The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

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Joint ICTP-IAEA School of Nuclear Energy Management

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Nuclear Applications Fundamentals: Materials for fission and fusion technology

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IAEA, Vienna
Austria

Lecture 3

Nuclear Applications Fundamentals:

Materials for fission and fusion technology

10 August 2011

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Courtesy to Andrej Zeman

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International Atomic Energy Agency

Outline

- Introduction
- Issues and challenges
- Materials R&D for fission and fusion
- International efforts

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Major Activities within Physics Section

<u>Assistance and support of Member States in the field of</u>

1. Accelerators
2. Research Reactors
3. Controlled Fusion
4. Nuclear Instrumentation
5. **Cross-cutting Material Research**

<u>Based on Member States needs, requests & recommendations</u>

- Planning & implementation of P&B activities
- Proposal and implementation of CRPs
- Management of Data Bases
- Organization of Conferences, Technical & Consultancy Meetings
- Organization of ICTP workshops, training schools and courses
- Support of TC projects
- Promotion of Nuclear Sciences, Applications and Technologies

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Materials R&D – cross-cutting activity

→ Multi-departmental involvement: NE, NA, NS, & TC

→Present in many areas of the IAEA's Projects

- 1.1.4 (INPRO)
- 1.1.5 (Technology development for advanced reactor lines)
- 1.2.2 (Nuclear power reactor fuel engineering)
- 1.2.4 (Nuclear fuels & fuel cycles for advanced and innovative reactors)
- 1.4.2.1 (Enhancement of utilization and applications of RRs)
- 1.4.3.1 (Improvement of knowledge and data for the design and engineering of advanced materials of economic importance)
- 1.4.4 (Nuclear fusion) Nuclear Science Programme
- (1.4) Towards supporting materials research for advanced reactors

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Materials in nuclear industry (1)

- Structural materials of critical reactor components (replaceable / non-replaceable components), assure that all (designed) parameters will remain in defined margins
- Assessment / prediction of key parameters due to degradation process (End Of Life), linked with safety (part of licensing)
- Reactor core components – degradation due to ageing and other external factors (radiation, stress, temperature, coolant media, etc.), it could affect components' reliability

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Materials in nuclear industry (2)

- Radiation damage mechanisms: embrittlement, thermal creep, swelling, cracking, etc. to be carefully considered in design phase (engineering approach and safety margins).

- Need to understand material behaviour at least in range of specified limits - enhancement of design lifetime aspects (Gen II+ up to 60 and more, FR ~ 60y), important for new reactors systems.

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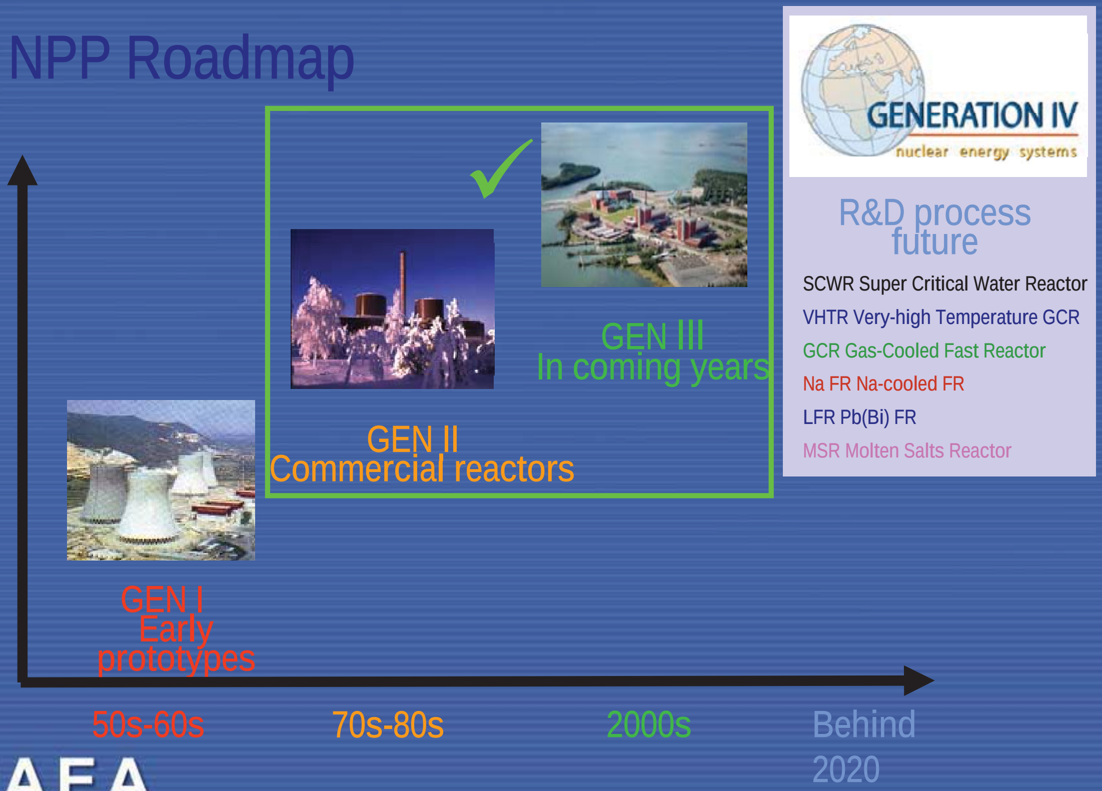
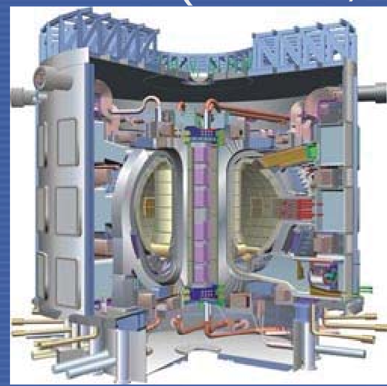
Materials future nuclear industry

