Reactor noise analysis applications in NPPs

A potential new application: detecting fuel failure

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Presentation Scope

This presentation discusses the feasibility of using noise analysis to detect abnormalities in the mechanical integrity of nuclear fuel in the reactor.

Background

Hundreds of NPP signals might be available to noise analysis:

- Fuel channel inlet and outlet coolant flow
- Fuel channel inlet and outlet coolant temperature
- Fuel channel inlet-outlet coolant delta T
- In-core flux detectors
- Ex-core ion chamber

Establishing a baseline of noise signatures would involve

- Large number of multi-signal coherence/phase functions of the above signals sets
- Simulatanous availability of signals and synchronized sampling

Background

Many spatially distributed ”competing” noise sources generating fluctuations in standard NPP signals

- Vibration of core internals
- Coolant flow fluctuations
- Coolant temperature/density fluctuations
- Coolant boiling
- Automatic control actions

Where would ”fuel failure” fit in?

Convoluted effects in the measured noise signals hinder the solutions of reversed problems: identifying the parameters of noise sources (diagnostics)

Question of the presentation:

Utilizing NPP signals that are traditionally used in noise analysis, can reactor noise analysis detect/locate fuel failure or indicate early signs of that?

Mechanical failure of:

- Fuel pins/pencil/rods, cladding, end plugs
- Fuel assembly structural elements, grids, spacers, springs, end plates

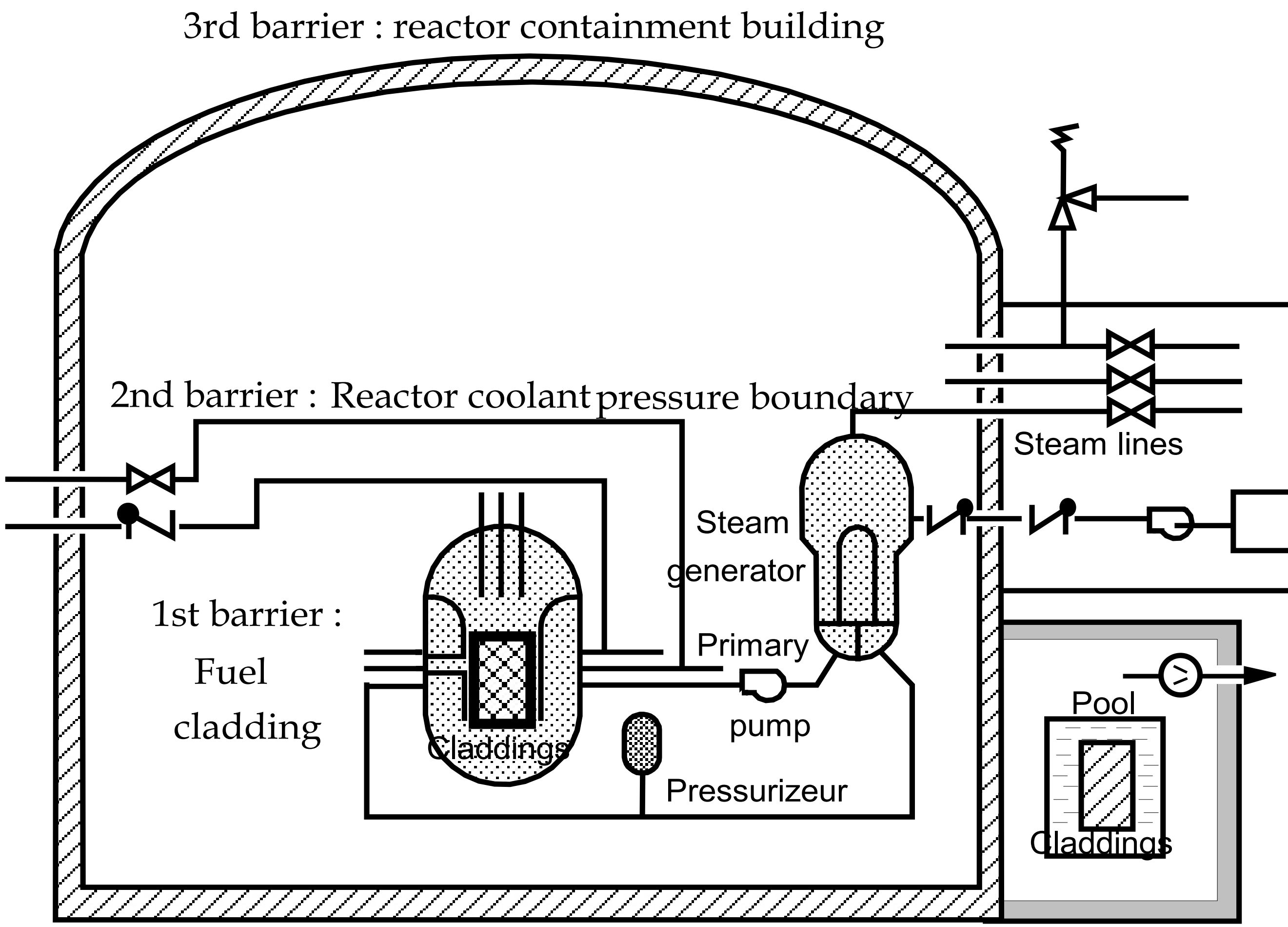
Assumption:

