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Introduction to Fuel Behaviour Modelling

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Introduction to Fuel Behaviour Modelling

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Joint ICTP-IAEA Workshop on

The Training in Basic Radiation Materials Science and its Application to Radiation Effects Studies and Development of Advanced Radiation-Resistant Materials

Trieste, April 12-23, 2010

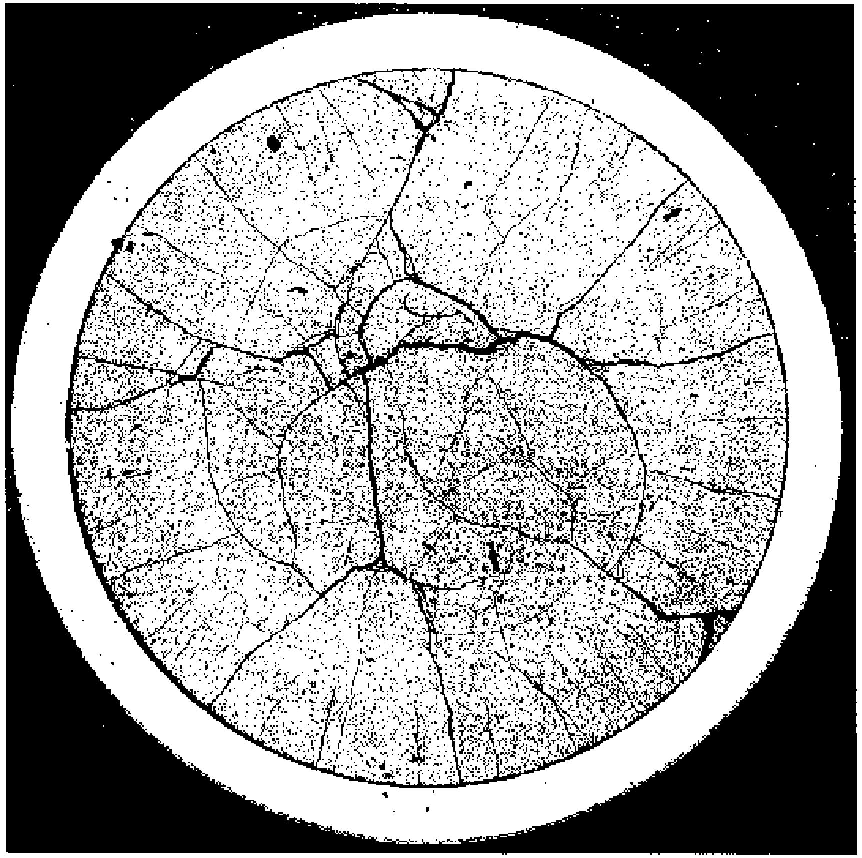
Overview

- Purpose and application of fuel modelling codes
- Main components
  1. temperature calculations
  2. fission gas release
  3. dimensional changes and mechanical loads
- Code structure
- Basic measurements for in-core experiments
- Overview of codes

Application of Fuel Performance Codes

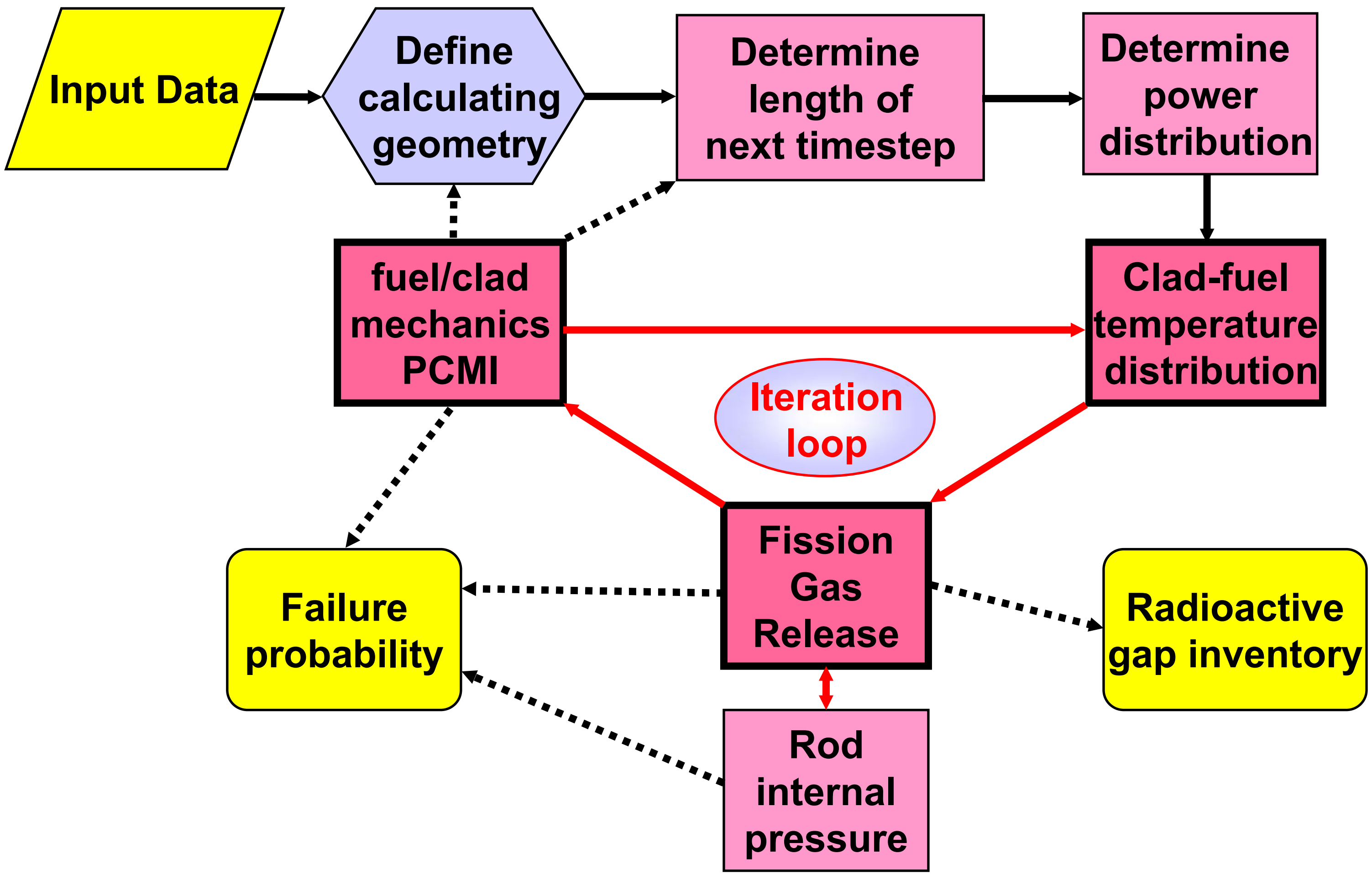
- Calculate the behaviour of a fuel rod during irradiation
  - steady state irradiation
  - transients
  - radiological source terms for accident analysis
- Applications include:
  - R & D purposes
  - design of new fuels and fuel cycles
  - prove that ***operational limitations and safety criteria*** are obeyed (safety case submission)

