Nuclear Theory - Course 227

FAILED FUEL MONITORING

The operating conditions in CANDU reactors impose severe stresses on the fuel. Sometimes fuel cladding failures occur. Failures vary in size from minute hair-line cracks to large ruptures or holes in the zircaloy cladding. It is important to locate failures as soon as possible. Activity monitoring systems are used (a) to detect the fuel failures and (b) to locate the fuel channel containing the defective element.

Reasons for Activity Monitoring

Upon fuel failure, some of the active fission products, and uranium and plutonium are able to escape, and go into the primary coolant circuit. There is a limit on the amount of activity allowed to circulate in the coolant, and this is stipulated by the AECB through federal radiation protection regulations. The reasons for being concerned about activity release to the heat transport system are listed below:

(1) The released activity, which depends upon the defect size and rate of fuel burnup can be extremely high and may constitute a health hazard because (a) increased radiation from the primary coolant circuit equipment may reach unacceptable levels for operating personnel and (b) coolant water leaks and contamination of coolant circuit equipment would bring maintenance staff into direct contact with highly active fission products and plutonium.

(2) A fuel cladding failure may result in a distorted element making removal from the reactor difficult and also expensive in terms of a clean up operation and a reduced capacity factor.

(3) Fissile uranium or plutonium released from a fuel failure may become plated out on parts of the coolant circuit. In the presence of a neutron flux they will continue to produce and release fission products into the coolant, making the detection of further fuel failures more difficult.

Properties of the Fission Products

To detect and locate a failed fuel element the activity of the fission products is measured with a suitable detector situated in the coolant circuit. To determine which fission products we should monitor, the factors to be considered are decay modes, half lives and recirculation behaviour in the coolant, of the most important fission products, and also the background activities present in the coolant.

The fission products may be conveniently classified into three distinct groups according to their chemical properties. These groups are shown in Tables I, II and III which give the corresponding half lives and decay modes of the nuclides.

Group I Gaseous Fission Products

These gases, comprising various isotopes of Kr and Xe (Table I) that are fairly easily released into the coolant through a defect, recirculate continuously in solution until they decay. The decay mode is by β, γ emission, and the γ energies are unique for each isotope.

Gaseous Fission Products (GFP)

TABLE I

Nuclide	Half Life	
^{87}Kr	76 min	β,γ decay modes
^{88}Kr	2.8 h	
^{85m}Kr	4.4 h	
^{135m}Xe	15.6 min	
^{138}Xe	14 min	
^{135}Xe	9.2 h	
^{133}Xe	5.7 d	

Halogen Fission Products

TABLE II

	Nuclide	Half Life		
Short Lived	^{87}Br	56 s	Delayed Neutron Precursors	β,γ decay modes
	^{88}Br	16 s		
	^{137}I	23 s		
Long Lived	^{132}I	2.4 h		
	^{134}I	52 m		
	^{135}I	6.7 h		
	^{133}I	21 h		
	^{131}I	8.1 d		

Depositing Fission Products (DFP)

TABLE III

Nuclide	Half Life		
^{132}Te	78 h	Short Lived	β,γ Decay Mode
^{99}Mo	67 h		
^{99m}Tc			
^{95}Zr	66 Days		
^{95}Nb			
^{103}Ru	40 Days		
^{106}Rh	1 Year		
^{106}Ru			
^{141}Ce	33 Days		
^{144}Ce	285 Days		

Group II Halogen Fission Products

This group (Table II) consisting of volatile iodine and Bromine isotopes, is fairly easily released through a defect and subsequently carried in the coolant as negative ions ie, anions. These ions may be removed to some extent in the anion ion exchange (IX) column situated in a clean up line normally in parallel with the primary coolant flow line as shown for the typical activity monitoring system at NPD in Figure 1. The decay mode is by β,γ emission but an important feature of the three short lived isotopes listed here is that they are delayed neutron precursors ie, the β decay leads to a highly excited nucleus which is then able to decay further by emitting a delayed neutron.

Group III Depositing Fission Products

This group of β,γ emitting non volatile nuclides (Table III) is not so easily released through a defect as the above groups. Because of their low solubility they plate out (deposit) on the walls of the boiler. They are also removed in the anion ion exchange (IX) column so that most of the activity from this group does not recirculate.

Fission Product Yield

The relative quantities of the above fission product nuclides produced by fission may be determined by inspection of Figure 2. This double peaked curve shows the % production of the fission products from fission of U-235. The positions of the three groups of fission products are indicated, the yields of those important in activity monitoring are between 1% and 7%.

Choice of Fission Products for Detection of Fuel Failures

It can be seen that there is a large variation in the half lives of the various fission products and this fact enables us to distinguish between a minor and major fuel cladding failure. A finite time is taken for the fission products to diffuse through a small defect in the cladding during which time the fission products with short half lives will have been decaying. A larger defect occurring under the same steady conditions will release its fission products more quickly and the activity in the coolant will now contain a higher proportion of short lived fission products than in the case of the smaller defect. In order to monitor for detection of a fuel cladding failure under steady reactor operation a fission product with a long life is chosen.

