KANUPP – IAEA Training

Primary Heat Transport System
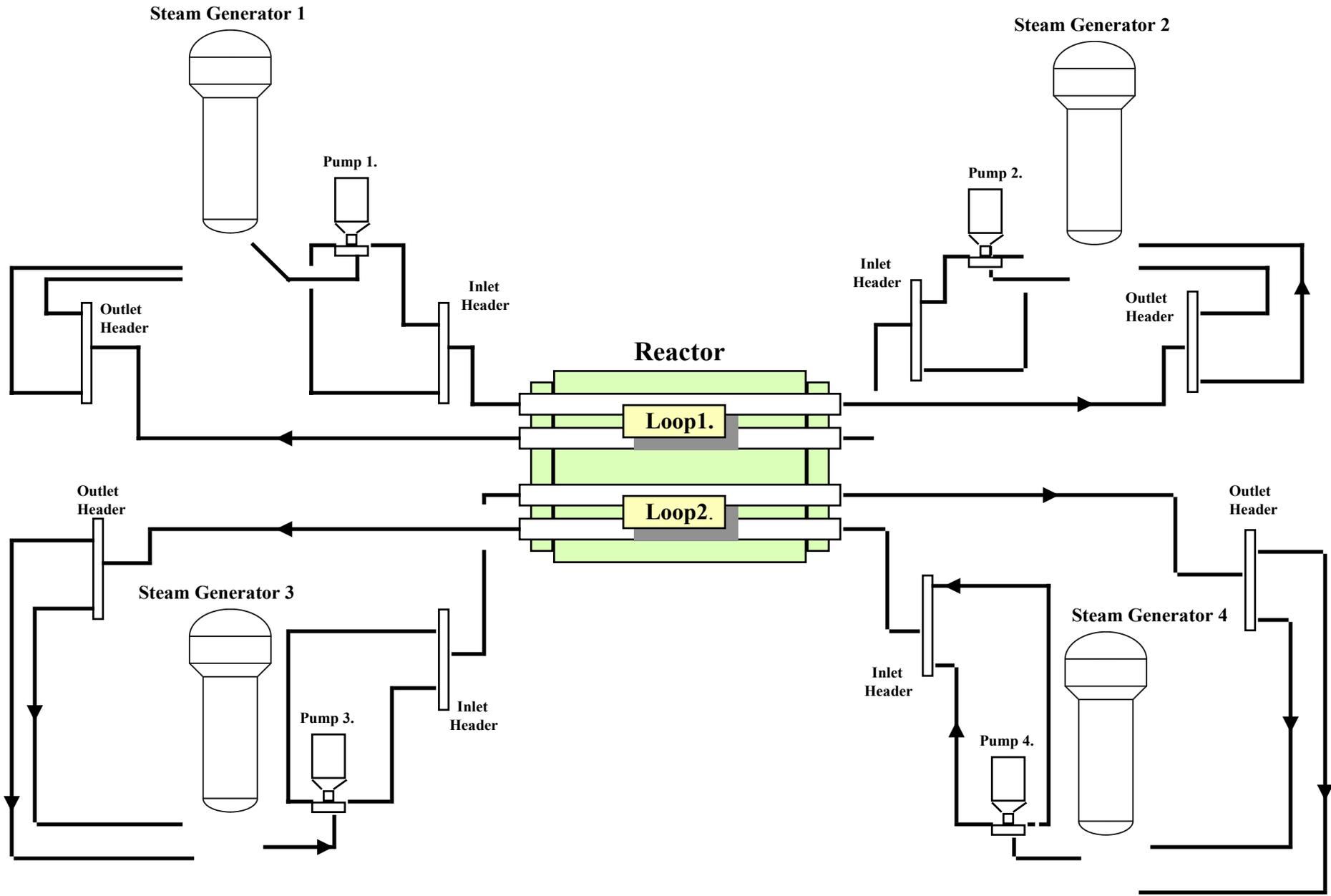## Chemistry Control

Primary Heat Transport System

System Purpose

- Transport heat from the fission of natural uranium fuel in the reactor fuel channels to steam generators, where the heat is transferred to light water to produce steam.

- Provide adequate cooling to the reactor fuel at all times including operation, shutdown, maintenance and loss of Class IV power.

- Provide overpressure protection for the system and system components.

- Minimize heavy water leakage.

Primary Heat Transport System

Major Components

- **380 fuel channel assemblies**

- **four steam generators**

- **four electrically driven heat transport pumps**

- **one pressurizer**

- **four inlet and four outlet headers**

Steam Generator 1

Steam Generator 2

Pump 1.

Pump 2.

Inlet
Header

Inlet
Header

Outlet
Header

Outlet
Header

Reactor

Loop1.

Loop2.

Outlet
Header

Outlet
Header

Steam Generator 3

Steam Generator 4

Inlet
Header

Pump 3.

Inlet
Header

Pump 4.

Primary Heat Transport System

System Parameters

System Volume   122400 Mg

- **Temperatures**

  - **Reactor Inlet Header**   266ºC
  - **Reactor Outlet Header**   310ºC

- **Pressures**

  - **Reactor Inlet Header**   11.33 Mpa
  - **Reactor Outlet Header**   9.99 MPa

- **Flow Rates**

  - **Total Core Flow**   7.7 Mg/s
  - **Flow/channel (max)**   23.9 Kg/s
  - **Purification Flow (max)**   24 Kg/s

    $(T_{1/2} = 60 \text{ min.})$

Primary Heat Transport System

Auxiliary Systems

- **Pressure and Inventory Control System**
  - maintains heavy water inventory and pressure in the main heat transport system

- **Purification System**
  - removes ionic impurities (corrosion & fission products) as well as crud from the main heat transport system.

- **Shutdown Cooling System**
  - circulates and removes heat from the reactor coolant when the reactor is shut down, and when the reactor coolant is drained to the header elevation for equipment maintenance.

Primary Heat Transport System

Auxiliary Systems

- **Emergency Core Cooling**

    - provides light water flow to the primary heat transport system in the event of a Loss of Coolant Accident.

- **D_2O Storage, Transfer & Recovery System**

    - accommodate heat transport system swell when the reactor is warmed from cold to hot, stores D_2O removed from the heat transport system when the coolant level is reduced for equipment maintenance, and recovers D_2O spillage from the vault floor.

- **D.N. & G.F.P. Monitoring Systems**

    - the gaseous fission product (G.F.P.) monitoring system detects, and the delayed neutron (D.N.) monitoring system locates defective fuel in the reactor

Primary Heat Transport System

Chemistry Objectives

- **Minimize the corrosion of system components.**

- **Control the quantity of radioactive crud in the system by controlling the rates of crud production, movement and activation and by crud removal in the purification system.**

- **Control the concentrations of dissolved fission products by removing them by ion exchange or by degassing.**

- **Minimize the fouling of the Heat Transport surfaces by the crud principally by pH control and also through crud removal in the purification system.**

Primary Heat Transport System

Materials of Construction

Metal/Alloy	**System Component**
• Carbon Steel	• Piping
	• Feeders
	• Headers
	• Bleed Condenser
	• Bleed Cooler
	• D_2O Storage Tank
	• IX Columns
• Stainless Steel	• End Fittings (403/410)
	• Instrument Tubing (304L)
	• IX Column Inlet Nozzles
• Zirconium Alloys	• Pressure Tubes (Zr-2.5% Nb)
	• Fuel Cladding (Zr-4)

SUMMARY OF CHEMISTRY CONTROL PARAMETERS

Parameter	Permissible Range	Notes
pH (25°C)	10.2 to 10.8	Controls corrosion and activity transport
Li mg Li/Kg D_2O	0.35 to 1.4	
Conductivity mS/m - 25°C	0.9 to 3.6	Conductivity, pH & Li must be considered together for effective control.
D_2 ml(STP)/Kg D_2O	3 to 10	Oxidizing conditions if too low; possible hydriding of Zr alloys if too low or too high

SUMMARY OF CHEMISTRY CONTROL PARAMETERS

Parameter	Permissible Range	Notes
O_2 ug/Kg D_2O	<10	Controlled by level of dissolved D_2
Cl^- mg/Kg D_2O	<0.2	Stress corrosion cracking of stainless steels. Possible crevice and pitting corrosion.
Crud mg/Kg D_2O	<0.1	High crud levels increase activity transport
I-131 MBq/L	500	OP & P Limit.

KANUPP Primary Heat Transport System
Chemistry Specification

- pH   =   > 10.3
- Conductivity   =   < 25 umho/cm
- Chloride   =   < 0.1 ppm
- Carbonate   =   ND
- Copper   =   ND
- Iron   (dissolved) =   ND
- Lithium   =   1.2 ppm
- Crud   =   < 25 ppb
- Oxygen   =   < 70 ppb
- Hydrogen   =   < 3 ml/Kg
- Isotopic   =   < 99.0 % D20

pH

- **Current Specification**   **10.2 to 10.8**

  apparent pH

  $$pH_A = pH + 0.457$$

- **Minimize corrosion of carbon steel and zirconium alloys.**
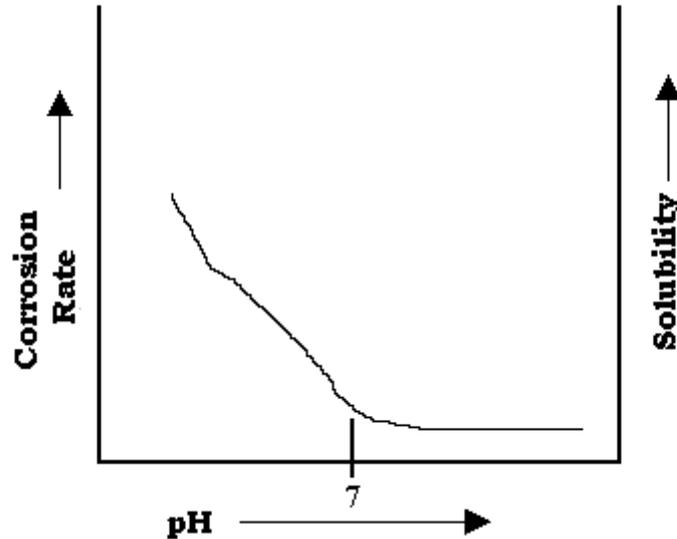
  - High pH optimum for preservation of the carbon steel magnetite layer.

  - Too high a pH can result in increased corrosion in localized areas where lithium hydroxide can concentrate (between fuel bearing pads & pressure tubes would be one location). The upper specification of 10.8 has been set as the point where it has been judged that corrosion even in localized regions will be acceptably low.

- **Maintaining low activity transport throughout the system.**

  - pH values above 10.2 will ensure low deposition of crud (magnetite) in the core - at core temperatures, magnetite solubility increases with increasing pH.

