Update on IAEA Coordinated Research Project on Accident TOlerant Fuel Concepts for LWRs (ACTOF)

M. Veshchunov

Technical Lead (Fuel Engineering)
Nuclear Fuel Cycle and Materials Section
Division of Nuclear Fuel Cycle and Waste Technology
Department of Nuclear Energy
IAEA, Vienna, Austria

5th Meeting Of The Expert Group On Accident Tolerant Fuels for Light Water Reactors (EGATFL-05)

12-14 April 2016
NEA HQ,
Boulogne Billancourt,
France

IAEA
International Atomic Energy Agency

IAEA Fuel Engineering Programme
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 Programme (MP) 1: NUCLEAR POWER AND FUEL CYCLE
  - Programme (P) 1.2: Nuclear Fuel Cycle and Materials Technologies
    - Subprogramme (SP) 1.2.2: Nuclear Power Reactor Fuel
      - ✓ Project 1.2.2.001: Nuclear Power Reactor Fuel Engineering
      - ✓ Project 1.2.2.003: AP Support Related to Nuclear Power Reactor Fuel

IAEA

Major tools of the Fuel Engineering programme implementation

1. **Technical Meetings:** mini-conferences on the most relevant issues: outputs/conclusions usually published as IAEA-TECDOCs

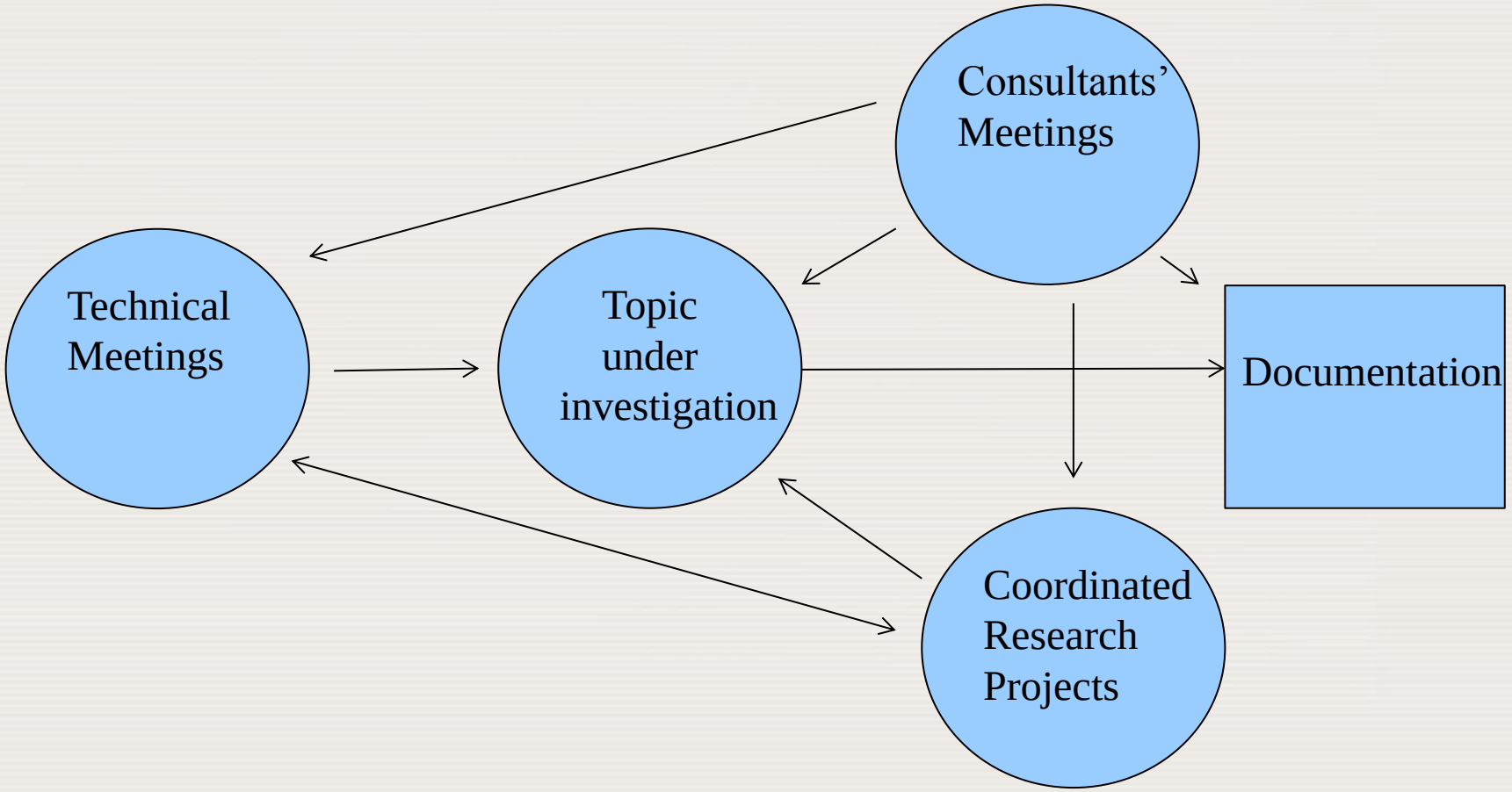
2. **Expert Reviews:** studies usually made through a chain of Consultants Meetings and Contracts

