# Role of innovative nuclear fuel technologies to improve nuclear reactors' operation safety

## (Роль инновационных технологий ядерного топлива в повышении безопасности эксплуатации ядерных реакторов)


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# Outline

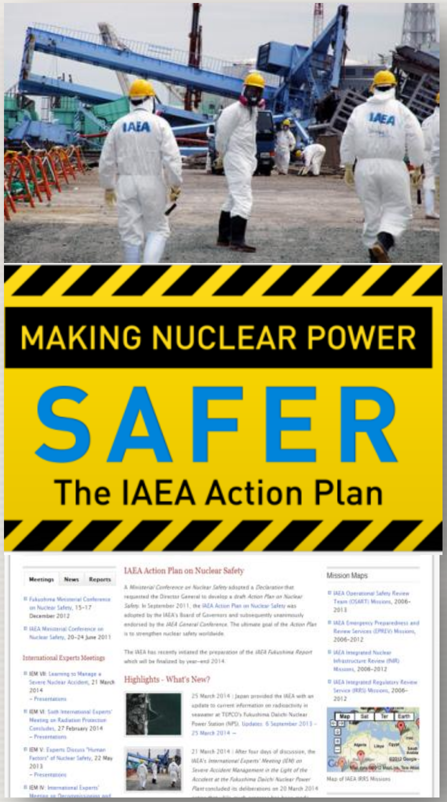
- IAEA Nuclear Safety Action Plan
- INPRO
- IAEA Fuel Engineering Programme
- CRP on FUel Modelling in Accident Conditions (FUMAC)
- CRP on Analysis of Options and Experimental Examination of Fuels with Increased Accident Tolerance (ACTOF)

# IAEA Nuclear Safety Action Plan

## Background

**Nuclear Safety Action Plan (NSAP) built on:**

- Following the Fukushima Dai-ichi accident in March 2011
- IAEA Ministerial Conference on Nuclear Safety *(June 2011)*
- $1^{st}$ IAEA Fact Finding Mission to Japan *(May/Jun 2011)*
- INSAG Letter Report *(Jul 2011)*
- Consultation with Member States




**NSAP endorsed by all MSs at $55^{th}$ IAEA GC** *(Sep 2011)*

- Defines a programme of work to strengthen the global nuclear safety framework
- As further lessons are learned they are incorporated into the Action Plan as new activities

**Importance of Transparency sharing and dissemination:**

http://www.iaea.org/newscenter/focus/actionplan/
http://www.iaea.org/newscenter/focus/fukushima/

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# IAEA Nuclear Safety Action Plan

## Contents

### 12 key actions, including 39 sub-actions:

Safety Assessments

IAEA Peer Reviews

Emergency Preparedness and Response

National Regulatory Bodies

Operating Organizations

IAEA Safety Standards


International Legal Framework

Member States Embarking on Nuclear Power

Capacity Building

Protection from Ionizing Radiation

Communication

Research & Development

**Technical Support Organizations Forum**
*(at the IAEA General Conference, September 2013)*

**International Conference on Challenges Faced by Technical and Scientific Support Organizations (TSO) in Enhancing Nuclear Safety and Security** *(October 2014)*

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# INPRO

## Origins

- Established in 2000  by initiative of President of the Russian Federation
- Authorized by IAEA General Conference resolutions

## Basic Characteristics

- International Project inside IAEA based on voluntary membership
- 42 Members participate currently
- Predominantly funded by extra-budgetary contributions (>70%)
- Provides cross-cutting activities with other technical Departments
- Essential part of the integrated services of the IAEA provided to MS considering initial development or expansion of NE programmes
- Section of NENP, with average 15 to 20 staff (mostly CFEs from Member States)