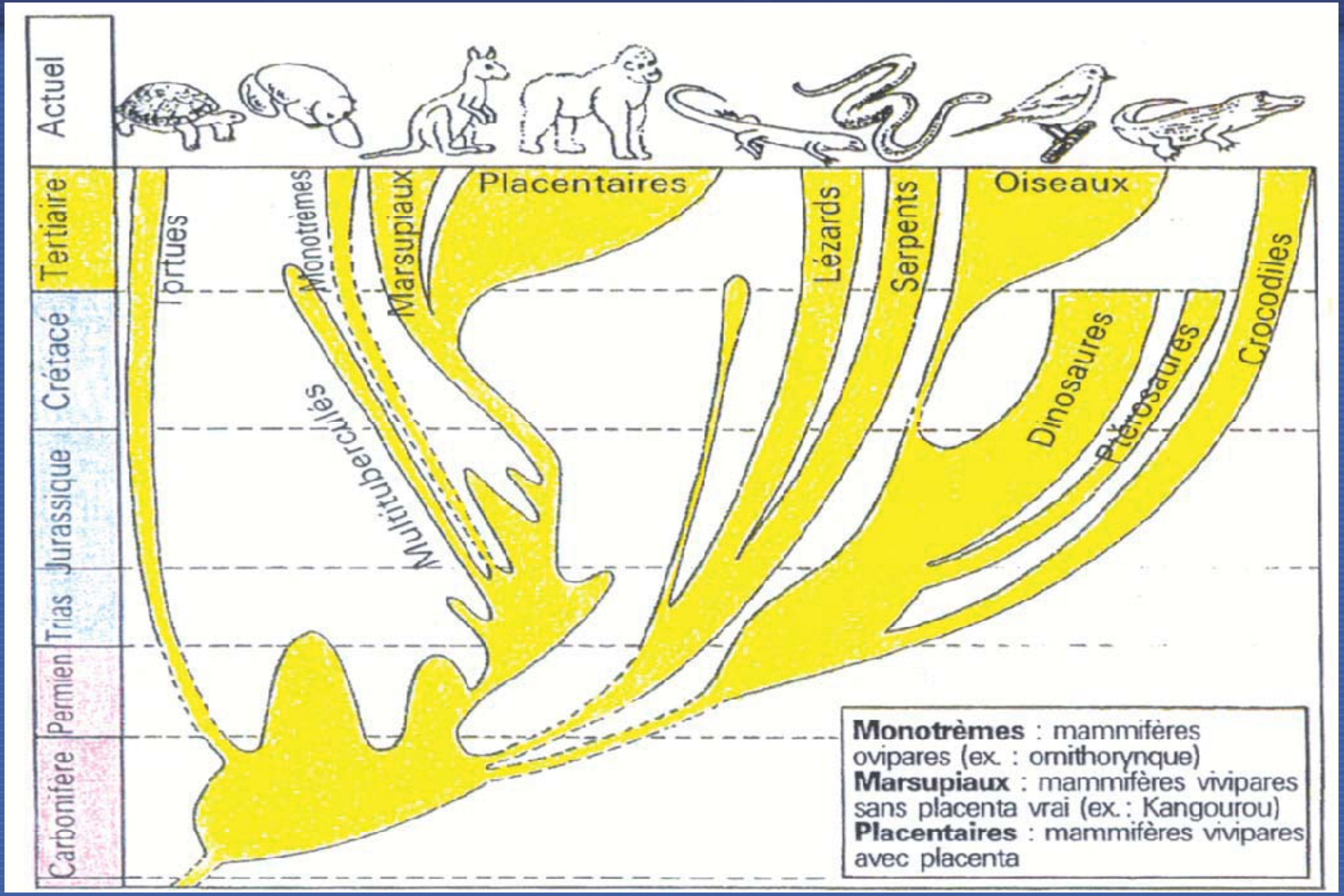
- Structural materials of present NPPs – lessons learned
- Analysis degradation mechanisms and prediction of long term behaviour
- R&D programmes for development of advanced materials (RAFM, ODS, SiC/SiC, etc.)

NPP Roadmap





Paleontological Analogy



« If any species do not become modified and improved in a corresponding degree with its competitors, it will soon be exterminated »

Charles Darwin. The origin of species, 1859

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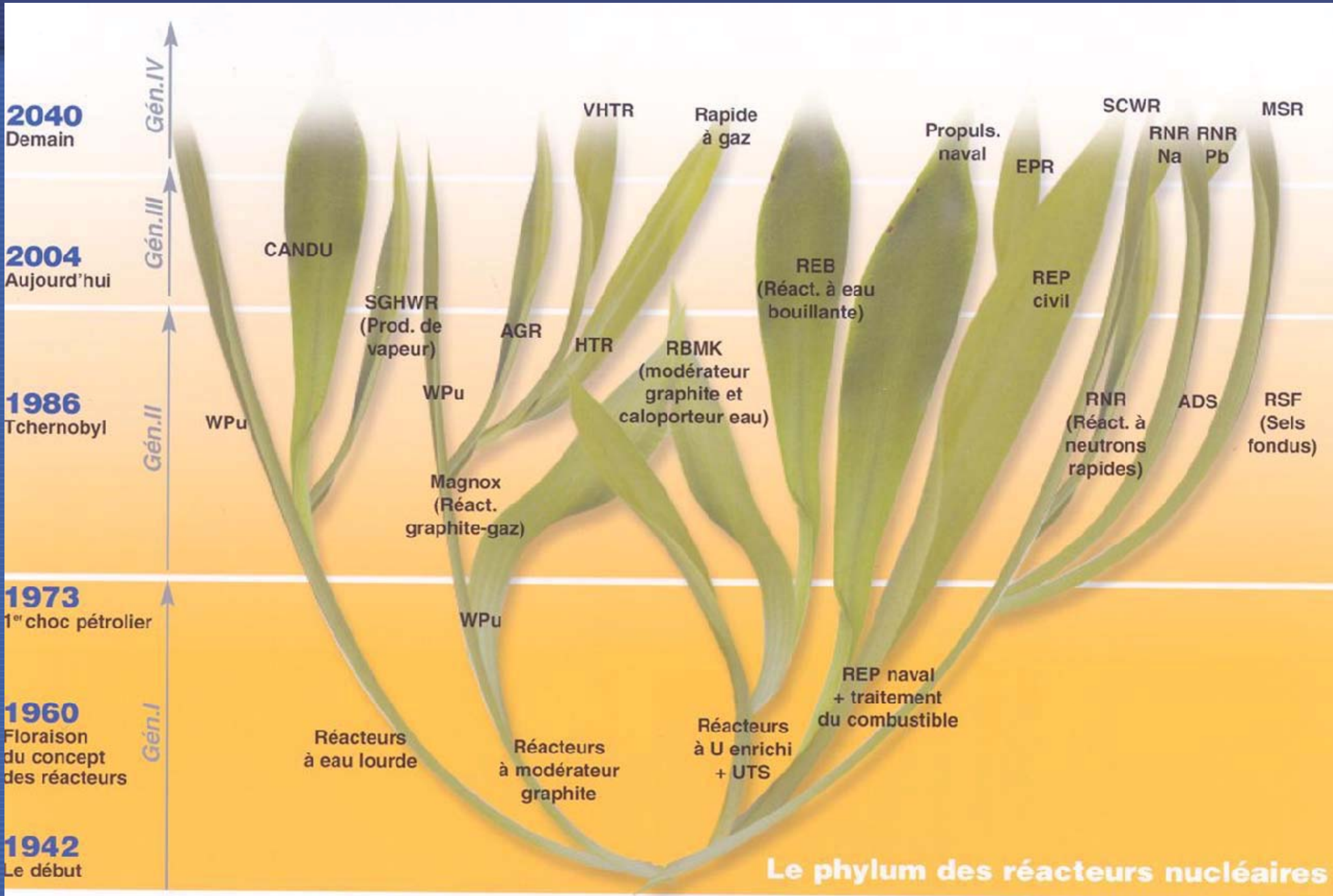
Genealogical tree of nuclear reactors