3. **Coordinated Research Projects (CRP):**
   - Duration about 4 years
   - Members are institutes/organizations
   - Joint plan based on members' proposals
   - For all details and procedures, visit http://cra.iaea.org/cra/index.html

❖ CRPs are the most systematic, durable and expensive tools of the Fuel Engineering programme implementation

IAEA

Major tools of the Fuel Engineering programme implementation



Technical Meetings organized during 2005-2015

Technical Meetings		Host	2005	06	07	08	09	10	11	12	13	14	15
Behaviour of high corrosion resistant Zr-based alloys	www.iaea.org/OurWork/ST/NE/NESeries/Working Materials/HighCorrosionResistanceWM.pdf	Argentina											
High burnup fuel experience and economics	(www.iaea.org/OurWork/ST/NE/NESeries/Working Materials/HighFuelBurnupExperienceWM.pdf	Bulgaria											
Hot cell PIE and pool-side inspection of techniques for water reactor fuel	TECDOC-CD-1635	Argentina											
PHWR fuel modelling	www.iaea.org/OurWork/ST/NE/NESeries/Working Materials/PHWR-fuel-WM.pdf	India											
Fuel rod instrumentation and in-pile measurement techniques	TECDOC-CD-1635	Norway											
PHWR fuel design, fabrication and performance	www.iaea.org/OurWork/ST/NE/NESeries/Working Materials/PHWR-fuel-WM.pdf	Argentina											
Advanced pellet materials and rod designs	TECDOC-1654	Switzerland											
Current issues in fuel quality and reliability assurance	NE Series Guide NF-G-2.1	Austria											
Water chemistry and clad corrosion including fuel failures	TECDOC-CD-1692	Ukraine											
Hot-cell PIE and pool-side inspection	TECDOC-CD-1693	Slovakia											
Design, manufacturing and radiation behaviour of fast reactor fuels	TECDOC-1689	Russia											
Fuel behavior and modeling under severe transient and LOCA conditions	TECDOC-1709	Japan											
Fuel design and licensing of mixed cores, with NS and NP	TECDOC-1720	Austria											
Fuel integrity during normal operation and accident conditions in PHWR	TECDOC-CD-1751	Romania											
In-pile testing and instrumentation for development of Gen-IV materials	TECDOC-CD-1726	Norway											
Primary Radiation Damage	www-nds.iaea.org/dpa	Austria											
Modelling of water-cooled fuel including design basis and severe accidents	TECDOC-CD-1775	China											
Advanced Fuel Cycles in PHWRs	TECDOC-CD-1751	India											
Management and use of RepU in water-cooled reactors		Austria											
High burnup fuel experience and economics	TECDOC in publication	Argentina											
Trends in the development of advanced fuels for fast reactors	TECDOC in publication	India											
Accident Tolerant Fuel concepts for Light Water Reactors, 13-17 October 2014	TECDOC in publication	USA											
Characterization and thermo-physical properties of advanced nuclear fuels		Austria											
Towards zero fuel failure rates: challenges and perspectives	Included into WWER Fuel 2015 Proceedings	Bulgaria											
PHWR fuel safety criteria and licensing		Canada											
Beyond 5% enrichment limit for LWR: perspectives and problems	TECDOC planned	Austria											