Ideally we want to predict ...

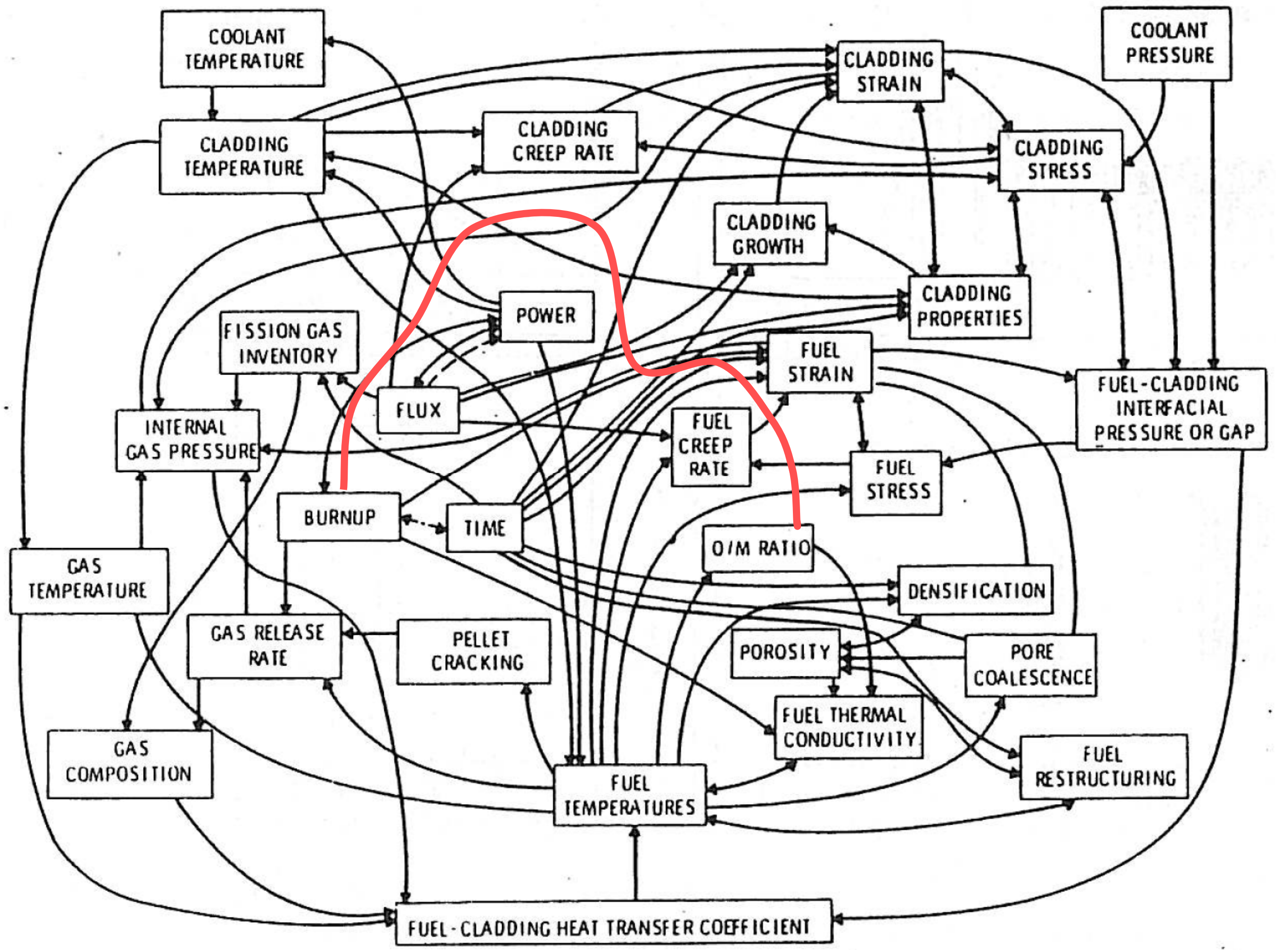


- oxide thickness
- temperature distribution
- stored heat
- clad diameter
- fuel diameter
- PCMI
- ridging?
- (crack distribution)
- porosity distribution
- grain size distribution
- FGR, ^{131}I inventory
- rod pressure
- did it fail?