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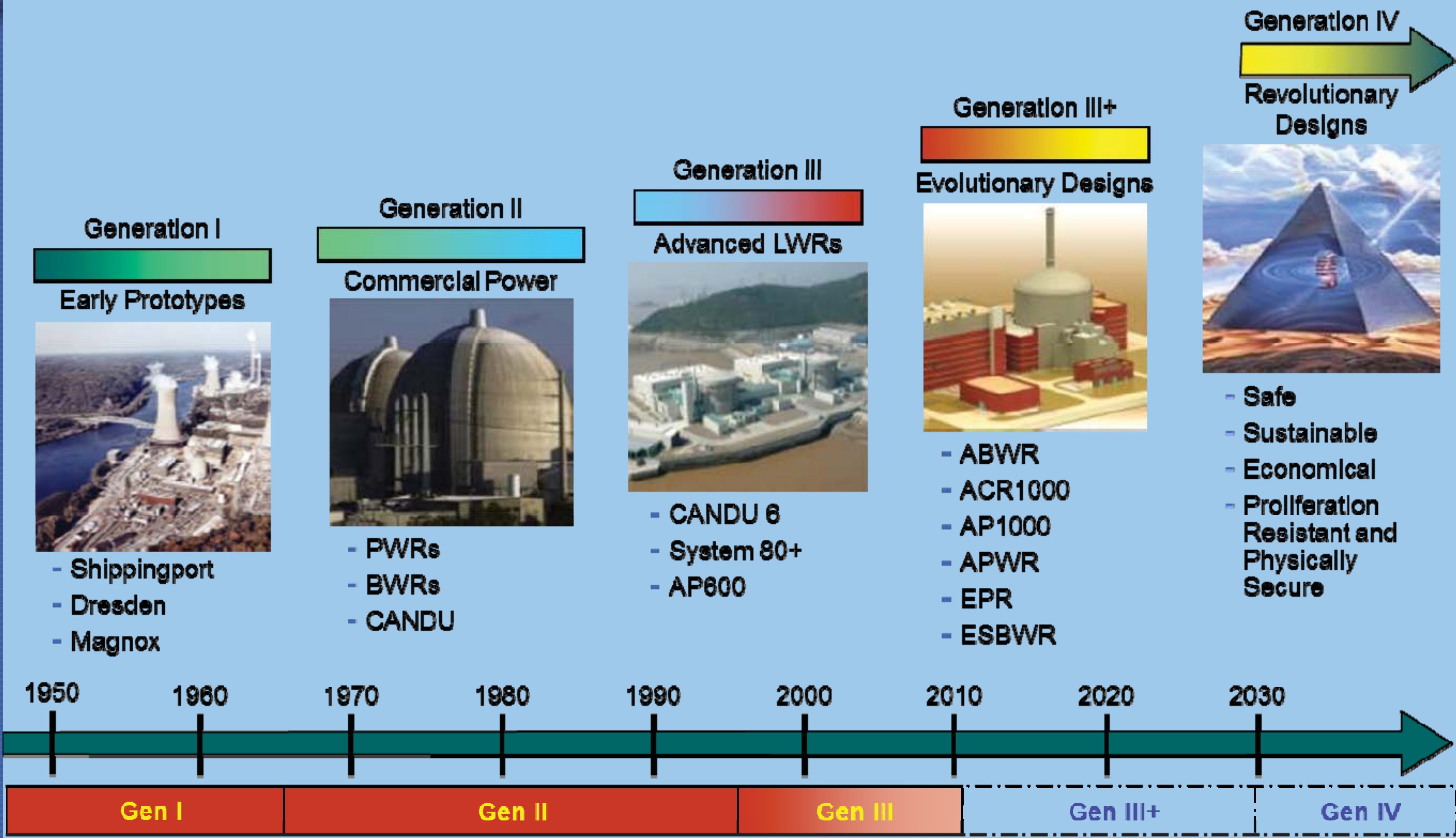
Generations of Nuclear Reactors



http://www.gen-4.org/Technology/evolution.htm

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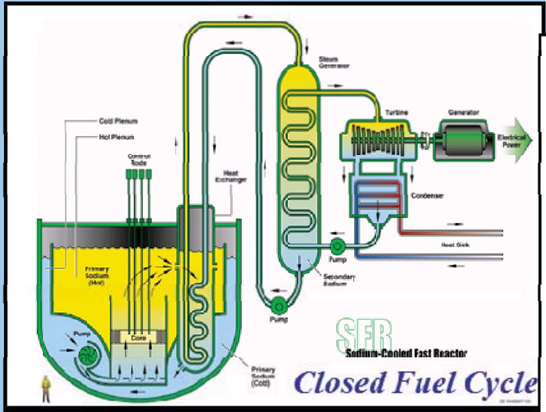
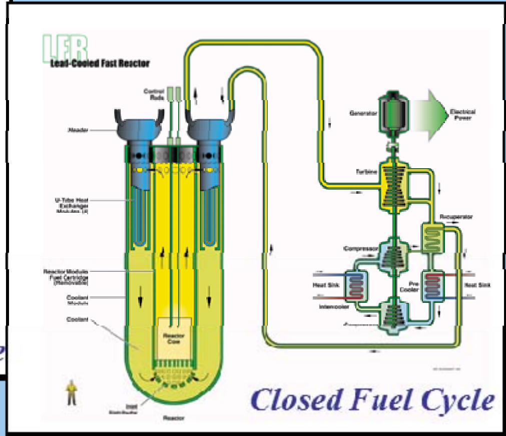
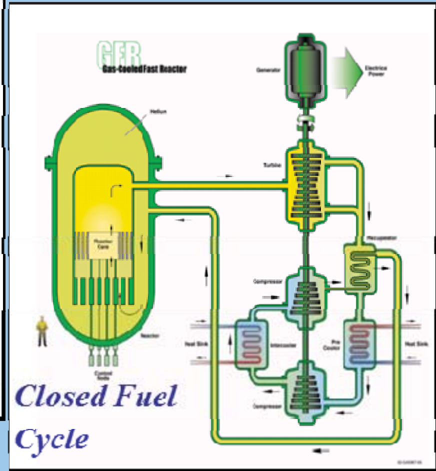
6 innovative concepts under study