IAEA

Expert Reviews organized during 2010-2015

Expert Reviews		2010	11	12	13	14	15
Review of fuel failures in water-cooled power reactors, 1994-2006	NE Series Report NF-T-2.1						
Use of reprocessed Uranium: challenges and options	NESeries Report NF-T-4.4						
Status and trends of nuclear fuel technology for sodium cooled fast reactors	NE Series Report NF-T-4.1						
Structural materials for liquid metal cooled fast reactor fuel assemblies	NE Series Report NF-T-4.3						
Experiences and trends of manufacturing technology of advanced nuclear fuels	TECDOC-1686						
Operation and licensing of Mixed Cores in water-cooled reactors	TECDOC-1720						
Quality and reliability aspects in Nuclear Power Reactor Fuel Engineering	NE Series Guide NF-G-2.1						
Zirconium in nuclear industry	IAEA book, in publication						
Accelerator simulation and theoretical modelling of radiation effects	NE Series Report, in publication						
Review of fuel failures in water-cooled power reactors, 2006-2015	TECDOC planned						

IAEA

Coordinated Research Projects organized during 2005-2015

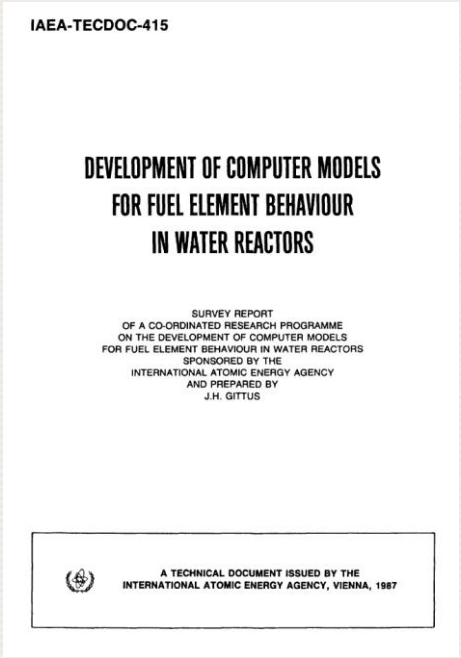
Coordinated Research Projects		2005	06	07	08	09	10	11	12	13	14	15
Delayed Hydride Cracking of zirconium alloy fuel cladding, DHC-2	TECDOC-1649											
Optimization of water chemistry to ensure reliable fuel performance at high burnup and in aging plant, FUWAC	TECDOC-1666											
Modelling of transport of radioactive substances in the primary circuit	TECDOC-1672											
Fuel behaviour modelling at extended burnup, FUMEX-2	TECDOC-1687											
Improvement of computer codes used for fuel behaviour simulation, FUMEX-3	TECDOC-1697											
Accelerator simulation and theoretical modelling of radiation effects, SMoRE	NE Series Report draft											
Development, characterization and testing of materials of relevance to nuclear energy sector using neutron beams	TECDOC-CD-1773											
Evaluation of conditions for hydrogen-induced degradation of zirconium alloys, DHC-3	TECDOC-1781											
Benchmarking of structural materials preselected for advanced nuclear reactors	TECDOC in preparation											
Options for deployment of thorium-based nuclear energy	TECDOC-1761, one more planned											
Reliability of high power, extended burnup and advanced PHWR fuels	CRP-T12027, started in 2014											
Fuel modelling in accident conditions, FUMAC	CRP-T12028, started in 2014											
Analysis of options and experimental examination of fuels for water-cooled reactors with increased accident tolerance, ACTOF	CRP-T12030, started in 2015											
Simulation and modelling of radiation effects, SMoRE-2	CRP-2017, open for proposals											

IAEA

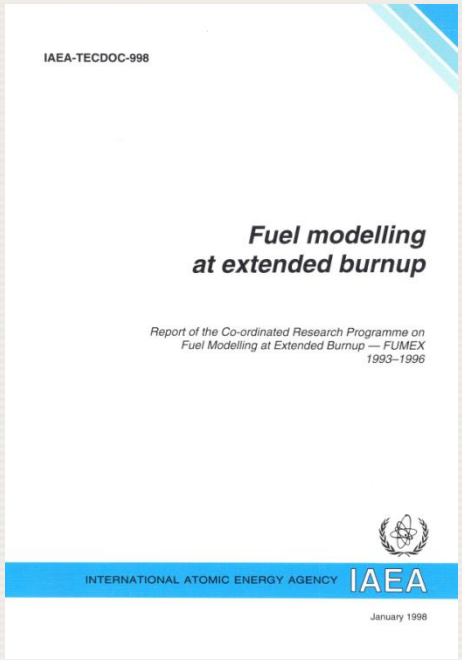
CRP series on fuel modelling (1982-2012)