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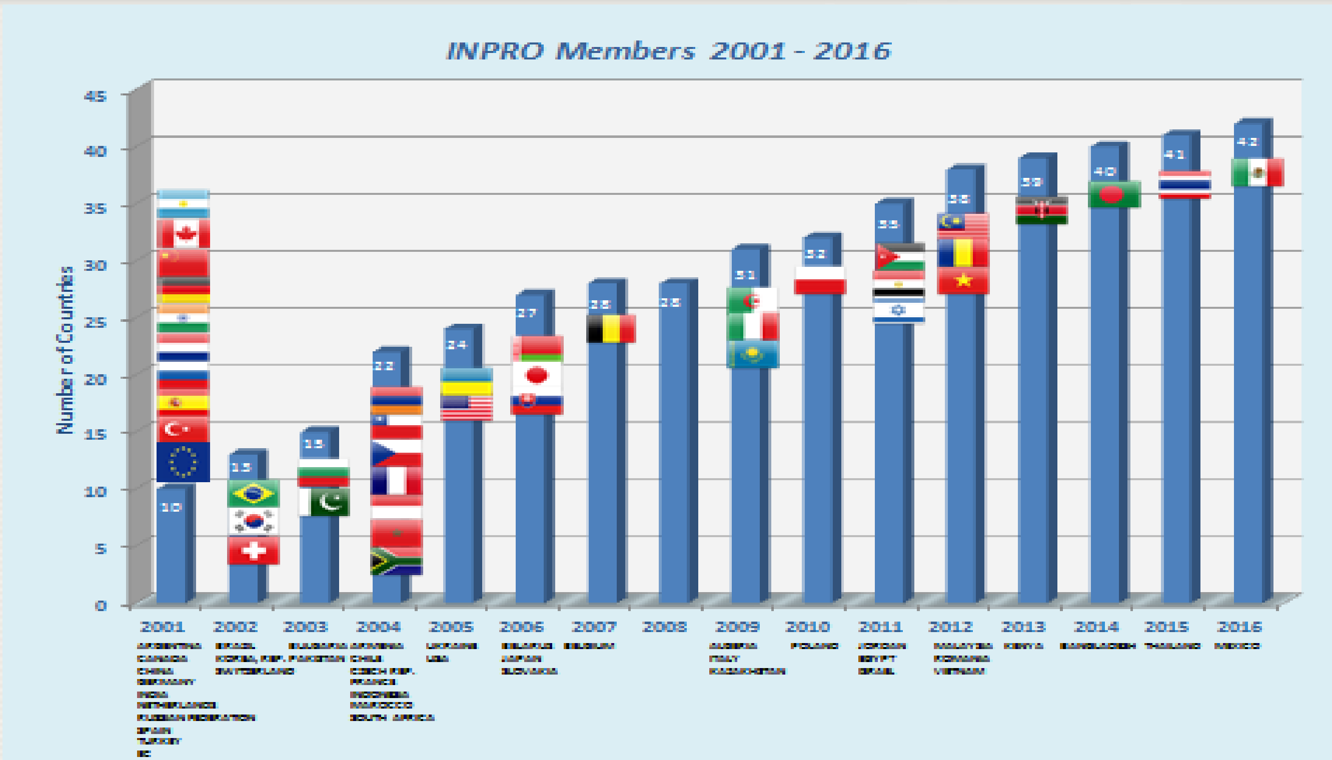
# INPRO Membership 2001-2016




In 2016 Mexico became the 42nd member of INPRO and INPRO membership has grown from an initial 10 to 42, which represents over 65% of the world population and 75% of the world's GDP. Several other countries have observer status as they consider membership or are participating on a project working level.

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# INPRO: CP Nuclear Fuel and Fuel Cycle Analysis for Future Nuclear Energy Systems (FANES)

## Objectives

- Provides overview of current fuel and fuel cycles and visions for future fuel and fuel cycles
- Conducts feasibility analyses of selected advanced and innovative fuels for different reactor systems
- Conducts feasibility analyses of selected fuel cycle options
- Identifies and discusses potential future nuclear energy systems (NES) using selected fuel and fuel cycles
- Considers possible recommendations for further international cooperation in this area

## Current participating countries and organizations:

Armenia, France, India, Israel, Romania, Russia, Ukraine, USA

It was proposed to ask Canada, China, Japan and Republic of Korea to join CP FANES

**Duration: 2014 - 2017**

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# IAEA Fuel Engineering Programme
## Nuclear Energy (NE) Department

## General Objectives

- To enable Member States to organize adequate R&D programmes to support effective design and manufacturing technologies and to optimize in-pile performance of current and advanced fuels and materials for reliability and efficiency

## Major tools

- **Technical Meetings:** Mini-conferences on the most relevant issues: outputs/conclusions usually published as IAEA-TECDOCs
- **Expert Reviews:** Studies usually made through a chain of Consultancy Meetings and Contracts
- **Coordinated Research Projects (CRP):**
  - Duration about 4 years
  - Members are Research Institutes/Organizations
  - Joint plan based on members' proposals

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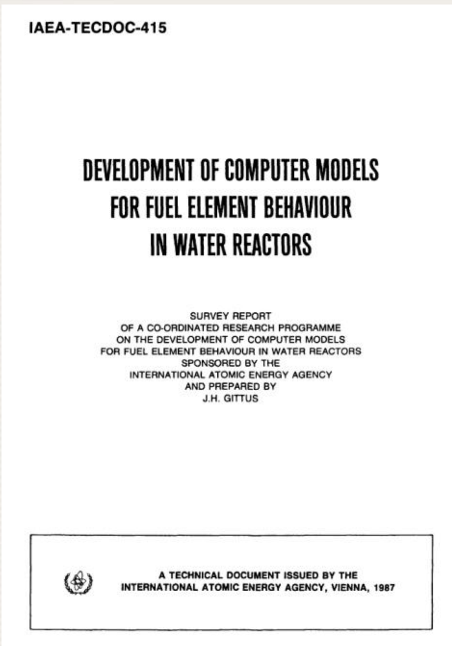
# CRP series on fuel modelling (1982-2012)

