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Modelling Validation of Transients and Initial Phase of Accident Scenarios for Sodium Fast Reactors

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Simulation Codes

For designing and licensing a core design, validated and qualified simulation codes are required.

1. Understanding the transient **fuel behaviour** and the **post-failure phenomena** occurring during power transients in all kinds of coolant channel conditions
2. Reflecting all that physical information into analytical **code implementation**
3. **Validating** fuel pin thermo-mechanical modelling and the interface with coolant thermo-hydraulics (FCI).

CABRI Programmes

- For this purpose different CABRI programs were carried out in the time period from 1973-2002.

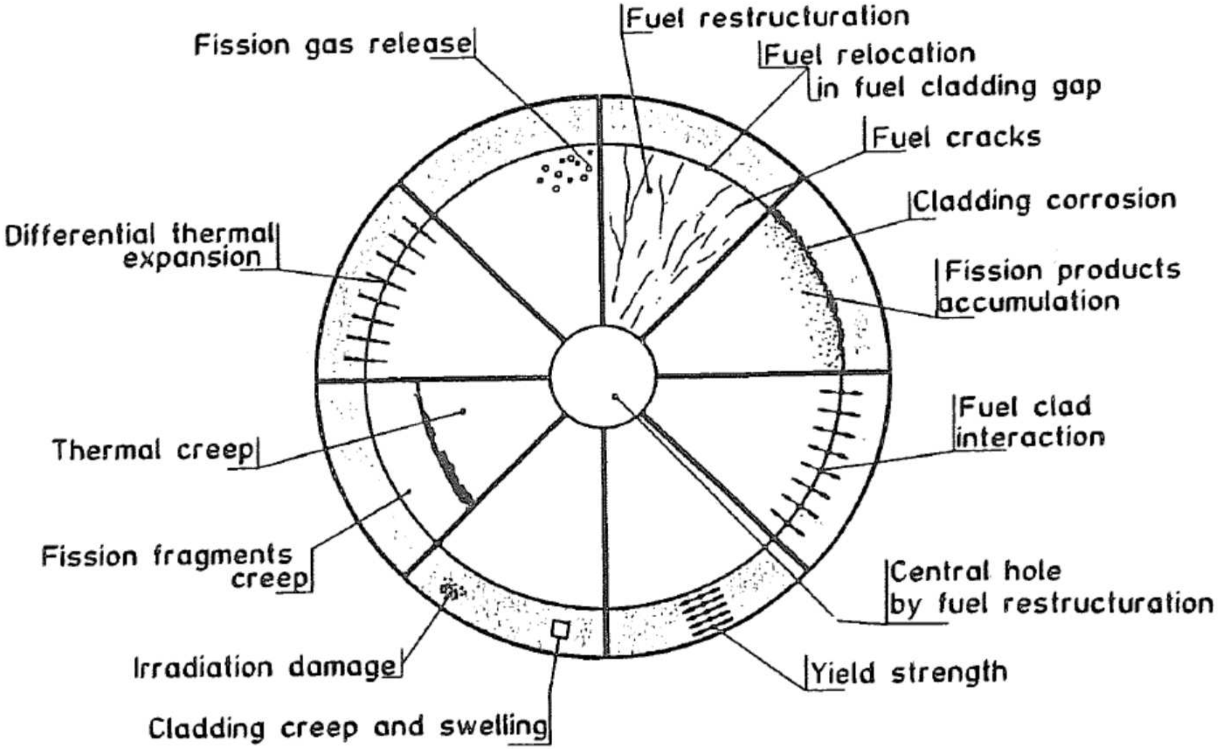
- It was a common research program by the French **IRSN** (formerly IPSN) in conjunction with the French **CEA** and the German **KIT** (formerly KFK) as Senior Partners within a large international collaboration with part time participation of the **UKAEA**, the **US/DOE** and the **US/NRC** and with an important contribution from the Japanese **PNC** over the whole time period.

