Sodium Fast Reactor

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Session II
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The SFR system was identified during the Generation IV Technology Roadmap as a promising technology to perform the actinide management mission and if enhanced economics for the system could be realized, also the electricity and heat production missions. The main characteristics of the SFR that make it especially suitable for the actinide management mission are:

- **Consumption of transuranics in a closed fuel cycle, thus reducing the radiotoxicity and heat load which facilitates waste disposal and geologic isolation.**
- **Enhanced utilization of uranium resources through efficient management of fissile materials and multi-recycle.**
- **High level of safety achieved through inherent and passive means that accommodate transients and bounding events with significant safety margins.**

System Research Plan

Development Targets and Design Requirements

SFR R&D Projects

- ***System Integration and Assessment (SIA)***
- ***Safety and Operations***
- ***Advanced Fuel***
- ***Component Design and Balance of Plant***
- ***Global Actinide Cycle International Demonstration (GACID)***

SFR Design Concepts

- ***Loop Option (JSFR Design Track)***
- ***Pool Option (KALIMER-600 & ESFR Design Tracks)***
- ***Small Modular Option (SMFR Design Track)***

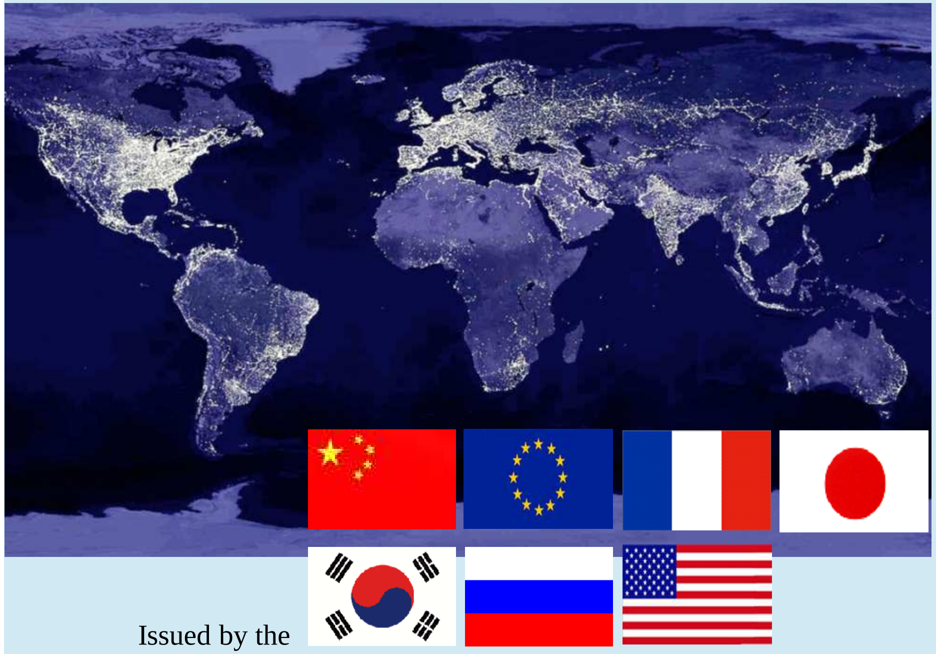
SRP was updated and released in July 2013

Generation IV Nuclear Energy Systems
System Research Plan
for the Sodium-cooled Fast Reactor

Revision 2

July 12, 2013

Preparing Today for Tomorrow's Energy Needs



Issued by the
Generation IV International Forum
SFR System Steering Committee

Status of SFR Arrangements

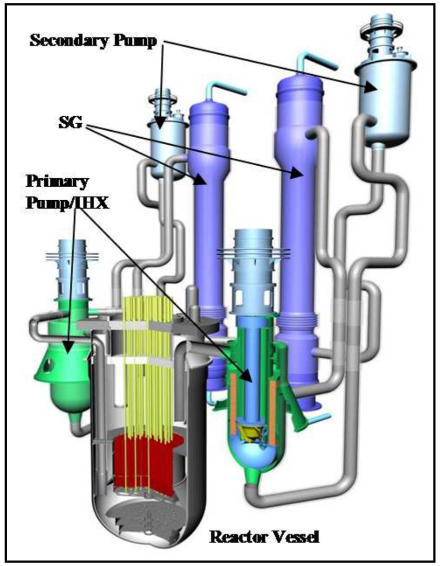
	EUR	FRA	JPN	PRC	ROK	RUF	USA
SFR System Arrangement (Signed - 15 Feb 2006)	X	X	X	X	X	X	X
SFR AF PA (Signed - 21 Mar 2007)	X	X	X	P	X	P	X
SFR GACID PA (Signed - Sept 2007)		X	X				X
SFR CDBOP PA (Signed - 11 Oct 2007)	P	X	X	2016	X	2016	X
SFR SO PA (Signed - 11 June 2009, Resigned – 15 Nov 2012)	X	X	X	X	X	X	X
SFR SIA PA (Signed - 22 Oct 2014)	X	X	X	X	X	X	X

X=Signatory, **D**=Under Discussion, P=In Progress

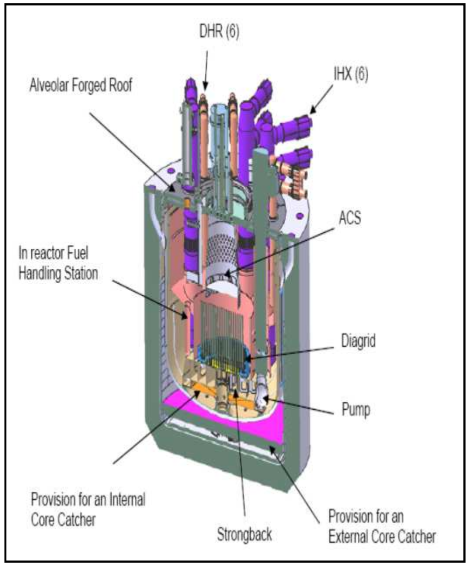
Gen IV SFR System Options and Design Tracks

Loop | **Pool** | **Small Modular**

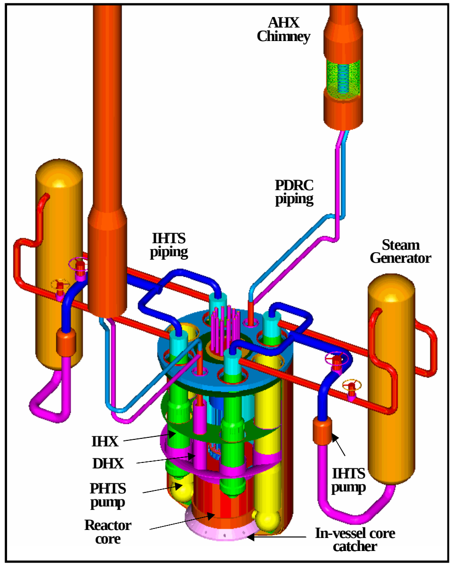
JSFR



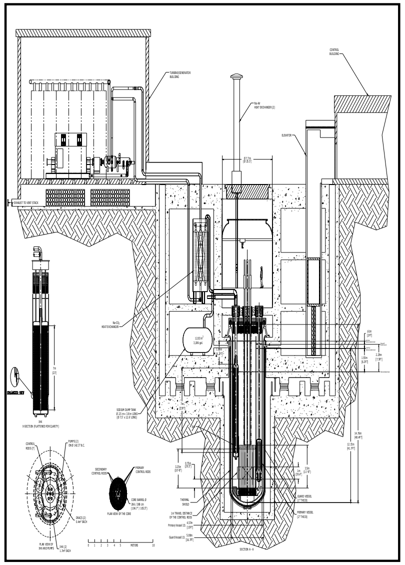
ESFR



KALIMER



SMFR



BN-1200 will be presented by Russia as new Gen-IV SFR design track for the next SIA meeting

System Integration & Assessment Project

System Integration & Assessment Project

Objectives

- *Integration of the results of R&D Projects*
- *Performance of design and safety studies*
- *Assessment of the SFR System against the goals and criteria set out in the Gen IV Technology Roadmap*

Integration Role

Specific tasks have been developed and refined

- *Identify Generation-IV SFR Options*
  - *General system options*
  - *Specific design tracks*
  - *Contributed trade studies*
- *Maintain comprehensive list of R&D needs*
- *Review Generation-IV SFR Technical Projects*
- *Unlike the technical Projects, based on synthesis of results produced by other Projects*