Corrosion Rate of Carbon Steel in Acids and Bases @ 310°C

pH 0-14

APPROX. pH AT 25C

Relative Attack

pH values: 1 2 3 4 5 6 7 8 9 10 11 12 13

250
200
150
100
50
0

36 50   365   36.5   0   400   4,000   20,000   100,000   200,000
365
0.36   10,000   40,000

HCℓ mg/kg   NaOH mg/kg

97146-221

pH Versus Metal Corrosion

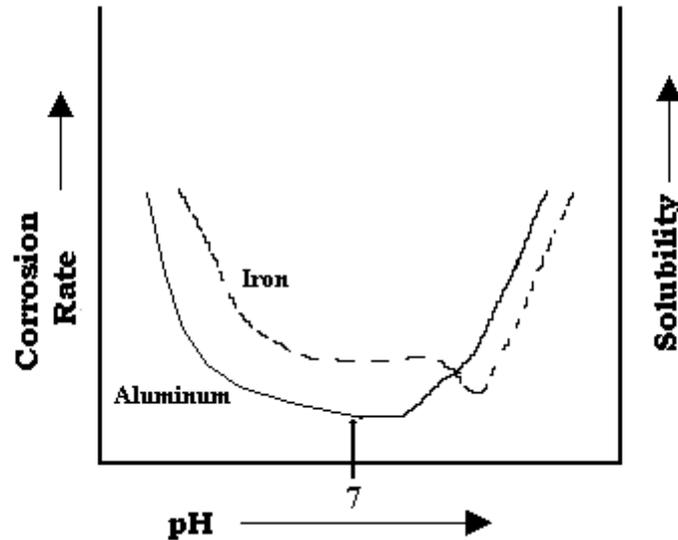## High Solubility in Acid

Examples: **Copper**
                Nickel
                Chromium
                Cobalt
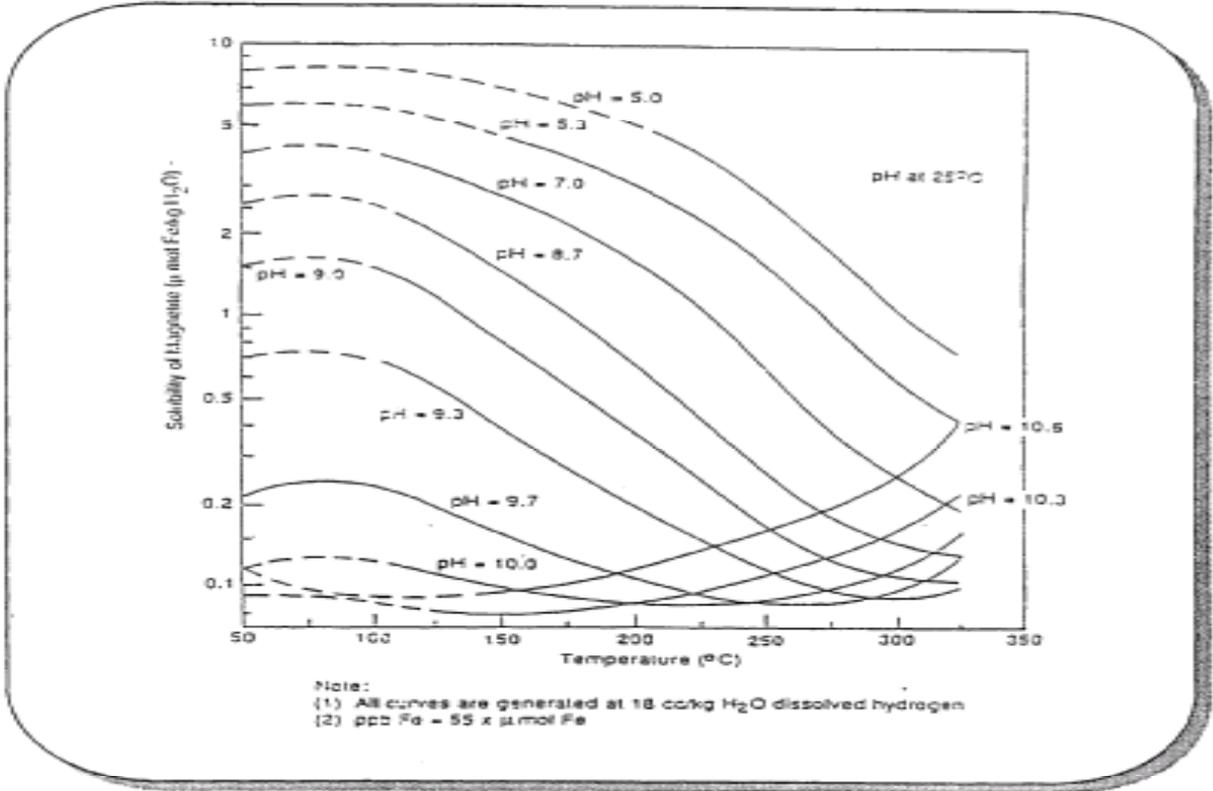
pH Versus Metal Corrosion

AMPHOTERIC METALS

- High Solubility in Acid and Base.
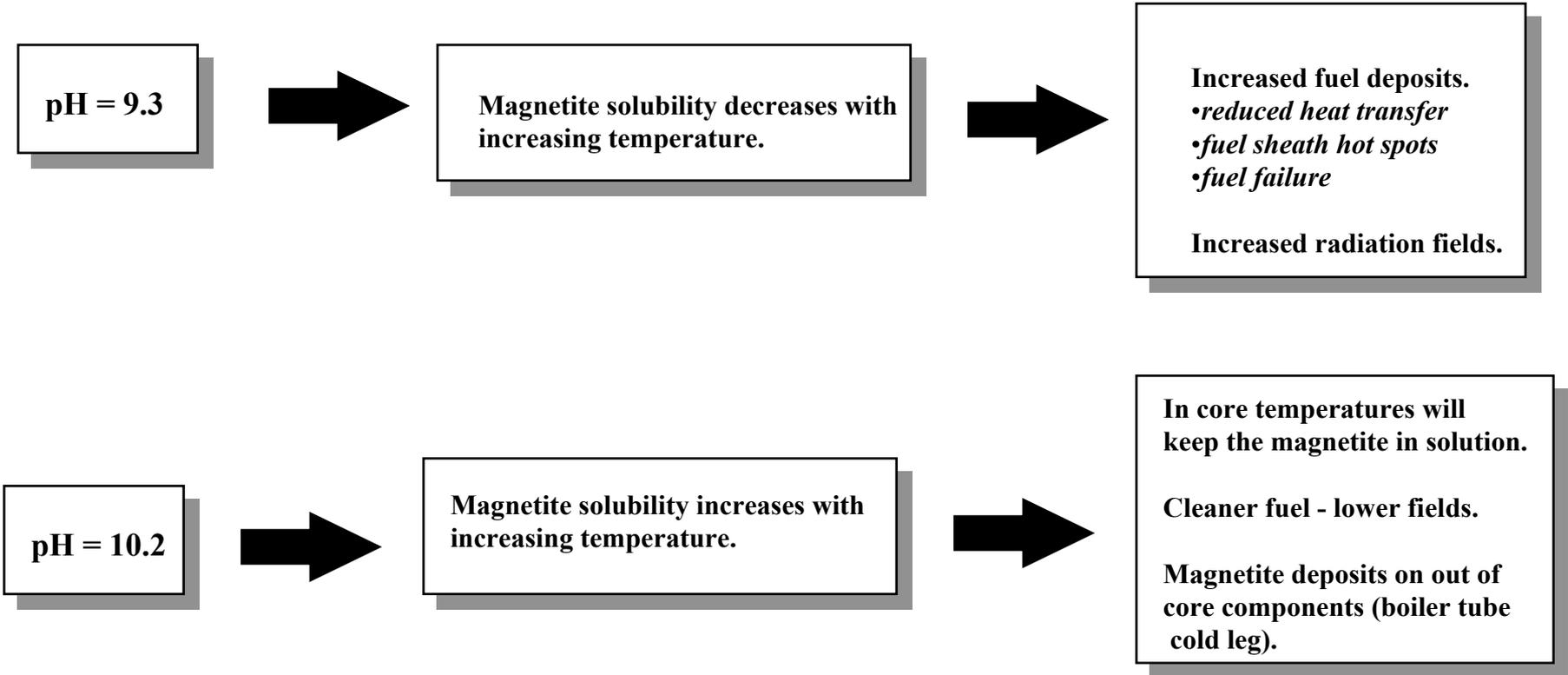- Characteristic pH where solubility is minium.

EXAMPLES: Aluminum
Iron
Titanium
Zirconium

97146-221

Magnetite Solubility

Note:
(1) All curves are generated at 18 cc/kg H_2O dissolved hydrogen
(2) ppb Fe = 55 x μ mol Fe

Overhead 76
AECB Conventional/Nuclear General

Effect of pH on Magnetite Solubility

pH = 9.3 ➤ Magnetite solubility decreases with increasing temperature. ➤ Increased fuel deposits.
- *reduced heat transfer*
- *fuel sheath hot spots*
- *fuel failure*

Increased radiation fields.

pH = 10.2 ➤ Magnetite solubility increases with increasing temperature. ➤ In core temperatures will keep the magnetite in solution.

Cleaner fuel - lower fields.

Magnetite deposits on out of core components (boiler tube cold leg).

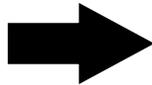# Effect of pH on Fuel Deposits & Radiation Fields

Results from AECL Loop Tests
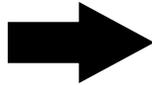
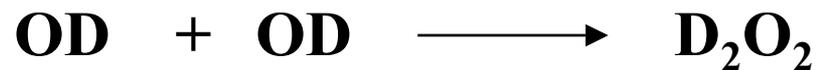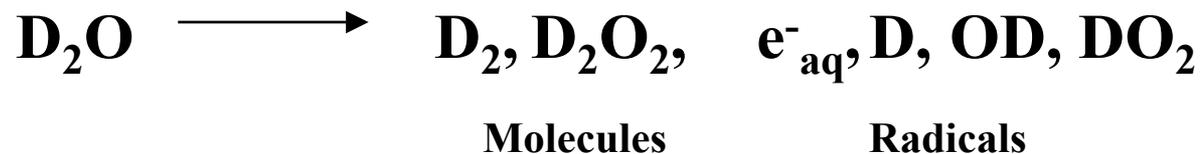| pH 9.3 to 9.7 | ➡ | Increased fuel deposits compared to operating at pH 10.3 |

| pH = 7.3 | ➡ | Heavy fuel deposits |

pH = 10.0 resulted in 40% higher radiation fields than at pH 10.5

pH = 11.0 - Radiation fields were approx. 70% lower compared to pH 10.5

Dissolved Oxygen

- **Current Specification**   **<10 ug/Kg**

- **Sources**
  - Radiolysis of the D_2O
  - D_2O Makeup

- **Concerns**
  - Localized & General corrosion of zirconium pressure tubes and steam generator tubes.
  - Corrosion of the carbon steel piping - loss of magnetite (conversion to hematite) - higher crud levels - increased radiation fields.

Oxygen Production by Radiolysis

$$D_2O \longrightarrow D_2, D_2O_2, \quad e^-_{aq}, D, OD, DO_2$$

Molecules   Radicals

$$OD + OD \longrightarrow D_2O_2$$

$$D_2O_2 \longrightarrow D_2O + \tfrac{1}{2} O_2$$

Oxygen Suppression by Hydrogen Addition

$$OD \ + \ D_2 \ \longrightarrow \ D_2O \ + \ D \qquad (1)$$

$$D \ + \ D_2O_2 \ \longrightarrow \ D_2O \ + \ OD \qquad (2)$$

The rate of reaction 1 increases with increasing temperature. The reaction rate is @ 200 times faster at reactor temperatures compared to room temperature.