- Fuel failure manifests itself in Fuel Surface Irregularities (FSI) causing changes in coolant flow fluctuations

Definition

A fuel element failure is a rupture in a nuclear reactor’s fuel cladding that allows the nuclear fuel or fission products to enter the reactor coolant.

Main physical barrier to prevent the release of fission products in PWRs



Examples of Fuel Surface Irregularities

Fuel cladding is the first physical barrier to prevent the release of fission products, and its failure may be related to

- Stress corrosion cracking (SCC, induced by stretching force in corrosive environment)
- Surface wear caused by fretting between the fuel rods and grid/spacer/debris
- Excessive flow-induced vibration
- Power ramp-ups in load-following operation (fatigue)
- Debris lodged in fuel assembly increasing flow resistance
- External damage to surface caused by coolant pump pulsation, fueling handling, manufacturing defects

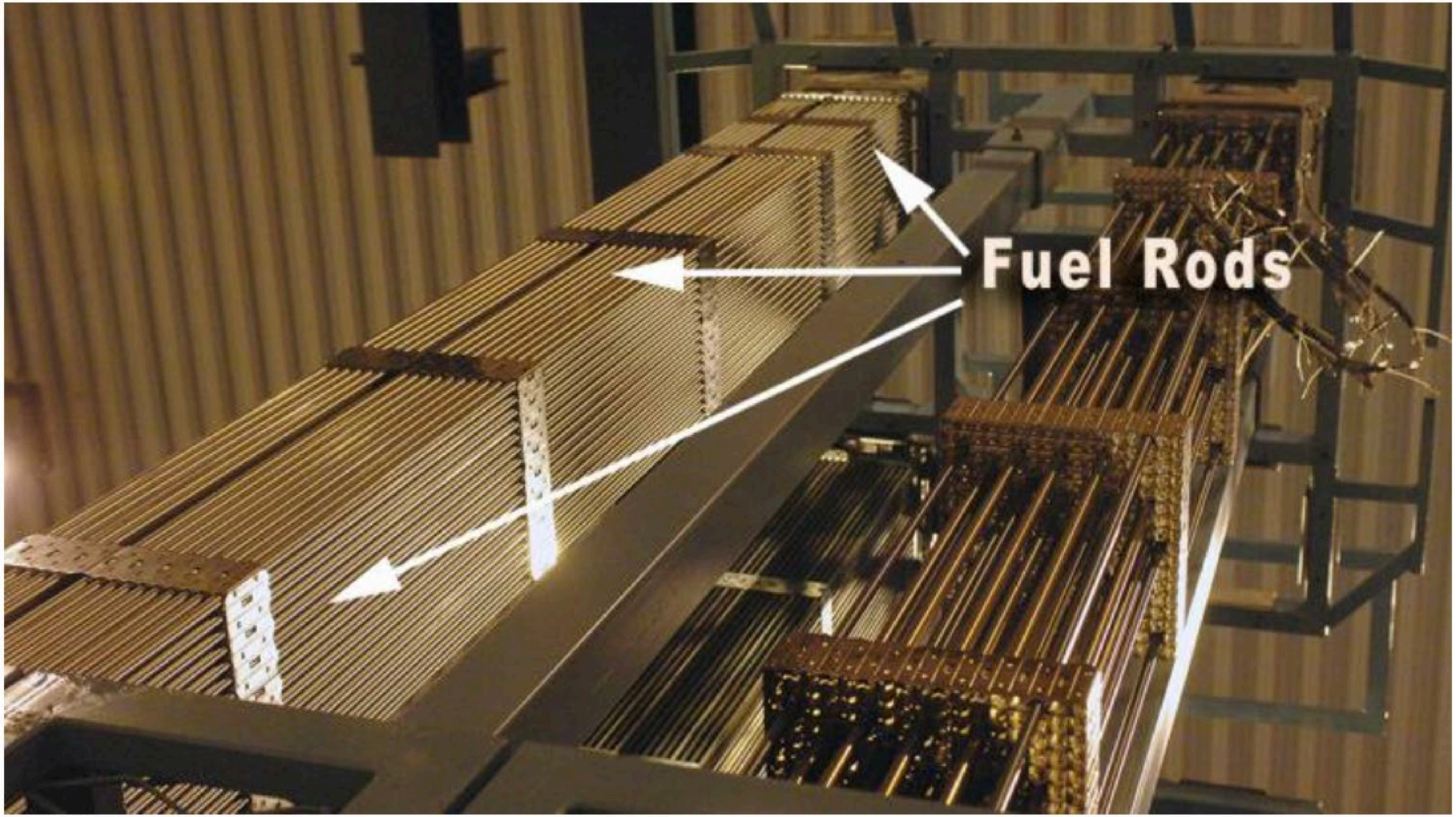
Examples of Fuel Surface Irregularities (continued)

- Chemical deposits increasing fuel surface roughness (example in a PWR: steam generator cleaning chemicals got into the reactor vessel and deposited on the surface of core internals)

When fuel cladding is ruptured, the radioactive fission products stored within the cladding are released into the coolant through the defect site.

In some NPP designs, on-line monitoring systems for detecting the presence of fission products in the coolant are installed

