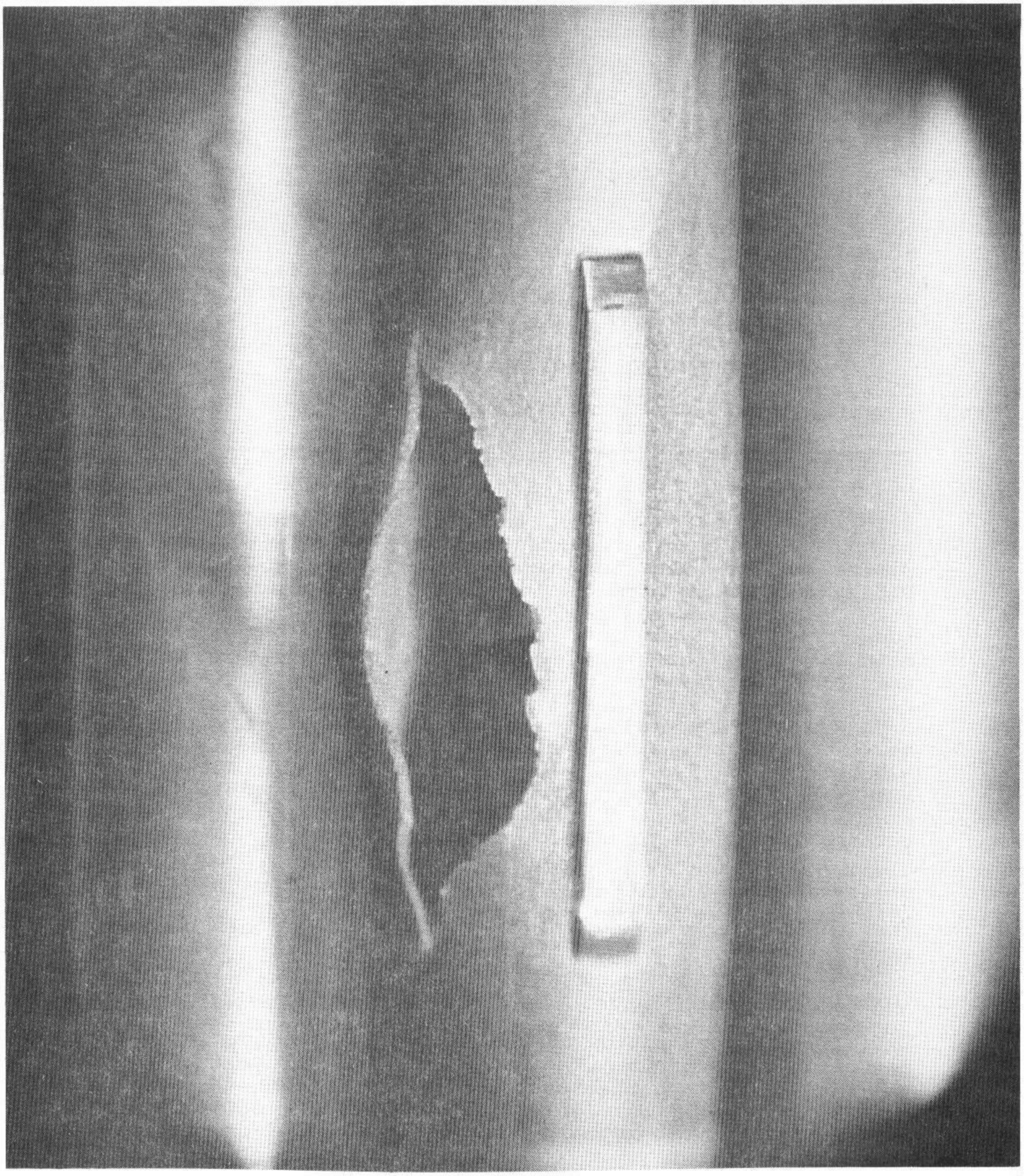


Figure 6: Example of a Failed Fuel Element

As a result of the above, the AECB has set limits for all plants which are specified in Station Operating Policies and Principles. For example, at Bruce NGS-A there is an action limit at 500 Curies I-131 in the HT D_2O and a shutdown limit of 1000 Curies I-131.

As a precaution against further increases of I-131 at the action limit, reactor power should not be increased 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 shutdown and HT system cooled down and the HT purification flow rate maximized, until the iodine concentration is reduced.

Although iodine limits are set primarily because of potential environmental releases, the in-plant consequences of high HT iodine concentrations is also important. In this case, iodine uptake by plant personnel due to HT D_2O leaks and subsequent iodine vapour release is the reason.