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

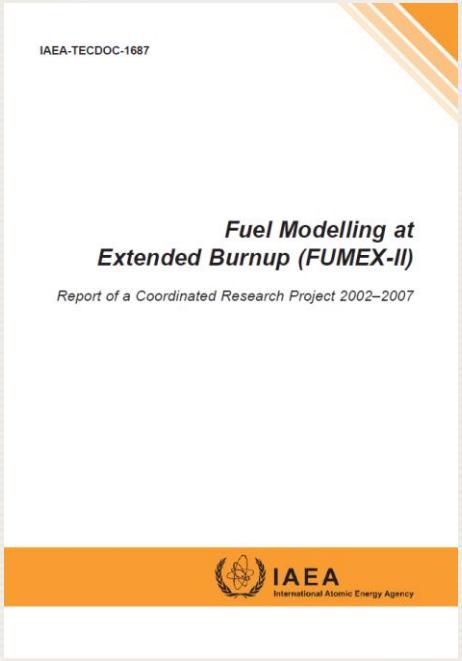
Blind exercises



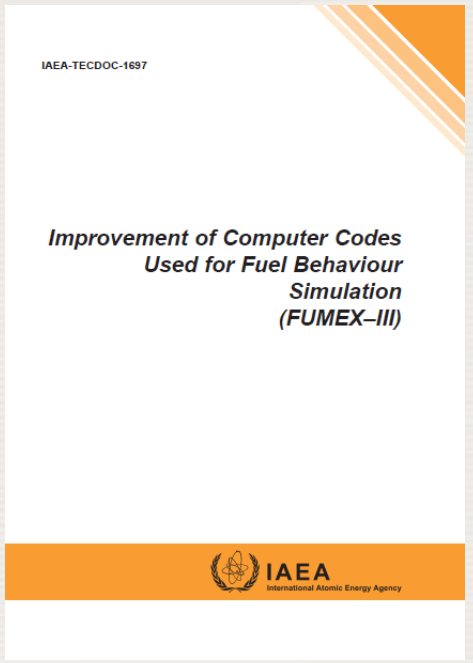
CRP D-COM
1982-1984
published in 1987



CRP FUMEX
1993-1996
published in 1998



CRP FUMEX-2
2002-2007
published in 2012



CRP FUMEX-3
2008-2012
published in 2013

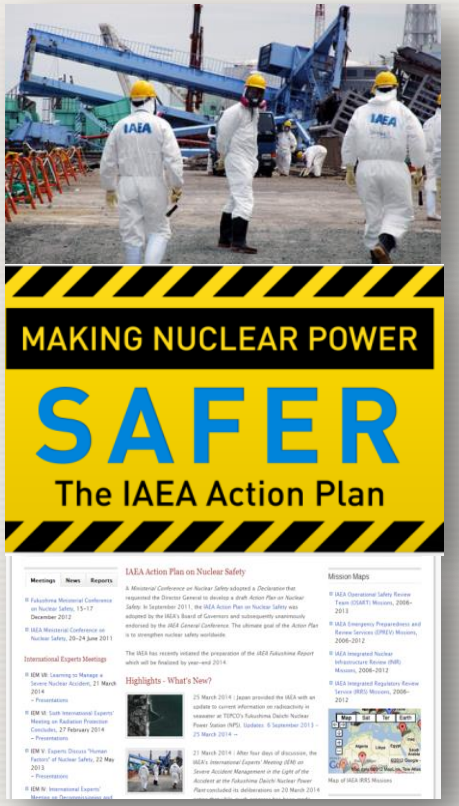
IAEA

IAEA Nuclear Safety Action Plan

Background

Nuclear Safety Action Plan (NSAP) built on:

- IAEA Ministerial Conference on Nuclear Safety *(June 2011)*
- 1st IAEA Fact Finding Mission to Japan *(May/Jun 2011)*
- INSAG Letter Report *(Jul 2011)*
- Consultation with Member States



NSAP unanimously endorsed at 55th 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/

IAEA

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)*

IAEA

IAEA Nuclear Safety Action Plan
CRP FUMAC

CRP "FUel Modelling in Accident Conditions" (FUMAC)