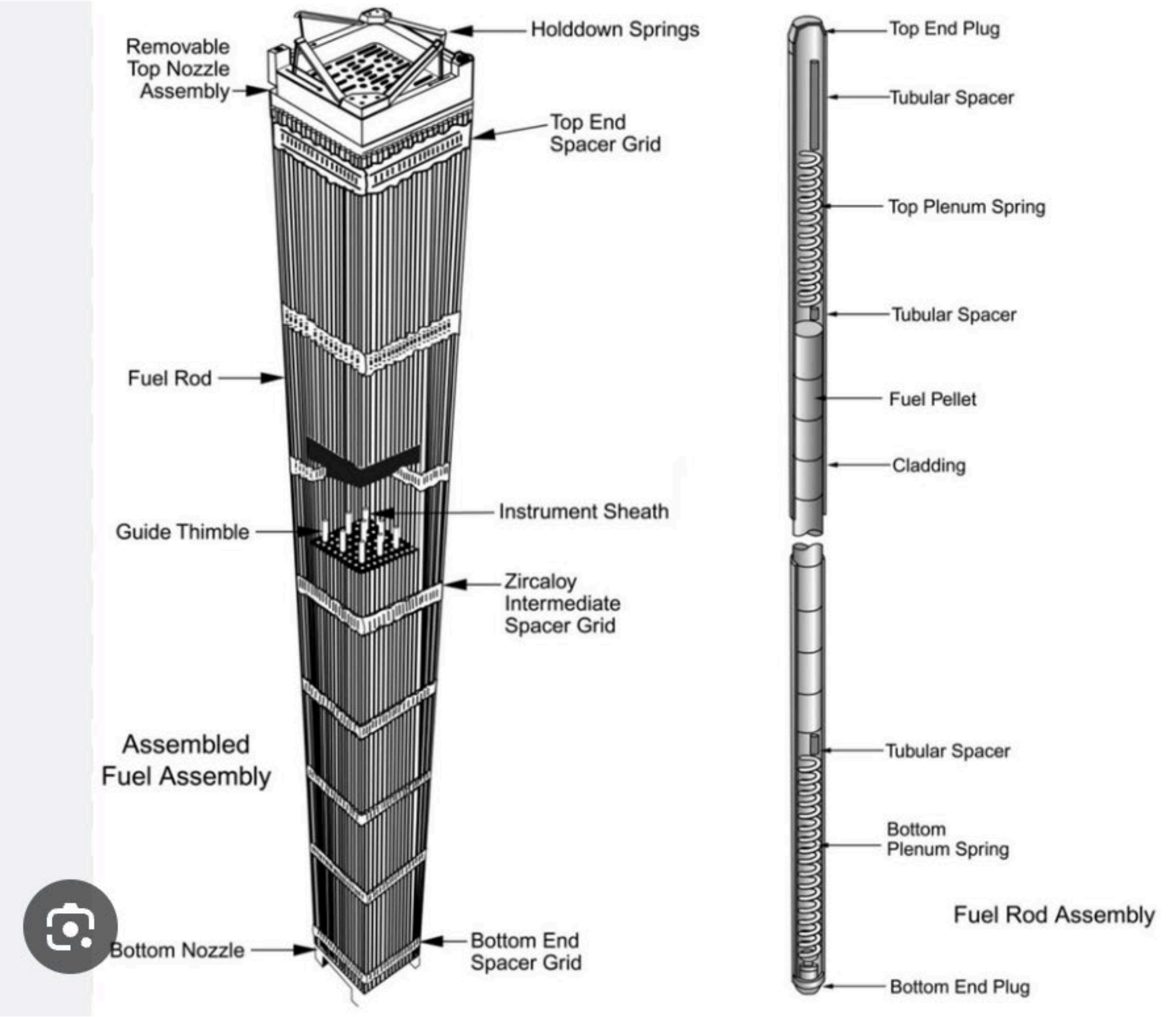
- gaseous fission product monitoring system (Xe-133, 135, Kr-88, I-131), and
- delayed neutron system (I-137, Br-87).



Fuel rods in a nuclear power reactor (Photo: IAEA)

The number of fuel rods in a reactor varies depending on the reactor's design. Some reactors could contain up to 60,000 fuel rods.

ResearchGate



4: Schematic view of a PWR fuel assembly and a PWR fuel pin ...