Blind exercises



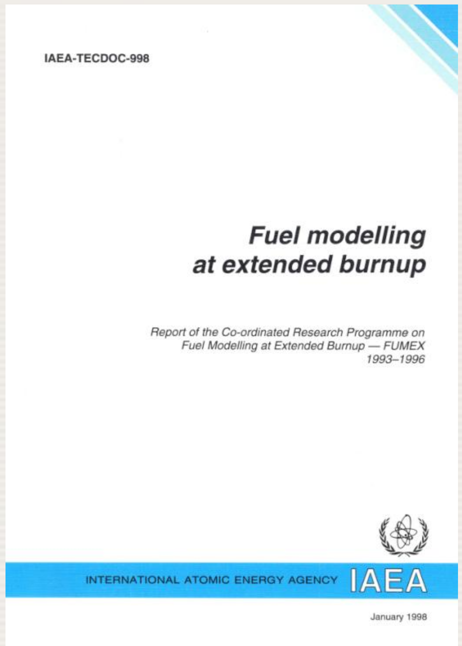
IAEA-TECDOC-415

DEVELOPMENT OF COMPUTER MODELS FOR FUEL ELEMENT BEHAVIOUR IN WATER REACTORS

SURVEY REPORT
OF A CO-ORDINATED RESEARCH PROGRAMME
ON THE DEVELOPMENT OF COMPUTER MODELS
FOR FUEL ELEMENT BEHAVIOUR IN WATER REACTORS
SPONSORED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND PREPARED BY
J.H. GITTUS

A TECHNICAL DOCUMENT ISSUED BY THE INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1987

CRP D-COM
1982-1984
published in 1987



IAEA-TECDOC-998

*Fuel modelling at extended burnup*

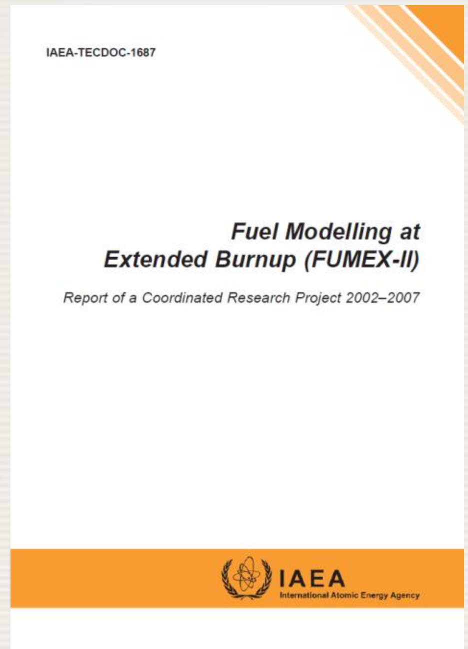
*Report of the Co-ordinated Research Programme on Fuel Modelling at Extended Burnup — FUMEX 1993–1996*

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

January 1998

CRP FUMEX
1993-1996
published in 1998

Joint NEA-IAEA International Fuel Performance Experiments (IFPE) Database



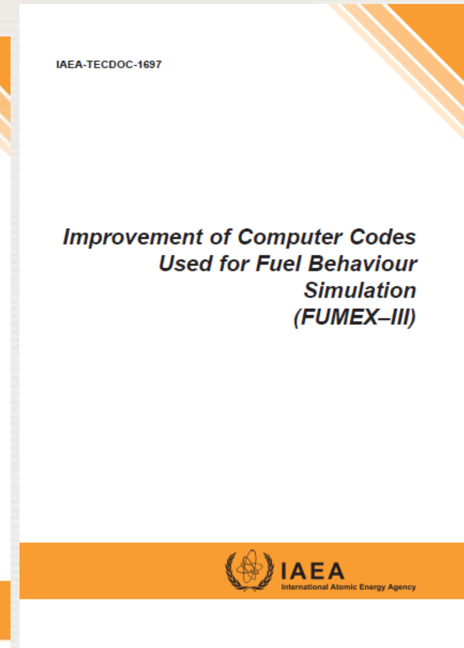
IAEA-TECDOC-1687

*Fuel Modelling at Extended Burnup (FUMEX-II)*

*Report of a Coordinated Research Project 2002–2007*

IAEA International Atomic Energy Agency

CRP FUMEX-2
2002-2007
published in 2012



IAEA-TECDOC-1697

*Improvement of Computer Codes Used for Fuel Behaviour Simulation (FUMEX–III)*

IAEA International Atomic Energy Agency

CRP FUMEX-3
2008-2012
published in 2013

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# CRP on FUel Modelling in Accident Conditions