(c) Effect of Reactor Trips, Shutdowns and Startups on I-131 Concentrations

Figure 7 illustrates a practical example of HT I-131 concentration (Bruce NGS-A Unit 2, December 1978) showing the effect of a reactor trip on Day 13. Up to Day 13 the I-131 concentration is relatively constant and indicates a small defect(s) in core (>740 kBq/kg). After the trip, the iodine concentration increases in this example by a factor of about 20, which is not unusual if defects are present in core.

This increase in iodine following a trip/shutdown does not mean more defects have been produced (recall that shutdowns were not a criteria for causing defects). What happens is that more iodine is released into the HT D_2O by stressing existing defects more, due to the temperature changes in the fuel pellets/sheaths on shutdown.

The rate of decrease in I-131 concentration after the shutdown is more rapid than the natural 8-day half life decay rate of I-131 (shown dashed in Figure 7). The rate of decrease is more rapid because of clean up purification. Notice that the startup on Day 16 does not produce any increases in I-131 concentration.

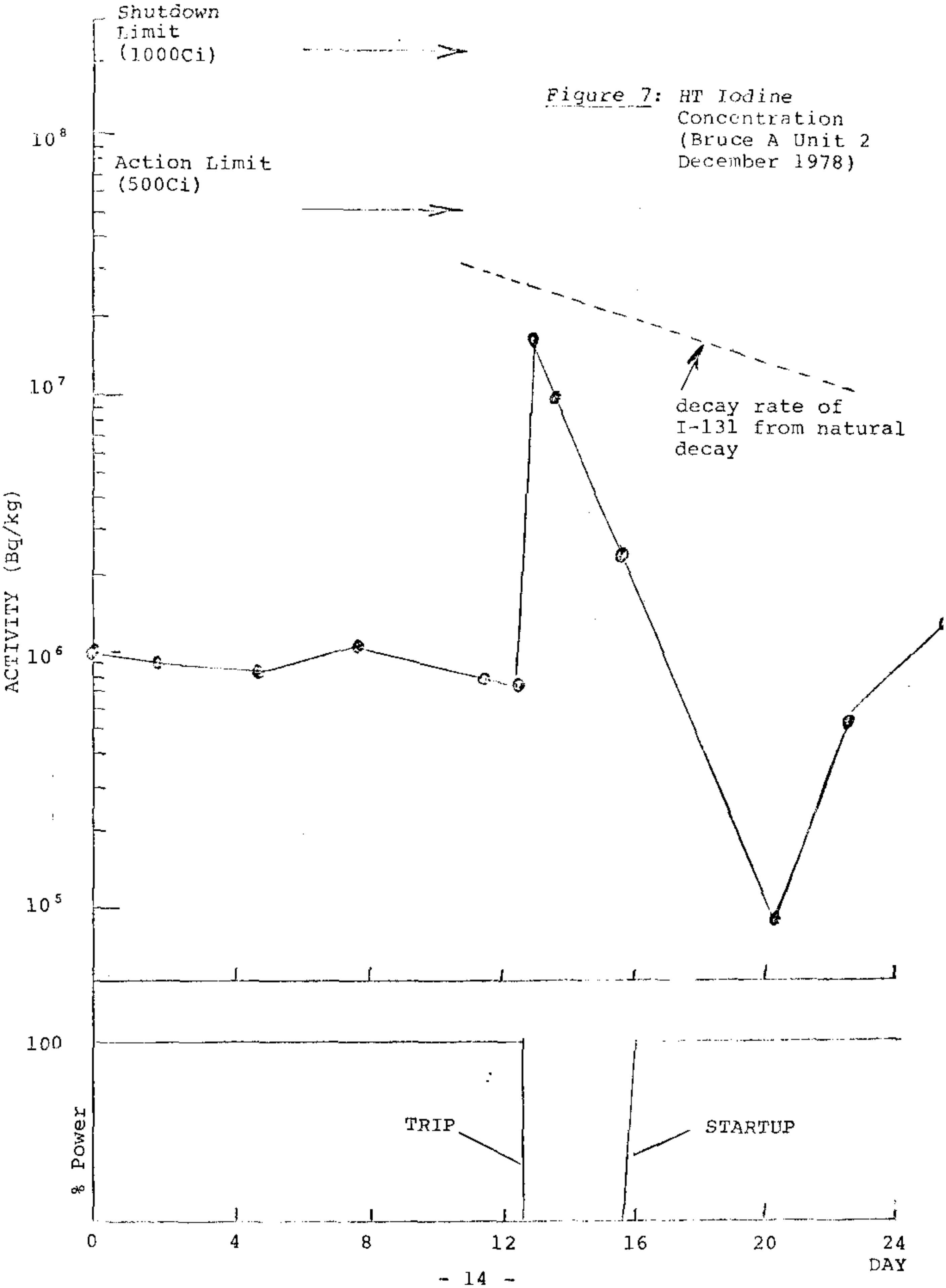


Figure 7: *HT Iodine* Concentration (Bruce A Unit 2 December 1978)