Safety & Operation Project

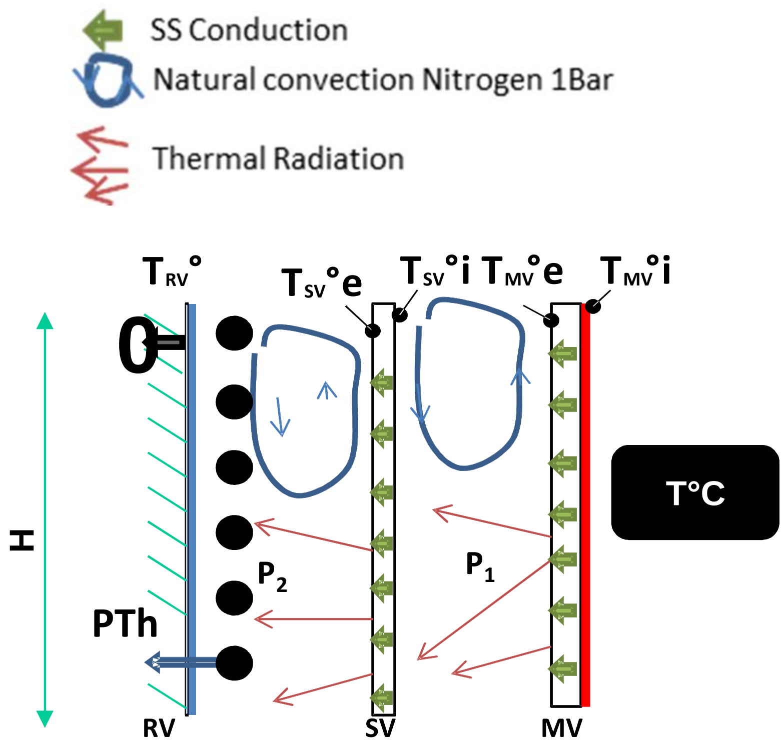
Members

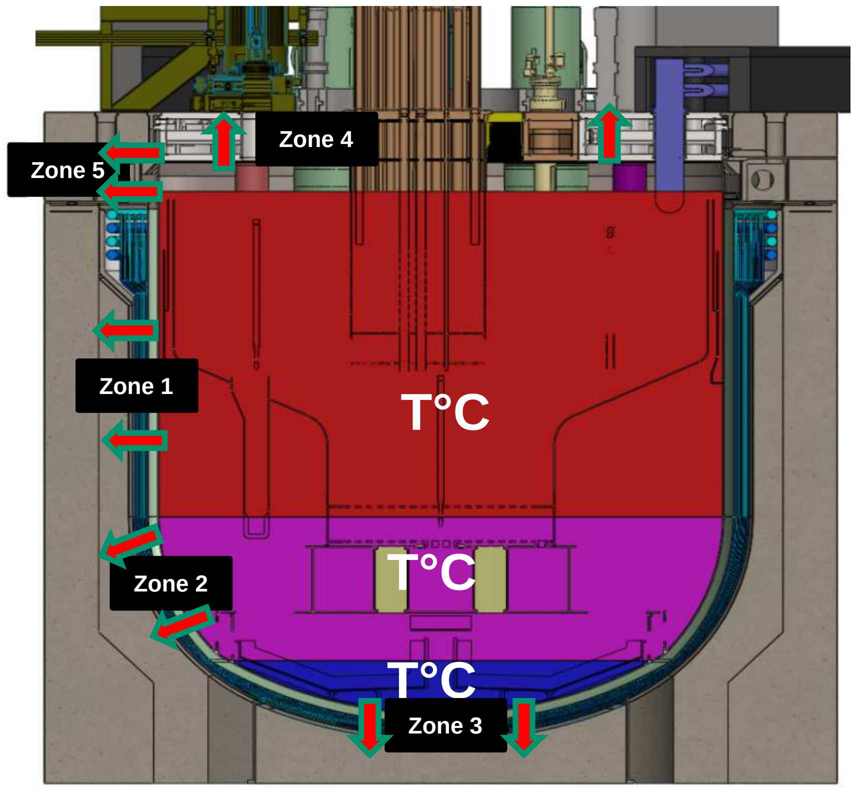
France (CEA)
US (USDOE)
Japan (JAEA)
Korea (KAERI)
EURATOM (JRC)
China (CIAE)
RF (Rosatom)

Project Objectives

- *Analyses and experiments that support safety approaches and validate specific safety features*
- *Development and validation of computational tools useful for such studies*
- *Acquisition of reactor operation technology, as determined largely from experience and testing in operating SFR plants*

DHR modeling through the PV

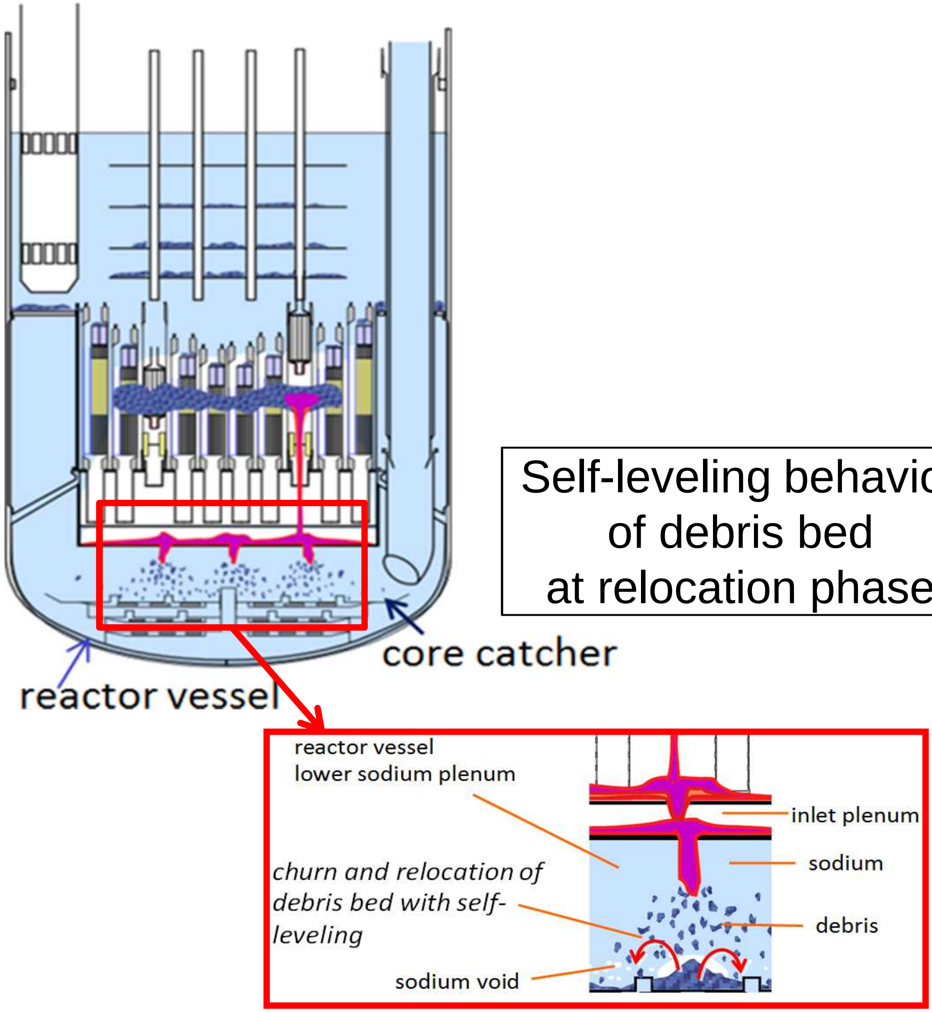




- Very severe conditions assumed. Blackout with loss of all in vessel DHRS.
- A model including convection, conduction and radiation was developed
- Sensitivity calculations on SS emissivity were performed
- Need of fill the space between the main and safety vessels with sodium to reach acceptable temperatures.