Physical phenomena

In-pile test programs were designed to study:

- pre-failure in-pin fuel motion
- PCMI
- fuel pin failure and failure propagation mechanisms
- clad melting
- fuel-to-liquid coolant interaction FCI
- post-failure materials relocation (specific fuel, cladding and coolant conditions)
- coolant boiling

Power operation characterization



- A **precise t_0-state characterization** (gap pressure, clad deformation, gas retention, etc.) is needed to correctly interpret the subsequent physical phenomena.

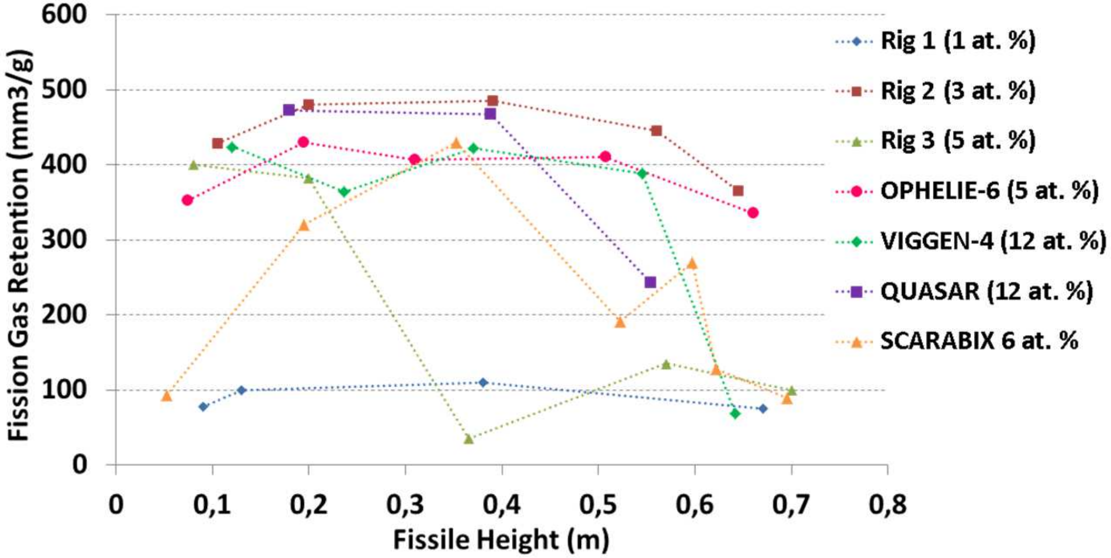
(Figure taken from *Fast breeder reactor fuel performances* R. Lallement Phil. Trans. R. Soc. Lond. A 331, 343-354 1990)

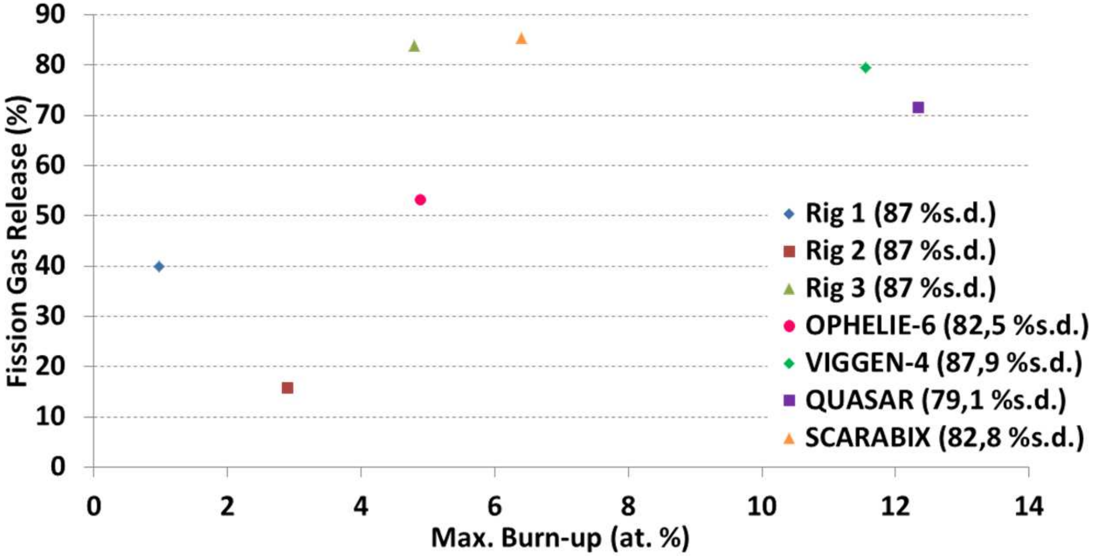
Pin characteristics in CABRI experiments