## ❑ Coordinated Research Project FUMAC

- IAEA CRP T12028 (2014-2017)
- Continuation of the previous FUMEX projects, but focus on the accident conditions, following the IAEA Nuclear Safety Action Plan at enhancing safety of nuclear reactor operations after the Fukushima accident
- 27 organizations from 25 countries

## ❑ Objectives

- Better understanding of fuel behaviour in accident situations through identification of best practices in the application of relevant physical models and computer codes, used in different Member States, and enhancement of their predictive capacities
- Selecting well checked results of accident simulation experiments, integrating into the joint NEA-IAEA International Fuel Performance Experiments (IFPE) Database and using codes for verification and benchmarking

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# CRP FUMAC

## Scope

- Focus on LOCA (DBA) fuel behaviour, in line with the early stage of the scenario of the Fukushima accident (BDBA)
- Preparation of experimental data sets for code benchmarking:
  - Separate-effect tests with fuel cladding segments (MTA EK, Hungary)
  - Out-of-pile single-rod tests (NRC Studsvik LOCA tests 192 and 198)
  - Out-of-pile bundle tests (QUENCH facility, KIT, Germany)
  - In-pile tests (IFA 650.9-11, HALDEN)
- Benchmark exercises against HALDEN tests by participants using various fuel performance codes: FRAPCON (USA), TRANSURANUS (JRC-ITU), START-3 (VNIINM, Russia), SFPR (IBRAE, Russia)
- Thermal hydraulic boundary conditions for benchmark exercises → Calculated with the best-estimate integral SA code SOCRAT (Russia)

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# CRP “Analysis of Options and Experimental Examination of Fuels with Increased Accident Tolerance” (ACTOF)

- Main field of activity
  - Nuclear fuel performance and safety
- Background
  - Fukushima accident: zirconium cladding exacerbated the problem
  - New and improved fuel designs are being considered by many Member States
  - TWGFPT’s recommendation arising from post-Fukushima review
  - IAEA expertise in supporting fuel modelling – FUMAC CRP considers standard fuel modelling under accident conditions
  - Technical Meeting on Accident Tolerant Fuel held in US, 2014
- MSs’ participation (14 organizations from 11 MSs):

  Argentina (CNEA), Brazil (USP), China (CNPRI, CIAE, NPIC), Finland (VTT), Germany (KIT), India (BARC), Italy (NIE), Korea (KAERI), Poland (INCT), Russian Federation (VNIINM), United States (Westinghouse, Batelle)

# Advanced core materials

## Cladding/Core Materials

- Properties of material candidates
  - Coated and improved Zr-based alloys
  - SiC and SiC/SiC composites
  - Advanced steels (ODS, FeCrAl, …)
  - Refractory metals
- Evaluation under normal operations and SA conditions

## Fuel Concepts

- Properties of material candidates
  - Modified $UO_2$ (BeO, $Cr_2O_3$,…)
  - High density fuel (UN, UC, (U,Pu)N, $U_3Si_2$,…)
  - Composite fuel (UN-$U_3Si_2$,…)
  - Coated particle fuel
- Evaluation under normal operations and SA conditions
- PCI

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# CRP ACTOF (2015-18)

## ❑ Objective

To support options for the development of nuclear fuel with an improved tolerance of severe accident conditions:

- To acquire data through experiments on new fuel types and cladding materials to support their use for fuel with improved accident tolerance
- To support modelling of new fuel designs with advanced cladding or fuel

## ❑ Expected Results

- Well checked experimental data on the behaviour of candidate materials for Accident Tolerant Fuel designs
- New models of materials behaviour in fuel modelling codes
- Results of computer modelling of advanced fuel types under normal and accident conditions

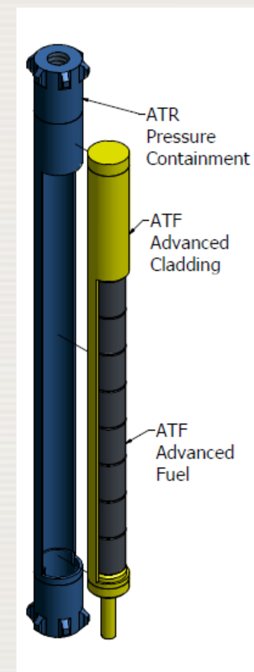
# Westinghouse, United States

➢ Design and development of:

- $U_3Si_2$ and UN-$U_3Si_2$ composite fuel
- SiC composite cladding
- $Ti_2AlC$ coated Zr cladding
- SiC wrapped Zr cladding

Coatings on ZIRLO® tubes


➢ Completion of test rods for research reactor testing




ATR irradiation capsule

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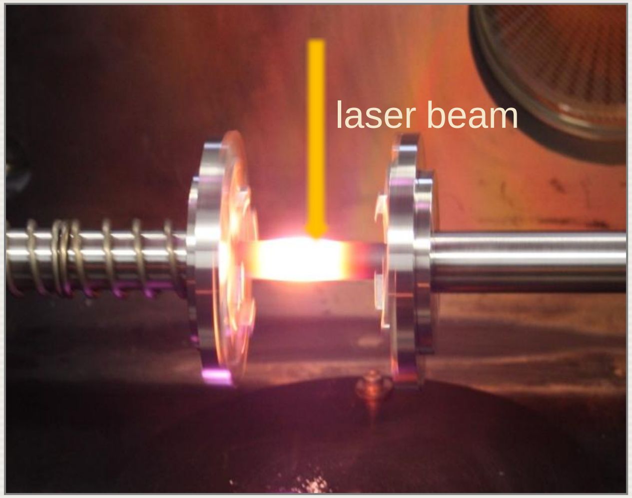
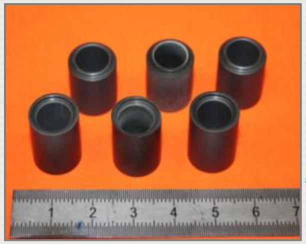
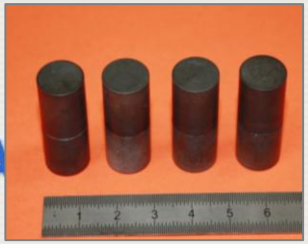
# KIT, Germany

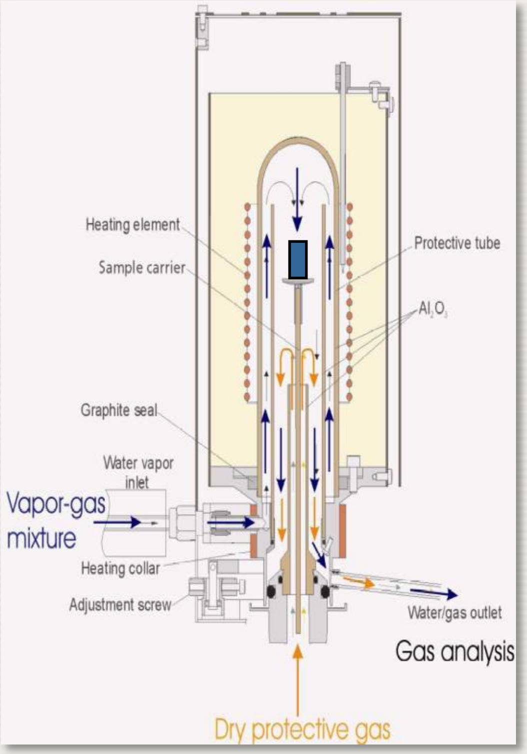
- Joining of SiC
- High temperature oxidation and quenching behavior of SiC
- Production, characterization and testing of coated zirconium alloys
- High temperature oxidation and quenching behavior of FeCrAl including large scale QUENCH test



