International Science and Technology Center

INVESTIGATION OF FISSION PRODUCT RELEASE FROM HIGH BURN-UP FUEL ANNEALED UNDER OXIDIZING AND REDUCTION CONDITION

VERONIKA

*(**V**VER **E**xperiments on **R**elease due to **O**ver-heating: **N**ormalization and **K**nowledge **A**ugmentation).*

Project Proposal

RIAR (Dimitrovgrad), IBRAE (Moscow)

10th CEG-SAM Meeting

Kurchatov-City, Republic of Kazakhstan

IAE NNC, September 5-8, 2006

Objectives of VERONIKA Project

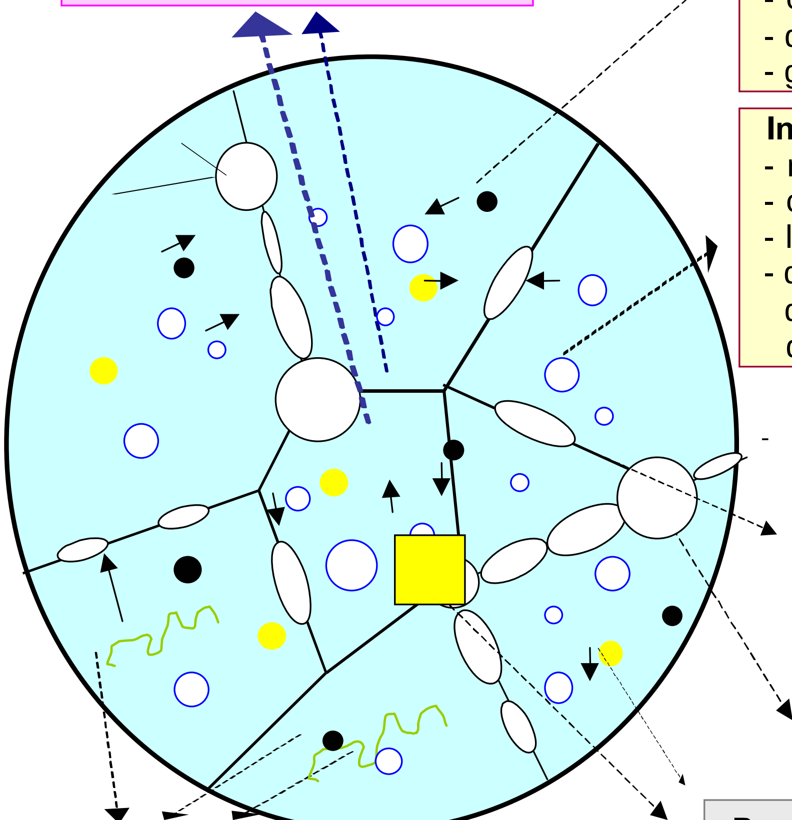
IBRAE

- *To obtain detailed experimental data on fission products release from highly irradiated VVER fuel along with fuel micro-structure evolution under severe accident conditions*

- *To use these results for the development (and validation) of the physical models and numerical codes describing fuel behaviour and fission products release*

MFPR Basic Models

Grain
- growth & boundary sweeping



Intragranular gas atoms
- diffusion towards grain boundary (∇concentration)
- bubble nucleation & capture by bubbles
- capture by dislocations
- directional diffusion by ∇T
- grain-boundary sweeping, dislocation creep

Intragranular bubbles
- nucleation and coalescence
- capture of gas atoms
- loss of gas atoms by re-solution (thermal & recoil)
- diffusion towards grain boundaries (face bubbles): directional diffusion by ∇T, grain-boundary sweeping, dislocation creep, vacancy gradient.

Intragranular zone

Face bubbles
- fed by gas atoms, intragranular bubbles & vaporization of condensed-phase species
- growth & interconnection leading to release into edge bubbles