Hydrogen Addition for Oxygen Suppression

- ## Current Specification   10 to 25 ml/Kg

- ## Low Specification
    - Low Specification based on early work performed by AECL in their NRU Reactor. Studies showed that 0.3 ml/Kg hydrogen (critical hydrogen concentration) required in non-boiling coolant to suppress oxygen formation (equal to or less than 2 ppb). In boiling coolant, some of the hydrogen/deuterium is stripped into the steam phase. Thus in boiling coolants, higher concentrations of hydrogen/deuterium is required to suppress oxygen formation (3% steam quality requires 1 ml/Kg H_2. At 6% steam quality, about 1.5 ml/Kg is needed.)
    - **<u>The lower specification of 3 ml/Kg incorporates a small safety margin for dissolved deuterium concentrations</u>**

- ## High Specification
    - Hydrogen levels in excess of 25-35 ml/Kg may cause cracking of any I-600 steam generator tubes (Primary Water Stress Corrosion Cracking - PWSCC). Maintaining the hydrogen levels below 10 ml/Kg ensures that the risk of tube cracking is minimized in I-600, but is not a restraint with Monel 400 tubes.

Fuel Channel Assembly
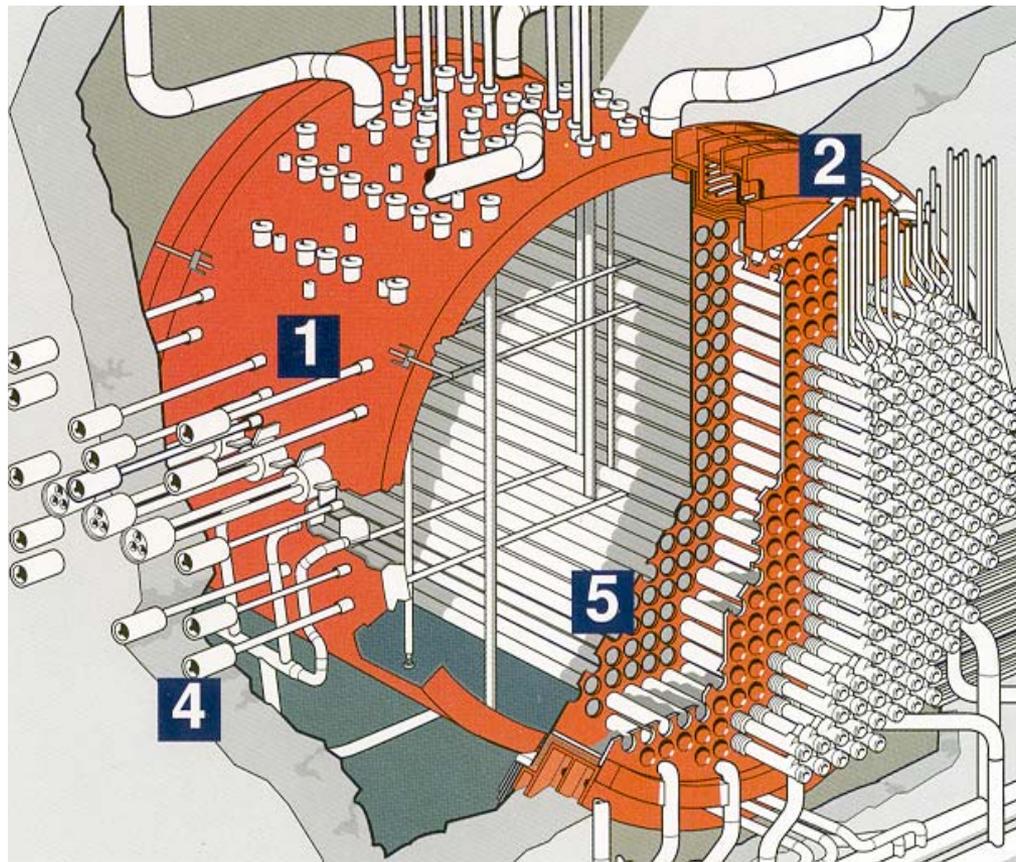
Calandria/Pressure Tube Arrangement
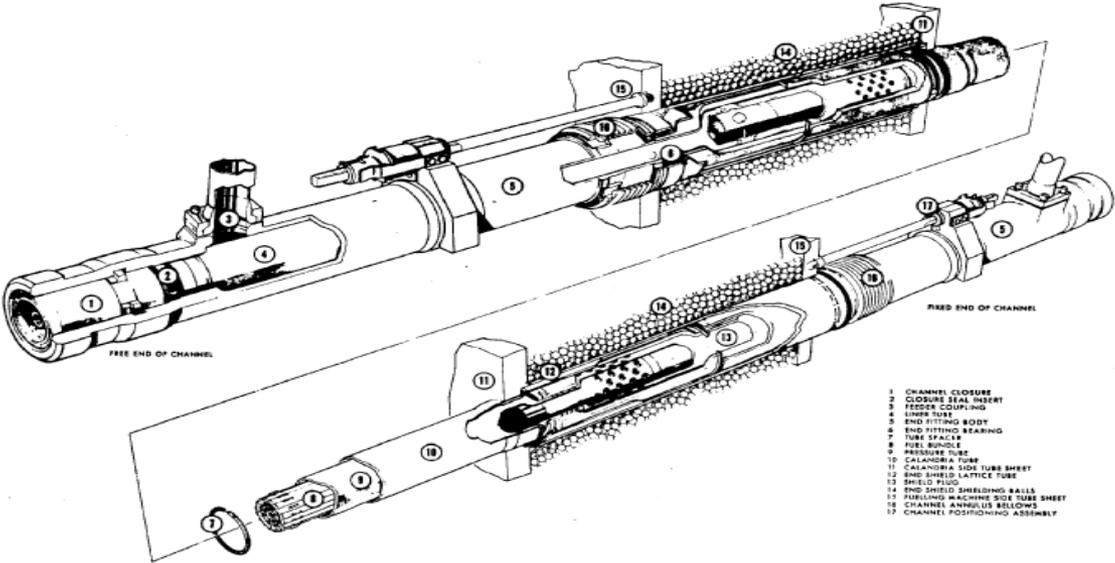
1 CHANNEL CLOSURE
2 CLOSURE SEAL INSERT
3 FEEDER COUPLING
4 LINER TUBE
5 END FITTING BODY
6 END FITTING BEARING
7 TUBE SPACER
8 FUEL BUNDLE
9 PRESSURE TUBE
10 CALANDRIA TUBE
11 CALANDRIA SIDE TUBE SHEET
12 END SHIELD LATTICE TUBE
13 SHIELD PLUG
14 END SHIELD SHIELDING BALLS
15 FUELLING MACHINE SIDE TUBE SHEET
16 CHANNEL ANNULUS BELLOWS
17 CHANNEL POSITIONING ASSEMBLY

FREE END OF CHANNEL

FIXED END OF CHANNEL

Fuel Channel Features
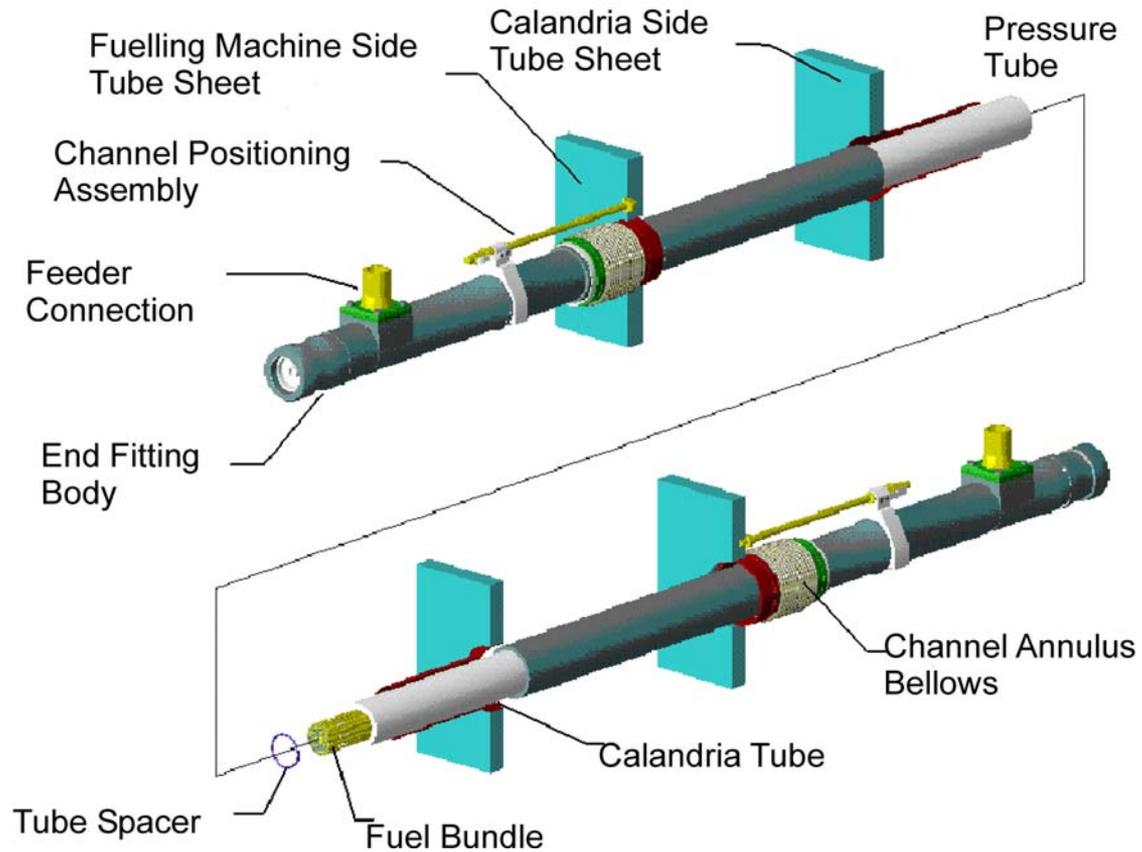
Primary Heat Transport System