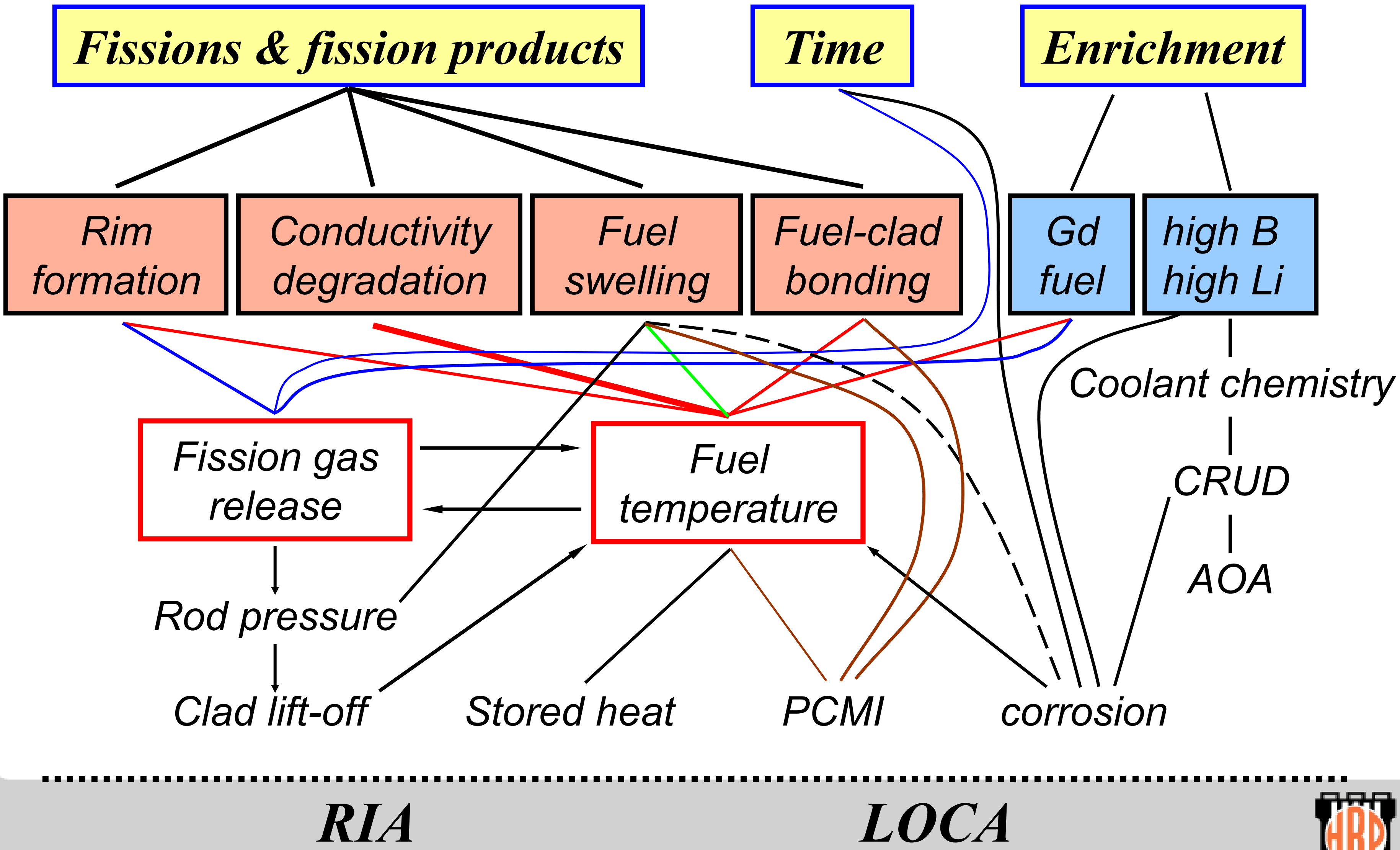
Typical code structure



... but it may be more complicated



Fuel behaviour codes must address and untangle interactions that become more and more complex as fuel burnup increases



1. Fuel rod temperature distribution

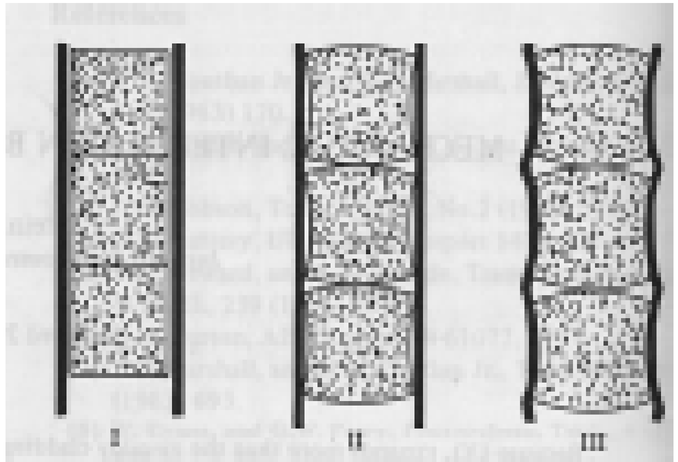
- Many properties are exponentially dependent on temperature. Therefore, accurate temperature estimates are important.
- The fuel temperature is strongly linked to
  - stored energy that must be removed in LOCA
  - thermal expansion of the fuel pellet as strong contribution to pellet-clad mechanical interaction and rod failure
  - fission gas release and thus rod pressure
- The fuel temperature distribution depends on design parameters, materials properties and on many phenomena which develop during irradiation.
- **The fuel temperature is important for many safety criteria**

2. Fission gas release

- Fission products are responsible for
  - fuel swelling and PCMI (solid fission products)
  - stress corrosion cracking and failure (iodine)
  - pressure build-up in the fuel rod (xenon, krypton)
    - feedback on gap conductance and fuel temperature
    - rod overpressure and clad lift-off
    - driving force for ballooning during LOCA
  - pressure build-up in the fuel pores
    - fuel fragmentation and expulsion during RIA and LOCA
    - gaseous swelling and PCMI (failure)
- Rod pressure is limited by safety criteria and must therefore be calculated for the safety case