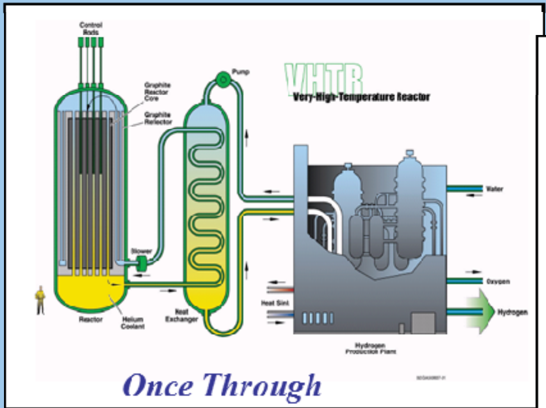
Sodium Fast reactor



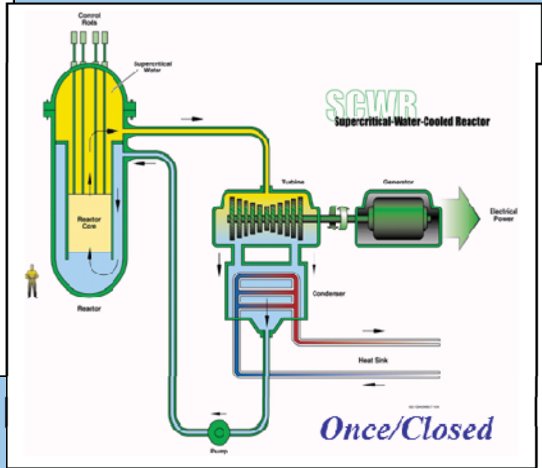
Lead Fast Reactor



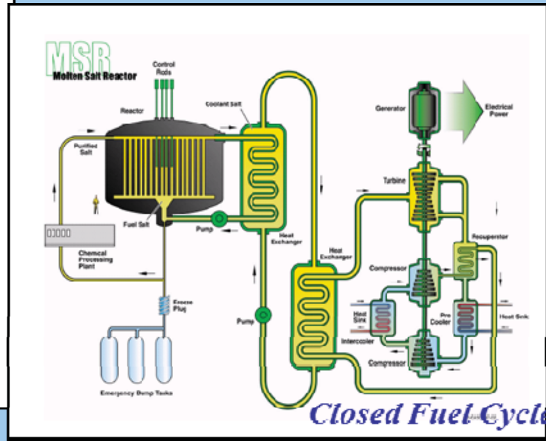
Gas Fast Reactor



Very High Temperature Reactor



Supercritical Water Reactor



Molten Salt Reactor

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R&D required in GenIV

System	*Neutron Spectrum*	*Fuel Cycle*	*Size (MWe)*	*Applications*	*R&D Needed*
Very-High-Temperature Reactor (VHTR)	Thermal	Open	250	Electricity, Hydrogen, Process Heat	**Fuels, Materials,** H_2 production
Supercritical-Water Reactor (SCWR)	Thermal, Fast	Open, Closed	1500	Electricity	**Materials**, Safety
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	200-1200	Electricity, Hydrogen, Actinide Management	**Fuels, Materials,** Safety
Lead-Cooled Fast Reactor (LFR)	Fast	Closed	50-150 300-600 1200	Electricity, Hydrogen Production	**Fuels, Materials**
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	300-1500	Electricity, Actinide Management	Advanced recycle options, **Fuels**
Molten Salt Reactor (MSR)	Epithermal	Closed	1000	Electricity, Hydrogen Production, Actinide Management	**Fuel treatment, Materials**, Safety, Reliability

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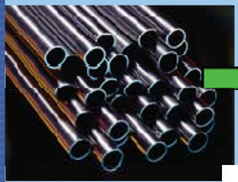
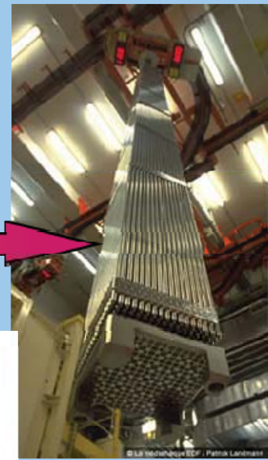
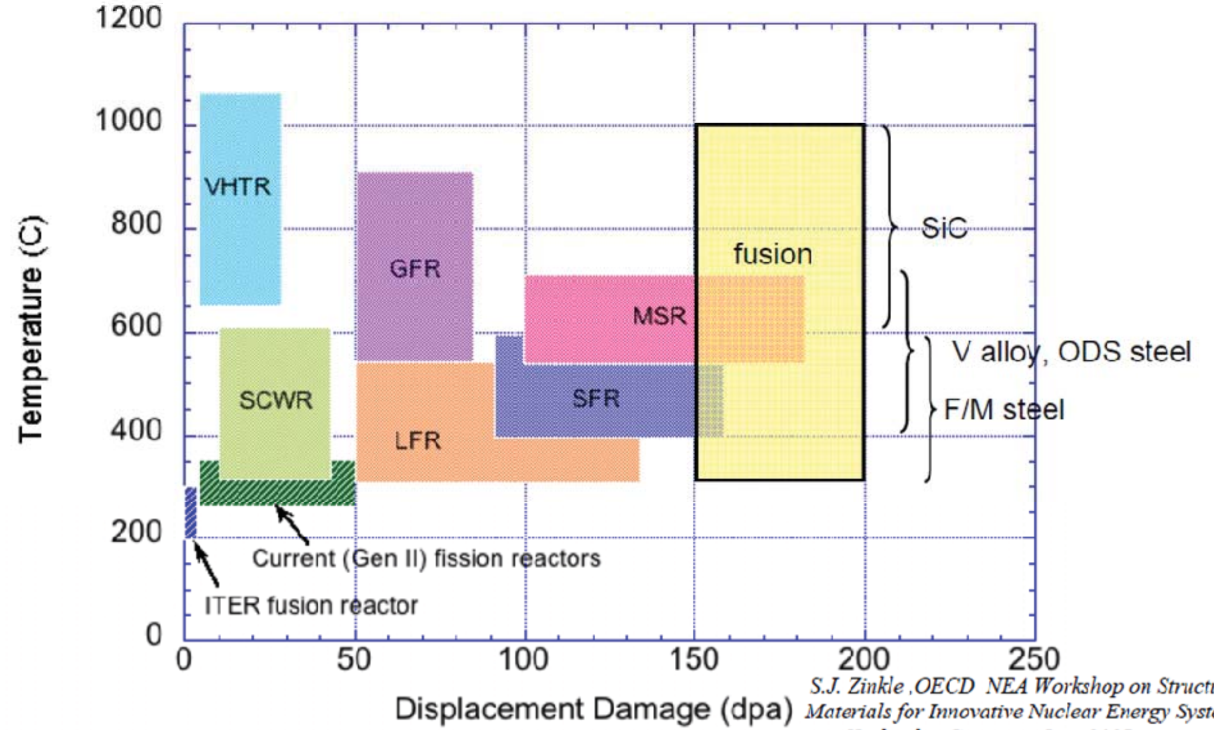
Material development in nuclear industry



Selection → Characterisation → Qualification

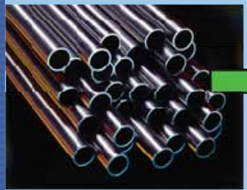




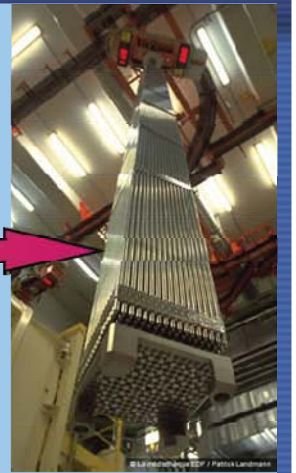
S.J. Zinkle, OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007, in press