CANDU 6 Fuel Bundle

Fuel Element

Fuel Pellet
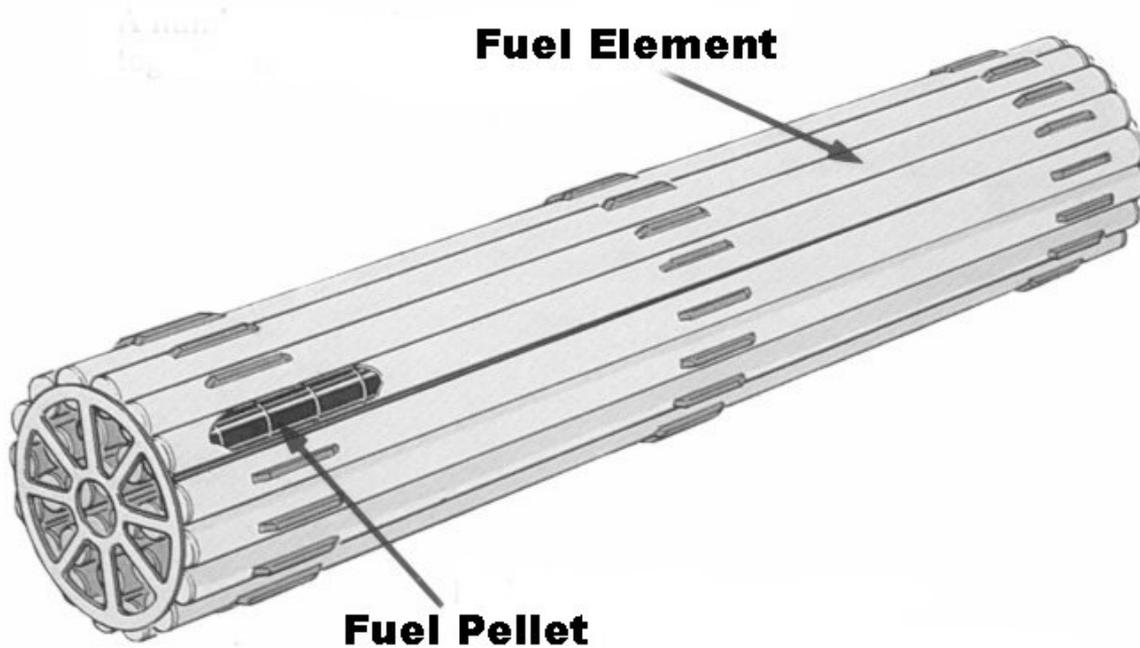
Typical Compositions of Zirconium Alloys
(wt %)

Element	Zr-2.5% Nb	Zircoloy-2
Tin	-	1.1 to 1.7
Iron	-	0.07 to 0.20
Chromium	-	0.05 to 0.15
Nickel	-	0.03 to 0.08
Niobium	2.4 to 2.8	-
Oxygen	900 to 1300 ppm	1400 ppm max.
Zirconium	Balance	Balance

Note :   *AECL Specification for Fr, Cr & Ni in Zr-2.5% Nb pressure tubes is:*

Fe - 1500 mg/g max.   *Ni - 70 mg/g max.*
Cr - 200 mg/g max.

Corrosion of Zirconium Alloys

$$Zr + H_2O \text{ (or } D_2O) \longrightarrow ZrO_2 + 2H_2 \text{ (}2D_2\text{)}$$

A percentage of the H_2 (D_2) generated by the above reaction is picked up or absorbed by the zirconium metal. The amount of H_2 (D_2) picked up will depend upon the composition of the zirconium alloy.

Alloy	%H_2/D_2 Pickup
Zr-2	50%
Zr-2.5% Nb	<5%

Corrosion of Zirconium Alloys

Zr-4

The rate of hydrogen/deuterium pickup by zirconium alloys is directly related to the composition of the alloy.

The presence of nickel in the alloy will affect the H_2/D_2 pickup rate. The higher the nickel content, the greater will be the H_2/D_2 pickup rate.

The reduction of nickel in zirconium alloys has resulted in alloys with much lower H_2/D_2 pickup rates.

Zr-4 is basically a low nickel version of the Zr-2 alloy

Note: Zr-2 is used for calandria tubes; Zr-4 for fuel sheath

Pressure Tube Deuterium Pickup From Corrosion

Zr-2 & Zr-2.5% Nb Pressure Tubes
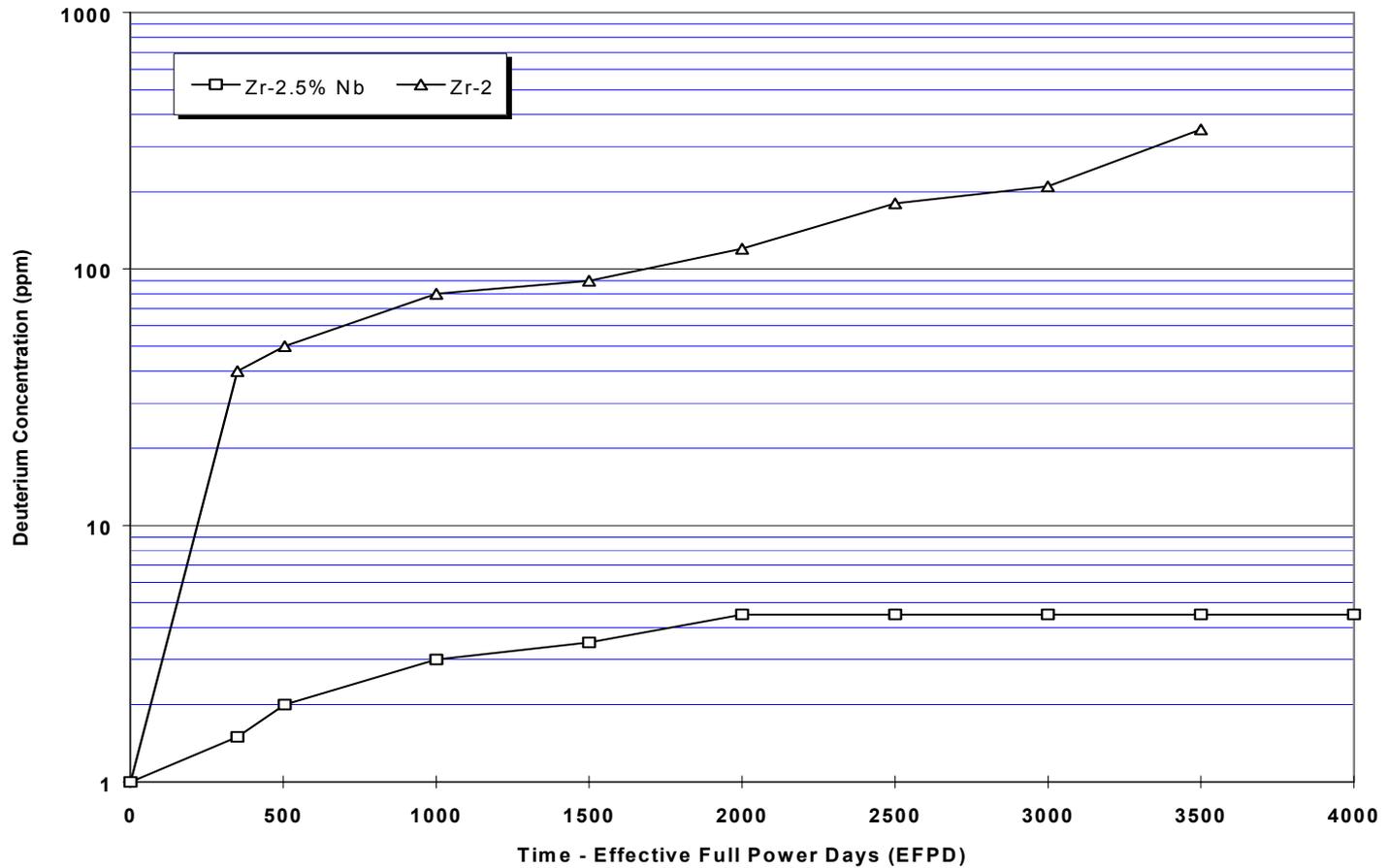
Oxidation of Pressure Tubes

Zr-2 & Zr-2.5% Nb Pressure Tubes

Effect of Temperature on the Solubility of Hydrogen in Zr-2.5 wt% Nb

Hydrogen in Solution

Hydrides Present

Temperature C

Hydrogen Concentration ppm
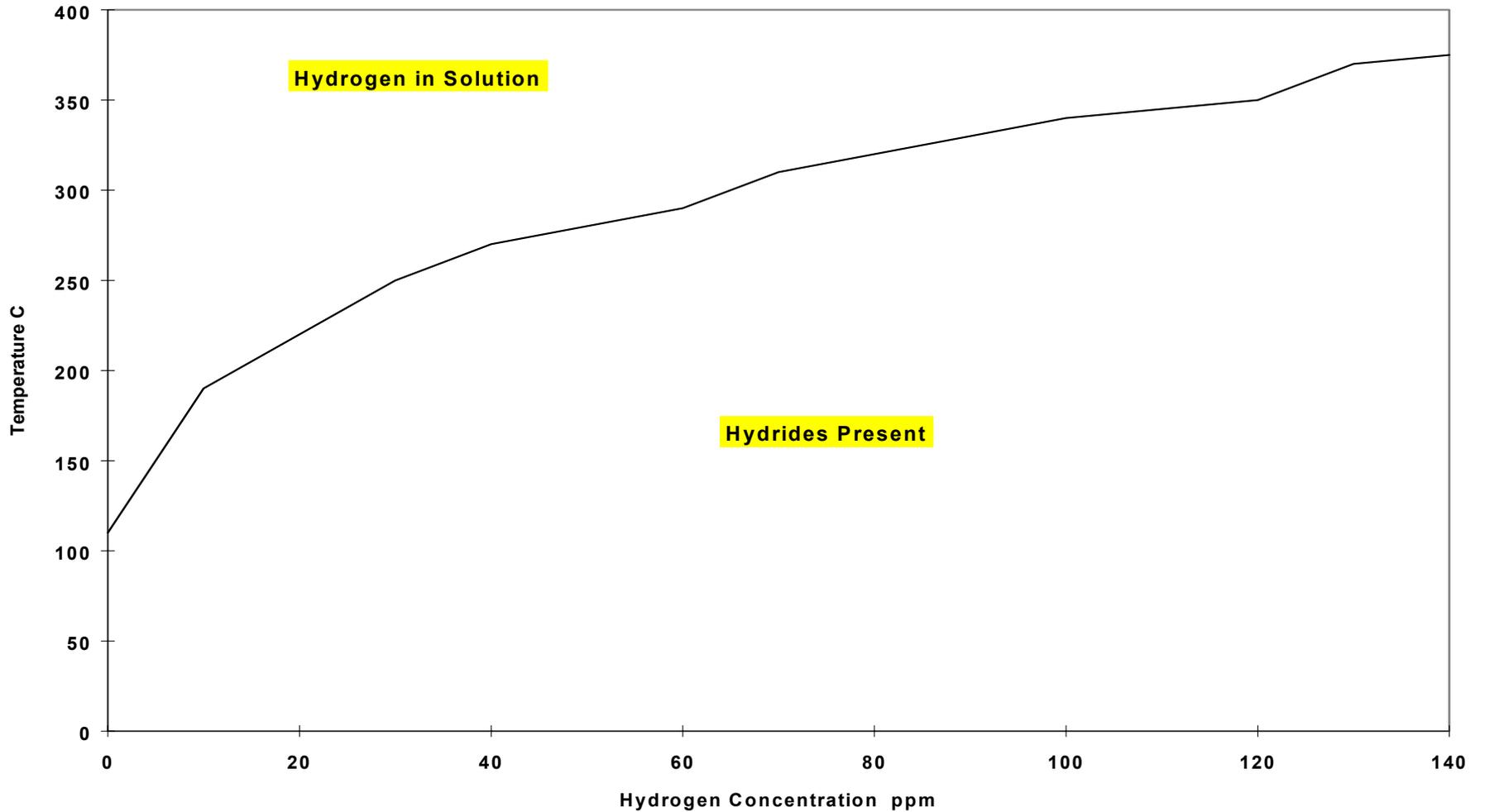
Pressure Tube Operating Experience