3. Dimensional changes and mechanical loads

- Reversible
  - Elastic deformation
  - Thermal expansion
- Partly reversible
  - Cracking
  - Fragment relocation
- Permanent
  - Plastic deformation
  - Creep
  - Fission product swelling
  - Densification

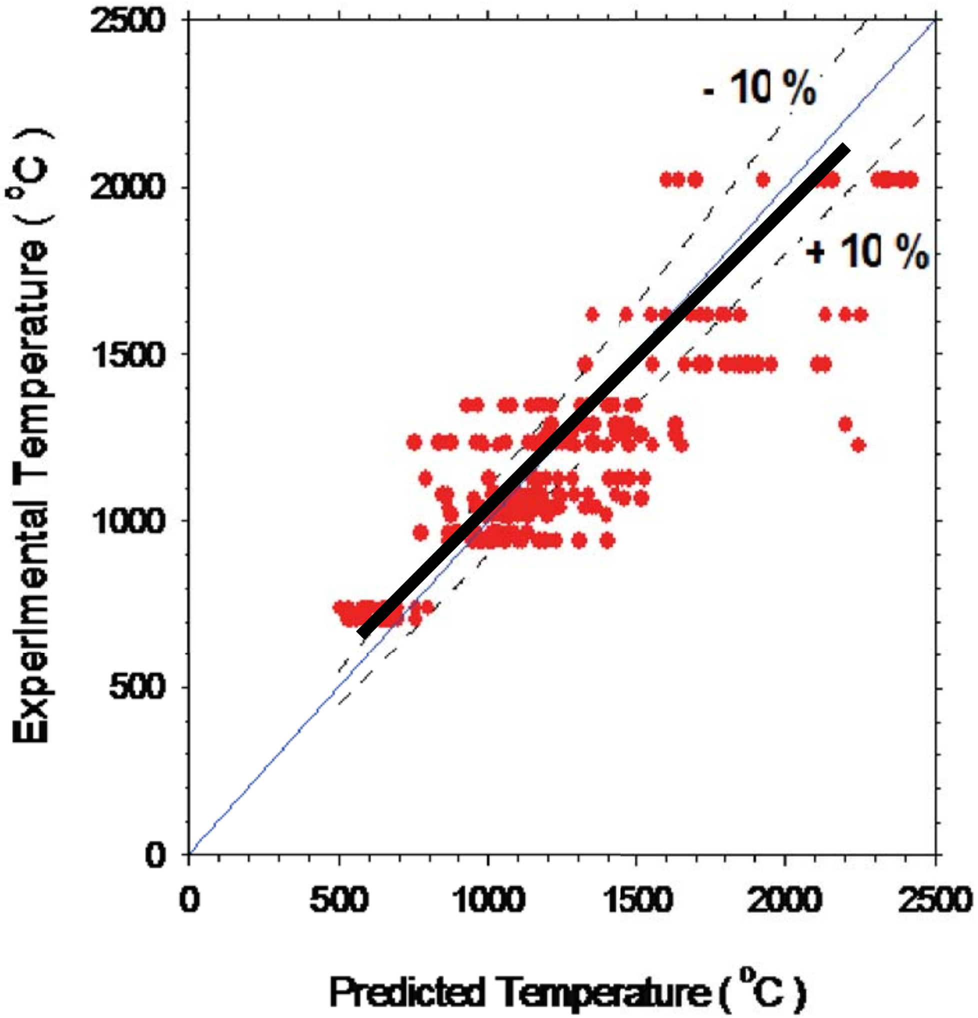


Thermal expansion of the pellet in a temperature gradient causes "ridging" at the pellet-pellet interfaces (also called wheat-sheafing, hour glassing)

Treatment in fuel behaviour modelling

- 1 ½ D codes
  - axi-symmetric 1D model (radial dependence only)
  - axial length (z direction) is divided into nodes
- 2D – 3D codes
  - more rigorous description of the geometry, but ...
  - restricted to a few pellets (2D: axi-symmetric r-z)
- Axial coupling
  - usually no axial heat flow
  - released fission gas is distributed, same pressure everywhere
  - mechanical coupling is complicated
    - codes must consider relative movement between pellet and cladding: no contact, frictional sliding, sticking
    - many 1 ½ D codes reduce the problem to no contact and sticking, thus avoiding the complications of axial coupling (a reasonable approximation valid for many situations, but not always)

How accurate can fuel modelling be?



- FUMEX-I started with blind predictions of HRP experiments
- The codes showed considerable variation even if the input was the same
  - temperature prediction
  - fission gas release
- Very few codes were able to reproduce the mechanical response

Useful Reading

- Donald R. Olander

  Fundamental Aspects of Nuclear Reactor Fuel Elements

  (Although from 1976, the *fundamentals* of most phenomena described in the book are unchanged. Look out for a new edition currently being prepared by Prof. Olander and a team of co-authors)

- SCDAP/RELAP5-3D© Code Development Team

  MATPRO - A Library of Materials Properties for Light-Water-Reactor Accident Analysis

  (Contains correlations for many nuclear fuel materials properties, discussion of the underlying data and how the correlations were derived. Latest edition is from 2002. The link is the 1993 edition: www.pnl.gov/frapcon3/documentation/matpro.pdf)

HRP fuel performance data base

- Experimental data since 1970
- Numerous experiments measuring
  - fuel temperature
  - rod pressure
  - clad strain (axial and circumferential)
- Separate effect studies
  - fission gas release (steady state, transient)
  - fuel conductivity
  - rod overpressure
- Various fuel types:
  - standard and modified UO_2
  - MOX and inert matrix fuel
  - UO_2 with gadolinia
  - VVER fuel
- Burnup range 0 – 90 (-150) MWd/kg

What can be measured on a fuel rod and to what fuel performance issue does the measurement relate?