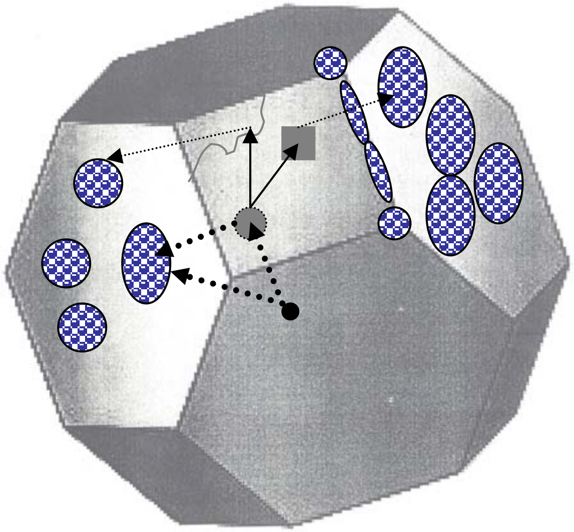
Edge bubbles
- supplied by face bubbles
- swelling until a critical threshold
- release into open porosities

Precipitates
- fed by intragranular diffusion of non-gas FPs
- formation of 3 condensed phases at grain boundary: ternary (e.g. *Cs_2MoO_4*), *CsI* & metallic (*Ru*, *Mo*, *Sb*)
- equilibrium between precipitates, face bubbles, *UO_{2+x}*

Intergranular zone

Dislocations
- creep towards grain boundaries
- trapping of intragranular gases (atoms & bubbles)

Transport of Fission Gases



System of equations:

$$\frac{\partial X_i}{\partial t} = F_i(X, t),$$

$$X = \{C_g, C_b, V_b, \rho_d, C_d, V_p, C_p, C_v, C_i\}$$

- *Diffusion of gas atoms (C_g)*
- *Intragranular bubbles (C_b, N_b) nucleation, growth and resolution (thermal and irradiation-induced)*
- *Intragranular bubbles diffusion (also biased in temperature gradient) and coalescence*
- *Interactions with dislocations (ρ_d), sintering pores (C_p), vacancies (C_v) and interstitials (C_i)*
- *Intergranular bubbles formation, coalescence and interconnection...*

Scope of VERONIKA Project Tests

- *Investigation of fission products release from fuel with burnup of 60 MW*d/kgU in oxidizing and reducing environments in the temperature range of 1400 - 2300^{o}C*
- *Investigation of the release of a wide list of fission products including short living isotopes: ^{85}Kr, ^{133}Xe, ^{131}I, ^{137}Cs, ^{134}Cs, ^{106}Ru, ^{103}Ru, ^{144}Ce, ^{99}Mo, ^{140}Ba, ^{95}Zr and other. That will be provided by pre-irradiation of the specimens in the research reactor*
- *Investigation of evolution of high burn-up fuel microstructure under tests conditions (by pre- and post-test microanalysis of samples)*

Test Matrix

- *Two kind of specimens: bare fuel (BF) and fuel rod segments (RS) of about 12mm long (1 pellet).*
- *Three test temperatures – 1400, 1700, 2300 °C.*
- *Oxidizing and reducing environments.*

Project stage	Gas environment	Flow rate, mg/s	Test temperature,°C		
			1400	1700	2300
First stage (3 years)	H_2/Ar	0,45/5	BF, RS	BF, RS	BF, RS
	H_2O	25	BF, RS	-	BF, RS
Second stage (2.5 years)	$(H_2O/H_2)_1$	25/0,45	BF, RS	BF, RS	BF, RS
	$(H_2O/H_2)_2$	25/0,2	BF, RS	-	BF, RS

Test matrix is aimed at 3 goals:

1. To determine the influence of gas medium (H_2O, $(H_2O/H_2)_1$, $(H_2O/H_2)_2$, H_2/He) on FP release from specimens with and without cladding
2. To determine the influence of temperature (1400, 1700 and 2300 °C) on FP release from specimens with and without cladding at the same gas-steam mixture content
3. To determine the influence of fuel-cladding interaction in the reducing gas medium on FP release at temperatures of 1400, 1700 and 2300 °C

SARNET group comments to the test matrix and test procedure

AEKI EDF IRSN JRC/ITU	The test matrix should be extended to include air atmosphere so that the complete range of oxygen potentials likely to be encountered in a severe accident is covered: hydrogen, hydrogen/steam, steam and air.
IRSN	The oxidation state of the clad pre-test needs definition.
CEA JRC/ITU	Technique for removing the clad minimising damage to the fuel outer rim zone needs to be defined and any damage sustained should be characterised.
CEA	The re-irradiation history needs attention too.
	The fuel will need to be well characterised, e.g. regarding the grain size.
IRSN	Gas flows and compositions in the case of mixtures, and exactly how and when the gas composition is to be changed (injection scenario).
EDF	Also care needs to be taken in the choice of crucible material.
CEA JRC/ITU	Use of SIMS and TEM.
CEA	Detailed point regarding collimator slits.
	To perform two more tests (both with steel component, one with B_4C and one without) in addition to their regular tests but without Niobium.