At NPD for example Iodine -133 with a half life of 20hrs is used to monitor all 132 channels in bulk for detection of failures, the set-up used being shown in Figure 1. The iodine monitor is actually called the GFP monitor although this isotope (I-133) is actually in the halogen group of fission products.

At Pickering, with 390 channels, bulk GFP monitors are also used to detect fuel failures in each of the two heat transport loops and utilize various fission products from groups I and II, the most common ones being ^{131}I, ^{133}I, ^{87}Kr and ^{135}Xe.

Choice of Fission Products for Location of Failures

Only a small portion of the activity from a fuel defect will be removed by the IX columns for each cycle of the circulating coolant. This means that the activity from a defect will spread throughout all the channels. To locate the defect, we must be able to discriminate between freshly released activity and recirculating activity.

Detection of GFP tells us only that there is a fuel failure and we use detection of the DFP or of the DN groups to home in on the defect.

The depositing fission product (DFP) group, in particular the isotopes ^{99}Mo and ^{132}Te, as well as being removed by decay have the property of plating out (depositing) on the boiler tubes and in monel traps used for the efficient deposition of these fission products in the DFP monitors themselves. Hence, the DFP's are more effectively removed from the coolant than the GFP's which are removed only in the clean up line and by natural decay. A DFP monitoring system is usually arranged so that each channel (or zone of channels) may be scanned individually in order to locate the defective channel (or zone).

Good discrimination against the circulating activity background can also be obtained by monitoring the delayed neutrons from the precursors ^{137}I and ^{87}Br. This good discrimination results because the delayed neutron (DN) monitors are insensitive to γ rays and the short half lives of the precursors give an inherently low recirculating activity background.

The short half lives of the DN precursors are advantageous in discrimination but cause the system to be rather insensitive in the case of small fuel cladding failures. When small defects are suspected the reactor power is cycled, this should have the effect of greatly increasing the proportion of short lived fission products which leak into the coolant. Very small defects can then be detected by the DN monitors.

Monitoring of the delayed neutrons using the reactor power cycling techniques can be used to locate defective elements in individual or groups of channels in conjunction with a DFP monitoring system. Examples of specific systems are briefly described below.

For location purposes at NPD a DFP monitor is used detecting ^{99}Mo and ^{132}Te, it is able to scan all reactor channels independently so that single defective channels may be found. In addition, a DN monitor making use of ^{137}I and ^{87}Br is used to monitor two individual experimental fuel channels.

The locating system at Pickering utilizes 12 DFP monitors, again detecting ^{99}Mo and ^{132}Te, to determine the location of a failure to within the zone of channels feeding one of the 12 boilers. When the DFP monitor has indicated the presence of a failure in a particular zone the fuelling machines are then located onto each suspected channel and a search made using a DN monitor on the fuelling machine heads, until the defective channel is found.

Difficulties Encountered with Fuel Failure Monitoring Systems

The circulating background activity problem results in poor channel discrimination for the GFP system necessitating the use of a DFP and/or DN system for location purposes. Other background activities are also present in the system making the problem of both detection and location of failures more difficult. One of these activities is the manufacturing contamination from uranium dioxide on (or in) the cladding. The contaminant uranium undergoes fission and results in the continual release of fission products into the coolant without the cladding being defective. Additional short lived γ activity is continually present in the coolant, independent of fuel defects, from the presence of ^{19}O ($t_{1/2}$ = 29s) and ^{16}N ($t_{1/2}$ = 7.3s) produced by neutron activation of the oxygen in the heavy water coolant.

Another γ activity source in the coolant, independent of fuel defects, is from activated corrosion products such as ^{60}Co, ^{59}Fe, ^{124}Sb, ^{65}Zr and ^{54}Mn resulting from the corrosive effect of coolant on the reactor components. These corrosion products circulate mainly as cations and are removed by a cation ion exchange column situated before the iodine monitor, as shown in Figure 1.

In the case of the DFP and GFP monitors all these additional γ activities present an undesirable spectrum of γ background which makes the electronic discrimination, used to detect a single γ ray energy of a particular isotope, more difficult.

For the DN monitors there is little direct background from these additional γ ray activities but the γ activity of ^{16}N in the coolant circuit presents a problem. This isotope emits γ rays of 6.1 and 7.1 MeV whcih are of sufficient energy to cause emission of photo-neutrons in the D_2O coolant by the $\gamma(D,p)n$ reaction. This results in an undesirable neutron background in the DN monitors reducing their sensitivity.

ASSIGNMENTS

1. What may be the operational consequences of neglecting to monitor the fuel channel activity?

2. What properties of I^{133} make it a useful isotope in a fuel monitoring system?

3. What properties of the depositing fission products make them useful in a fuel defect locating system.

4. What are the sources of background activities in an activity monitoring system.

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