1.	Fuel Temperature	Heat transfer (fuel thermal conductivity, gap conductance)
2.	Rod Internal Pressure Change	Fission gas release, fuel densification & swelling
3.	Fuel Stack Length Change	Fuel densification & swelling
4.	Fuel Cladding Length Change	PCMI, (or when no PCMI, surface heat transfer, growth)
5.	Fuel Rod Outer Diameter Change	PCMI, (or when no PCMI, creep & growth, corrosion)

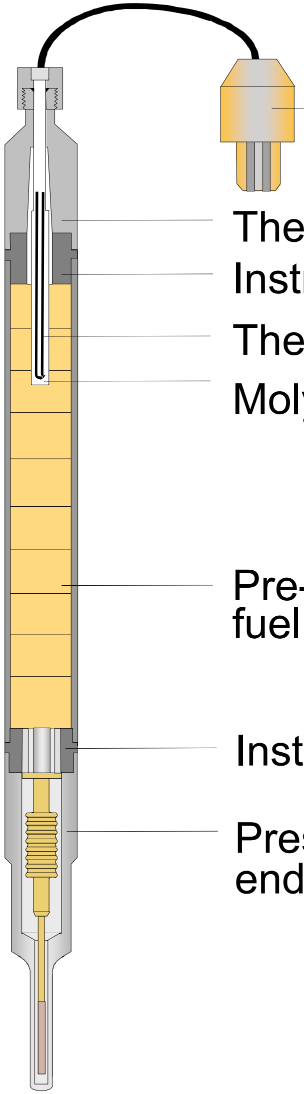
1. Fuel Temperature

- A good prediction of fuel temperature is an essential requirement for any fuel performance code
- Fuel centreline temperature is measure
  - at a single point in an annular fuel pellet with a thermocouple
  - along the length of an annular fuel stack (average fuel centreline temperature) with an expansion thermometer
- Fuel centreline temperature measurements enable modellers to test their code predictions with respect to:
  - Fuel thermal conductivity and its degradation with burn-up
  - Gap conductance / gas composition (fission gas release)
  - Gap width (fuel densification & swelling, cladding creep)
  - Fuel pellet surface roughness
  - Eccentricity in the fuel stack

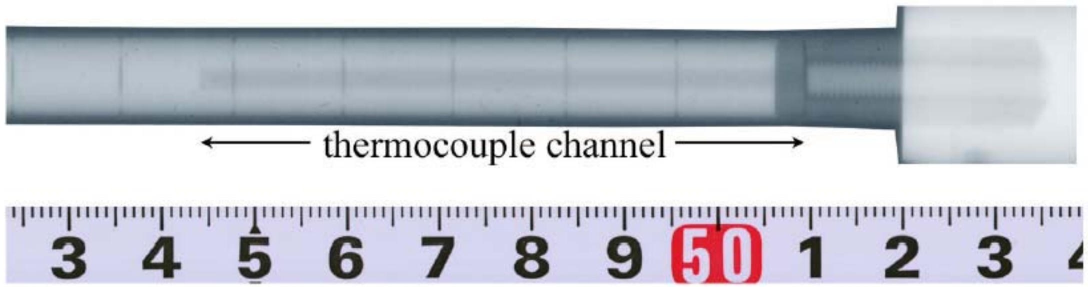
Measuring Fuel Temperature with a Thermocouple

- High temperature thermocouples suitable for measuring inside a fuel stack are:
  - W / Re
  - Nicrosil / Nisil
- **Strengths of thermocouples**
  - Reliable measurement: up to 1400 - 1600°C, thermocouples can last several years and will even manage a few hours at 2000°C
  - Accurate measurement: easy to calculate from measured to solid fuel pellet temperature
- **Weaknesses of thermocouples**
  - Tendency to premature failure at high fuel temperatures or in failed rods
  - Need to account for decalibration due to transmutation at high fluence

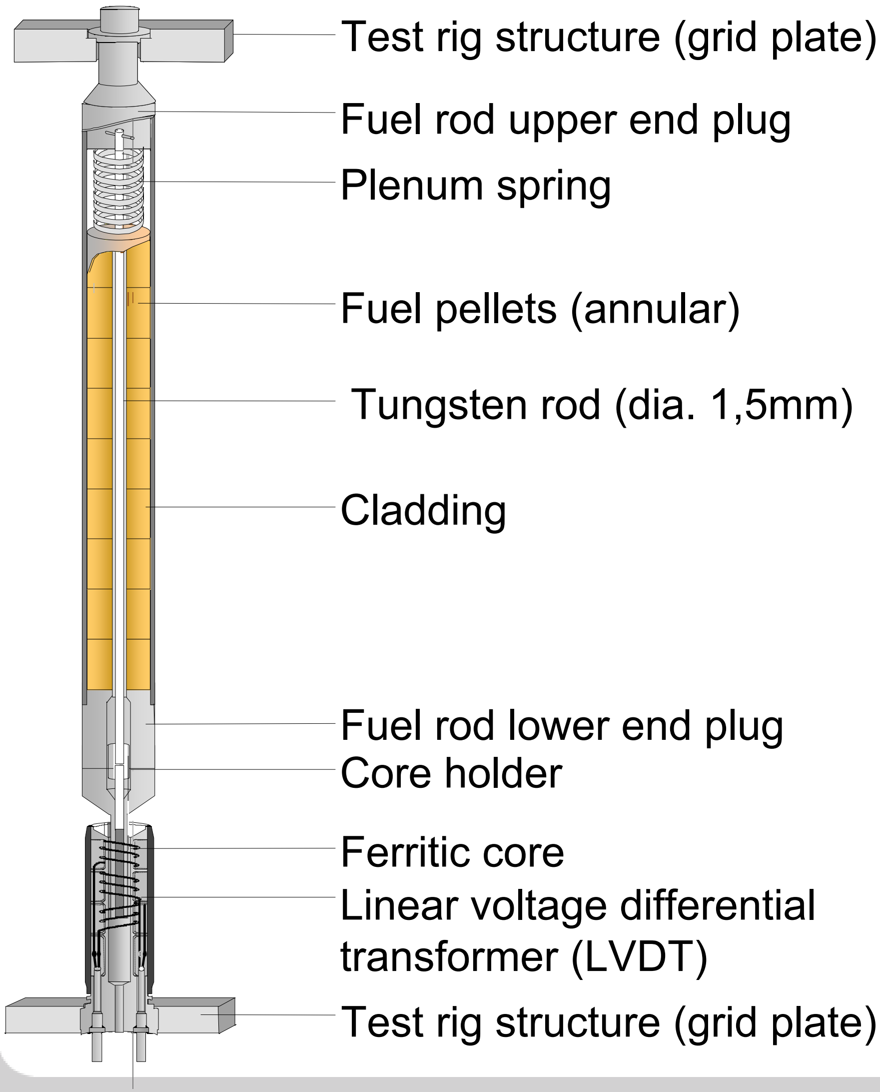
Measuring Fuel Temperature with a Thermocouple