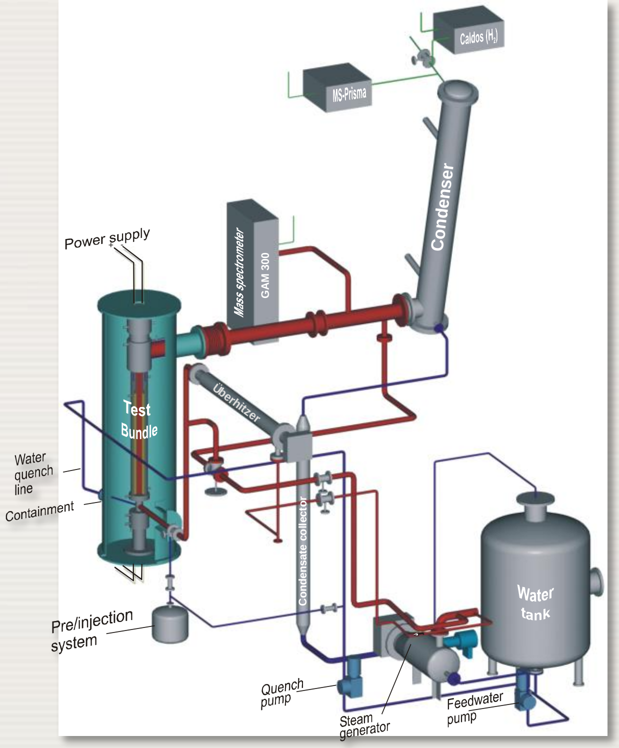

Joining process







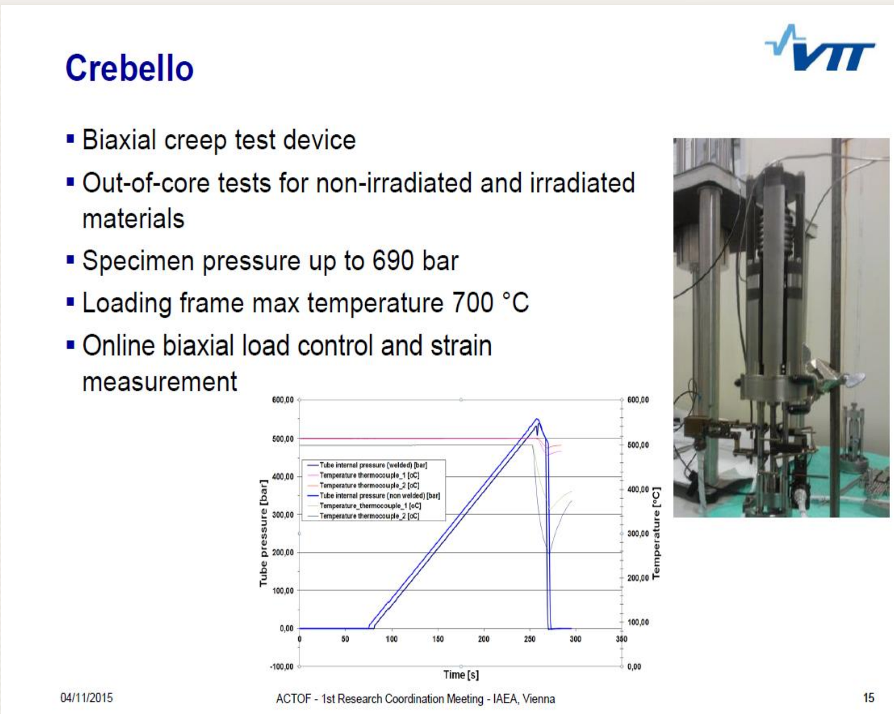

Steam furnace for TGA

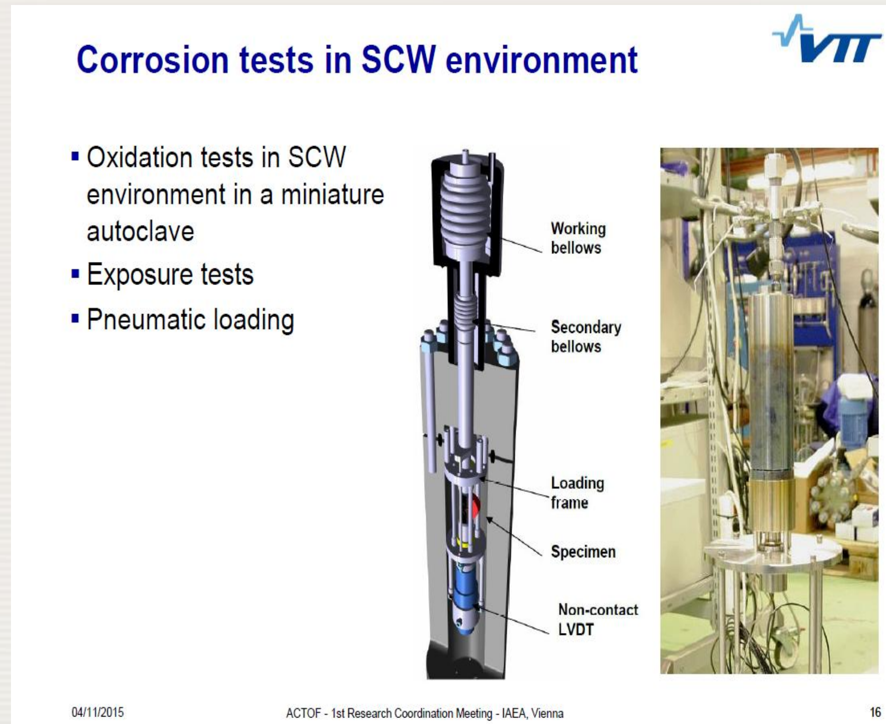



QUENCH test facility

# VTT, Finland

- Corrosion properties and creep and growth of candidate ATF cladding materials

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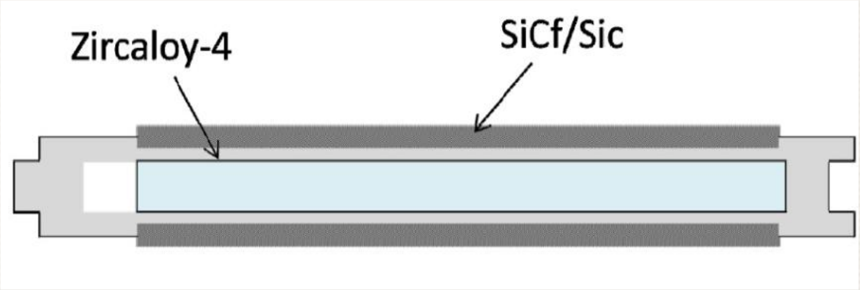
# Bhabha Atomic Research Centre, India

- Development of techniques for SiC coating on zirconium alloys and its characterisation
- Working out design improvement by using SiC tube, development of joining techniques for the ceramics performance
- Evaluation of the coated clad tube and the suggested modified design under high temperature steam environment