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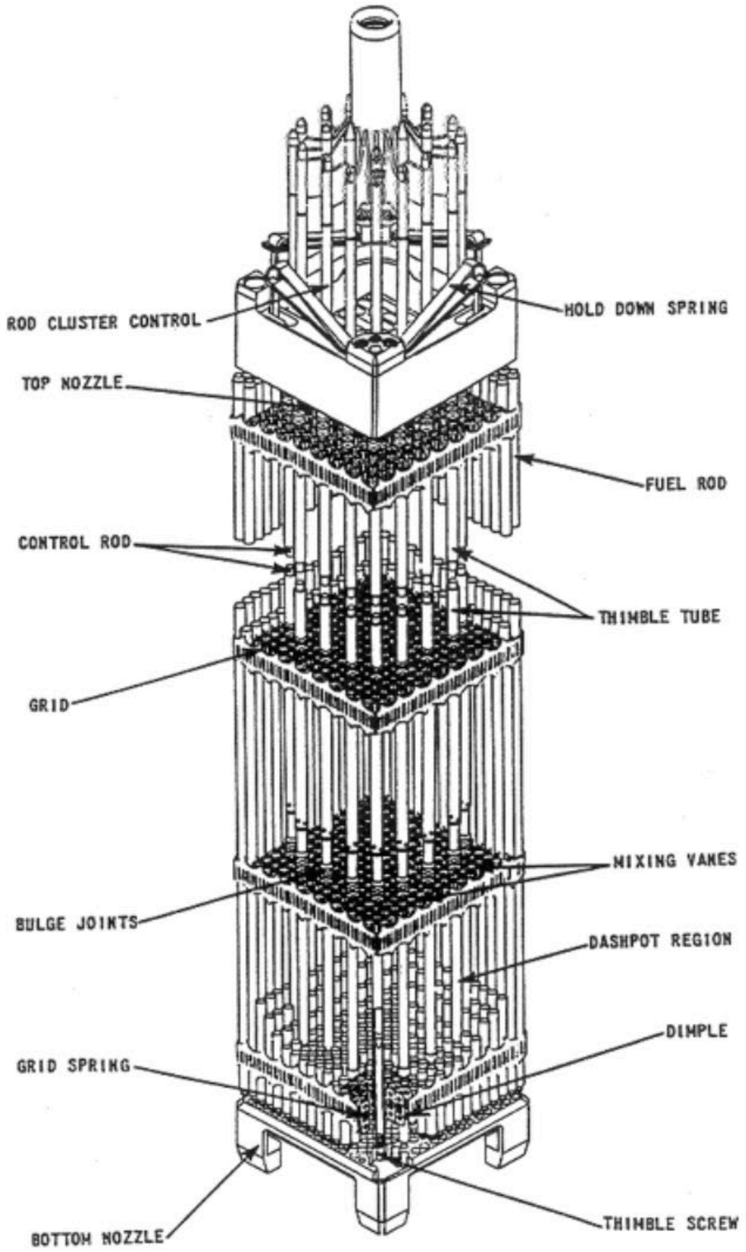

Reactor Fuel Assembly

Fuel assemblies (not to scale) from Olkiluoto 1-2 (BWR) and Olkiluoto 3 (EPR/PWR) and Loviisa 1-2 (VVER-440) nuclear power plants units. Figure by Posiva (n.d.)Posiva.