- Both fresh and irradiated fuel pellets in a stack can be drilled to allow insertion of a thermocouple
- Neutron radiography shows exactly where the thermocouple tip (hot junction) is positioned

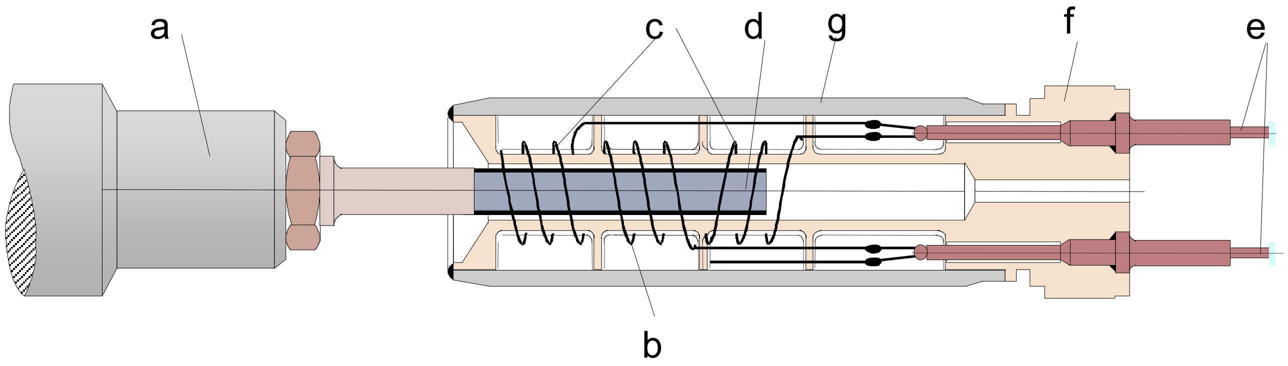


Measuring Fuel Temperature with an Expansion Thermometer



- A thin tungsten rod is inserted through a centre hole drilled in the entire fuel stack
- One end of W-rod fixed to fuel rod end-plug, other end is free and fitted with a magnetic core, movement of core sensed by an LVDT (Linear Voltage Differential Transformer)
- Average centreline temperature in fuel stack derived from measured axial expansion of tungsten rod

Linear Variable Differential Transformer (LVDT)



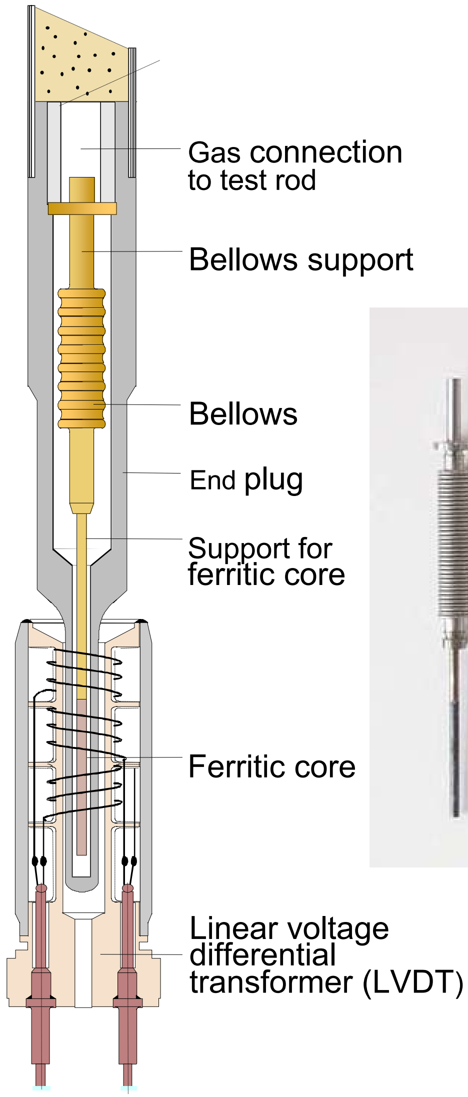
a: Test rod end plug assembly
b: Primary coil
c: Secondary coils
d: Ferritic core
e: Twin-lead signal cables
f: Body
g: Housing

- Developed for measuring fuel rod pressure, temperature, fuel stack and cladding elongation
- Primary coil with two secondary coils connected in opposition. Movable magnetic core concentrically located inside coil system
- Core movement affects the balance of the secondary coils and generates the signal output