A report on analytical methods to simulate phenomena in self-leveling behavior of the debris bed

Development of the debris bed self-leveling model for IVR confirmation



Self-leveling behavior of debris bed at relocation phase

Proposed model

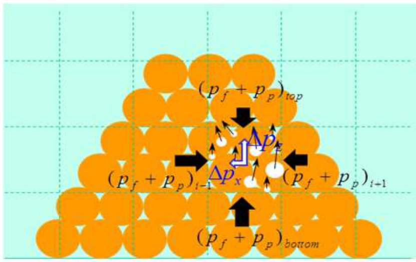
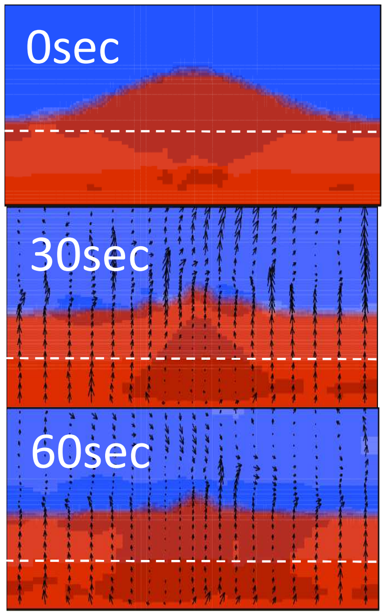
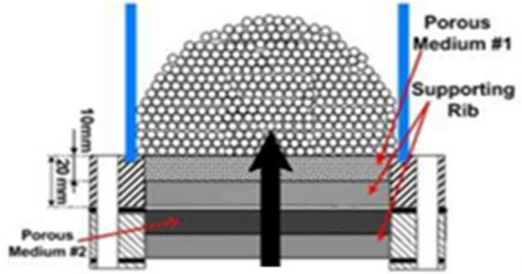


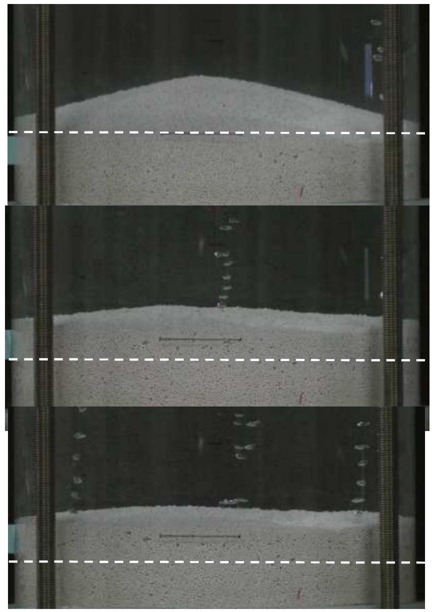
Image of particle bed in multi-phase flow



Experiment

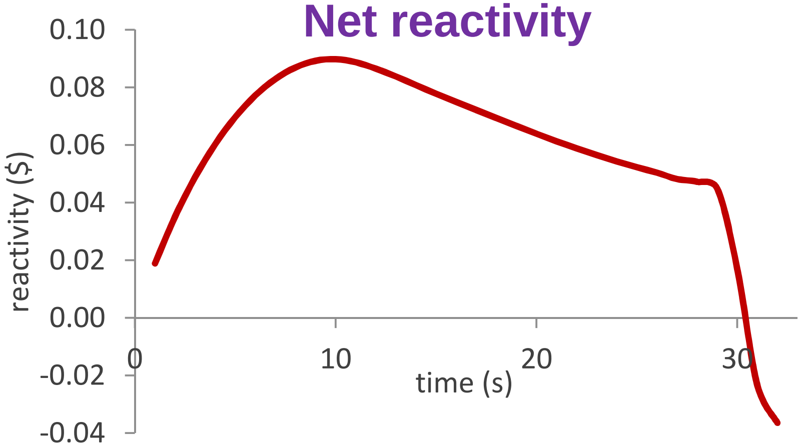


Gas Flow

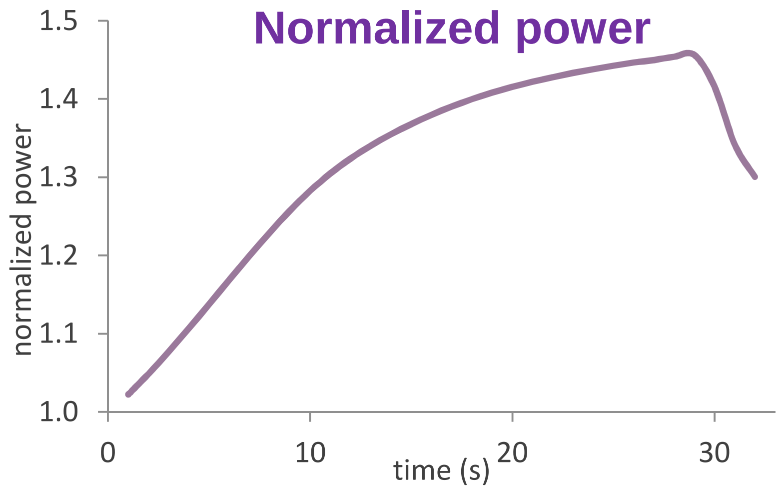


SAS4A severe accident model development and preliminary analysis

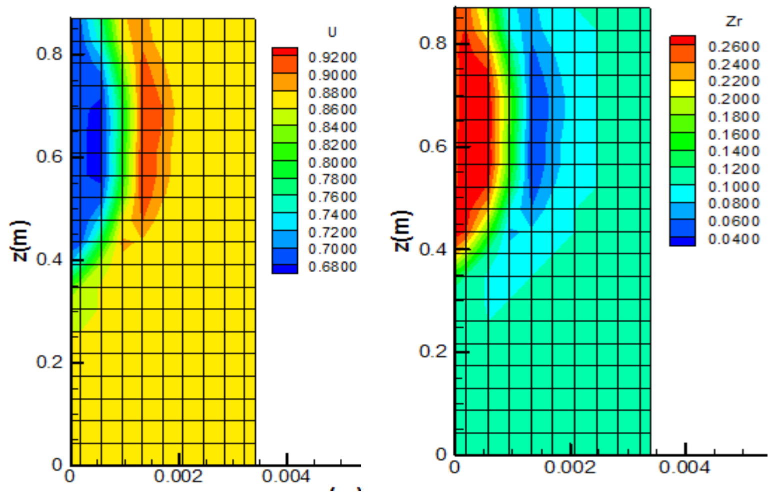
Net reactivity



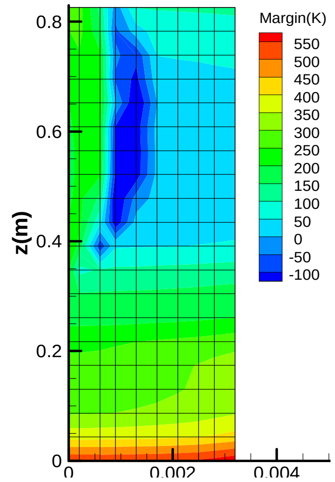
Normalized power



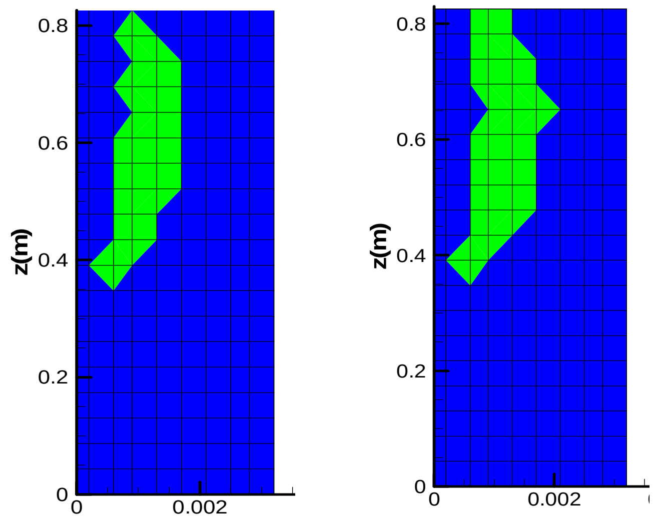
U, Zr weight fraction



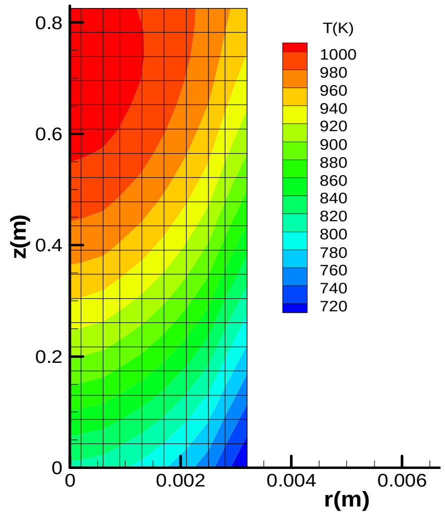
Margin to melt



Map of molten fuel



Temperature



Advanced Fuel Project

Advanced Fuel Project

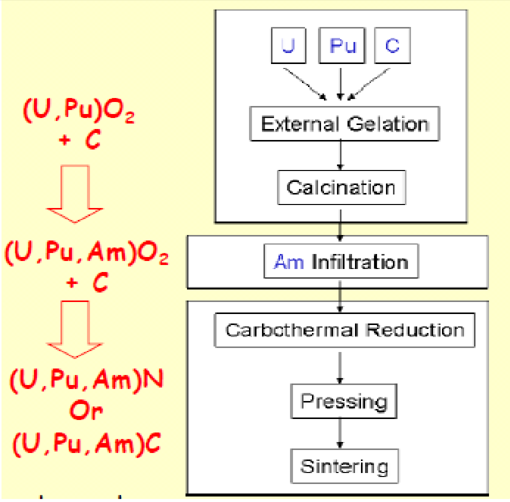
- ***Objective***
  - ***Selection of high burn-up MA bearing fuel(s), cladding and wrapper withstanding high neutron doses and temperatures***
- ***Candidates:***
  - ***Driver fuels: Oxide, Metal, Nitride & Carbide (since 2008)***
    Inert Matrix fuels & MA Bearing Blankets (since 2009)
  - ***Core materials: Ferritic/Martensitic & ODS steels***
- ***Scope***
  - ***Fabrication***
  - ***Behavior under irradiation***
- ***Signatories (country – implementing agent): France - CEA, USA - DOE, EURATOM - JRC/ITU, Japan - JAEA, Korea -KAERI***

