

CHAPTER 10: FUEL DESIGN ANALYSIS

MODULE OBJECTIVES:

At the end of this module, you will be able to describe:

- 1. The factors affecting fuel performance**
- 2. How these factors are controlled by fueling**
- 3. The link between fuel performance and license limits**

Fuel Bundle Performance

Statistics of Fuel Bundle Performance

- **The in-service performance of CANDU fuel [its been excellent. Of the 92,593 fuel bundles irradiated up to March 1976, in nine CANDU reactors, 99.73% have performed as designed (16,17). It should be noted that these statistics are based on bundles, not defective pins, elements or rods, which, if used, would improve the statistics by an order of magnitude i.e. 0.03% defective.**
- **Of the relatively few defects that have occurred in CANDU fuel, Most Could be attributed to a single cause - sheath rupture due to a substantial power increase following a prolonged period of low power. These power increases can be caused by the movement of fuel during fuelling or by changes in flux due to nearby reactivity mechanisms. It is suggested that this behaviour will also apply to other reactors where the fuel is exposed to power changes caused by fuelling, movement of control rods and gross reactor power changes after periods at low power.**
- **This behaviour was originally indicated by analyses of the operating records from the Douglas Point reactor, and later, from the records of Pickering Unit 1.**

Defect Mechanisms

- **Laboratory and in-reactor experiments identified two mechanisms which can cause cracking of fuel cladding during power ramps.**
- **The primary mechanism is stress corrosion cracking associated with the fission product iodine at specific combinations of stress and iodine concentrations.**
- **The other mechanism is mechanical interaction of the pellet with the sheath causing tensile failure of the fuel cladding without the assistance of iodine stress corrosion cracking.**
- **It has been found that the necessary concentration of both stress and strain can be produced by the radial cracks formed by**

thermal expansion of the UO_2 at interfaces between pellets, and over small chips of UO_2 wedged between the fuel and sheath.

- **Cracks in the sheath are formed at high stress areas when there is a boost in power after a low power soak.**
- **After identifying the cause of the fuel defects, the immediate remedy at the stations was to modify the fuel management schedule to avoid power increases that led to the original defects.**
- **Since 1972 this has resulted in a marked drop in the defect rate equal to, or below the design target of 0.1%.**
- **A "zero defect" target appears to be an unwarranted expense, in view of the fact that defects can be removed from CANDU plants without shutting down.**
- **A preferred solution is designated Canlub (24, 25, 26) which incorporates a thin graphite layer between the UO_2 and the sheath.**
- **The graphite acts as a lubricant between the UO_2 and the sheath, reducing stress concentrations and possibly also acts as a barrier to the chemical attack of the Zircaloy by the iodine under these stress conditions.**

Fuel Performance Criterion

- **Analyses of fuel performance data has produced a reliable fuel performance criterion. This criterion has been successfully employed to avoid defects which can be induced by fuel management, reactivity mechanism movement, and gross reactor power increases.**

- **The four important parameters affecting the defect behaviour are:**

- 1) **Maximum element power per unit length during power change**
- 2) **Power increase**

- 3) Fuel burnup
- 4) Time at maximum power

- The proposed fuel sheath interaction model using these parameters is shown in Figure 35.