- ## Hydrogen Pickup
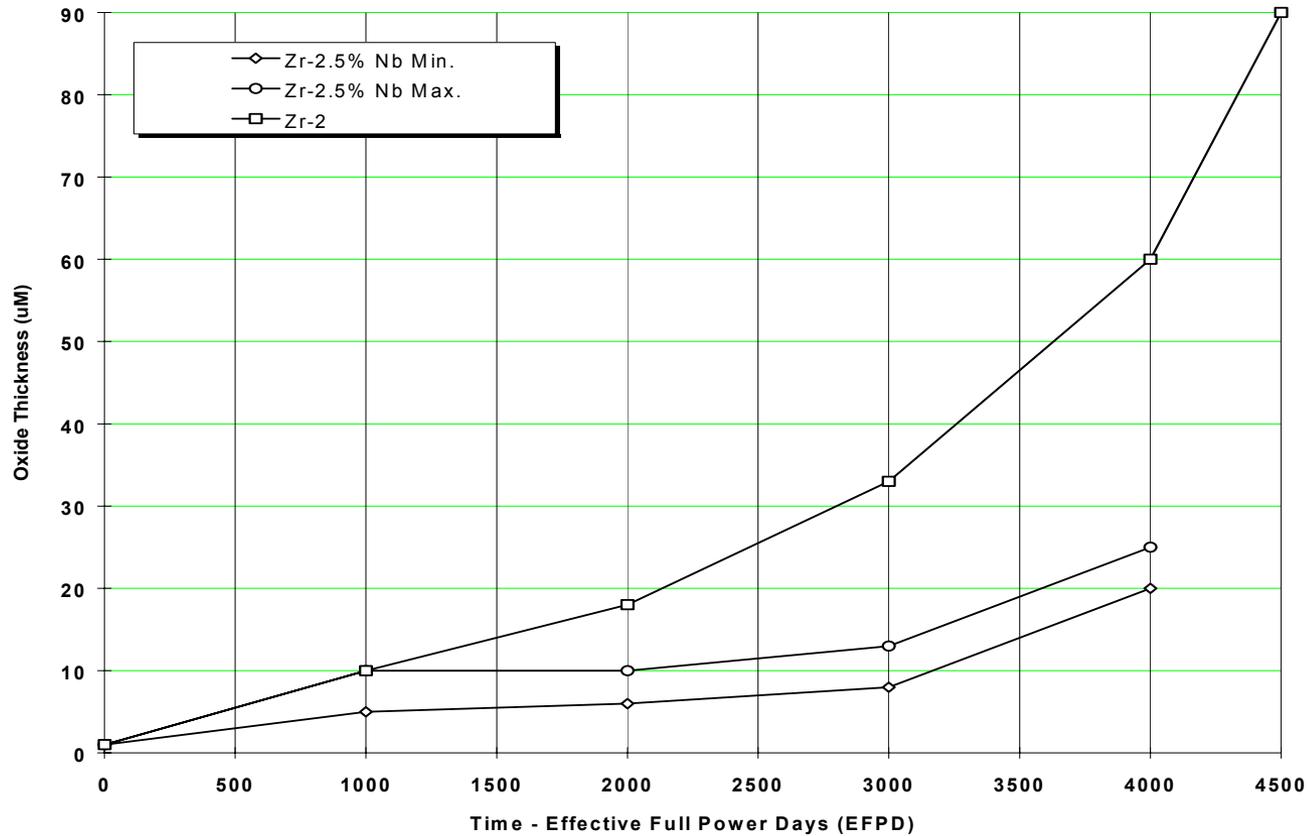 - Oxidation of the zirconium alloy surface in the presence of water results in the evolution of hydrogen (deuterium). The hydrogen released is very soluble in the Zr metal matrix where it tends to accumulate. Zr-2.5% Nd alloy demonstrates reduced rates of oxide growth and thus reduced pickup of hydrogen (deuterium) as compared to Zr-2.

- ## Delayed Hydrogen Cracking
  - Accumulation of hydrogen to the concentrations in the range of 20 to 50 ug per gram of Zr results in the precipitation of a zirconium-hydride (ZrH_2). These hydrides can cause the metal to crack under large tensile stresses (thermal cycling).

Pressure Tube Operating Experience

- ## Blisters

  - At very large concentrations of hydrogen (about 350 ug/g Zr), blisters of ZrH_2 may form. When these blisters reach a critical size, cracks appear in the metal. One of the causes of the pressure tube failure (P2 G16) at Pickering Unit 2. Blister formation is accelerated when the pressure tube is allowed to come in contact with the calandria tube.

- ## Creep & Growth

  - Volumetric expansion of the pressure tubes will occur during warnup to operating range of 256 to 310°C, and from pressurizing the coolant inside the tubes to 10 MPa. In addition, prolonged exposure of the Zr-Nb material to neutron and gamma radiation results in a continuous additional expansion of the tube (less than 2.5% over 30 years). Recovery of the thermal and pressure effects will occur following reactor shutdown. Expansion due to radiation exposure will remain.

Pressure Tube Failures

Factors leading to the failure of the Pickering Unit 2 G16 Pressure Tube

- **Garder springs not in their design location.**

- **resultant contact between the pressure tube and calandria tube due to creep sag.**

- **high deuterium content in the pressure tube combined with the pressure tube to calandria tube contact led to the formation of hydride blisters, and the eventual cracking of the pressure tube material as a result of the stresses from blister growth.**

Pressure Tube Failures

Conditions required for Delayed Hydride Cracking to occur

- **Hydrogen (deuterium) must be in the form of a hydride (i.e., if the hydrogen is all in solution, cracking will not occur).**

- **Sufficient stress must be present.**

- **There must be sufficient time for the above two conditions to occur. Initiation is enhanced by temperature cycling under stress.**

- **Time is needed for cracking to proceed once it has been initiated.**

Preventing Pressure Tube Failures

- **Use Zr-2.5% Nb pressure tubes instead of Zr-2 (used in older reactors).** This alloy displays a reduced tendency for oxidation and thus hydrogen/deuterium pickup (50% less than Zr-2).

- **Increase the number of garder springs from 2 garder springs per channel to 4 garder springs per channel.** Better support along the length of the pressure tube.

- **Maintain reducing chemistry conditions.** Maintain dissolved oxygen as low as possible by keeping a minimum of 3 ml/Kg of dissolved deuterium in the water.

- **Maintain an oxide layer on the outside of the pressure tubes.** Trace amounts of oxygen in the annulus gas system are sufficient to maintain this oxide layer.

Primary Heat Transport

Crud

<u>Concerns</u>

- **Increased deposits in core.**
  - activation of crud - increased radiation fields
  - deposits on fuel - decreased heat transfer - fuel failures.

- **Increased Deposits out-of-core.**
  - increased radiation fields on out-of-core components
  - Deposition of crud on the inside of the Steam Generator tubes - reduced heat transfer - increased RIHT temperatures.

Primary Heat Transport

Crud

- Main corrosion product in the HTS is magnetite.

- Co-60 the main contributor to radiation fields on out-of-core piping and components. The Co-60 is in the magnetite. Transport of Co-60 is influenced by solubility and corrosion of iron in the system.

- Main method of reducing radiation fields is to reduce magnetite deposition in the reactor core.

- Deposition of magnetite in the reactor core is influenced by temperature and coolant pH.

Primary Heat Transport

Crud

Reducing System Crud & Radiation Fields

- Elimination of cobalt from materials of construction in the Primary Heat Transport System.

- Maintain proper system chemistry to reduce magnetite deposition in the reactor core. High pH and low dissolved oxygen required.

Primary Heat Transport

Comparison of Loop 1 & Loop 2 Crud Analysis at Point Lepreau
January 1, 1994
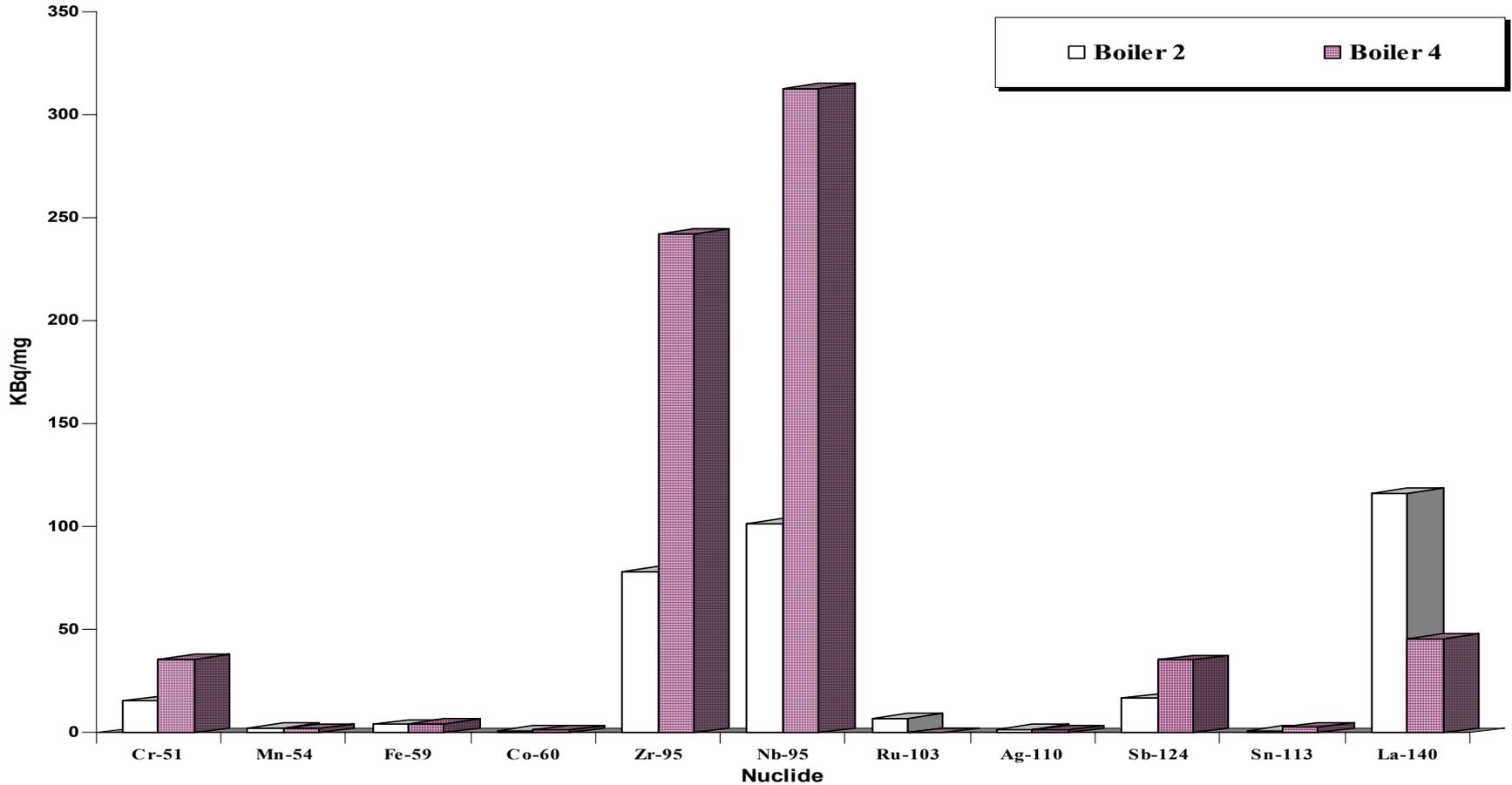
Primary Heat Transport