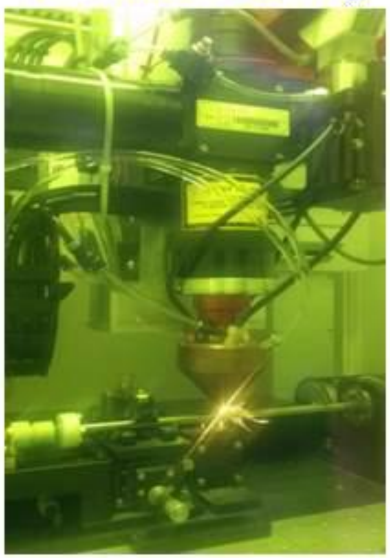

- SiC
- SiC-CMC
- SiC/SiC - composite
- Triplex SiC
- Hybrid Clading: SiC-CMC overbraid on Metal Hybrid

Round 6 after 30 months in MIT Reactor

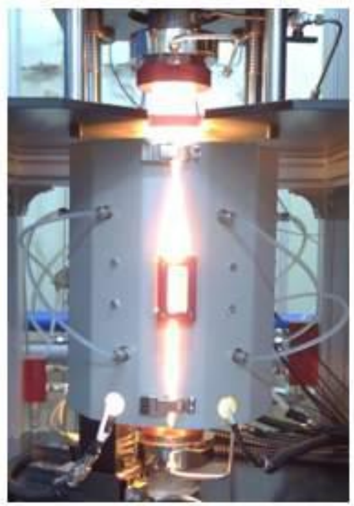
# KAERI, Korea

- Feasibility study of ATF fuel in the view of neutronics and safety analysis
- Development and implementation of ATF models for Cr-coated cladding and micro cell pellet
- Model validation using data from the out-of-pile data and in-pile data
- Continuing collaborative relationships and information exchange with international fuel modelling experts

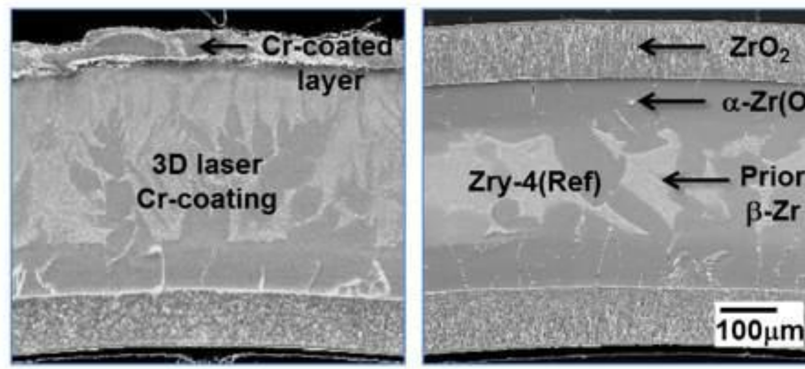
❖ 3D laser coating



Integral LOCA simulation test



Oxidation behavior at high temperature (1200°C)