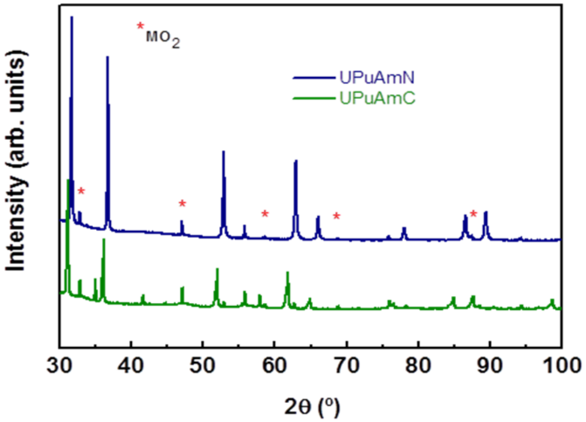
Progress / carbide & nitride fuels

Carbothermal reduction process revisited -> Identification of reaction schemes & intermediate species (Handschuh et al, 2010, Conf. Pu future)

$$(1\text{-}x)UO_2 + xPuO_2 + (3+y)C \xrightarrow[1450\text{-}1650°C]{\text{Primary Vacuum}} U_{1\text{-}x}Pu_xC_{1+y} + 2CO$$

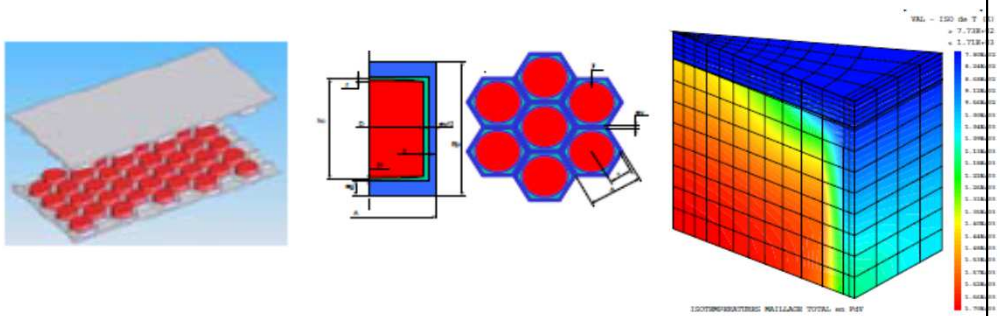
Am bearing fuels synthesis





(Carvajal et al., JNM, 2014, accepted)

Fuel element advanced pre-design -> plate



(Rimpault et al., proceedings GLOBAL 2009)

Non Destructive Examinations of a $(U_{0.5}Pu_{0.25}Am_{0.15}Np_{0.10})N$ fuel rodlet, Na bonded, irradiated in ATR (17at%, 270W.cm-1) within the series AFC-1 -> satisfactory results consistent with predicted behavior

Progress / metal fuels

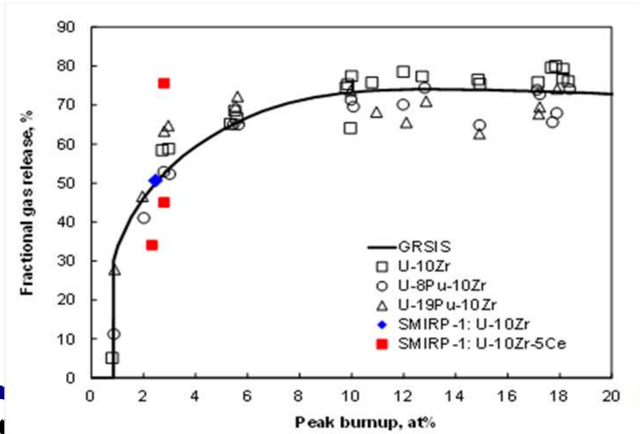
- ***Fuel slug fabrication:***
  - gravity-casting & pressurized injection casting (Lee et al., proceedings FR-13):
    - » U-Zr-Mn & U-10Zr-RE-Mn (RE: 1-10%, Mn :0 & 5%)
    - » retention of Mn (Am surrogate)
  - Implementation of the Glovebox Advanced Casting System at INL

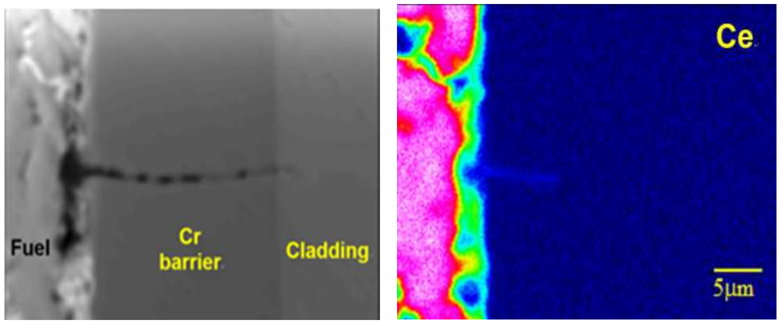
    ->Pu & Am bearing fuels**,** 3 slugs/batch, Φ: 4,5mm & 250mm long

    with a re-usable mold (Fielding et al., FR-13)

- ***Irradiations:***
  - SMIRP-1: PIE on UZr & UCeZr slugs irradiated (2.7at%) in HANARO (Lee et al., FR13)

    -> satisfactory behavior & Cr layer at fuel/cladding interface to prevent FFCI performed well, despite some cracks in the Cr layer

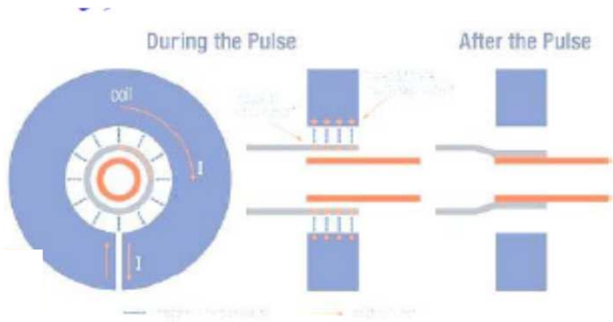




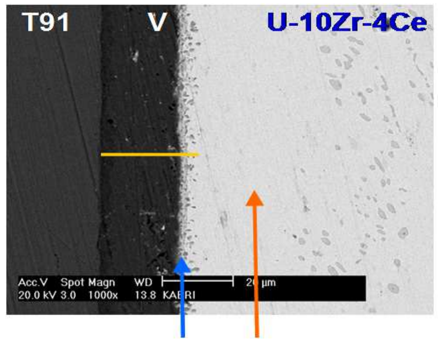
Progress / core materials

- ***F/M & ODS steels***
  - *HT9 cladding tube manufacturing processes*
    -> melting, forging, machining, hot-extruding
    drawing & pilgering, annealings …

  - *Welding : Electro-Magnetic Pulse Technology*
    -> joining of tubing and end caps for T91
    and ODS



  - *Metallic Fuel / Cladding Chemical Interaction mitigation:*
    - » *investigation of cladding liner materials & liner deposition processes*
      - *barriers : Cr, V, Cr2O3, …*
      - *methods : CVD, electroplating, …*



  - *ODS fuel pin irradiation in JOYO under preparation*

Component Design & BOP Project

CD & BOP Project Subjects for 2012-2016

(1) In-Service Inspection & Instrumentation (ISI) technology

- ***Ultrasonic inspection in sodium using different approaches and technologies, codes and standards (CEA, Euratom, JAEA, KAERI)***

(2) Repair experience

- ***Phénix, Monju, (CEA, JAEA)***

(3) Leak Before Break (LBB) Assessment technology

- ***Creep, fatigue, and creep-fatigue crack initiation & growth evaluation for Mod. 9Cr-1Mo (Grade 91) steel, Na leak detection by laser spectroscopy (JAEA, KAERI)***