- IAEA Coordinated Research Project CRP T12028 (2014-2017).
- Continuation of the previous FUMEX projects, but focus on the accident conditions, following the IAEA Nuclear Safety Action Plan, after the Fukushima accident, aiming at enhancing the safety of nuclear reactors' operation

❑ 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
- Well checked results of accident simulation experiments are selected, integrated into the joint NEA-IAEA International Fuel Performance Experiments (IFPE) Database, and used for codes verification and comparisons

IAEA

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 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

IAEA

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
  - Support modelling of new fuel designs with advanced cladding or fuel

IAEA

Overall Expected Outcome

- Provision of information to Member States to support decision making on the choices available to improve the safety of Nuclear Power Plants under severe accident conditions
- Provision of data, analyses and advanced techniques to understand and predict the behaviour of the components and the integral performance of accident tolerant fuel designs under normal and transient conditions, and to demonstrate improvements under severe accident conditions

IAEA

Nuclear Component

- The performance of nuclear fuel is key to the safe operation of nuclear power plants
- Development and modelling of advanced fuel types that can better withstand the extreme conditions found in severe accident conditions will improve safety margins
- The subject of CRP ACTOF fully corresponds to the aim of the IAEA Nuclear Safety Action Plan to enhance safety of nuclear reactors' operation

IAEA

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

IAEA

Duration, Budget and MSs' participation

- Planned duration of CRP T12030: 2015-2018
  - The first RCM was held from 2 to 4 November 2015 in Vienna
  - Collection and preparation of all data (ACTOF Project website): https://nucleus.iaea.org/sites/nefw-projects/crpactof/SitePages/Home.aspx
- Budget: Regular Budget (Project 1.2.2.003: AP Support Related to Nuclear Power Reactor Fuel)
- 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)

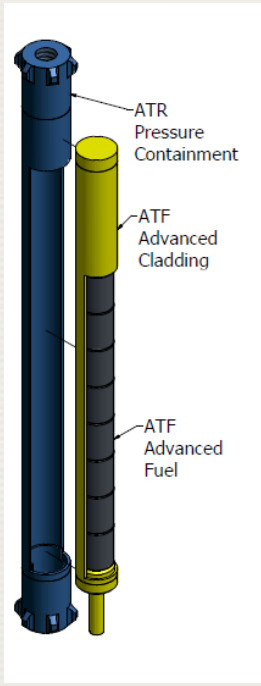
IAEA

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

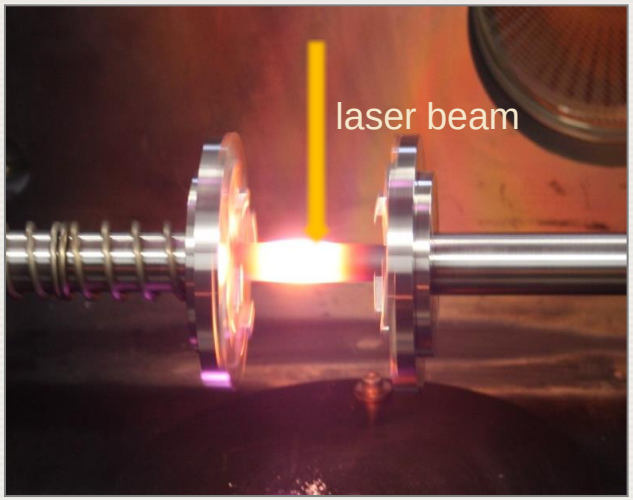
- Completion of test rods for research reactor testing