Revised test matrix

1 Stage

Test	Sample type	Environment	Test temperature,°C
1	Bare fuel	H_2 /Ar	1400
2	Bare fuel	H_2 / Ar	1700
3	Bare fuel	H_2 / Ar	2300
4	Fuel rod segment	Air / Ar	1400
5	Fuel rod segment	Air / Ar	1700
6	Fuel rod segment	Air / Ar	2300
7	Bare fuel	Air / Ar	1400
8	Bare fuel	Air / Ar	1700
9	Bare fuel	Air / Ar	2300
10	Reference sample of initial irradiated fuel		

Project stage	Gas environment	Test temperature,°C		
		1400	1700	2300
First stage (3 years)	H_2/Ar	BF	BF	BF
	Air/Ar	BF, RS	BF, RS	BF, RS
Second stage (2.5 years)	H_2O/H_2	BF, RS	BF, RS	BF, RS
	H_2O	BF, RS	-	BF, RS

Main Test Procedures

- ***Manufacturing of the experimental rig***
- ***Initial fuel rod examinations***
- ***Refabricated fuel rods manufacturing***
- ***Refabricated fuel rods irradiation***
- ***Preparation and certification of fuel specimens (fuel pellets and fragments of fuel rods)***
- ***FP release tests***
- ***Post-test examination of fuel specimens***

Initial fuel rod examination

Objectives:

- ***Selection of the typical spent fuel rod***
- ***Avoid the cladding defects – debris, nodules etc***
- ***Initial fuel and cladding certification***

Test procedures

- ***Eddy-current defectoscopy***
- ***Y-scanning***
- ***Profilometry***
- ***Plenum gas analysis***

Fuel and cladding structure characterization

Metallography – ***Pellet crack pattern, fuel-cladding interaction/gap, fuel porosity, fuel grain size measurement.***

SEM - ***(polished surface and fractography) porosity, intra- and intergranular bubbles pattern.***

EPMA – ***Fission product distribution, precipitates composition.***

Refabricated fuel rods manufacturing

- Manufacturing of the short fuel rods (200 mm long) sealed by the welded end plugs and filled with He at 2-2.5 MPa from the fragments of initial fuel rod.

Refabricated fuel rods irradiation

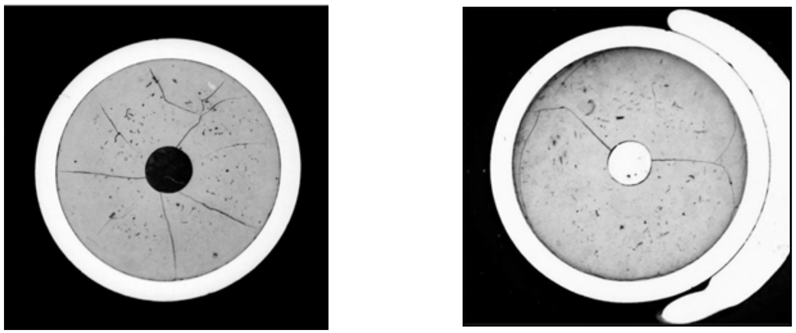
- Low power (30-50 Wt/cm)
- Low temperature (to be defined in pre-test calculations)

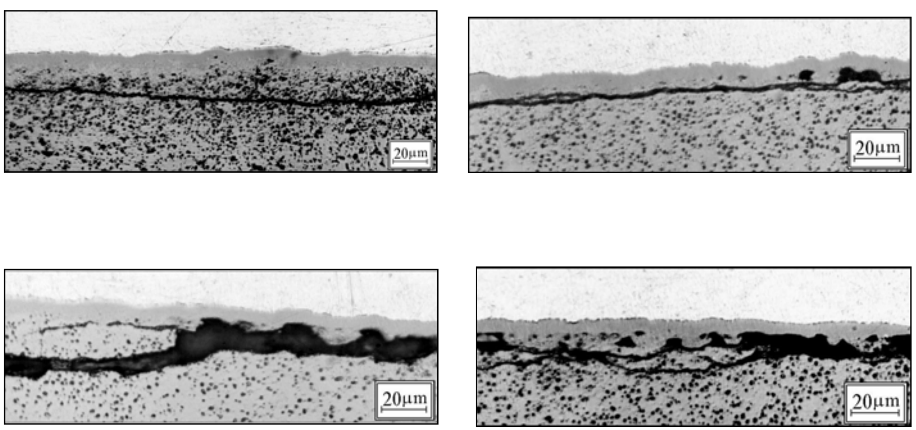
Objective: accumulation of the short-lived isotopes in the solid solution; prevent any fuel structure transformation