Variety of power operation histories and several fuel pin designs

	Rig 1/2/3	OPHELIE-6	SCARABIX	VIGGEN-4	QUASAR
Pellet diameter, inner/outer (mm)	**0 / 6,4**	**2,0 / 7,3**	**2,0 / 7,1**	**0 / 5,4**	**1,7 / 5,4**
Smear density - s.d. (%)	**87**	**83**	**81**	**88**	**80**
As fabr. pellet porosity (%)	**7.5/7.0**	**4,5**	**4**	**4,5**	**4,5**
As fabr. O/M ratio	**1,98**	**1,97**	**1,98**	**1,97**	**1,96**
Peak burn-up (%)	**1/3/5**	**4,8**	**6,4**	**11,8**	**12,1**
Clad material	**316 - CW**	**316 - CW**	**15–15 Ti**	**15–15 Ti**	**15–15 Ti**

Fission Gas Retention / Release



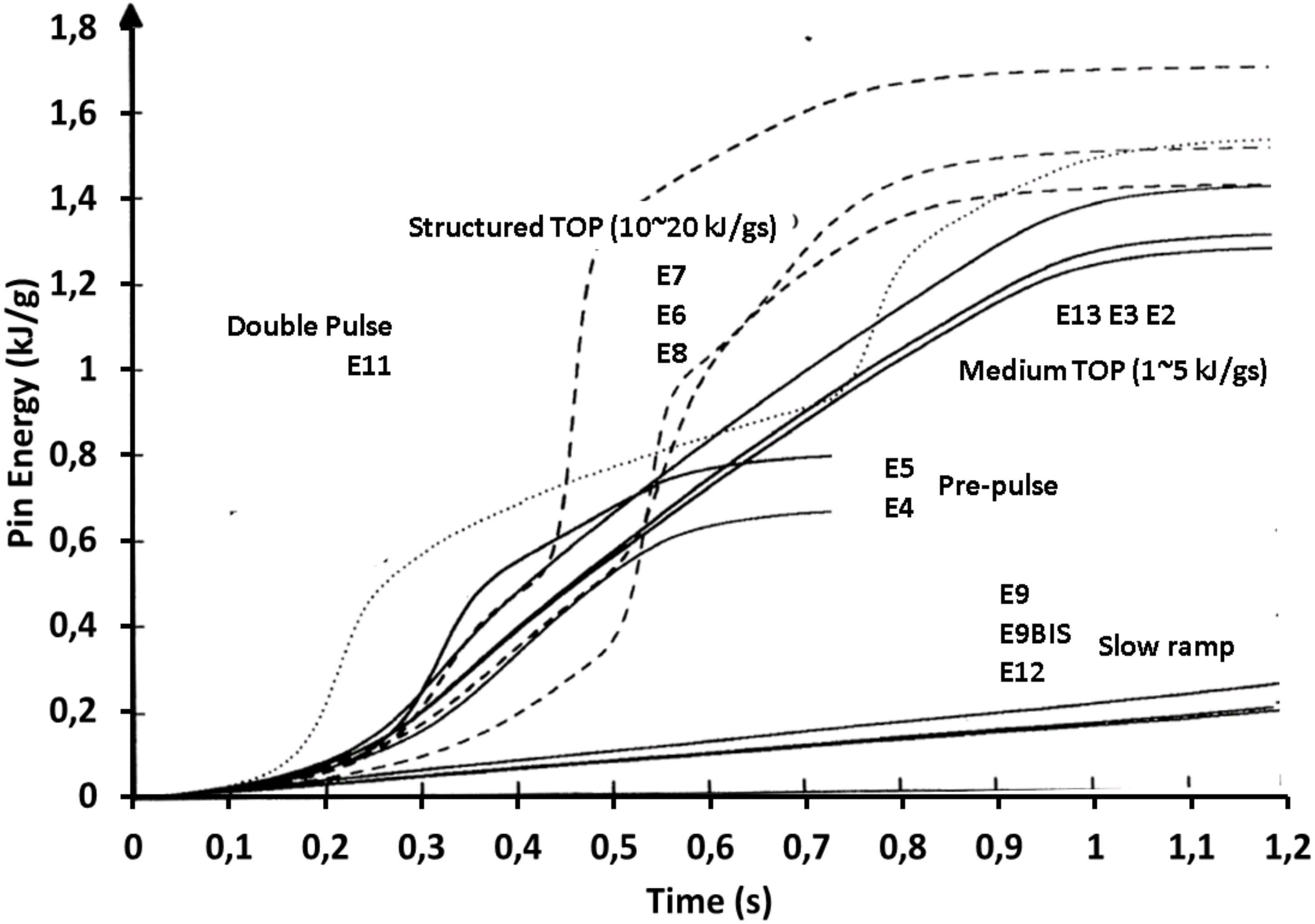


CABRI test matrix

	Slow ramp	Medium TOP	Energetic TOP	LOF + Medium TOP	LOF + Energetic TOP	Pure LOF
No pin failure, partial fuel melting	PF1 PFX	A1 A1R AI1 AGS0 AH1 E4 PF2	A5 LT2			
No pin failure, fuel melting	E9 E9BIS MF2	A2 E5				
Mechanical Clad Rupture	E12 BCF1	AI2	A3 A4 A4R AI3 AGS3 AH3 E7 E6	B2	B3 BI2 BI4 BI6 E8 E2 E3	
Clad Melting Rupture				B4 BGS0 BGS3 BGS4	B5 BI3 BI5 E13 E11 LT1 BH3 EFM1 LT4	B1 BI1 BG1 BH1

green for fresh and 1at. %, blue for 3-7 at. %, and red for 11-12 at. %

Energy injection profiles



CABRI on-line and post-test measurements

The relevant data are:

1) **failure location and time** (hodoscope signals and acoustic measurements)