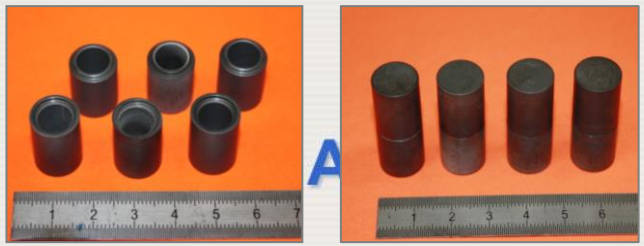
ATR irradiation capsule

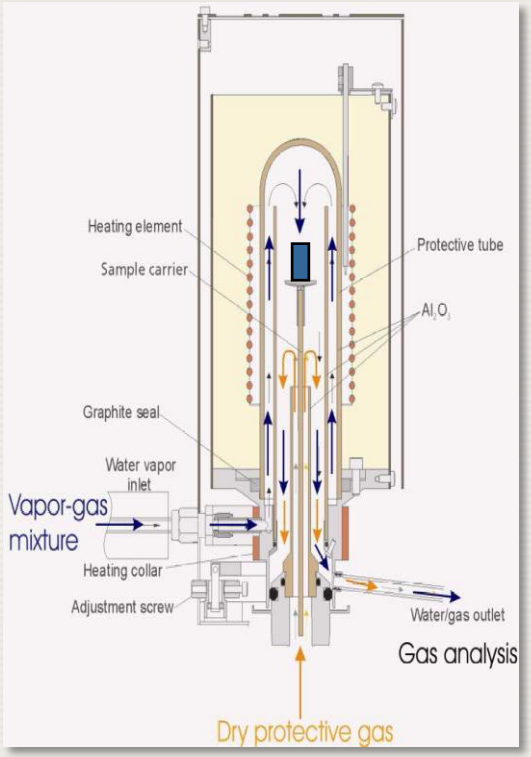
KIT, Germany

- 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

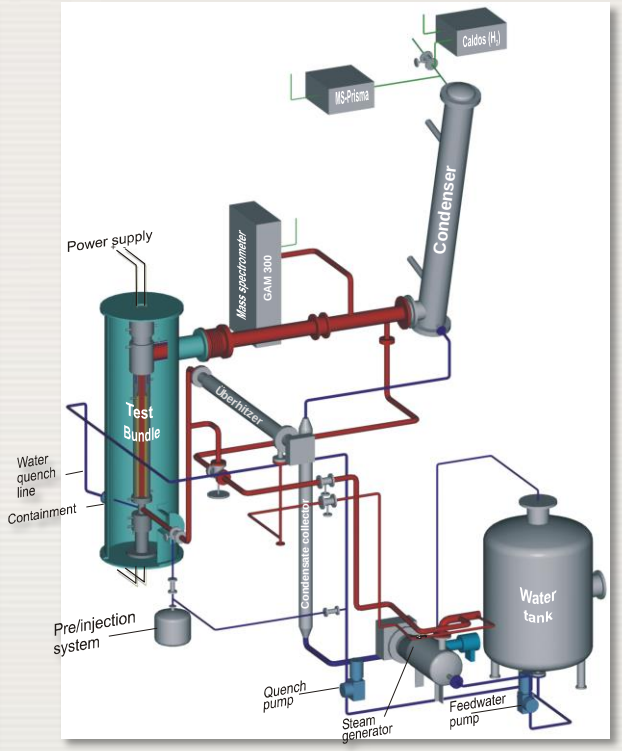


Joining process





Steam furnace for TGA



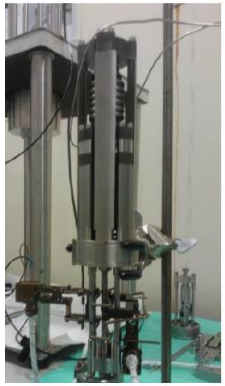
QUENCH test facility

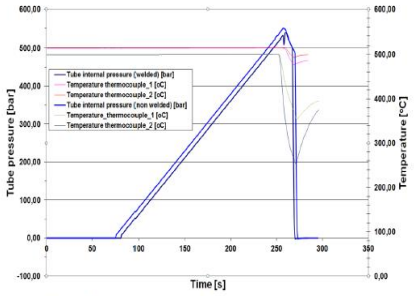
VTT, Finland

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

Crebello

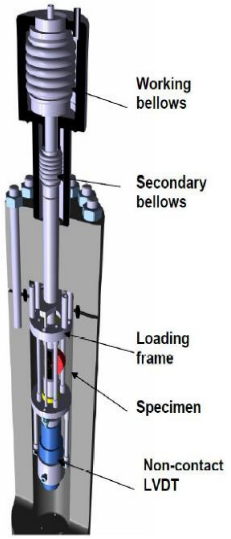
- Biaxial creep test device
- Out-of-core tests for non-irradiated and irradiated materials
- Specimen pressure up to 690 bar
- Loading frame max temperature 700 °C
- Online biaxial load control and strain measurement