2. Fuel Rod Internal Pressure Change

- Measuring changes in rod internal pressure provides data on
  - Fission gas release (FGR)
  - Fuel stack densification and swelling (in absence of FGR)
- Understanding or being able to adequately model fission gas release mechanisms is important especially for development of new fuel types for better fuel performance
  - Rod pressure measurements often combined with fuel temperature measurements e.g. investigating threshold temperature for FGR onset
- Fuel rod internal pressure is a key issue for extending the discharge burn-up of fuel for power reactors - most licensing bodies limit allowable fuel rod internal pressure

Measuring Fuel Rod Internal Pressure Change

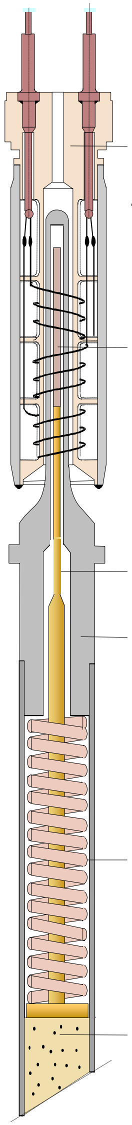


- Small stainless steel or Inconel sealed bellows unit inserted in a fuel rod end-plug
- Gas pressure in fuel rod acts on bellows
- One end of bellows fixed to end-plug, other end is free and fitted with a magnetic core, movement of core sensed by an LVDT
- In-pile calibration at start of life (know rod pressure), then subsequent signal gives change in rod pressure
- Different bellows used for different expected measuring ranges: up to 15, 30 or 70 bar ΔP

3. Fuel Stack Length Change

- Measuring changes in fuel stack length provides data on
  - Fuel densification and swelling (fuel-clad gap open)
- Fuel densification and swelling are of interest because of the way they affect the development of the fuel-clad gap e.g. as fresh fuel densifies initially, the gap size increases inducing an increase in the fuel temperature
- Dimensional stability behaviour varies between different fuel types and this is something that fuel models need to capture
  - Fuel density
  - Pellet shape (flat ended versus dished, hollow versus solid)
  - MOX fuel, Gd-doped fuel, other additive fuels

Measuring Fuel Stack Length Change

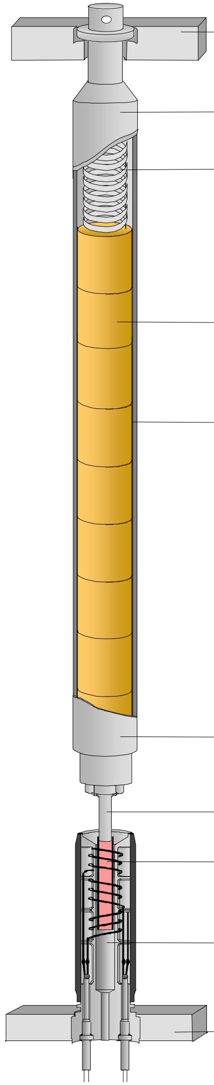


- Magnetic core holder fitted in fuel rod end-plug and spring loaded against fuel stack end
- Axial densification / swelling of the fuel stack acts on spring so magnetic core holder position moves
- Core movement sensed by LVDT
- In-pile calibration at start of life (zero point), then subsequent signal gives change in fuel stack length
- Stops being relevant once fuel-clad gap closes
- Because of connection between fuel dimensional changes and fuel temperature, fuel thermocouple often inserted at other end of same fuel rod

4. Fuel Cladding Length Change

- Measuring changes in fuel cladding length can provide data on cladding strain from fuel pellet to cladding mechanical interaction (PCMI) under different conditions which can be used for
  - model development
  - predicting the outcome of situations where clad integrity may be jeopardised
- When there is no PCMI, measurements provide data on
  - Heat transfer properties of surface layers (oxide, crud)
  - Irradiation growth of cladding
  - Onset of dry-out (in dry-out testing)

Measuring Fuel Cladding Length Change

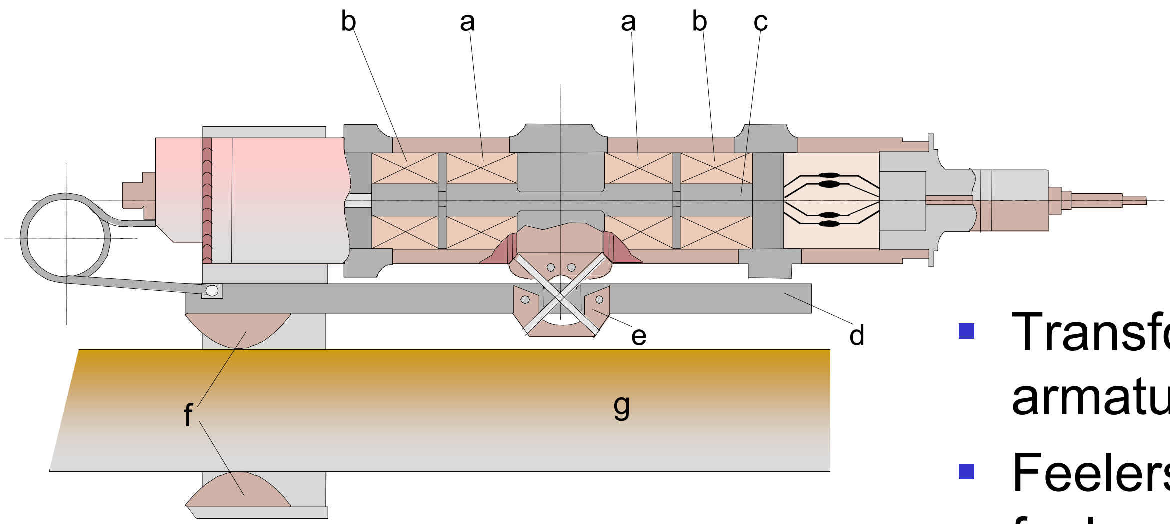


- Upper end of fuel rod fixed to test rig structure
- Magnetic core holder fitted to end-plug at lower (free) end of fuel rod
- Change in fuel cladding length causes core holder position to move relative to an LVDT
- In-pile calibration at start of life (zero point), then subsequent signal gives change in cladding length