2) evolution of **sodium temperatures** and of **sodium voiding** (thermocouples, flowmeters and void detectors)

3) in-pin and channel axial **fuel motion** (hodoscope signals)

4) configuration and morphology of **fuel/steel accumulations** and **final state** of fuel pin (post-test, hodoscope and various PTE examinations: γ scans, neutron/radiographs, axial/radial cuts).

Non-failure tests

Characteristics of non-failure TOP test:

Test	P_{max}/P_0	PPN energy injection at scram (kJ/g)	Fuel Pin
A2	318	1.05	solid fresh 316 CW
A5	106	1.56	solid fresh 316 CW
E4	10	0.51	solid 12 at. % 15-15 Ti
E5	26	0.64	hollow 5 at. % 316 CW
PF2	7	0.91	hollow 12 at. % 15-15Ti
LT2	26	1.26	hollow 12 at. % 15-15Ti

Potentially, in-pin fuel motion is an important reactivity feedback mechanism

TOP tests

Characteristics at failure time:

Test	P_{max}/P_0	PPN energy injection at failure (kJ/g)	Energy injection rate at failure (kJ/g·s)	Failure time (ms)	Failure location (cm BFC)	Fuel Pin
A3	624	1.04	68	58	48	solid fresh 316 CW
A4	756	1.09	107	56	49	solid fresh 316 CW
A4R	716	1.06	105	57	40	solid fresh 316 CW
AI2	108	0.88	0.9	230	46	solid 1 at. % 316 CW
AI3	250	0.86	36	82	45	solid 1 at. % 316 CW
AGS3	96	0.67	12	524	47	solid 3 at. %316 CW
AH3	398	0.93	47	78	54	solid 5 at. % 316 CW
E7	154	1.06	20	467	53	hollow 5 at. % 316 CW
E6	30	0.82	6	567	54	solid 12 at. % 15-15 Ti