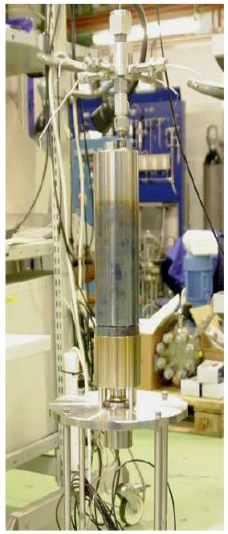




Corrosion tests in SCW environment

- Oxidation tests in SCW environment in a miniature autoclave
- Exposure tests
- Pneumatic loading



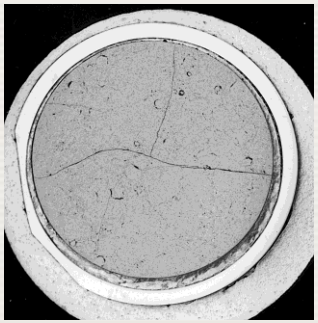


A.A. Bochvar Institute (VNIINM), Russia

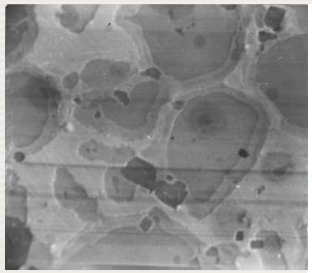
- Optimization of the R&D Programme of Accident Tolerant Fuel developments, including:
  - development of high density cold fuel
  - coated zirconium-based claddings
  - investigation and development of steel claddings
  - other directions: combination of methods, calculations and modeling ATF behavior,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

Composite fuel

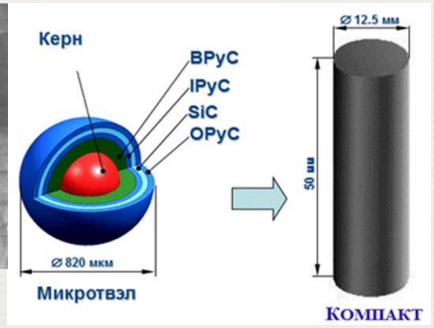
UN-U(Pu)N



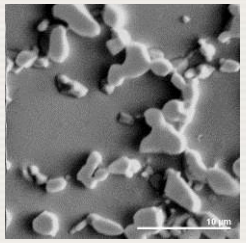
U_3Si – U_3Si_2



Micro-capsulated fuel

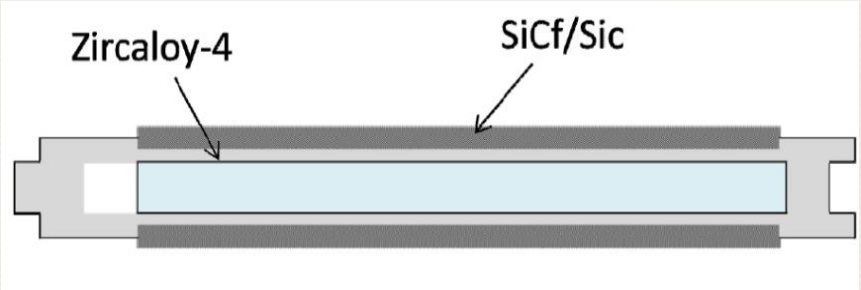


Multiphase fuel



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



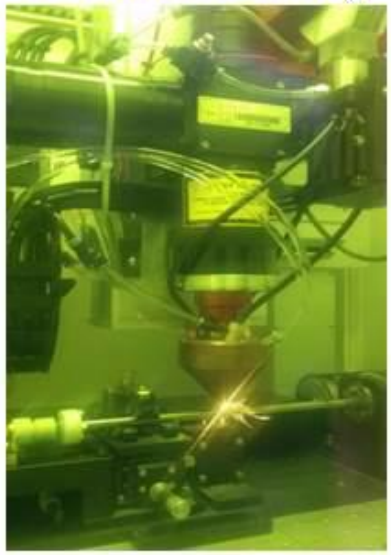
- SiC
- SiC-CMC
- SiC/SiC - composite
- Triplex SiC
- Hybrid Clading: SiC-CMC overbraid on Metal Hybrid