(4) Supercritical CO_2 Brayton Cycle Energy Conversion

- ***S-CO2 compressor tests, S-CO_2 cycle demonstration tests, Compact heat exchanger tests, Material oxidation tests in S-CO_2, Sodium-CO_2 reaction tests, S-CO_2 SFR plant dynamic analyses and control strategy development, Computer code analysis, S-CO_2 SFR design study, Validation of S-CO_2 plant dynamic analyses with S-CO_2 loop data, Sodium plugging tests (CEA, DOE, Euratom, JAEA, KAERI)***

(5) Steam Generator design and associated safety & instrumentation (since 2011)

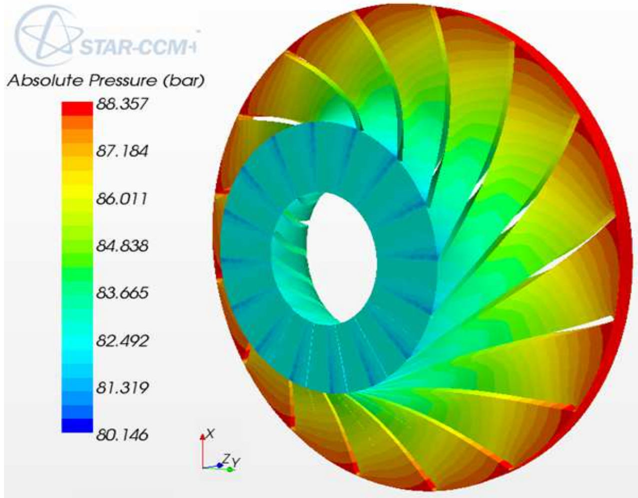
- ***Na/water reaction, thermal-hydraulics, thermal performance, DWT structural evaluation and heat exchange performance, DWT-SG fabrication (CEA, JAEA, KAERI)***

S-CO_2 Brayton Cycle Energy Conversion

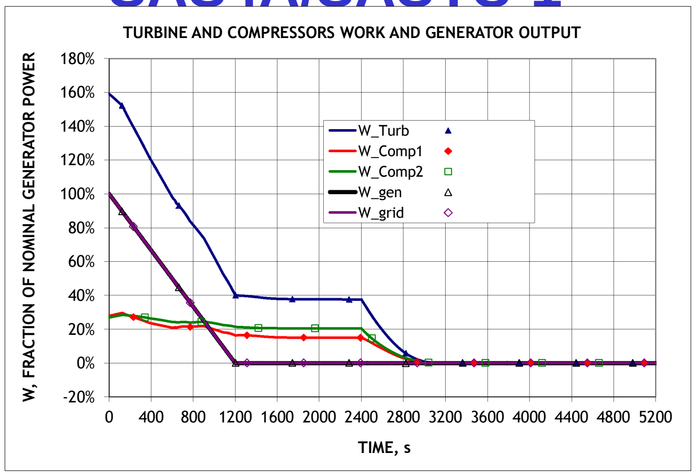
study of the supercritical CO_2 cycle

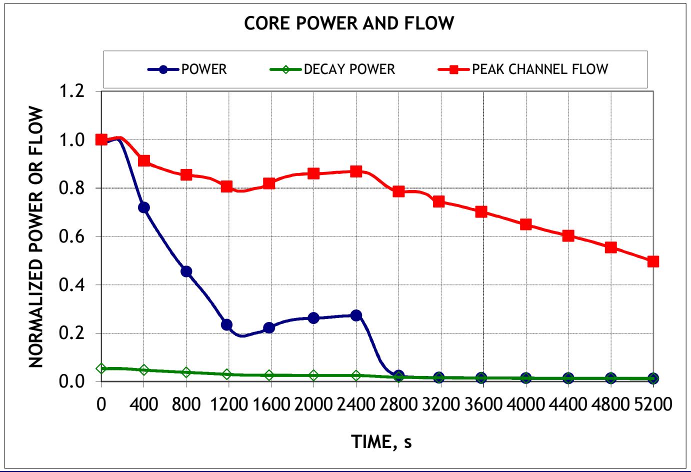
- **CFD simulations of the small scale S-CO_2 compressor have shown good agreement with the experiment data**

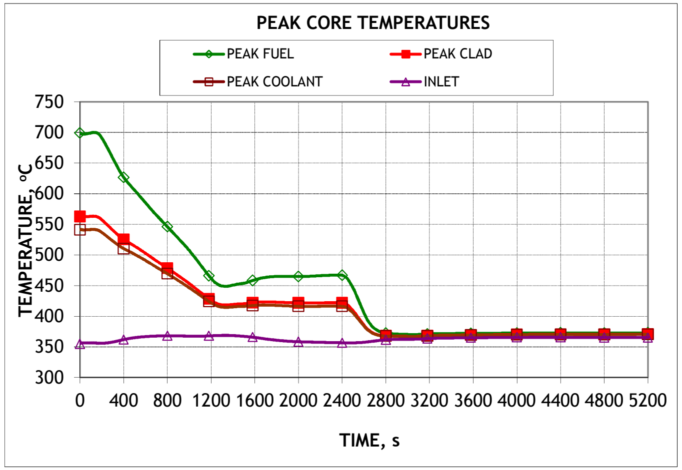
	Experiment data	CFD simulation
Shaft speed, rpm	12000	
Mass flow rate, kg/s	4.008 ± 0.007	4.008
Inlet temperature, °C	35.35 ± 0.5	35.35
Inlet pressure, bar	82.71 ± 0.20	82.71
Outlet temperature, °C	38.35 ± 0.5	38.98
Outlet pressure, bar	91.34 ± 0.20	91.31



- **Calculations were carried out with the ANL Plant Dynamics Code that performs system level transient analysis for S-CO2 cycles coupled to SAS4A/SASYS-1**







S-CO_2 Brayton Cycle Energy Conversion

Corrosion behavior of metallic materials in SC-CO_2

- <u>Fruitfull collaboration</u> between CEA and JAEA for more comprehensive understanding of corrosion mechanisms in SC-CO_2 (2012-2014).
- More than 350 corrodes samples, 11 steel grades, 5 temperatures (400 to 600C), up to 8000h exposure.

JAEA facility

CEA facility

- <u>Fast oxidation and carburization</u> of 9-12Cr steels : successful modeling of oxide growth rate and carburization rate.
- Much slower oxide growth (more than 100 times slower than 9-12Cr) and almost no carburization of 18-25Cr steels. Increasing %Cr decreases the degradation of the steel.
- No strong influence of CO_2 pressure on the corrosion behavior was observed.
- <u>At T > 400C, the use of austenitic steels are recommended.</u>

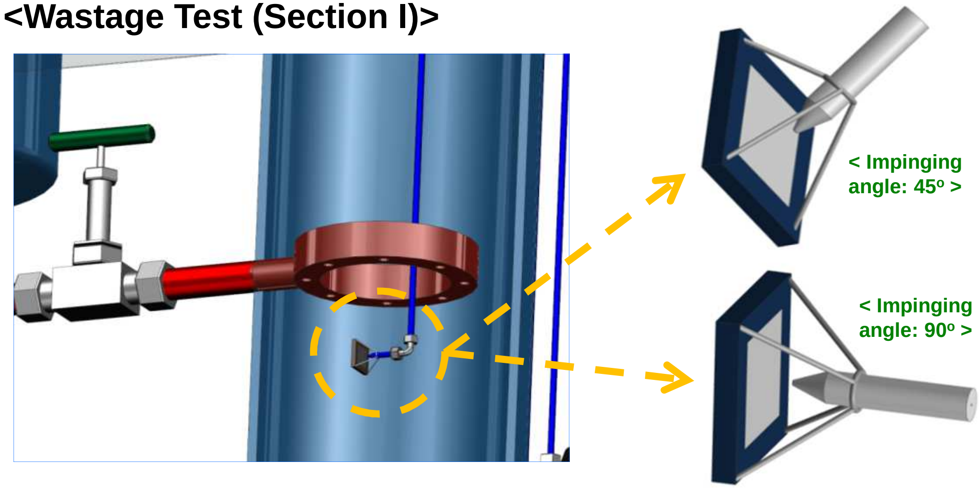
S-CO_2 Brayton Cycle Energy Conversion

Preparation of a Sodium-CO2 interaction test facility

- **The fabrication of test facility for wastage and plugging issues is supposed to be finished by Mar. 2014 and main experiments will be carried out in FY2014.**
  - **Wastage test : Damage propagation on the pressure boundary in Na-CO_2 HXs**
  - **Plugging test : Channel plugging in Na-CO_2 HXs**