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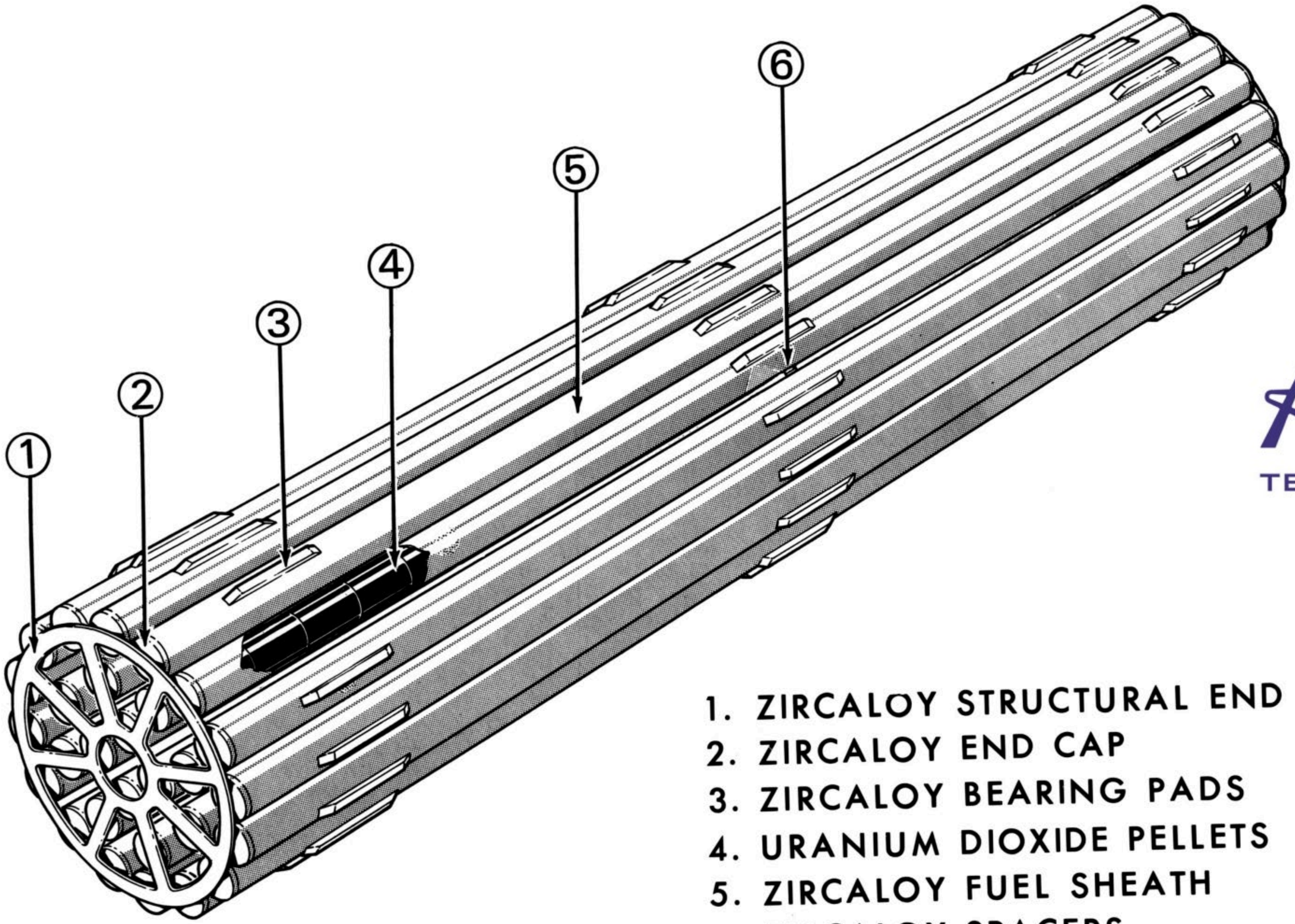