IAEA

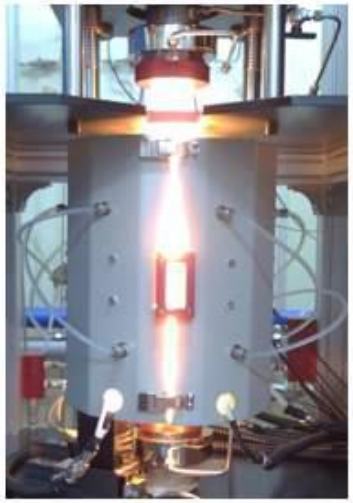
KAERI, Korea

- 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

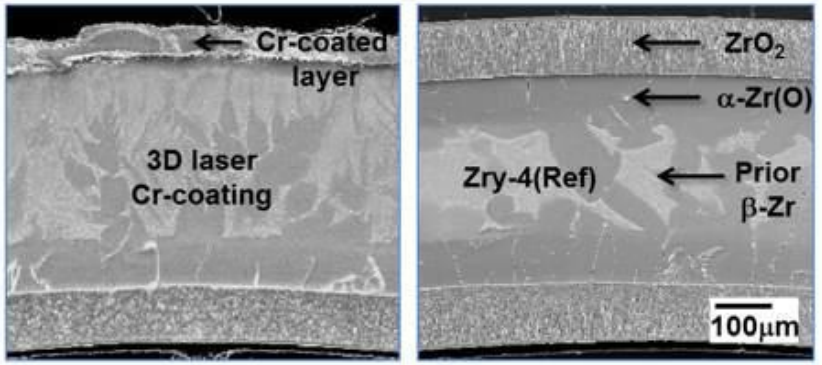
❖ 3D laser coating



Integral LOCA simulation test



Oxidation behavior at high temperature (1200°C)

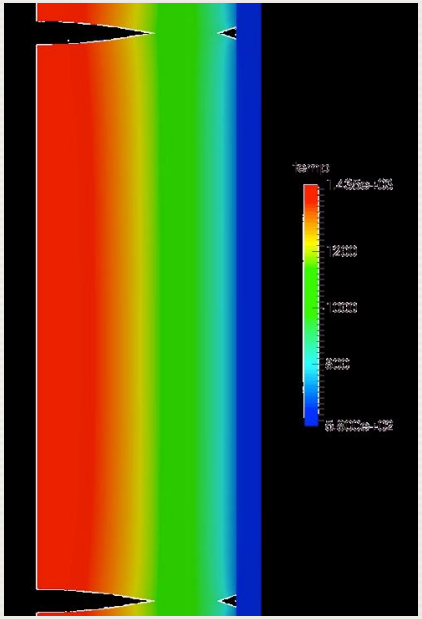


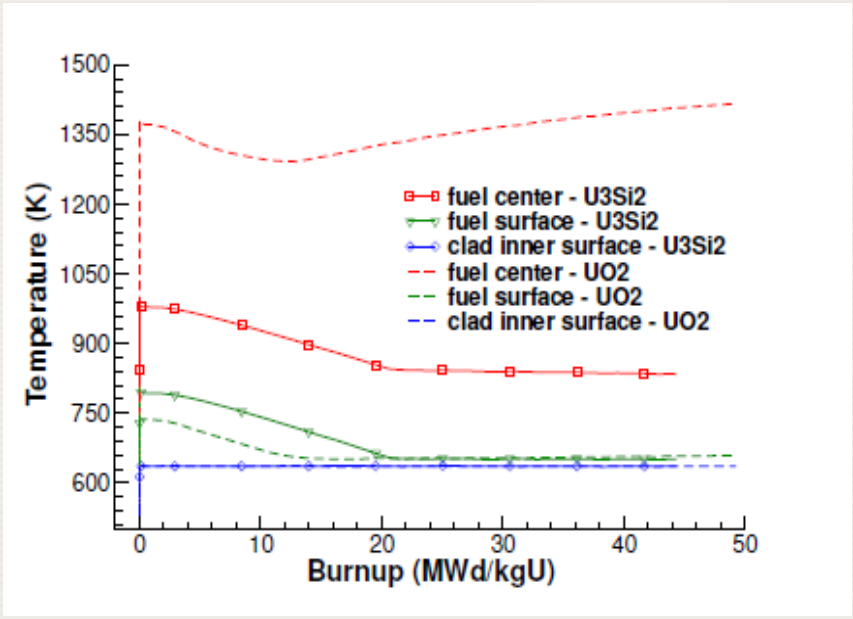
Cr-coating	Zry-4
4 micron (1/30 of Zry-4)	~113 micron

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





IAEA

UO_2/FeCrAl

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

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

(ACTOF is still open for new proposals)

IAEA
International Atomic Energy Agency