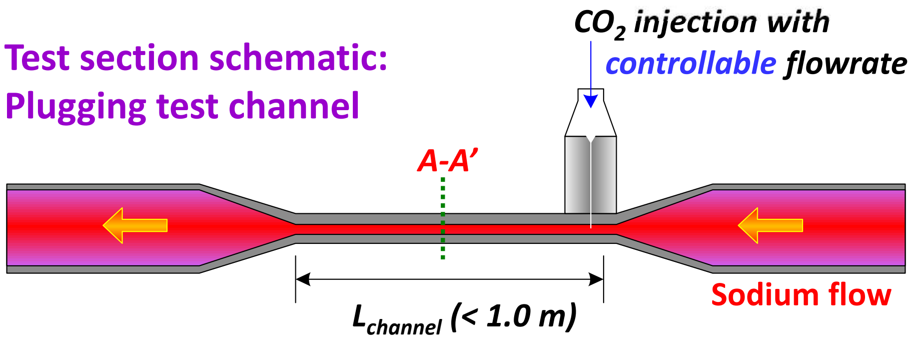
< Construction of test loop (Photo of Mar. 3, 2014) >

<Wastage Test (Section I)>



<Plugging Test (Section II)>

Test section schematic:
Plugging test channel

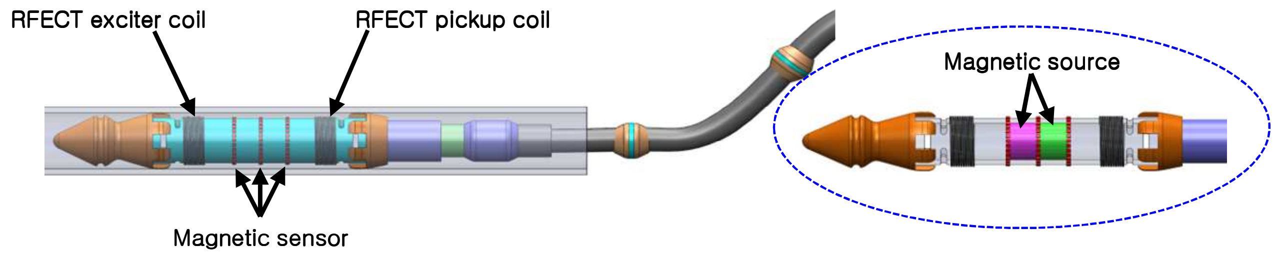


Preparation of a basic heat transfer test facility for Double Wall Tubes and G91 tube inspection technology

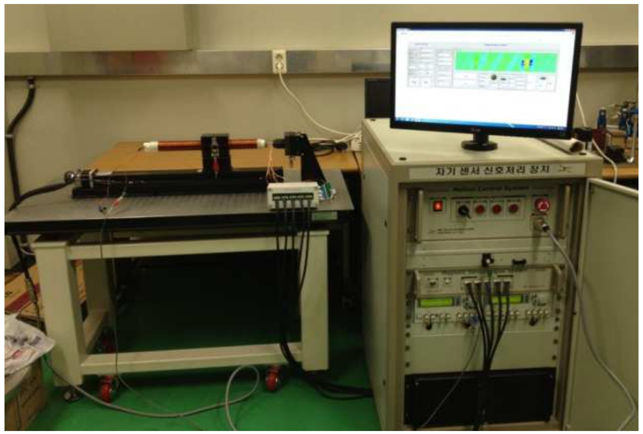
- ***Construction of a basic heat transfer test facility for DWT has been finished.***

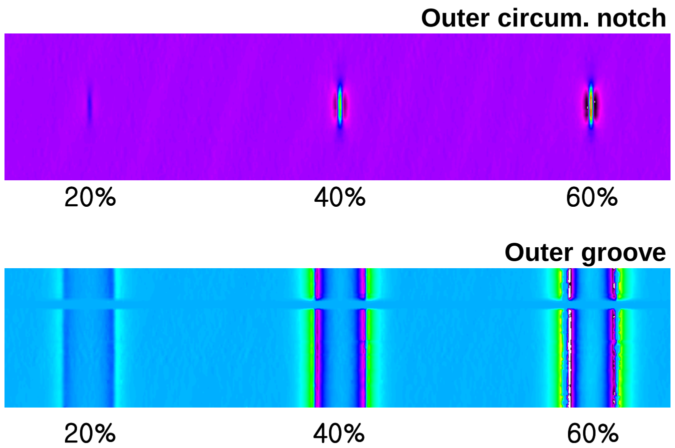
Basic heat transfer test facility for DWT **(5.3 x 4.6 x 11.8 m)**

- *Combined SG tube inspection sensor*
  RFECT + Magnetic sensor testing
- *Preliminary test of magnetic sensor testing system has been carried out.*



Combined SG tube inspection sensor (design example)

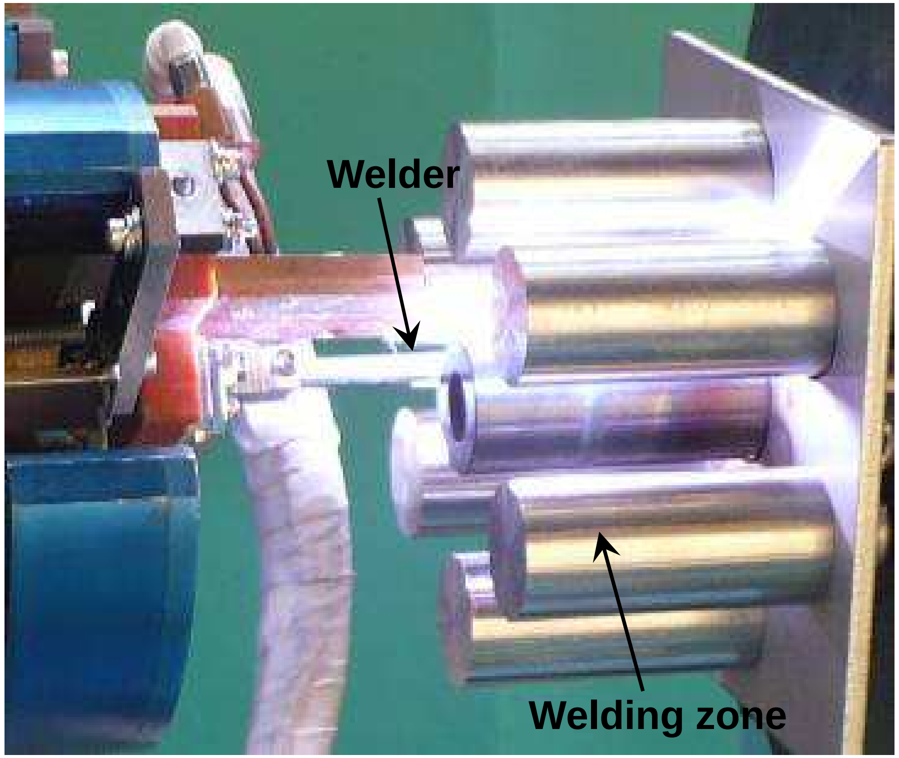




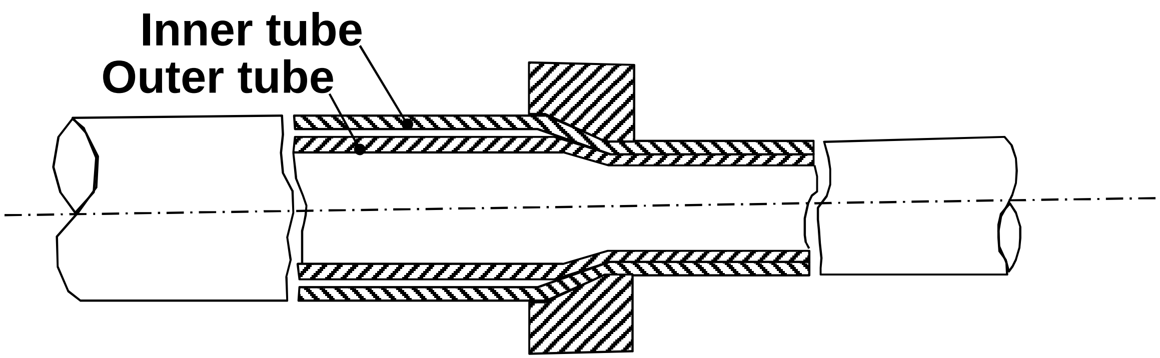
Magnetic sensor testing system and preliminary test results

Trial fabrication of main parts of double-walled-tube steam generator

(Double-walled tube, tube-sheet, tube to tube-sheet junction)