VII. FUEL SCHEDULING

This term is used to describe the pattern of fuel replacement in the reactors. The pattern is fairly flexible, but does follow certain basic rules. Fuelling is planned a few days in advance, and a specific list of channels to be fuelled is issued by the fuel engineer to the F/M section, which performs the fuelling. The fuel channel list is specified on a "Fuel Change Order" form.

The channels to be fuelled are determined by the fuel engineer with the aid of a computer program called SORO (Simulation Of Reactor Operation). Data is fed into this program of various parameters such as average zone level, reactivity mechanism rod positions, reactor power level, number and type of fuel bundles last inserted in core. From this data SORO calculates a number of parameters that enable the fuel engineer to select the next channels for refuelling. Channels are selected by consideration of the following items. Some of these vary from station to station and the order of their importance may vary according to day-to-day operation, although they are listed essentially in hierarchical order.

- Defect fuel is removed as soon as possible.
- Highest burnup channels are refuelled.
- A refuelled channel does not contain bundles exceeding bundle license power limits nor exceed the limits set for maximum channel power*.
- Equal number of east and west channels are fuelled alternately for axial symmetry.
- Equal numbers of channels are fuelled per liquid control zone to maintain zone level symmetry.
- High temperature regions near recently refuelled channels are avoided for fuelling to prevent possible further channel outlet temperature increases.
- High reactivity gain per channel. The channel which will give the largest reactivity gain or refuelling may be selected if the overall reactor excess reactivity is low.

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*The Term:

$$\text{Channel Ripple} = \frac{\text{Actual Channel Power}}{\text{Reference Channel Power}}$$

is used in reference to this and is kept <110%.

VIII. IRRADIATED FUEL BUNDLE EXPOSURE TO AIR

One of the most important features of irradiated fuel is the fact that discharged fuel from the reactor still generates a significant amount of heat. For example, a day after discharge a bundle will still be generating a few kW of heat. The decay heat drops off as illustrated in Figure 4, section 30-1. In the absence of adequate water cooling, where a bundle is exposed to air, the bundle will soon overheat, resulting in loss of fuel sheath integrity, and begin to release fission product gases and vapours, which is highly undesirable.

Typically for a high powered bundle provided with ∿15 minutes of water cooling following removal from the reactor, defects can be expected to occur after only a few minutes of air exposure. For low powered bundles and longer water cooling time, the time to defect will be considerably longer.

ASSIGNMENTS

1. Using the basic criteria for fuel failure illustrated by Figure 4 explain in each of the following cases whether a fuel defect might be likely somewhere in core.
   - (a) Operation at constant power.
   - (b) Start up from depressurized to full power without use of boosters or adjusters.
   - (c) A shut off rod drops in core, and remains there, and the reactor is maintained at constant power.
   - (d) An adjuster is pulled out of core for a few hours and power is maintained constant.
   - (e) An adjuster rod is pulled out of core for a few minutes and then reinserted and power is maintained constant.
2. Using Figure 3, would a fresh fuel bundle for Pickering NGS-A that is put straight into a fuel channel and procudes the maximum bundle power be likely to fail? On the basis of your answer, is it permissible to fuel in 12 bundle shifts? If it is, why to we not do this to avoid the possible problem shown in Figure 5 with 8 bundle shifts?
3. State 3 operating events (not necessarily for any one plant) that could potentially lead to fuel failures.
4. How would you know from the control room whether a bundle had exceeded the AECB license limit?
5. The flux depression in the fuel was mentioned under bundle power rating. Make sure you know from Nuclear Theory why the flux is a minimum in the centre of the bundle (because the flux is a maximum in the outer elements, usually these are the ones which fail more frequently.
6. Explain why Operating Policies and Principles sets limits on iodine concentration in HT D_2O. What action is taken at these limits?
7. If shutting down a unit with fuel defects in will increase the I-131 concentration as shown in Figure 7 why do we shut down and cool down the HT system at a 1000 Ci shutdown limit, rather than continue to operate at constant power?

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