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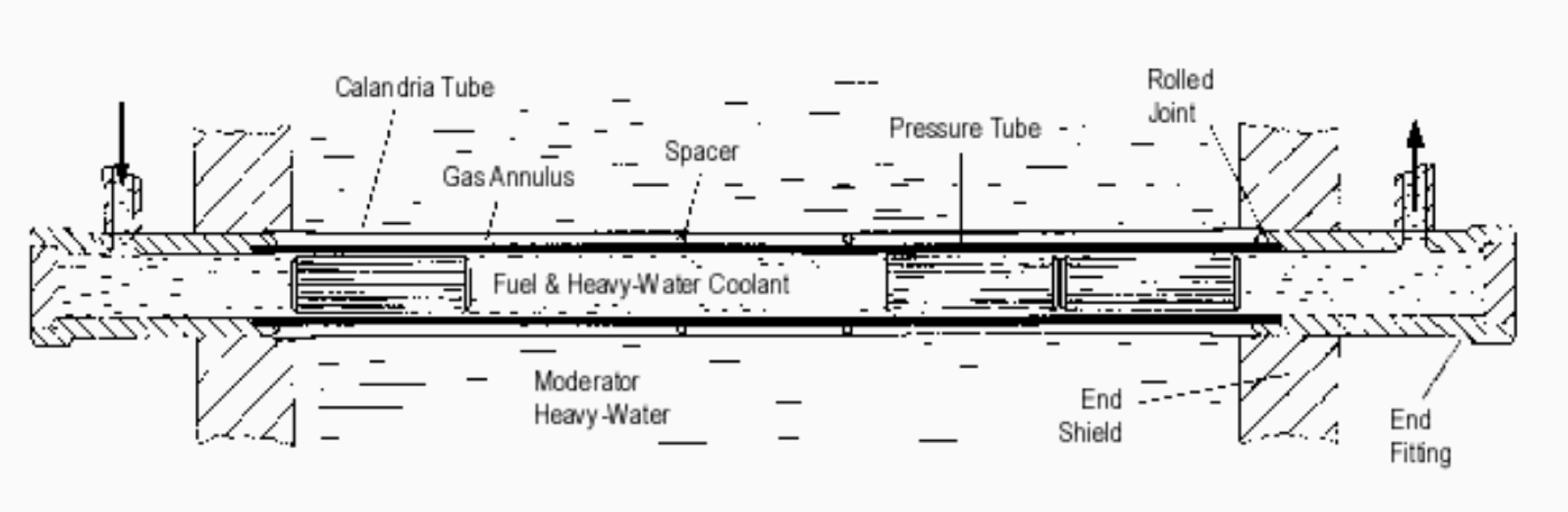
Figure 1 - uploaded by R.W.L. Fong