Material irradiation needs

- **Material product development in the nuclear industry**



Selection → Characterisation → Qualification



Selection

- Main objectives
  - ✓ Basic irradiation of several innovative products under similar conditions
- Main requirements
  - ✓ High embarking capacity
  - ✓ Few instrumentation
  - ✓ Post irradiation examination

Characterisation

- Main objectives
  - ✓ Measurement of physical properties under neutron flux
  - ✓ Investigation of: Ageing effect / Mechanical properties / swelling / Chemical effect / Creep phenomena / effect on microstructure …
- Main requirements
  - ✓ High instrumentation
  - ✓ Accurate control of environment conditions (steady or transient)
  - ✓ Single effect experiments

Qualification

- Main objectives
  - ✓ Reproduction of environment conditions of power reactors in normal, incidental and accidental situation
  - ✓ Envelop situations targeted
- Main requirements
  - ✓ Good representativity of power reactor (steady and transient states)
  - ✓ Long term or short term irradiations

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On-going R&D activities

• Advanced / innovative nuclear reactor systems

▪ INPRO (2000)

Int. Project on Innovative Nuclear Reactors and Fuel Cycles
Membership = 30 IAEA countries and EC

▪ GIF (2000)

- Generation 4 International Forum, 13 Countries are members of GIF (Argentina, Brazil, Canada, China, EC, France, Japan, Korea, Russia, South Africa, Switzerland, UK, USA

▪ ITER (2003) & Broader Approach (2007)

- ITER members are EC (EURATOM), India, Japan, Korea, Russia and USA

▪ Several other initiative on fusion (e.g. inertial fusion)

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New structural materials

- Development & Qualification of materials for nuclear applications is long term process; Two approaches exist:
  - Engineering (traditional) and Scientific (innovative).

- From early 80's computer modelling has been used in material studies for **fission reactors** (IGRDM, EU PERFECT, PERFORM-60, etc.).
- Further application in nuclear technology is linked with demand from **fusion reactors,** development of new materials (ICFRM, ITER, BA).
- In principle, there are many similarities between fission reactors and fusion technology, especially for "core" structural materials, however from programmatic point of view these activities are separated in most of Member States.

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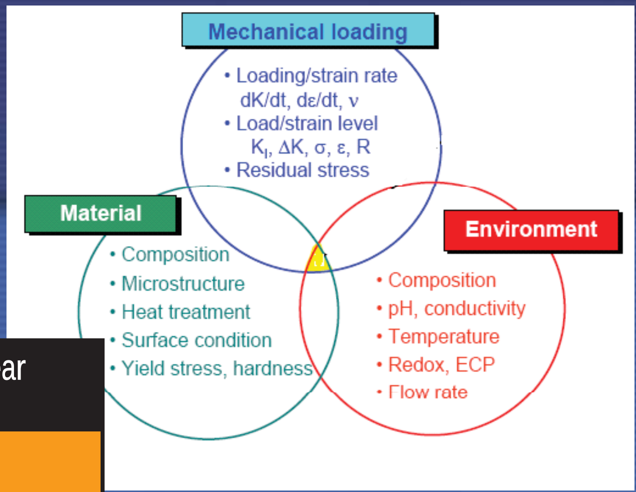
Degradation processes



Overview of material issues for LWRs

Component/ process	Irrad. embritt.	Fatigue	Corrosion fatigue	SCC	Corrosion	Thermal ageing	Wear
Reactor pressure vessel	X	X	X	(X)			
Control rod drive mechanisms		X		X			X
Reactor internals	X	X		X		X	
Reactor coolant pump casing		X	X		X	X	
Piping and safe ends		X		(X)	(X)	X	
Pressurizer		X	X				
Surge and spray lines		X					
Steam generator tubing		X	X	X	X		X
Steam generator shell and nozzle		X	X	X		X	

Identified problems of individual parts of reactor

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Main issues – Radiation damage

•L. Debarberis, B. Acosta, A. Zeman, Scripta Materialia, 53 (2005) 769-773

- Direct impact on mechanical properties.
- Effects like: Direct Matrix Damage **(dpa),** Precipitation, Segregation, Phase transformation, etc.
- Alloying elements (Ni, Mn, Cr, V) and impurities (Cu, P) play important role.
- Thermal and mechanical treatment can accelerate or reduce such processes
  (e.g. impact on distribution and size of grains),
  elimination of “bad” phases (e.g. α’).
- Effect of flux & dose rate, energy spectra (En > 0.5 MeV) and temperature.
- Higher doses (> 10 dpa) – Transmutation.

LWR: RPV ~ 0.1 dpa, RVI (up 10 dpa)

Luckily, lattice behaves differently, thanks to defect recombination mechanism, however only under certain conditions.

(1 dpa = every single atom in lattice has been displaced)

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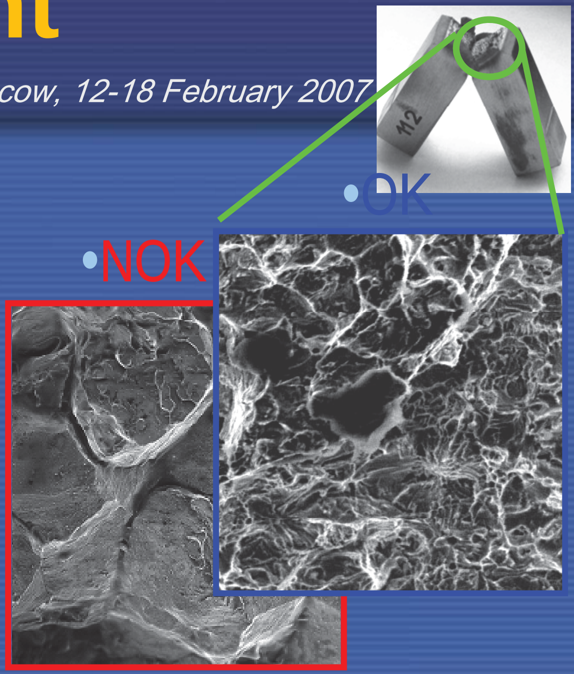
Main issues – Embrittlement

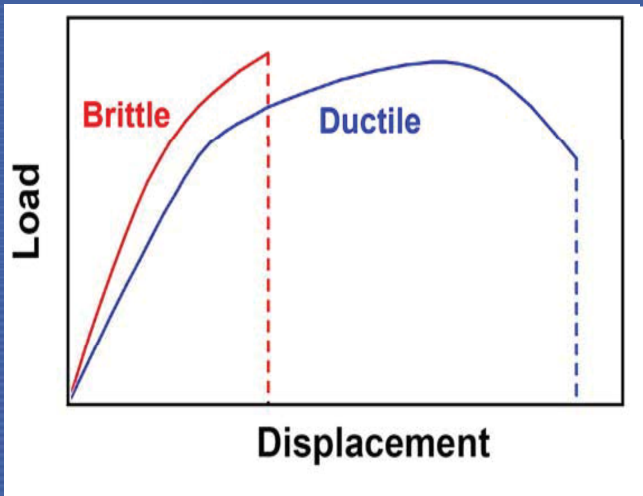
•*Zeman et al., Int. School of Physics (ITEP), Moscow, 12-18 February 2007*