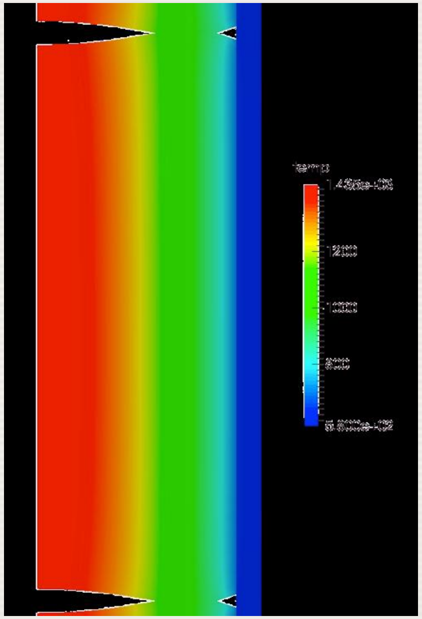



| Cr-coating | Zry-4 |
|---|---|
| 4 micron (1/30 of Zry-4) | ~113 micron |

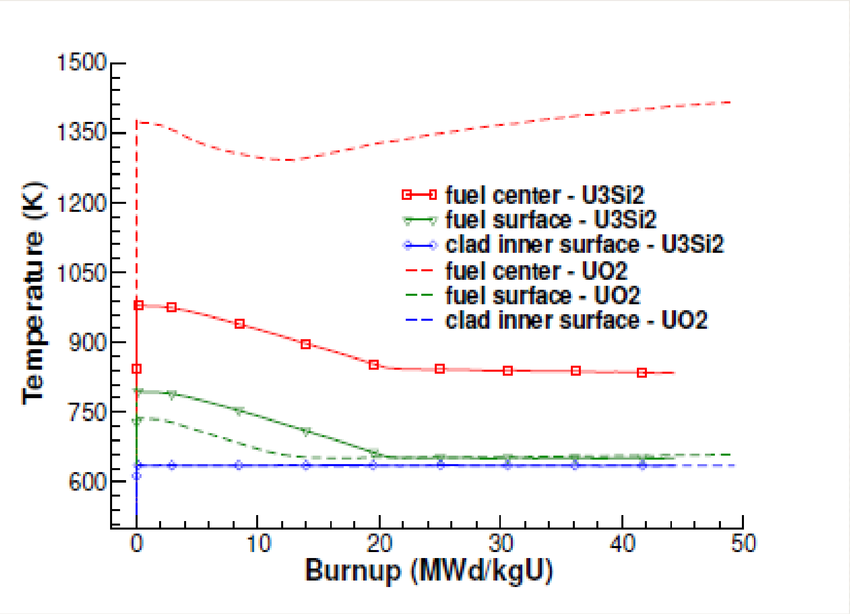
Surface coating of Zr cladding: Decreased corrosion at high temperature
→ Reduced hydrogen generation during accident

# Battelle Energy Alliance, USA

- Implement in INL's fuel performance code **BISON** material models and properties for FeCrAl and $U_3Si_2$
- Validate models against experiments
- Perform simulations of fuel rod behaviour with ATF cladding and/or fuel, both during normal operation and accidents
- Perform sensitivity studies on critical material properties using BISON interfaced to DOE uncertainty quantification tools



$UO_2$/FeCrAl

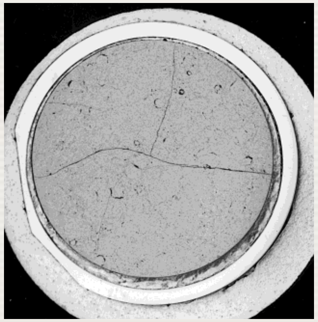


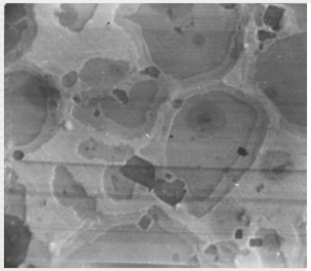

$UO_2$/Zry-4 vs. $U_3Si_2$/Zry-4

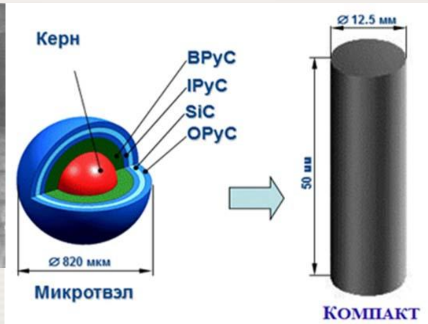
# A.A. Bochvar Institute (VNIINM), Russia

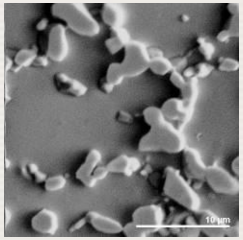
- Optimization of the R&D Programme of Accident Tolerant Fuel developments, including:
  - development of high density cold fuel
  - coated zirconium-based claddings
  - investigation and development of steel claddings
  - other directions: combination of methods, calculations and modeling ATF behavior, fuel cycle issues and economic aspects of ATF implementation

| **Composite fuel** | **UN-U(Pu)N** | **$U_3Si$ – $U_3Si_2$** | **Micro-capsulated fuel** | **Multiphase fuel** |
|---|---|---|---|---|





***Thanks***
***for your attention,***
***and welcome***
***to the IAEA projects!***

***(ACTOF is still open for new proposals)***

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