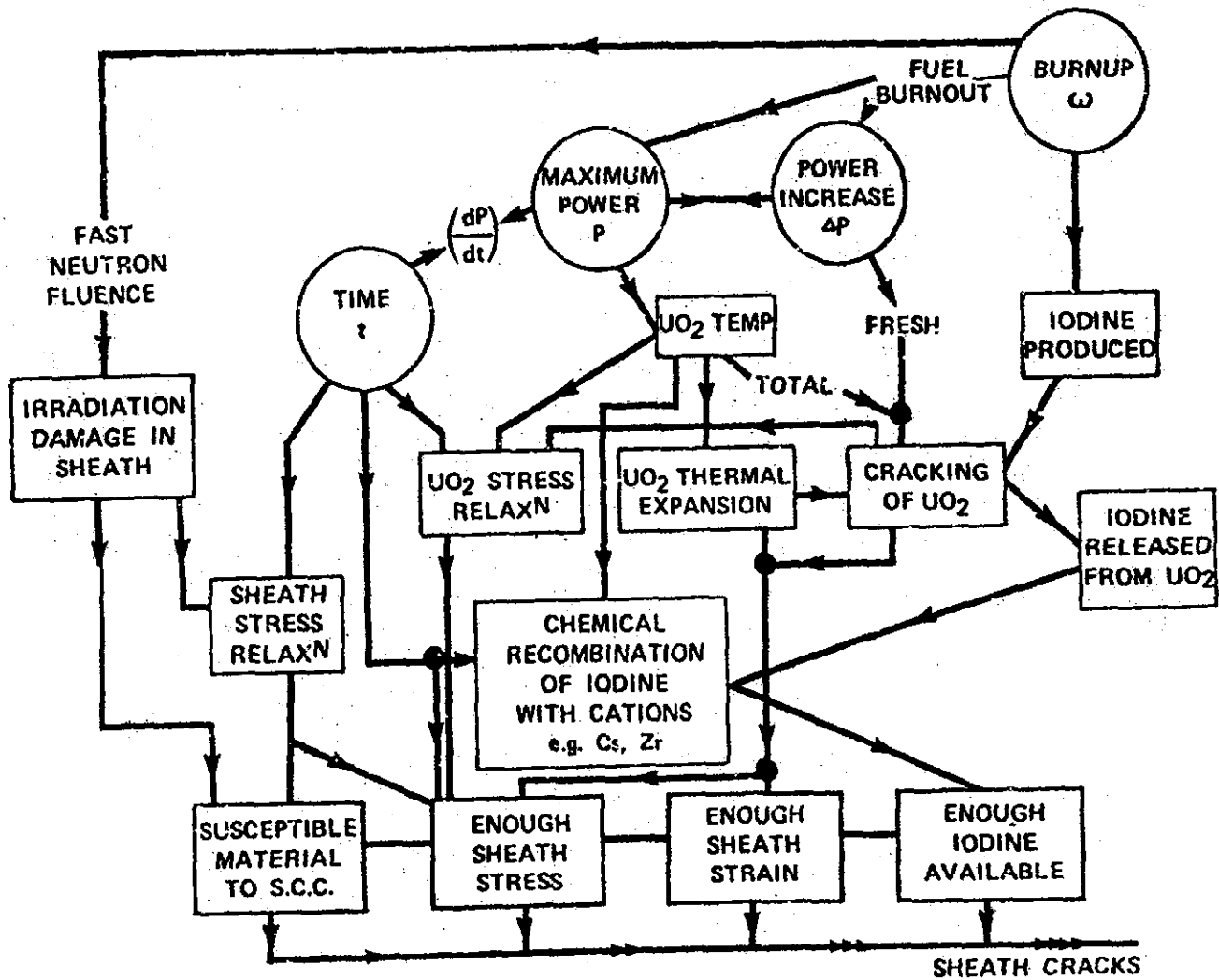


Figure 35 Stress Corrosion Cracking Model

- The fuel performance criterion is illustrated in Figure 36 in the form of a fuelogram which is a plot of element linear rating vs change in power for various element burnups. The probability of defect (at a given burnup) increases when the equations for both the maximum element power and power increase are greater than 0.