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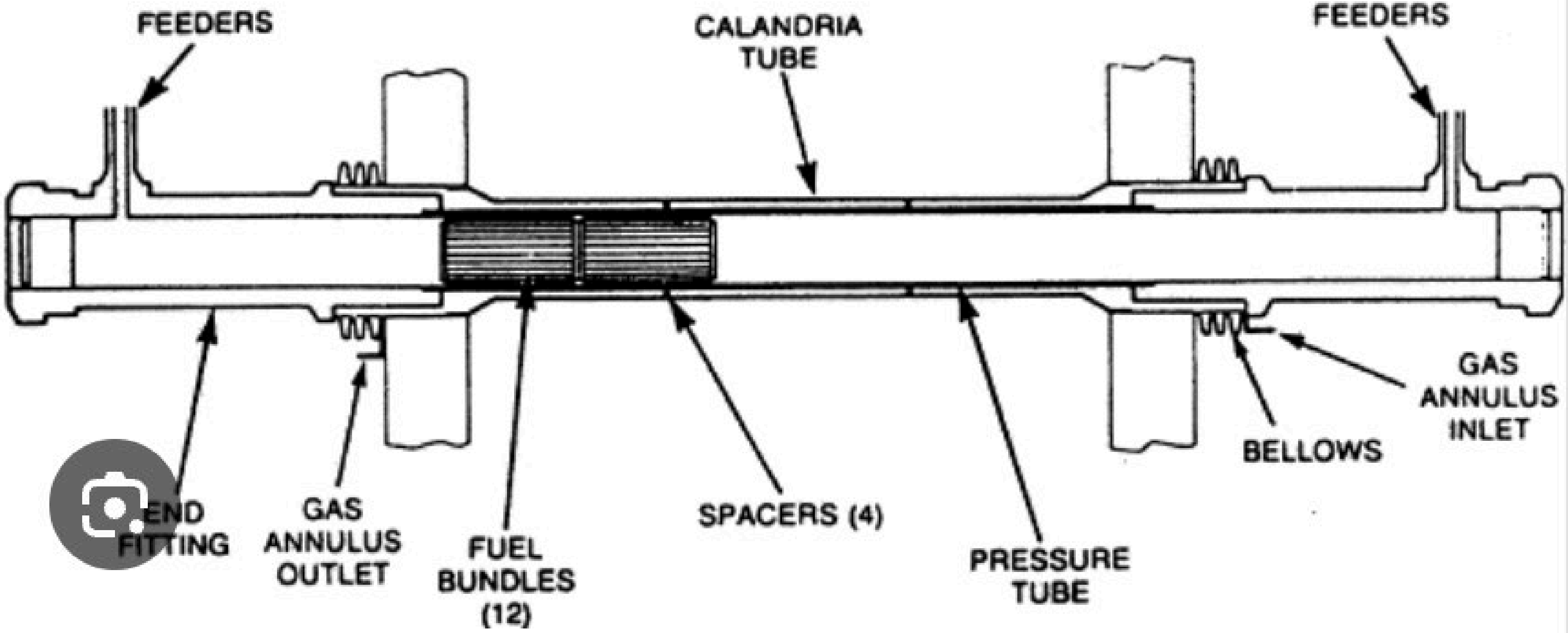