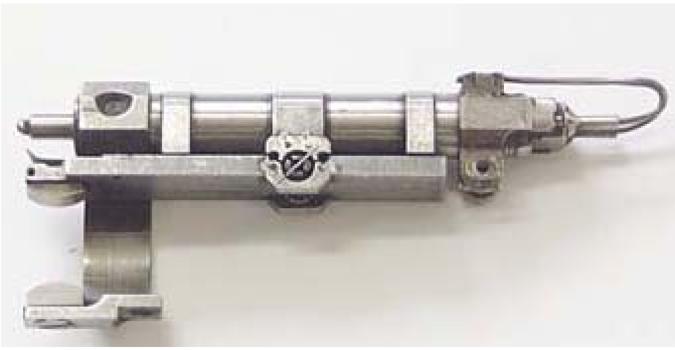
5. Fuel Rod Outer Diameter Change

- Measuring fuel cladding outer diameter changes can provide data on
  - PCMI during power transients (continuous measurement)
  - Cladding creep (measurement made once a week)
  - Oxide / crud build-up on a fuel rod (measurement made once a month)
- Monitoring diametral in addition to the axial components of PCMI enables better understanding of what occurs during power transients
- Most fuel performance codes contain models for cladding creep as this affects the development of the fuel-clad gap as well as influences a fuel rod's PCMI behaviour
- Discharge burn-ups are often limited by the corrosion behaviour of the fuel rod cladding – so knowing how different claddings behave in different water chemistries in-pile is a vital part of alloy development

Measuring Fuel Rod Outer Diameter



a: Primary coil
b: Secondary coil
c: Ferritic bobbin
d: Ferritic armature
e: Cross spring suspension
f: Feelers
g: Fuel rod



Instrument based on the LVDT principle

- Transformer body connected to armature via a pivot point
- Feelers on opposite sides of the fuel rod trace the fuel rod outer diameter profile
- Unit is driven along the fuel rod by a hydraulic system
- Position sensor used to sense axial position of DG along the rod
- Calibration steps machined into the fuel rod end-plug surface

Methods
(secondary measurements)

- Gas flow through a fuel stack (hydraulic diameter)
- Gas flushing plus gamma spectroscopy (fission gas release)
- Noise analysis
- Fuel temperature response to scram

Secondary measurements

- **Hydraulic diameter** measurements determine the resistance that the fuel stack offers against gas flow and is applied to
  - map changes of the fuel-clad gap with increasing burnup
  - determine loosening of the fuel column in clad lift-off tests
  - find the resistance of the fuel stack against axial gas transport (e.g. in LOCA or from local fission gas release).
- **Gamma spectrometry** (fission gas release) allows assessing
  - low temperature fission gas release,
  - recoil component,
  - microstructural properties such as the surface-to-volume ratio
- **Fuel time constant** can be derived through evaluation of
  - rapid power changes (reactor scram)
  - noise analysis (fuel thermocouples + fast response ND)

Origin and characteristics of codes (Fumex)

Code	Organization Country	Based on	Use	Special feature
BACO	CNEA Argentina	BACO	PHWR	UO2 & MOX
ELESIM	AECL Canada	ELESIM	CANDU	ANS5.4 fission product release
EIMUS	CRIEPI Japan	FEMAXI-3	Evaluation BWR PWR HBWR	
ENIGMA	BE, BNFL, UK		PWR CAGR (BE) MOX (BNFL)	ridging, ^{131}I release
ENIGMA	VTT Finland	ENIGMA (UK)	WWER	E110 clad properties
FAIR	BARC India	Ni-1	PHWR AHWR	2D capability clad failure model UO2 & MOX
FRAPCON	USNRC		BWR, PWR	Licensing benchmark
FRAPCON (VO)	CIAE China	US version	design, operation and safety evaluation	clad failure model trans. code input
FUDA	BARC India		design & licensing	ridging clad failure model

Origin and characteristics of codes (Fumex)

Code	Organization Country	Based on	Use	Special feature
PIN-micro	REZ Czech Rep	GT-2 PIN	LWR WWER	
PIN-W	RezCzech Rep	PIN-micro	WWER licensing	
PROFESS	BARC India		PIE analysis	UO_2 & MOX
ROFEM 1B	INR Romania	FEMAXI-3	PHWR CANDU	
START-3	IIM Russia		fuel behaviour R&D	Fuel failure calc.
TRUST	NFD Japan		R&D Fuel design	
TRANSURANUS	ITU Germany	URANUS	Fuel behaviour R&D	MOX, UC, UN fast reactor, Monte Carlo
TRANSURANUS	PSI Switzerland	ITU version	Fuel behaviour R&D	
METEOR	CEA France	ITU code	Fuel behaviour R&D	
COPERNIC	FRAMATOME France	TRANSUR	BWR, PWR fuel design and licensing	
COMETHE-IV	Belgo Nucleaire, Belgium		BWR, PWR fuel design and licensing	
COSMOS	KAERI South Korea		Fuel performance analysis	
CYRANO-3	EDF France		PWR licensing	
SIERRA	Siemens PC		BWR, PWR fuel design and licensing	

Origin and characteristics of codes (ANS Park City 2000)

Code	Organization Country	Based on	Use	Special feature
FRAPCON-2	USNRC	GAPCON THERMAL-2	BWR, PWR	Licensing benchmark
FRAPCON-3	USNRC	FRAPCON -2	BWR, PWR	Licensing benchmark
FRAPTRAN	USNRC	FRAPT-6	Transient analysis eg LOCA and RIA	Fast transient capability
SCANAIR	DRS/SEMAR France		Transient analysis eg LOCA and RIA	Fast transient capability
FRAS	Kurchatov Institute, Russia		Transient analysis eg RIA	Fast transient capability

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