TUCOP tests

Test	P_{max}/P_0	PPN energy injection (kJ/g)	Boiling onset (s)	Failure time (ms after TOP)	Fuel Pin
B2	396	1.2	-	340	solid fresh 316 CW
B3	596	1.4	-	116	solid fresh 316 CW
B4	227	0.9	21	87	solid fresh 316 CW
B5	546	0.8	22	58	solid fresh 316 CW
BI2	256	0.8	No	79	solid 1 at. % 316 CW
BI3	162	0.5	22	83	solid 1 at. % 316 CW
BI4	156	0.6	22	88	solid 1 at. % 316 CW
BI5	670	0.3	21	60	solid 1 at. % 316 CW
BI6	578	0.6	24	63	solid 1 at. % 316 CW
BGS0	19	~0.6	22	500-600	solid 3 at. % 316 CW
BGS3	86	0.7	21	548	solid 3 at. % 316 CW
BGS4	74	0.6	22	555	solid 3 at. % 316 CW
BH3	282	~0.6	22	74	solid 5 at. % 316 CW
E8	93	0.5	21	527	hollow 5 at. % 316 CW
E2	9	0.7	No	567	solid 12 at. % 15-15 Ti
E3	9	0.3	21	370	solid 12 at. % 15-15 Ti
E13	12	0.2	21	320	solid 12 at. % 15-15 Ti
E11	36	0.3	21	~200	solid 12 at. % 15-15 Ti
LT1	24	0.3	No	385	hollow 12 at. % 15-15 Ti
LT4	43	1.0	No	621	hollow 6 at. % 15-15Ti
EFM1	120	-	23	380-390	hollow 6 at. % 15-15Ti

Slow ramp test

Conditions of **control rod withdrawal** accident were performed with slow power ramps (~ 1 % P_0/s).

- The power to melt
- The risk of molten fuel ejection
- The potential for pin to pin propagation

	E9	**E9BIS**	**PF1**	**PFX**	**MF2**	**E12**	**BCF1**
Power ramp (%P_0/s)	**1.1**	**0.95**	**1.26**	**1.32**	**1.2**	**0.9**	**2.8**
Initial max. linear power (W/cm)	**603**	**594**	**414**	**403**	**396**	**474**	**472**
Final max. linear power (W/cm)	**1347**	**1075**	**883**	**791**	**1247**	**810**	**840**
Initial sodium heat-up (ºC)	**180**	**180**	**174**	**176**	**175**	**216**	**219**
Time of failure (s)	**No failure**	**No failure**	**No failure**	**No failure**	**No failure**	**76**	**28**

Failure mechanisms

- FCI and axial fuel motion in the channel

	Slow ramp	Medium TOP	Energetic TOP	LOF + Medium TOP	LOF + Energetic TOP
Mechanical Clad Rupture	E12 BCF1	AI2	A3 A4 A4R AI3 AGS3 AH3 E7 E6	B2	B3 BI2 BI4 BI6 E8 E2 E3

- Coolant boiling

	LOF + Medium TOP	LOF + Energetic TOP	LOF
Clad Melting Rupture	B4 BGS0 BGS3 BGS4	B5 BI3 BI5 E13 E11 LT1 BH3 EFM1 LT4	B1 BI1 BG1 BH1

Needs for future validation

- Definition of the reactor, the subassembly and the fuel pin design.

    1. manufacturing such pin designs
    2. irradiating them in a fast spectrum
    3. making the necessary experimental tests.

- Currently there is no fast reactor in Europe any more (as Phenix and PFR was used in the past) for high burn-up fuel levels and high clad dose .

- Second and third phases of the experimental procedure become critical.

Conclusions

- Computational codes are simplified representations of complex real phenomena, and therefore theoretical predictions should be considered **in the framework of validated conditions**.

- When new conditions outside the qualified ones are studied, **results have to be checked critically**. Extension of models might become necessary.

- Considerable investment should be done to develop in-pile test capability with the same **degree of confidence** as in the CABRI programmes.