1. Transmission Path from Fuel Surface Irregularities (FSI) to Detectable Changes in Coolant Temperature Fluctuations

- FSI causing changes in local flow fluctuations (due to change in surface roughness, lodged in debris, increased flow resistance)
- Flow fluctuations causing changes in local heat transfer fluctuations from fuel to coolant
- Causing changes in fuel channel exit temperature fluctuations, picked up by RTDs or TCs

2. Transmission Path from Fuel Surface Irregularities (FSI) to Detectable Changes in Coolant Flow Fluctuations

- FSI causing changes in local flow fluctuations (due to change in surface roughness, lodged in debris, increased flow resistance)
- Flow fluctuations causing changes in local heat transfer fluctuations from fuel to coolant
- Causing changes in local coolant density and flow fluctuations
- Causing changes in fuel channel exit flow fluctuations, picked up by flow transmitters in instrumented fuel channels

3. Transmission Path from Fuel Surface Irregularities (FSI) to Detectable Changes in Neutron Flux Fluctuations

- FSI causing changes in local flow fluctuations (due to change in surface roughness, lodged in debris, increased flow resistance)
- Flow fluctuations causing changes in local heat transfer fluctuations from fuel to coolant
- Causing changes in local coolant quality, causing coolant density fluctuations, possibly boiling
- Coolant density fluctuations causing changes in neutron flux, picked up by in-core flux detectors (ICFDs)

4. Transmission Path from Fuel Surface Irregularities (FSI) to Detectable Changes in Neutron Flux Fluctuations

- FSI causing changes in local flow fluctuations (due to change in surface roughness, lodged in debris, increased flow resistance)
- Causing changes in flow-induced fuel vibration
- Vibrating fuel causing changes in neutron flux, picked up by in-core flux detectors (ICFDs)

Notes on changes in measured signals caused by FSI (flow, temperature, neutron flux):

- Not looking for correlations or coincidence in individual time events, spikes, dips, etc. caused by FSI in measured signals – might be buried in other noise components

- Not looking for detectable changes in DC (averaged mean value) of signals due to FSI in measured signals – might be too small on DC

Notes on changes in measured signals caused by FSI (flow, temperature, neutron flux):

- Looking for changes in the long-term statistics of fluctuations in spectral functions averaged over 3-4 hours worth of recording
  - noise analysis: “averaging out” vs. “enhancing in”
  - noise analysis: up to 8 orders of magnitude sensitivity
- Looking for changes in the statistical coupling (pairwise coherence) between fluctuations within a group of signals, or the lack of that, compared to the majority of signal couples
- Detecting inconsistencies with previously established patterns

Example: Reduction in coupling/coherence of signal fluctuations due to FSI

- All channel-exits temperature sensors may have a characteristic coupling (coherence) between their signal fluctuations in normal conditions
- This is due to the fact that fuel channel temperature fluctuations have a large, slow, global and in-phase reactivity component
- Global power changes affect the coolant temperature in all fuel channels in the same way (regardless of the direction of coolant flow in CANDUs).

Example: Reduction in coupling/coherence of signal fluctuations due to FSI - continued

These expected statistical couplings of fuel channel exit temperature fluctuations may not be present in certain combinations of signal pairs, if the temperature fluctuations of one or more of the fuel channels are affected by surface irregularities, making them uncorrelated with the rest of the channel exit temperature signals.

Example: Reduction in coupling/coherence of signal fluctuations due to FSI - continued

Similarly, reduction in noise coupling may happen between the fluctuations of certain

- fuel channel exit flow signal pairs
- in-core flux detector pairs

due to fuel surface irregularities present in certain fuel channels.

Questions to address

- Are coolant flow fluctuations, caused by fuel surface irregularities, strong enough noise sources to affect the noise signatures of the NPP’s flow, temperature and neutron flux signals?
- Can changes detected in these noise signatures be attributed to fuel surface irregularities?

Thank you!

Any questions, suggestions?