Specimen preparation

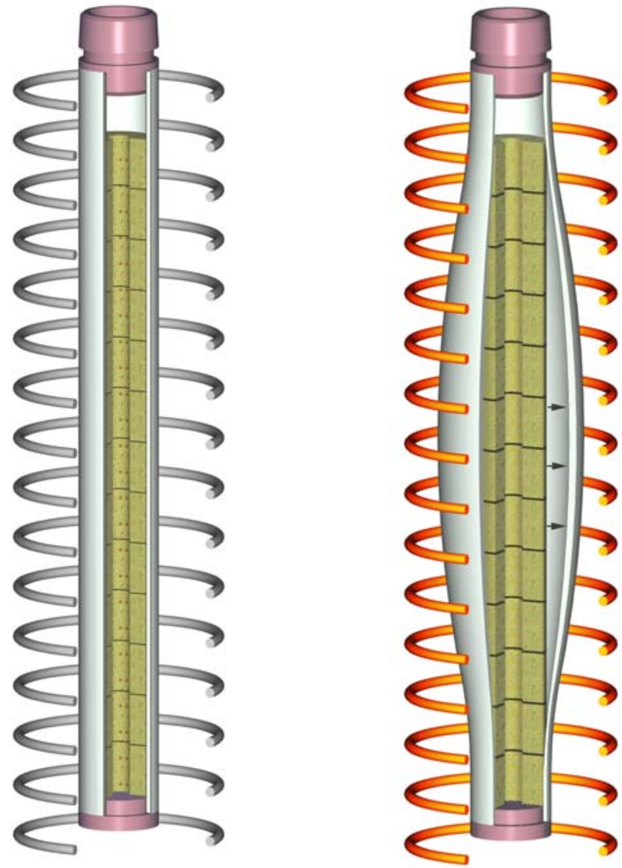
Bare fuel pellet extraction

Radial and contraction cracks in the fuel

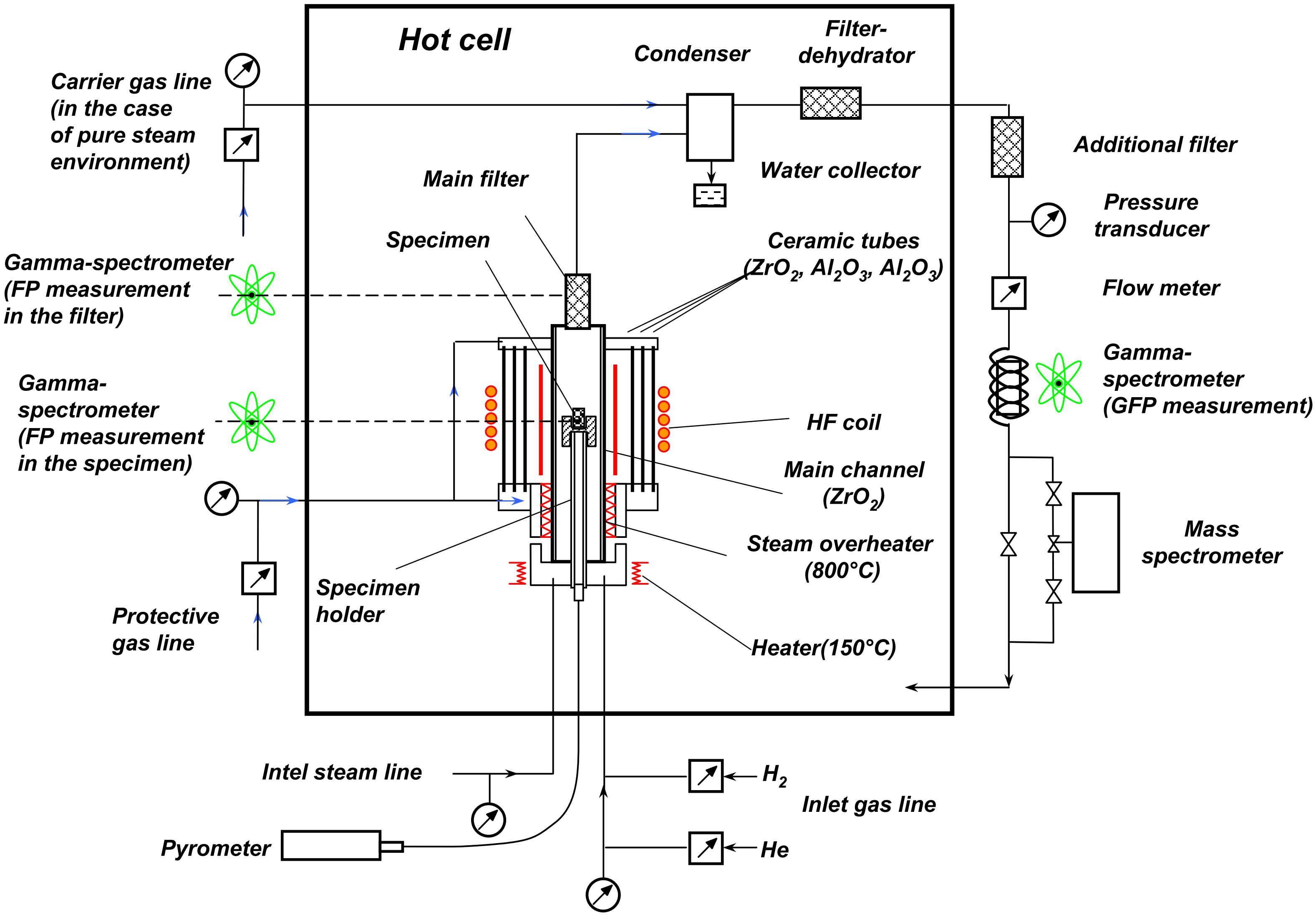




Pellet-clad separation by heating the pressurised rods up to 700°C

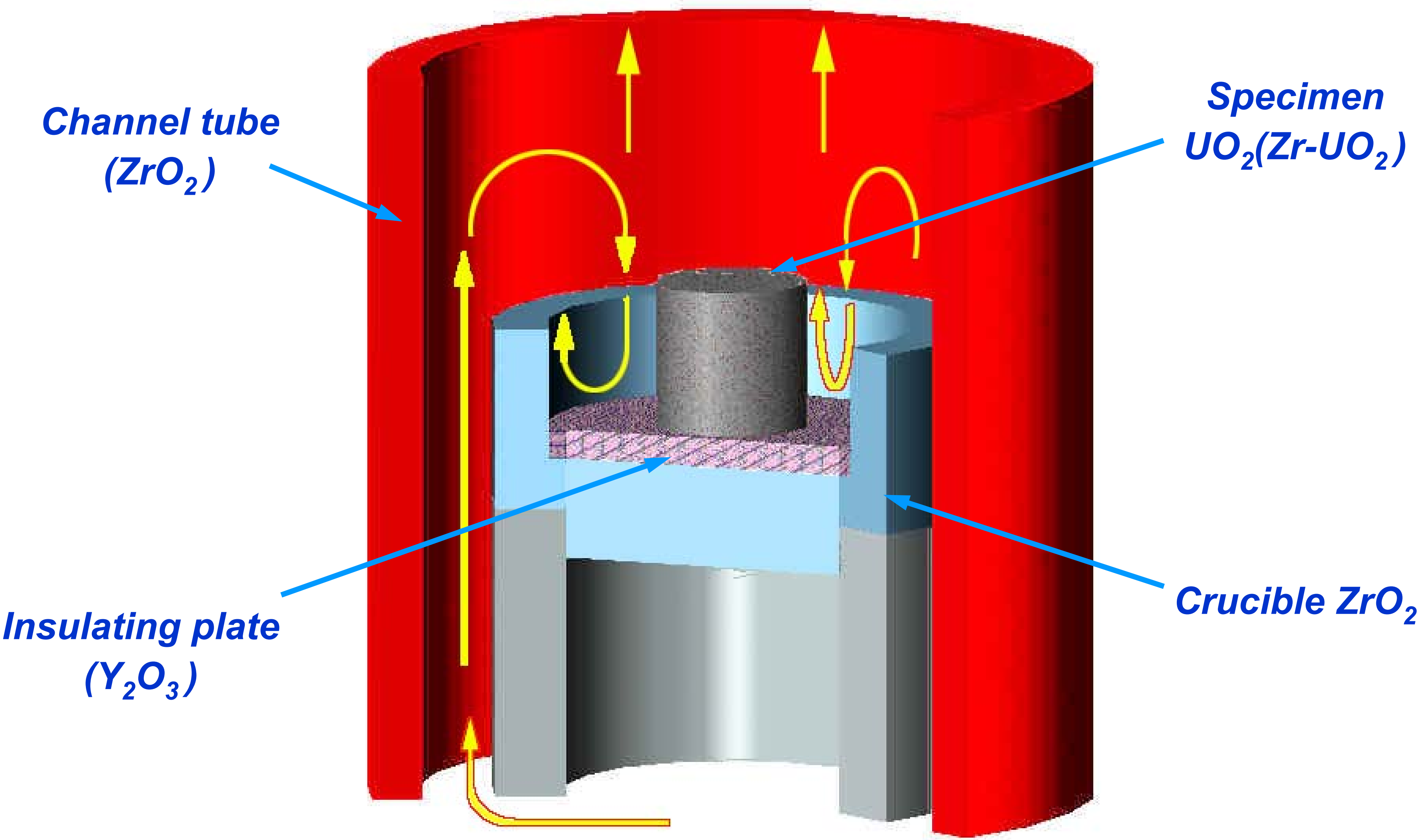


Test Rig



Hot cell
Condenser
Filter-
dehydrator
Carrier gas line
(in the case
of pure steam
environment)
Additional filter
Water collector
Main filter
Pressure
transducer
Specimen
Ceramic tubes
(ZrO_2, Al_2O_3, Al_2O_3)
Gamma-spectrometer
(FP measurement
in the filter)
Flow meter
Gamma-
spectrometer
(GFP measurement)
Gamma-
spectrometer
(FP measurement
in the specimen)
HF coil
Main channel
(ZrO_2)
Mass
spectrometer
Steam overheater
(800°C)
Specimen
holder
Protective
gas line
Heater(150°C)
Intel steam line
H_2
Inlet gas line
Pyrometer
He