Comparison of Loop 1 & Loop 2 Crud Analysis at Point Lepreau
November 7, 1994
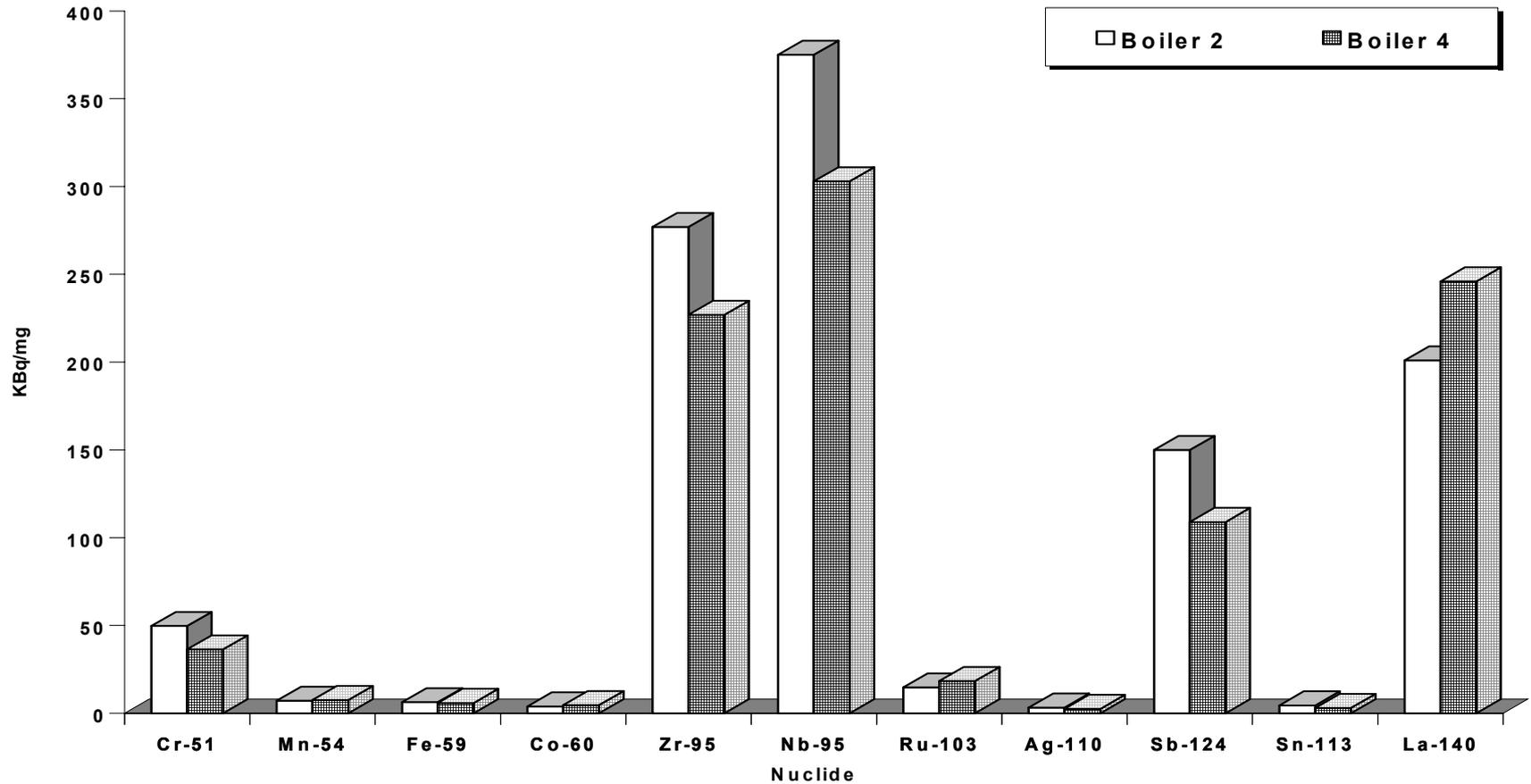
Chloride

Main Concern

- Stress Corrosion Cracking of Stainless Steel and Nickel based alloys. Examples include fuel channel end fittings, closure plugs, steam generator tubes.

- Pitting & General corrosion of carbon steel. This can occur in areas of low flow such as crevices where chloride can concentrate. Not as big of a concern as in the Secondary Side due to the fact that there are fewer crevices and low flow areas in the HTS.

- The presence of oxygen, greatly increases the effects of chloride in the system.

Iodine-131

- Radiodines (I-131) levels are controlled in the HTS to a limiting value to minimize the radiation dose received by plant staff and the population in the event of an accident - loss of coolant accident.

- Part of the Station Operating License - OP & P. Shutdown limit of 500 MBq/Kg.

- There are no chemistry or corrosion issues related to I-131 in the HTS because the chemical concentrations are extremely low. For example, 500 MBq/Kg corresponds to a concentration of about 0.12 ug/Kg (ppb).

Heat Transport Purification System

<u>System Purpose</u>

- **To minimize the build-up of activated corrosion products on PHTS components which are outside the core.**

- **To control the concentration of fission products, iodine in particular, released from fuel defects.**

- **To assist in controlling the coolant pH and coolant chemistry.**

- **To provide a source of clean water for Heat Transport bleed requirements.**

Heat Transport Purification System

<u>Major Components</u>

- **Purification Intercoolers (2)**

- **Purification Cooler**

- **Filters (2)**

- **Ion Exchange Vessels (2)**

Heat Transport Purification in CANDU 6

To Pump 1

To Pump 3

From Pump 1

From Pump 3

HX 1

HX 3

HX 2

To RCW

From RCW

IX 1   IX 2

HCV 5

To Pressure & Inventory Control Bleed Valves
(Bleed Path from HTS)

FR1   FR2
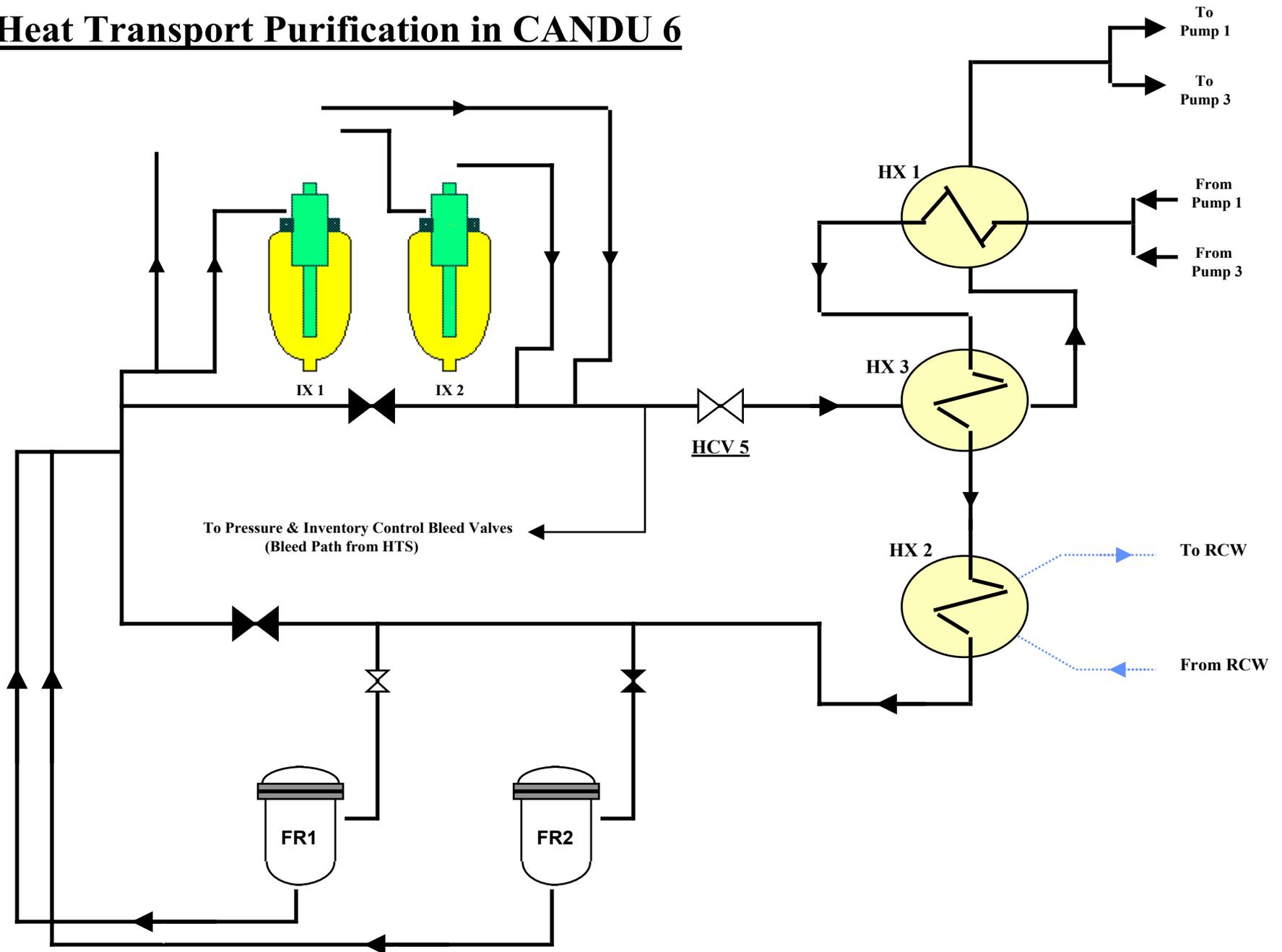
Heat Transport Purification System

Purification Intercoolers - HX1 & HX3

- *D_2O leaving the HTS flows through the tube side of each of the Intercoolers and is cooled by colder D_2O returning to the HTS. Cools water entering the purification System and also heats it back up again prior to re-entering the main system.*

HXI Conditions

Tube Side		Shell Side	
Inlet Temperature	265°C	Inlet Temperature	159°C
Outlet Temperature	194°C	Outlet Temperature	240°C

HX3 Conditions

Tube Side		Shell Side	
Inlet Temperature	194°C	Inlet Temperature	65°C
Outlet Temperature	103°C	Outlet Temperature	159°C

Heat Transport Purification System

Purification Cooler - HX2

- **Cools the D_2O leaving the Interchangers (HX3) to 65ºC. Water must be cooled to this temperature in order to prevent resin damage.**

- **RCW supplied to the shell side of the HX. Temperature adjusted by regulating the RCW flow.**

- **Purification is isolated if HX2 outlet temperature reaches 85ºC.**

Heat Transport Purification System

Filters -FR1 & FR2

- **Removes insoluble matter (crud) from the D_2O before it enters the Ion Exchange columns.**

- **Nominal Filter Rating - 5 uM**

- **Normal operation has one filter in service and the other on stand-by.**

Heat Transport Purification System

<u>Ion Exchange Vessels - IX1 & IX2</u>

- **Two carbon steel vessels.**

- **Each vessel contains 1080 liters of mixed bed ion exchange resin (cation resin Li^+ based).**

- **Normal operation is with both vessels in service.**

- **Normal purification flow rate is 24 Kg/sec (maximum flow).**

Heat Transport Purification System

Design Criteria

- Original design of the HTS Purification System was based on minimizing the build-up of activated corrosion products on HTS components outside the core (reducing out or core radiation fields).