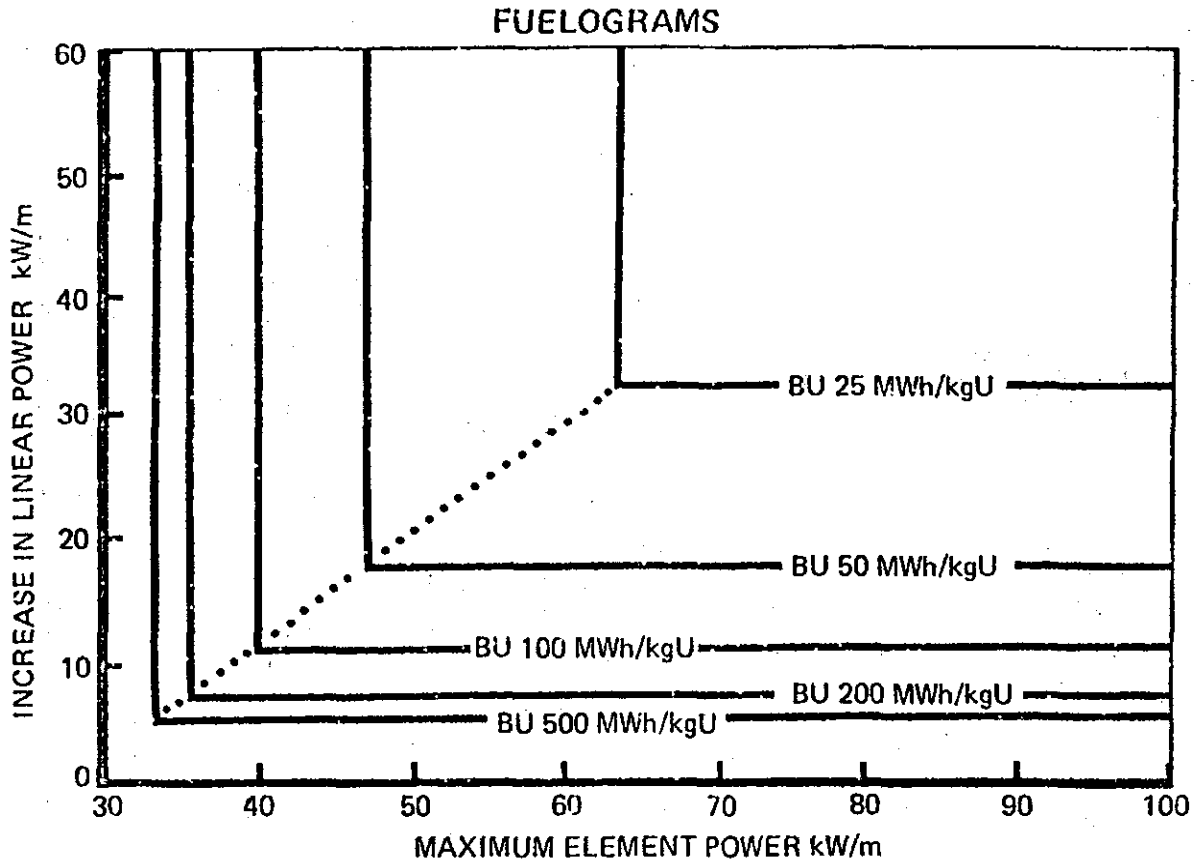


Figure 36 Fuelograms

- A long term solution is designated CANLUB: it incorporates a thin graphite layer between the UO_2 and the sheath.
- The graphite acts as a lubricant between the UO_2 and the sheath, reducing stress concentration and possibly also acts as a barrier to the chemical attack of the Zircaloy by the Iodine.
- The identification of the defects and their causes was greatly facilitated by CANDU reactor design.

- The capability of monitoring activity release from individual fuel channels allowed the incidence of failures to be correlated to reactor parameters. It was also possible to identify the defected bundle in the channel.
- The capability of on-power fuelling meant that fuel could be discharged immediately and examined before any evidence was destroyed by secondary damage.

Bundle and Element Behaviour Under Extreme Conditions

- Zircaloy clad UO_2 fuel can survive extreme conditions for limited periods of time such as gross overpower and dryout.

Gross Overpower

- Gross overpower can result in a small volume of UO_2 achieving central melting, which causes that fraction of UO_2 which melts to volumetrically expand 10% greater than normal.
- The resulting sheath strain can cause rupture.