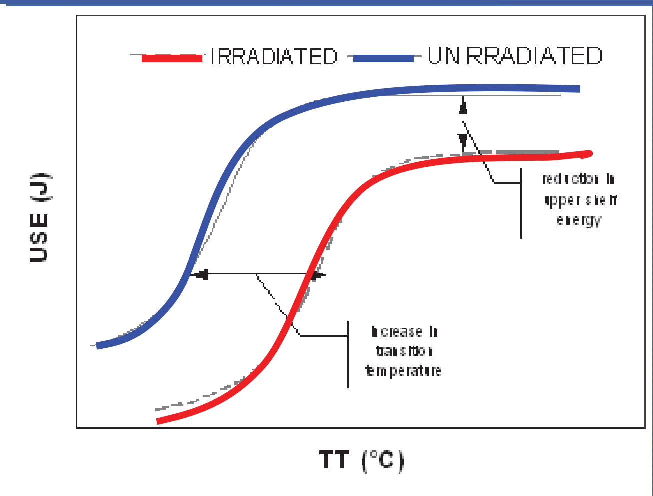


Problem related to the loss of ductility (RPV), non-replaceable components – determines NPP lifetime.

- **Normal (ductile) fracture,** plastic deformation takes place before fracture, strain at which the fracture happens is controlled by the purity of the materials.
- **Brittle fracture**, no apparent plastic deformation before fracture. Fracture occurs by cleavage as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes).

DBTT = Ductile to Brittle Transition Temperature – limits RPV operation





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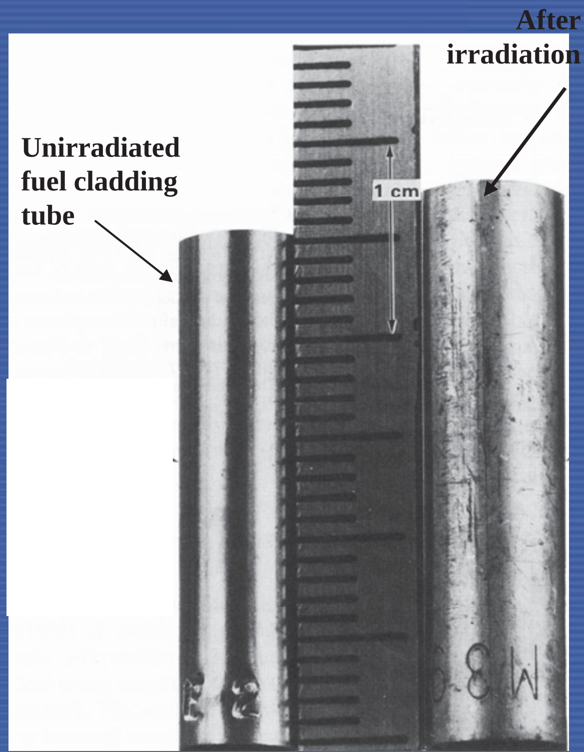
Main issues – Swelling

Issue for fuel cladding and core components

- Void swelling of reactor internals and fuel cladding (high burn up), apart of total dose, dpa rate plays important role.
- Variations in neutron flux-spectra can affect property changes, transmutation rate should be considered as well.
- In past, predictive swelling equations for steels have ignored such effects,



Formula for swelling (AISI 304):

- Old : % swelling = $A(T)\ (dpa)^2$
- New: % swelling = $A\ (dpa\ rate)^{-0.731}\ (dpa)^2$

•*Garner, IAEA Satellite meeting on Cross-cutting issues of structural materials for fusion and fission applications, ICFRM-13, Sapporo (Japan), 10-11 September 2009*

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Main issues – Corrosion and Cracking

Primary components

- Attachment welds: Stress Corrosion Cracking (SCC) significant at welded pad/bracket locations in the vessel shell
- Nozzles: SCC of nozzles is a significant issue
- Closure studs
- Penetrations: SCC of tubes (high residual stresses in sensitized weld material)
- Safe ends: Observed at several plants. SCC is a potentially significant degradation mechanism for safe ends

•Debarberis et al., IAEA-ICTP Advance Workshop on Development of Radiation resistan materials, ICTP Tieste, 20-24 April 2009

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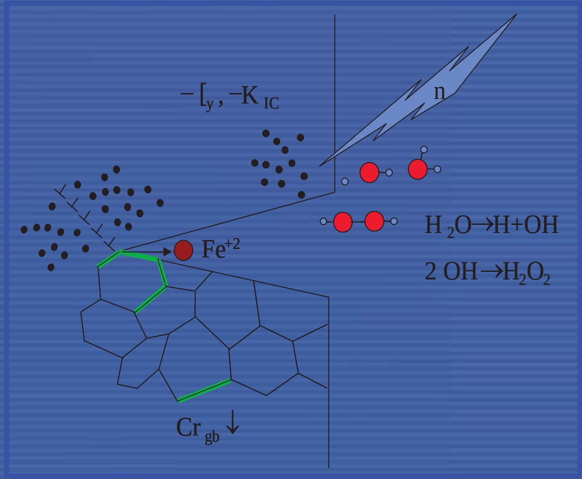
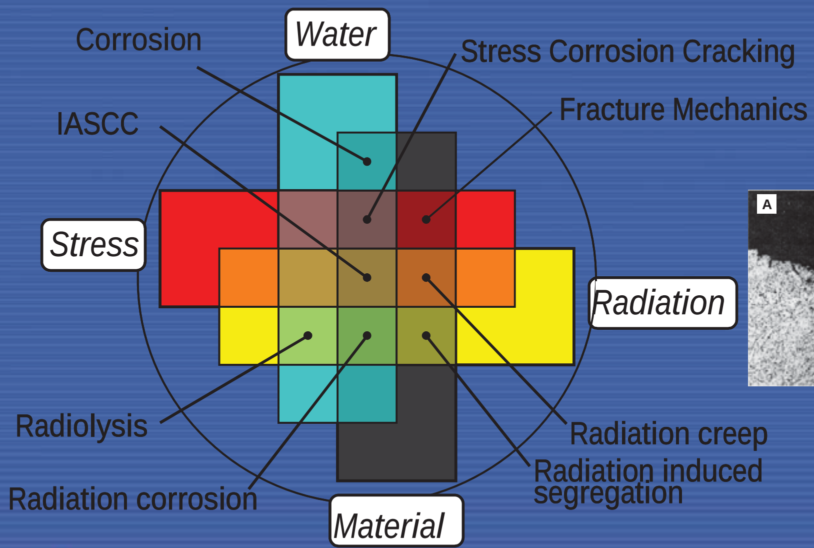
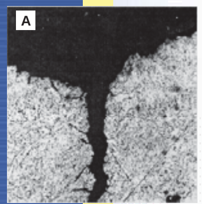
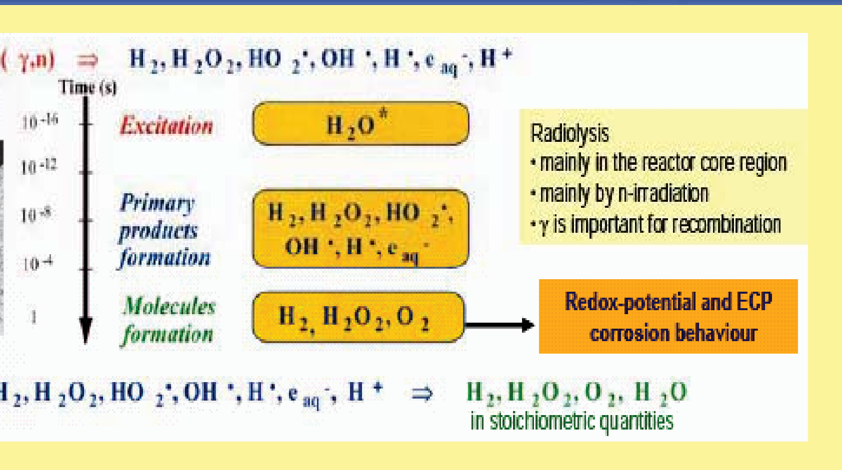
Main issues – Corrosion and Cracking