- Crud activated in-core will re-deposit on out of core components.

- If the purification system is to reduce activity build-up, its clean-up half time must be equal to the crud re-deposition half-time.

Heat Transport Purification System

Design Criteria

- **Original design of the HTS Purification System (CANDU 600) was based on experience at Douglas Point (had the most EFPD's). Crud deposition studies were conducted at this plant and the crud deposition half-time determined to be 8-12 minutes.**

- **Based on the above deposition half-time, purification flows of 70.7 Kg/sec are required ($T_{1/2}$ = 0.34 hours).**

- **The design of the Purification System on future CANDU 600 Stations was based on this experience at Douglas Point.**

Heat Transport Purification System

Design Criteria

- Later experience at Pickering "A" and Bruce "A" indicated that radiation fields (from activated corrosion products & fission products) were kept under control with purification half-lives between 2 to 3 hours.

- On this basis, the recommended purification half-life for CANDU 600 Plants is one hour. This corresponds to a purification flow rate of 24 Kg/sec.

- Purification flow rate should normally be operated at 24 Kg/sec (maximum flow rate). This will ensure low crud levels & radiation fields throughout the system.

CANDU 6 - Primary Heat Transport System
Purification Half Time as a function of Purification Flow Rate
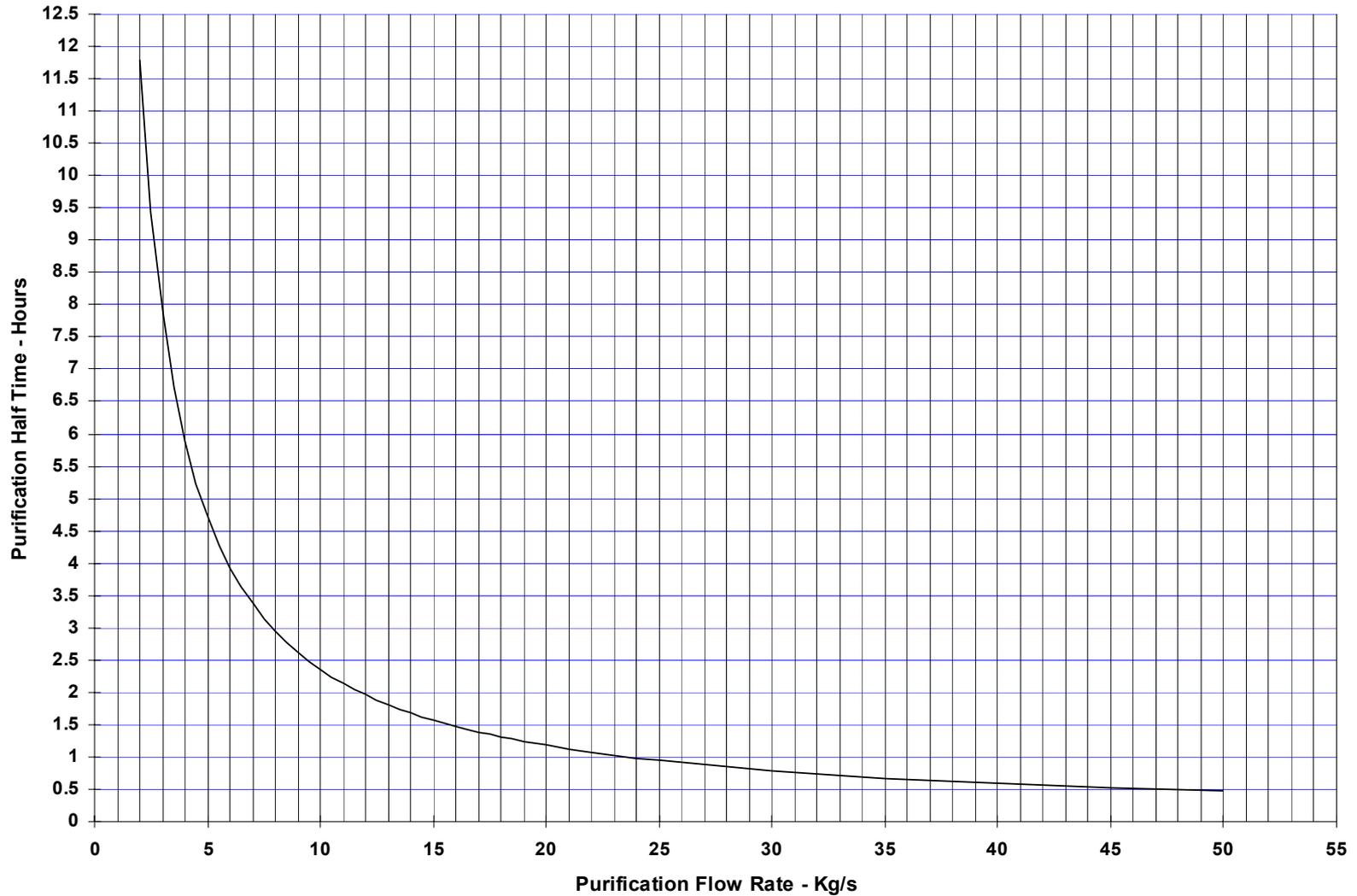
Primary Heat Transport System

Storage Tank Cover Gas

Parameter	High Specification	Upper Control Limit
D_2	4.0%	2.0%
O_2	1.0%	0.5%
N_2	6.0%	4.0%

Primary Heat Transport System

Storage Tank Cover Gas

Deuterium

- **Sources**
  - Dissolved Deuterium is produced from the radiolytic decomposition of D_2O.
  - System Corrosion.
  - Addition of Hydrogen to the Main System for dissolved oxygen control.

  - D_2O from the main system exchanges with the D_2O in the storage tank. Dissolved D_2 transfers from the water into the storage tank Helium Cover Gas. The reduction in pressure in going from the main system to the storage tank decreases the solubility of the dissolved deuterium thus increasing the degassing process.

Primary Heat Transport System

Storage Tank Cover Gas

Deuterium

- **Upper Control Limit**
  - Derived from the flammability limits for hydrogen/helium/oxygen mixtures and is set at 2% providing a safety factor of four below the lower flammability limit of 8%.

- **Specification**
  - Probability of an explosion occuring in the Storage Tank is much lower than in the Moderator Cover Gas since there are no recombiners or compressors - the main potential ignition sources. Specification set at 4% providing a safety factor of two below the flammability limit.

  - *There is no shut down specification associated with Storage Tank %D_2 (as compared to the Moderator Cover Gas). This is because shutdown does not immediately reduce the production of deuterium (as in the moderator) and also due to the lack of ignition sources.*

Primary Heat Transport System

Storage Tank Cover Gas

Oxygen

- **Sources**
  - Primarily from air in-leakage into the storage tank.

- **Specification**
  - Set at 1%. Ensures that the concentration required to create a flammable mixture is not reached (4% needed given enough hydrogen). The 1% limit provides a large safety factor.
  - The limit of 0.5% minimizes oxygen mass transfer from the gas into the liquid. Increases in the dissolved oxygen content of the storage tank D_2O and indirectly the main system through mixing are minimized.

Primary Heat Transport System

Storage Tank Cover Gas

Nitrogen

- **Sources**
  - Primarily from air in-leakage into the storage tank.

- **Specification**
  - Nitrogen can result in the production of nitrogen oxides by radiolysis which can then react with water producing nitric acid.
  - High levels of nitric acid increase the load on the heat transport ion exchange columns.

Chemistry Monitoring Requirements

Prior to Shutdown

- Collect PHT Cruds. Install new filters.

- Analyze both loops & IX columns for pH, Cond, Li, γ scans.

- Analyze Main System for D_2O, H-3 & Diss D_2.

- Storage Tank for D_2, O_2 & N_2

During Run Down

- γ scans at 60% F.P. additional scans if fuel defects detected.

- γ scans at 0% Power.

- Storage Tank for D_2, O_2 & N_2

Unit Outage

- Remove crud filters

  Install new Filters

- Valve orbispheres out of service. Calibrations

- Storage Tank Cover gas D_2, O_2 & N_2 once per day. Request purges as required.

Chemistry Monitoring Requirements

Pre Run-up

- **Valve in crud filters**

  Valve in orbisphers

- **Analyze both loops & IX columns for pH, Cond, Li, Cl, γ scans.**

- **Analyze Main System for D_2O & Diss D_2.**

- **Storage Tank for D_2, O_2 & N_2**

During Run-up

- **γ scans at Hold Points Both loops.**

- **Analyze both loops & IX columns for pH, Cond, Li & Cl 1/Shift**

- **Storage Tank Cover gas D_2, O_2 & N_2 1/shift.**

- **Analyze Main System for D_2O & Diss D_2 1/shift.**

Unit 100% F.P.

- **Analyze both loops & IX columns for pH, Cond, Li, Cl, γ scans & crud.**

- **Analyze Main System for D_2O, Diss D_2 & H-3**

- **Storage Tank for D_2, O_2 & N_2**

Primary Heat Transport System

Typical Activation Products

NUCLIDE	HALF-LIFE	MAJOR SOURCE
H-3	12.26 years	D_2O
N-16	7.1 seconds	D_2O
N-17	4.2 seconds	D_2O
O-19	29 seconds	D_2O
Ar-41	1.83 hours	Air ingress
Cr-51	27.8 days	Steel & Incoloy
Mn-54	312 days	Steel & Incoloy
Fe-59	45 days	Steel & Incoloy
Co-58	71 days	Nickel Alloys
Co-60	5.24 years	Steel & Incoloy
Zr-95	65 days	Zircoly
Sb-124	60 days	Carbon Steel

Heat Transport Standard Operating Conditions

SYSTEM	PARAMETER	SPECIFICATION	DESIRED VALUE	CONTROL METHOD
Main HTS	pH	* 10.3 - 10.7	10.3 - 10.5	LiOO IX resins
	Dissolved D_2	* 3-10 cc/kg	7	H_2 addition
	Cl⁻	< 0.2 mg/kg	* ALARA	IX resins. Bleed cooler temperature over-ride
	I-131	(1)	* ALARA	IX resins. Removing defective fuel.
HTS Storage Tank Cover Gas	D_2, O_2, N_2	$D_2 \leq 2\%$ $O_2 \leq 2\%$ $N_2 \leq 8\%$	ALARA	Purging with Helium.

(1) Pickering is required to shut a unit down if an inventory of 1000 curies is reached. At the Bruce and Darlington stations, the shutdown limit is ≥ 500 curies for ≥ 8 hours.