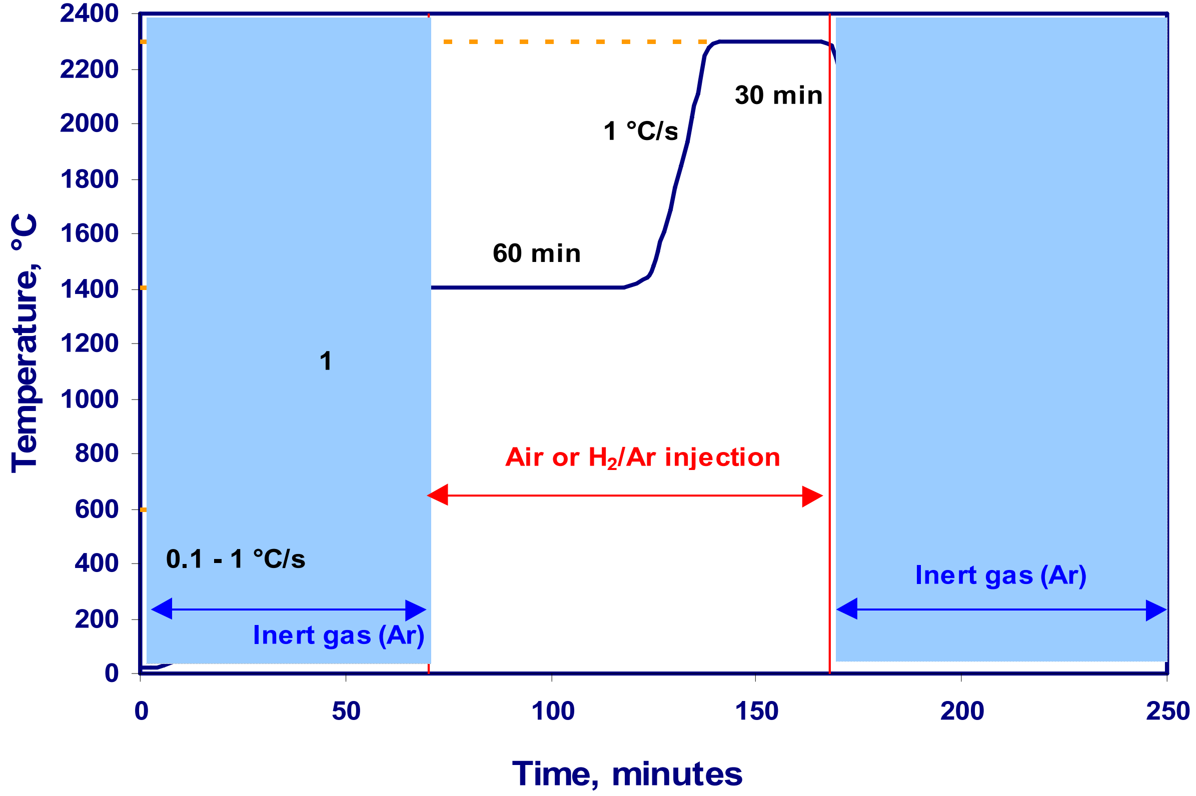
Crucible materials



Test Regime

Test temperature

- *heating in the inert atmosphere up to the temperature of 600 °C*
- *heating from 600 up to 1400 °C with a rate of 1 K/s*
- *annealing at 1400 °C during 1 hour (complete clad oxidation)*
- *heating with a rate of ~ 1 K/s up to the specified temperature (1700 or 2300 °C)*
- *annealing during 30 minutes*
- *end of heating*



Test Performance

Parameters to be measured during the test

- *intensity of GFP in the delay gas coil*
- *intensity of FP in a fuel specimen*
- *intensity of FP on the main filter*
- *hydrogen concentration in the carrier-gas at outlet*

Results to be obtained

- *relative FP release*
- *hydrogen generation* ***(in the case of steam injection)***

Post-Test Examinations

Fuel and cladding structure characterization

Optical metallography

- *grain size*
- *porosity*
- *gas swelling*
- *Fuel – cladding interaction*
- *Selection the positions for SEM / EPMA examinations*

SEM - *(polished surface and fractography) porosity, intra- and intergranular bubbles pattern.*

EPMA – *Fission product distribution, precipitates composition.*

TEM – *is not available*

SIMS – *May be applied to the very restricted number of specimens. Just the qualitative results are expected*

Part B. MFPR

(Model for Fission Products Release)

Objectives

On the base of new experimental results:

- ***to develop theoretical models of fission products and irradiated VVER fuel behaviour under conditions of severe accidents***
- ***to improve and to adapt physical models and codes developed for PWR fuel to VVER fuel***

MFPR Tasks in VERONIKA Project

- ***Pre-test calculations of new experiments for determination of parameters and conditions of the tests***
- ***Processing and analysis of results of new experiments***
- ***Development and improvement of the physical models on fission products release and high burnup VVER fuel behaviour under conditions of severe accident***
- ***Implementation of the developed and improved models in the MFPR code***
- ***Verification of the MFPR code against the new experimental database and other new available data at the end or during the program***

Project Costs

The first stage

(3 years duration, 777 400 $) :

- ***$T_1 0$ – beginning of the work under the project;***
- ***$T_1 0$+1 year – manufacturing and testing of the experimental rig, 315 k$;***
- ***$T_1 0$+1 year - adaptation of the MFPR code to the new experimental rig, pre-test calculations, 26.2 k$;***
- ***$T_1 0$+2,5 years – first series of tests (10 tests), 346.2 k$;***
- ***$T_1 0$+3,0 years – theoretical analysis of the obtained experimental data, development of models and codes, 80 k$.***

The second stage

(2.5 years duration, 494 000 $):

- ***$T_2 0$ – beginning of the second stage work;***
- ***$T_2 0$+1 year – second series of tests (10 tests), 343 k$;***
- ***$T_2 0$+2.5 years –post-test specimen examinations; theoretical analysis of the obtained experimental data, development of models and codes, 151 k$.***

The estimated total cost of the Project (2 stages) – 1 217 400 $