- Irradiation assisted stress corrosion cracking (IASCC), issue for BWR, SCWR
- Reactor Vessel Internals (RVI) issues (dose > 10 dpa)
- LWR Serious problem (RVI), high coolant flow rate (thermo-hydraulic stress)
- Chemistry extremely important (O, H)









•*Zeman et al., Int. School of Physics (ITEP), Moscow, 12-18 February 2007*

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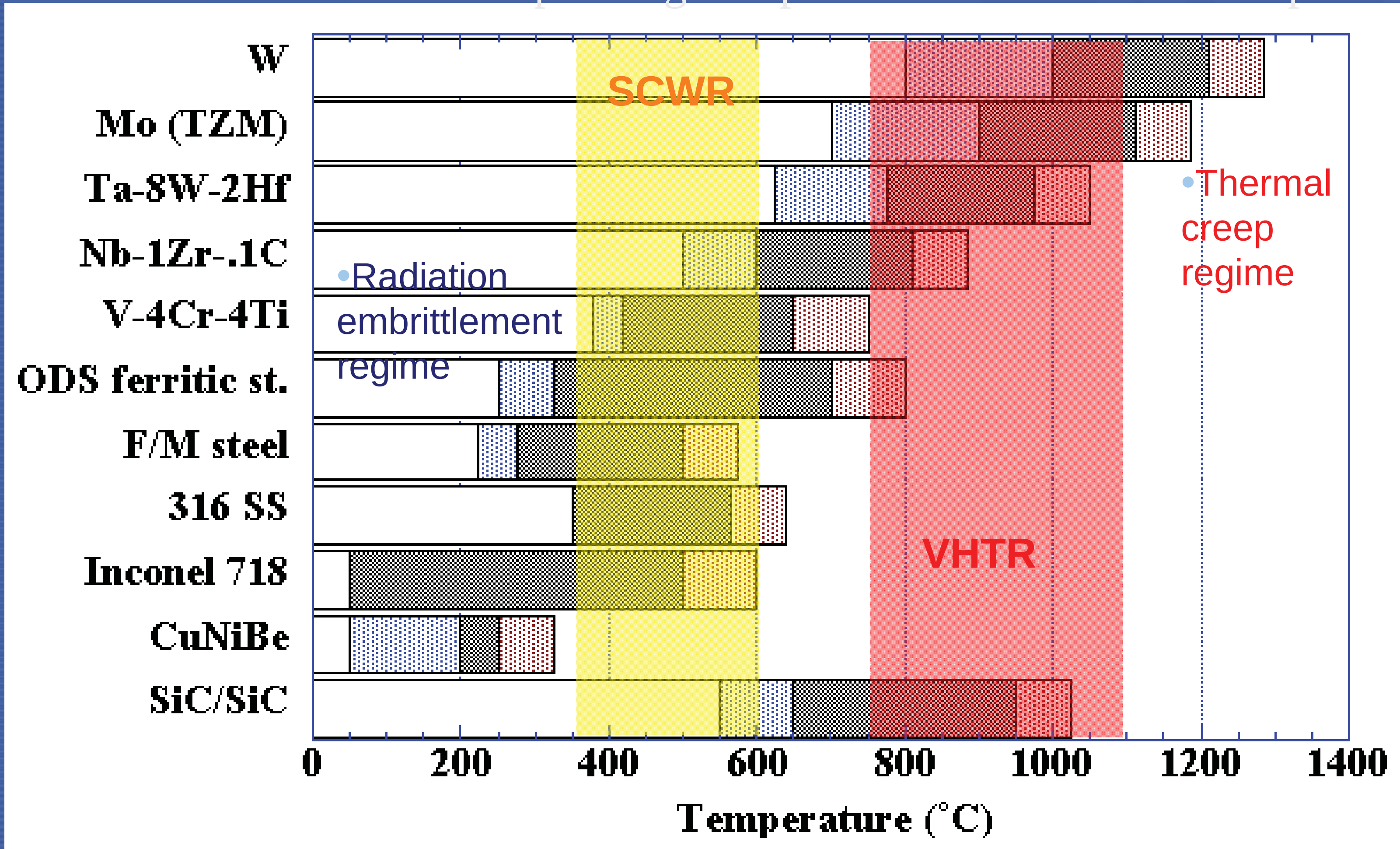
The restricted operating temperature window

•Structural Material Operating Temperature Windows: 10-50 dpa



$\eta_{Carnot}=1-T_{reject}/T_{high}$

•Low temperature radiation embrittlement typically occurs for damage levels ~0.1 dpa (0.01 MW-yr/m²)

•*Zinkle and Ghoniem, Fusion Engr. Des.* *51-52 (2000) 55*

Pending issues

- Basic information on physical processes of radiation damage
- Overview of structural materials for fission and fusion reactors including related R&D activities
- Recent R&D activities on advanced radiation resistant materials
- State-of-the-art information about modern nuclear, accelerator and research reactor based techniques used for simulation and studies of radiation damage in reactor core structural materials *(see next slide)*
- Overview of advanced physical models and computational codes developed for prediction of high-dose radiation effects

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Example: IAEA Coordinated Research Projects

Active new CRP 1575 (2009-2012):