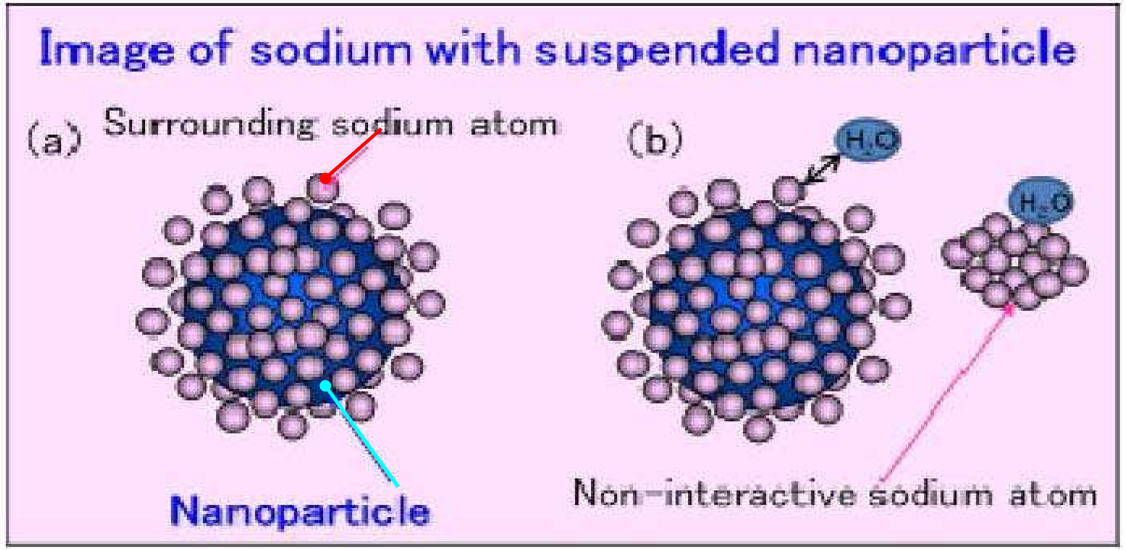
Tube and tube-sheet welding test



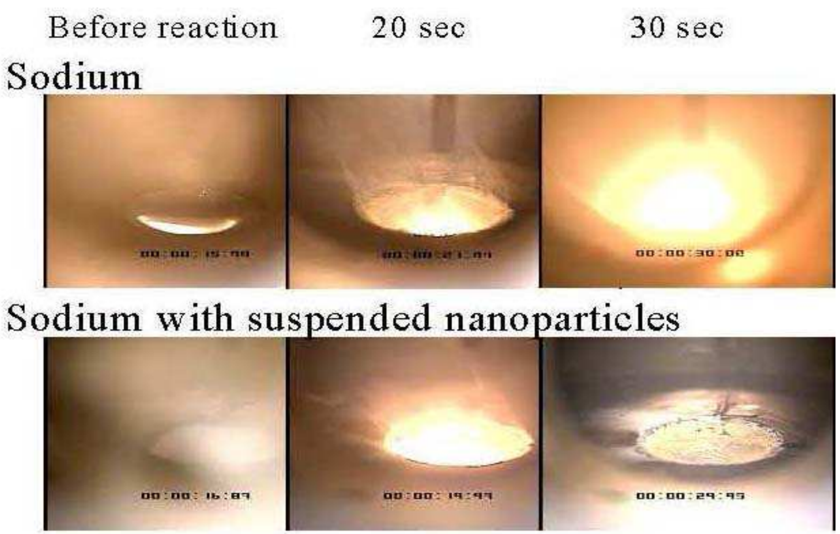
Double-wall-tube drawing process

Steam Generators

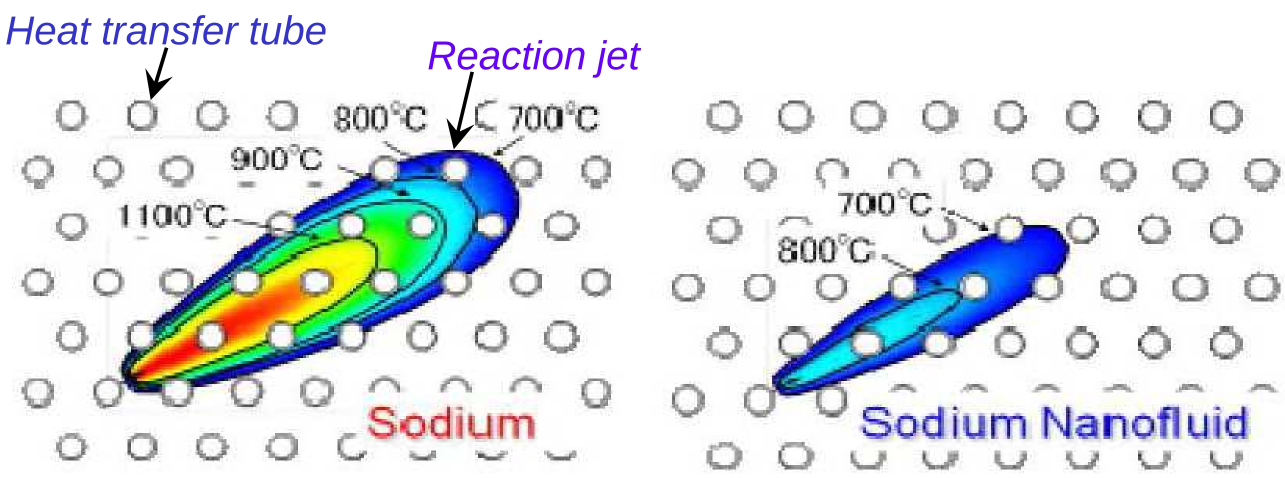
Sodium/water reaction control technology using nano-size particles in sodium



- *The technology is to reduce the chemical reactivity of liquid sodium using nano-particle.*
- *The sodium chemical reactivity can be suppressed by an atomic interaction between nano-particle and sodium atom.*



Sodium combustion



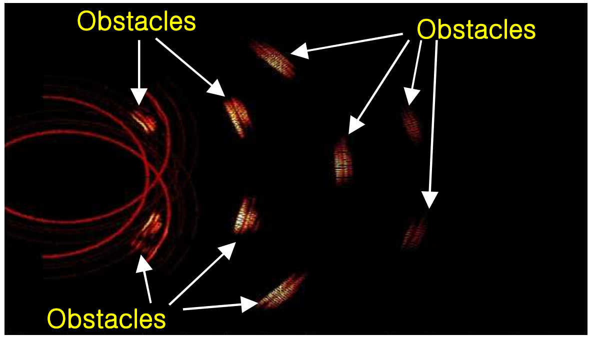
Na/water reaction (Computer analysis)

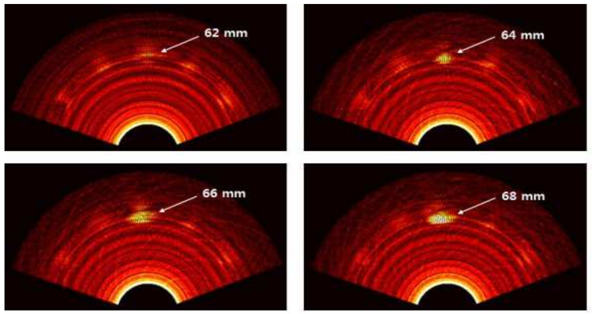
In-service Inspection

Recent progress in under-sodium viewing technology with waveguide sensor: Development and applicability verification of a remote inspection module

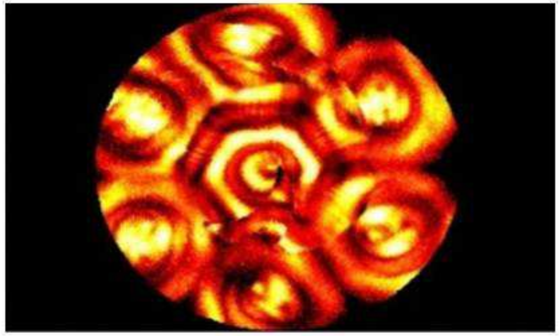
Remote Inspection Module (4 Ch. WG sensors)

- ***Remote inspection module employing 4Ch. 10 m long waveguide sensors was developed for ISI of reactor internals in an SFR.***
- ***Several verification tests were carried out and the applicability of the remote inspection module to ISI of reactor internals was successfully demonstrated.***