Overhead 78
AECB Conventional/Nuclear General

Primary Heat Transport System

Fission of U^{235}

Cs^{131}

$In^{131} \rightarrow Sn^{131} \rightarrow Sb^{131} \rightarrow Te^{131} \xrightarrow[25 \text{ min.}]{\beta^-, \ \gamma} I^{131} \xrightarrow[8 \text{ days}]{\beta^-, \ \gamma} Xe^{131}$

$In^{133} \rightarrow Sn^{133} \rightarrow Sb^{133} \rightarrow Te^{133} \rightarrow I^{133} \xrightarrow[21 \text{ hours}]{\beta^-, \ \gamma} Xe^{133}$

$Xe^{133} \xrightarrow[5.4 \text{ days}]{\beta^-, \ \gamma} Cs^{133}$

U^{235}

$n \ + \ n \ + \ \gamma$

$Sb^{135} \rightarrow Te^{135} \rightarrow I^{135} \xrightarrow[7 \text{ hours}]{\beta^-, \ \gamma} Xe^{135} \xrightarrow[9 \text{ hours}]{\beta^-, \ \gamma} Cs^{135}$

$Se^{88} \rightarrow Br^{88} \xrightarrow[6.4 \text{ sec.}]{\gamma} Kr^{88} \xrightarrow[3 \text{ hours}]{\beta^-, \ \gamma} Rb^{88} \rightarrow Sr^{88}$
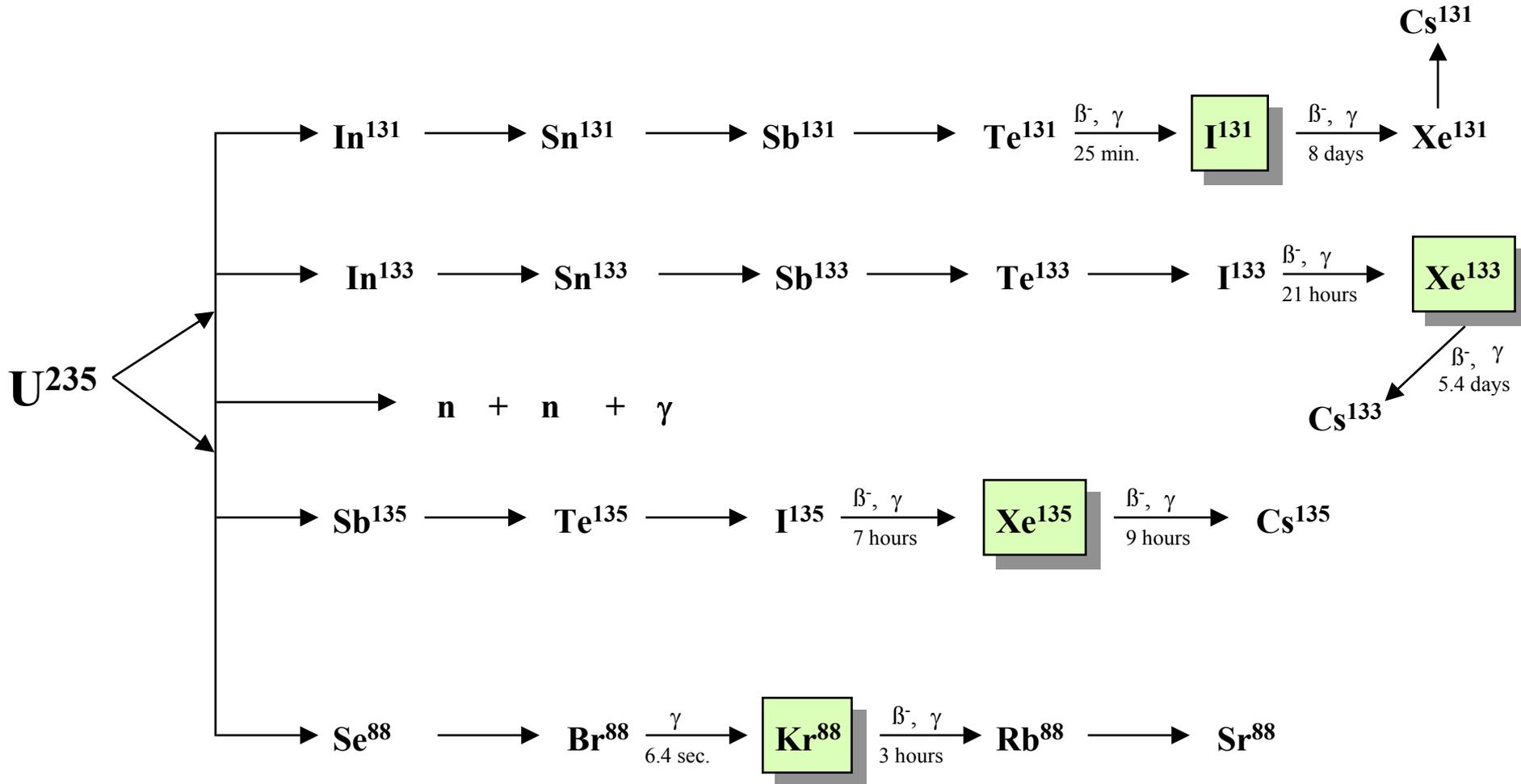
Primary Heat Transport System

Sources of Fission Products

- ## Uranium Contamination

  - Uranium contamination in the fuel cladding and other zirconium structural materials in the core. Total approximate uranium contamination present 3.5 mg/kg (Tramp Uranium).

- ## Fuel Failures

  - Penetration of the fuel bundle cladding.

Primary Heat Transport System

Control of Fission Products

- **Location of failed fuel bundles in the core**
    - Gaseous Fission Product Monitor
    - Delayed Neutron Monitor

- **Removal of soluble ionic fission products by the HTS Purification System**
    - Iodine's and Cesium

- **Removal of fission product gases by degassing the HTS**
    - Noble Gases - Xenon, Krypton
    - Abnormal mode of operation

Primary Heat Transport System

Failed Fuel Detection & Location Systems

- ## Detection Using:

  - ### Gaseous Fission Product Monitor on-line

- ## Location Using:

  - ### Delayed Neutron Monitoring

Primary Heat Transport System

Gaseous Fission Product Monitor

- **The Gaseous Fission Product Monitor (GFP) is a computer controlled, high resolution gamma ray spectrometer. It operates continuously and measures Xe-133, Kr-88, Xe-135 and I-131 present in continuous sample flows from each of the two Heat Transport loops.**

- **The relative concentrations of the various nuclides will indicate the presence of failed fuel as well as give information on the size of the defect.**

Primary Heat Transport System

Fuel Failures

- **Main indicator of a fuel failure is an increase in the Xe-133 concentration.**

  – Normal Xe-133 levels in the HTS coolant are 1-2 MBq/Kg (core free from fuel defects).

  – When a small leak develops, an increase in Xe-133 & Kr-88 will be observed (Xe-133 will increase the most).

  – Confirmation of a defective fuel bundle can be done by comparing the ratio of Xe-133 to Kr-88. A ratio of > 10 would confirm the presence of a leak.

$$\frac{\text{Xe-133}}{\text{Kr-88}} \quad > 10 \quad \Longrightarrow \quad \text{Fuel Failure}$$

Primary Heat Transport System

Half-Lives of nuclides monitored by the GFP

- **Xe-133**   **5.4 days**

- **Xe-135**   **7 hours**

- **Kr-88**   **3 hours**

- **I-131**   **8 days**

Primary Heat Transport System

Fuel Failures

- **No Leaks**

    - Fission products are contained within the fuel sheath.

- **Small leak**

    - Fission product gases are allowed to escape from the small hole in the fuel sheathing and enter the coolant. Water must enter the fuel sheath in order to permit Iodine release. Water is needed to dissolve the iodine's and make them available for release. Very little water will enter the fuel sheath with small defects, thus very little increase in I-131 concentrations will be observed.

- **Large Leak**

    - Coolant can enter the fuel element dissolving the iodine's in the process. This type of failure will result in large increases in coolant iodine's & fission gas concentrations.

Primary Heat Transport System

Types of Fuel Failures

- **Type 1**

    - A pinhole defect in new fuel. Results in xenon & krypton releases. Low iodine releases.

- **Type 2**

    - A pinhole defect in fuel at one-half burnup. Results in release rates about 2.5 times higher than Type 1. Fission products are in the same ratio as in a Type 1 leak (high xenon & krypton - low iodine's).

- **Type 3**

    - A small crack in the fuel cladding at one-half burnup. Results in similar Xe-133 release rates as a Type 2. Much higher Kr-88 and especially I-131 release rates. Thus the main indicator is the isotopic proportions.

Primary Heat Transport System

Gaseous Fission Product Monitor

- **Xe-133**
    - Long lived fission product (5.4 day half-life). It has a high release rate from defective fuel.
    - Its concentration when compared to the short lived fission gas - Kr-88, provides information about the source, the extent of fuel sheath damage and the buildup of Tramp uranium in the core. Main indicator of failed fuel.

- **Kr-88**
    - High release rate from fuel defects. Lower concentration in coolant due to its low half-life.

Primary Heat Transport System

Gaseous Fission Product Monitor

- **Xe-135**

    - Provides information about the iodine release rates when high purification rates are removing fission products. I-135 decays to Xe-135 in the IX system. The Xe-135 is not retained by the resin, it becomes a secondary source of Xe-135.

- **I-131**

    - Not a reliable indicator for assessing fuel damage due to the fact that it is removed by the purification system. Monitored for public safety reasons due to its biological hazard (OP& P limitations on its concentration in the coolant).

Primary Heat Transport System

Delayed Neutron Monitor

- Design Basis for CANDU 6
  - Based on KANUPP design
  - Uses samples extracted from outlet feeders
  - Monitors for presence of delayed neutrons

Primary Heat Transport System

Delayed Neutron Monitor

- **Used to locate the fuel channel containing the defective fuel.**

- **Locate the position of the defective fuel within the fuel channel.**

Sample lines from each of the 380 fuel channels carry coolant to the DN Rooms (RI-303 & RI-304). Each sample then flows through sample coils which are contained in cylinders called sample coil dry wells. Each of these dry wells are located in a moderator tank filled with light water. The light water is used for cooling and also to thermalize the delayed neutrons which is required for accurate detection.

Above the moderator tank is located a carriage which is used to carry and position the thermal neutron detectors (BF_3) into the sample coil dry wells.   During fuel sheath failure, I-137 & Br-87 are released into the coolant.   Both are delayed neutron emitters and will be detected by the BF_3 detectors.

Primary Heat Transport System

Delayed Neutron Monitor

Isotope	Half-Life	Source
N-17	4 seconds	Activation
N-16	7 seconds	Activation
I-137	22 seconds	Failed Fuel & Tramp Uranium
Br-87	57 seconds	Failed Fuel & Tramp Uranium

The four neutron emitting isotopes are always present in the core. N-17 & N-16 are activation products. I-137 & Br-87 are due to the presence of Tramp Uranium. Sample lines are sized as to provide a 50 second delay time before the sample reaches the detector. This is to allow for decay of the N-17 & N-16 in the sample.

During a fuel sheath failure, I-137 & Br-87 will be released into the coolant and thus their concentrations will increase above background concentrations.