Dryout

- Canada has pioneered in-reactor heat transfer testing with experimental and power reactor fuels and therefore has gained a large amount of operating experience with fuel in two-phase flow and critical heat flux (CHF) condition or dryout.
- All reactor fuel channel conditions are specified so that a significant margin of safety is available to prevent dryout occurring during normal operation.
- As noted in Figure 38, dryout will significantly increase the sheath temperature, the amount depending on the coolant conditions and surface heat flux.
- Zircaloy clad UO_2 fuel elements can operate at those elevated temperatures for limited periods of time, inversely proportional to temperature.

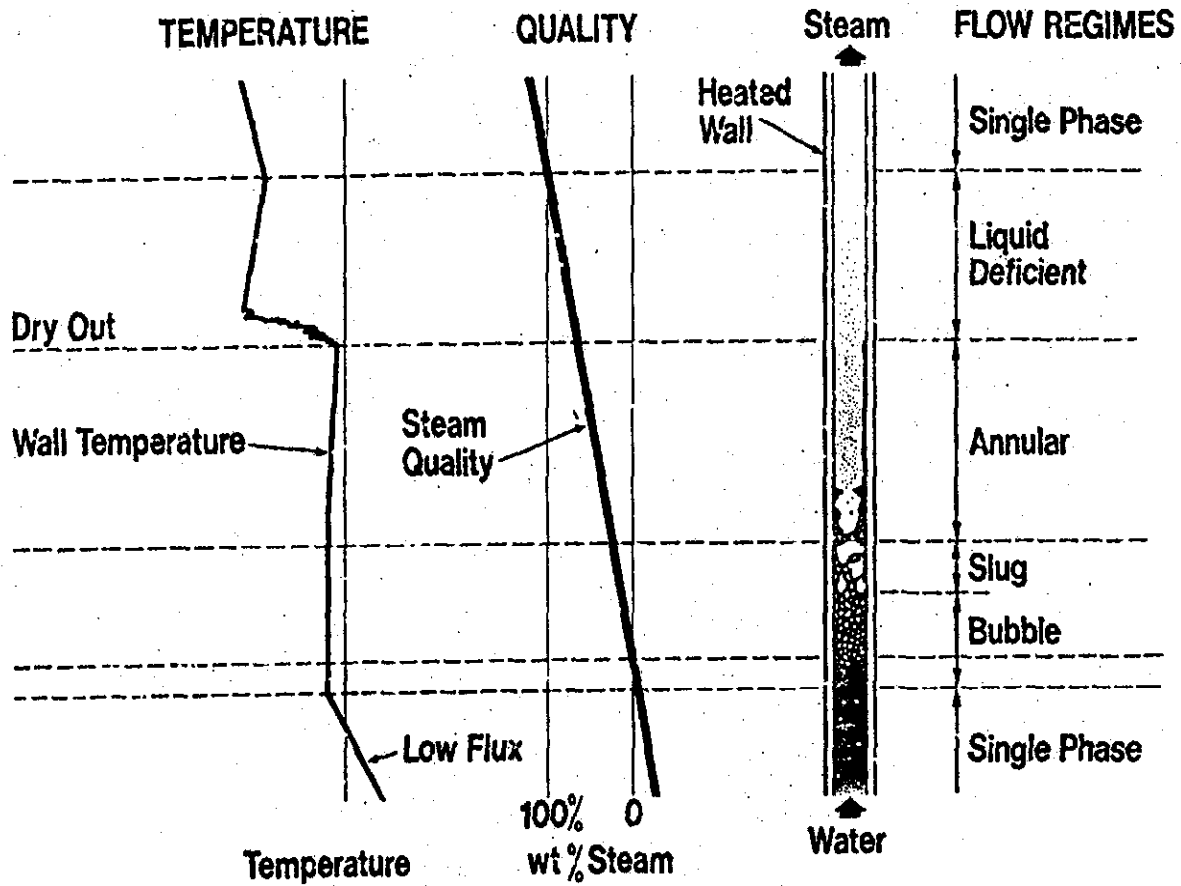


Figure 38 Thermal and Hydraulic Regimes in Vertical Upward Flow