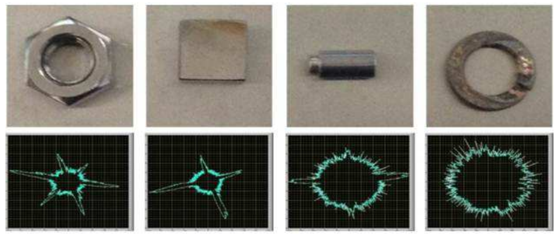




Ranging inspection results



Viewing inspection results

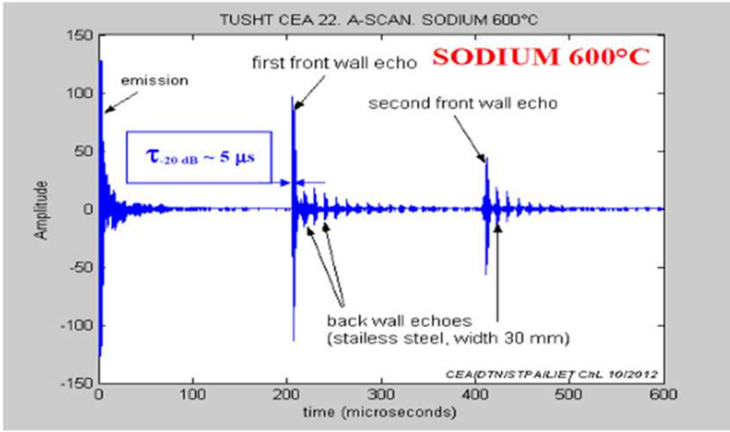


Identification inspection results

In-service Inspection

Recent Developments of Ultrasonic Sensors for NDE in liquid sodium

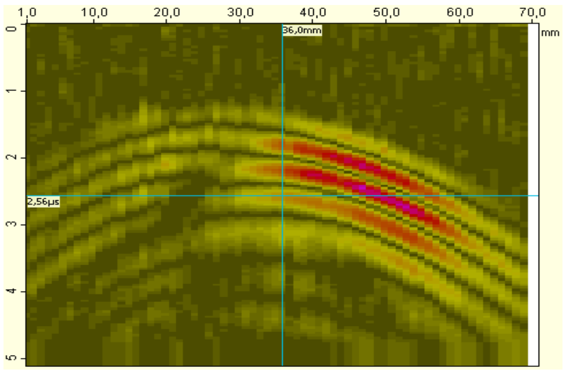
- New TUSHT (High Temperature Ultrasonic Transducers) were manufactured and performance tests were realized
  - These sensors were immerged in sodium up to 600 °C



< TUHST tested on DOLMEN Na facility at CEA >

- Optimization of the sensor to limit the piezoelement crystal chemical reduction
- Potential use in SONAR for in sodium telemetry application

- New multielement EMAT (Electromagnetic transducer) – 8 phased array

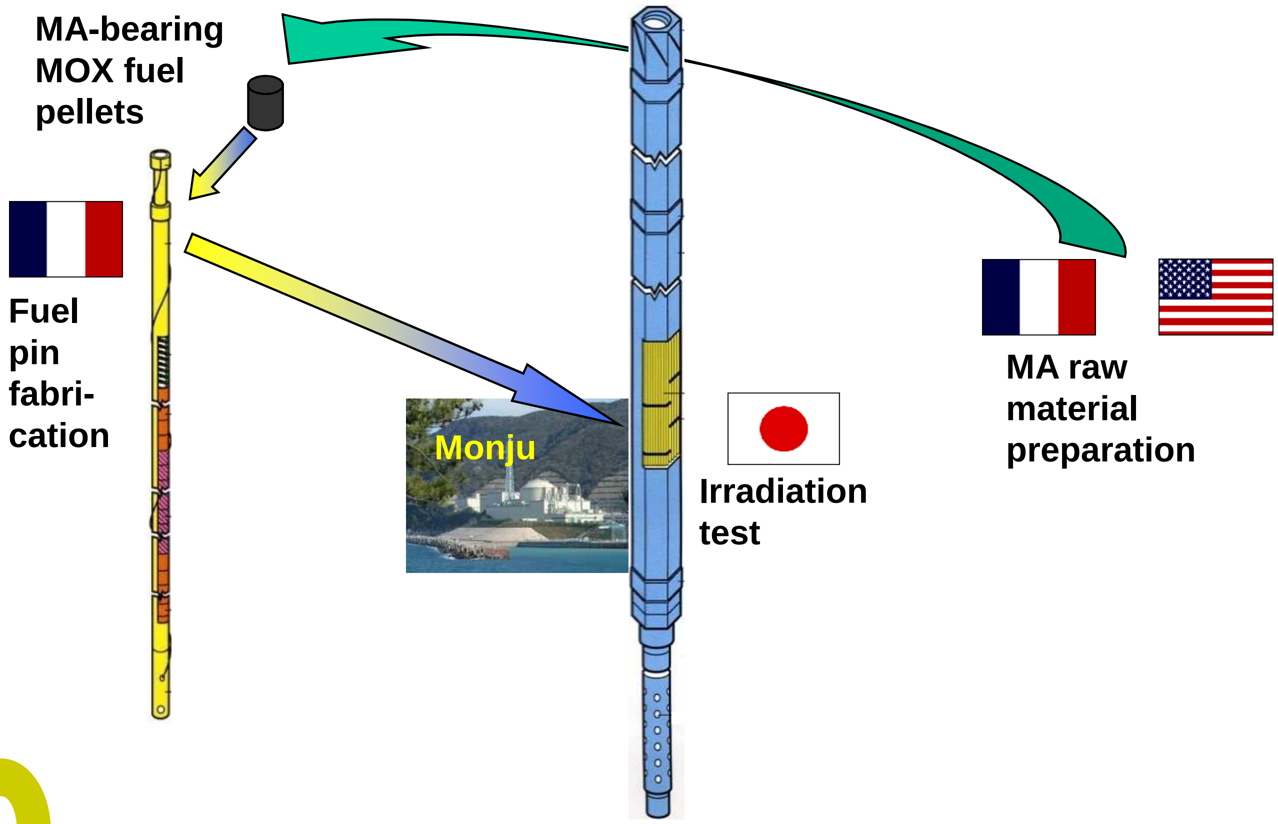


- Demonstration of operation at 180°C
- Ability to deflect the wave direction
- New design to optimise the sensor (enhance deflection, size reduction of focal spot)

GACID Project

Overview of GACID Conceptual Scheme

- ***Objective: to demonstrate, using Joyo and Monju, that FR's can transmute MA's (Np/Am/Cm) and thereby reduce the concerns of HL radioactive wastes and proliferation risks.***
- ***A phased approach in three steps.***
- ***Material properties and irradiation behavior are also studied and investigated.***

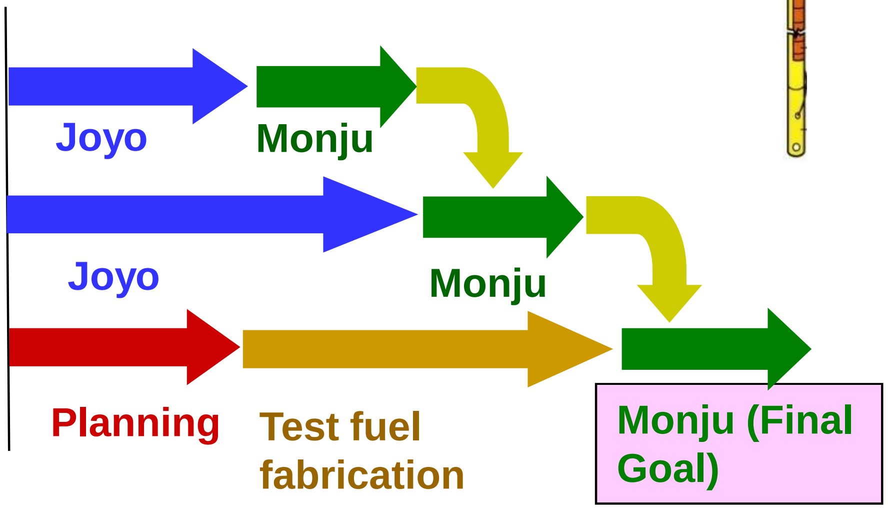


GACID overall schedule

Step-1
Np/Am pin irrad. test

Step-2
Np/Am/Cm pin irrad. test

Step-3
Np/Am/Cm bundle irrad. test



- ***The Project is being conducted by CEA, USDOE and JAEA as a GIF/SFR Project, covering the initial 5 years since Sep. 27, 2007.***

Summary

- ***System Research Plan has been updated in order to incorporate changes in Project Plans and design concepts***

- ***Various collaborative activities are being conducted in the areas of advanced fuels, transmutation of MAs, component design and BOP, and safety and operation within the SFR Technical R&D Project Arrangements***

- ***Procedures of resigning SFR Technical R&D Project Arrangements is under way***

- ***Signing SFR SIA PA will permit to integrate and assess the results of R&D work conducted under SFR Technical R&D Project Arrangements***

Thank you
for your attention !

Primary Roles of SIA Project and Relation to Technical Projects