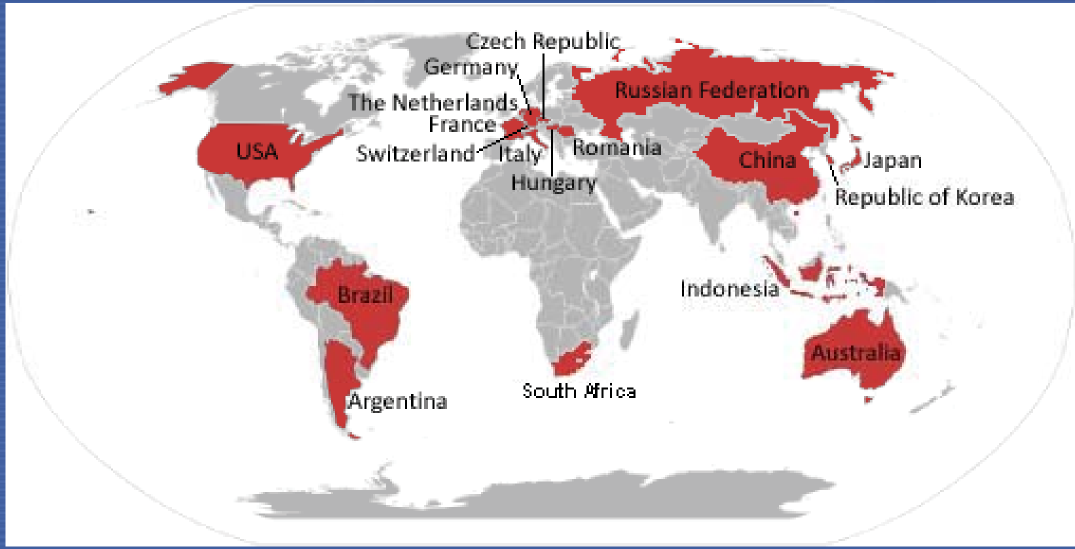
- Development, Characterization and Testing of Materials of Relevance to Nuclear Energy Sector Using Neutron Beams (SANS, diffraction and neutron radiography)

•**Objectives:**

- investigation and characterization of materials relevant to nuclear energy applications
- optimization and validation of experimental and modelling methods
- creation of a database of reference data for nuclear materials research
- enhancement of the capacity of research reactors for nuclear materials research

•**10 Research Contracts + 9 Research Agreements**

1. Argentina
2. Australia
3. Brazil
4. China
5. Czech Republic
6. France
7. Germany
8. Hungary
9. Indonesia
10. Italy
11. Japan
12. Korea
13. The Netherlands
14. Romania
15. Russian Federation (2)
16. South Africa
17. Switzerland
18. USA



•**Expected output:**

- Creation of multilateral network in the field of advanced nuclear materials research
- Creation of an experimental reference database for models and calculations
- Final project publication

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Needs for future NPPs

- Better understanding of radiation effects and mechanisms of material damage and basic physics of accelerator irradiation under specific conditions.

- Developmental of theoretical models for radiation degradation mechanism

- Improvement of knowledge and data for the present and new generation of structural materials

- Fostering the advanced or innovative technologies by promotion of information exchange, collaboration and networking *(see next slide).*

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Overview of operational conditions for various generation NPPs

GENERATION / PARAMETERS	FISSION (GEN. I)	FISSION (GEN. IV)	FUSION (DEMO/PROTO)	SPALLATION (ADS)
STRUCTURAL ALLOY T_{MAX}	<300˚C	500-1000˚C	550-1000˚C	400-600˚C
MAX DOSE FOR CORE INTERNAL STRUCTURES	~1 dpa	~30-100 dpa	~150 dpa	≤60 dpa/fpy
MAX TRANSMUTATION HELIUM CONCENTRATION	~0.1 appm	~3-10 appm	~1500 appm (~10000 appm for SiC)	~2000 appm/fpy
COOLANTS STRUCTURAL MATERIALS	H_2O Zircaloy, stainless steel	He, H_2O, Pb-Bi, Na Ferritic steel, SS, Superalloys, C-composite	He, PbLi, Li Ferritic/ martensitic steel, V alloy, SiC composite	PbLi, PbBi Ferritic/ martensitic steel

A. Möslang and S. Zinkle, IAEA Technical Meeting on
“First Generation of Fusion Power Plants Design and Technology“ (2005)

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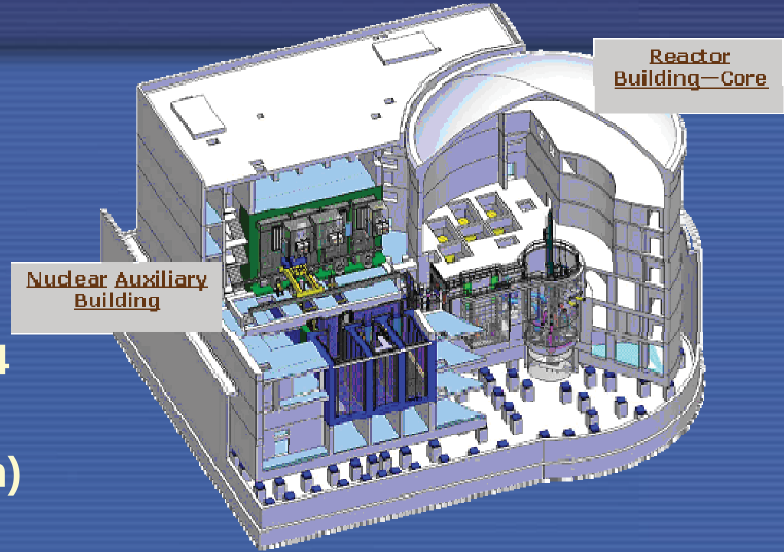
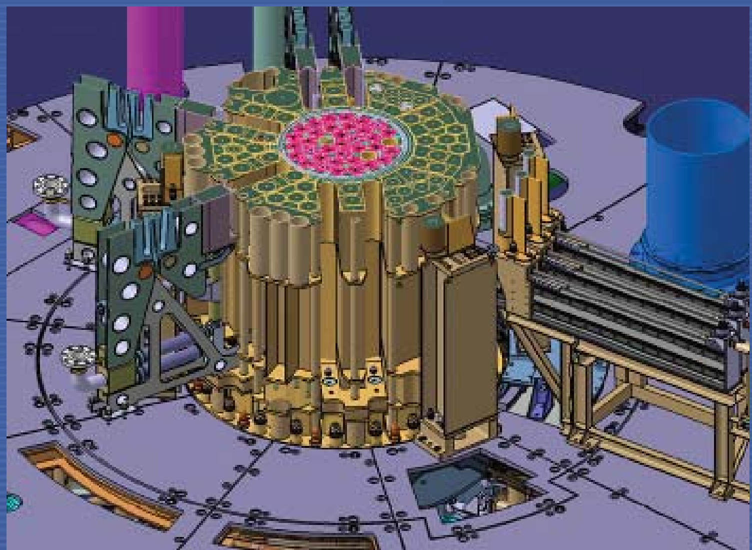
Dedicated Material Test Reactors

RR under construction

JHR, France, operation expected in 2015



- MTR pool, 100 MW, in core flux ~1*10^{15} n/(s cm^2)
- Fuel: Ref. UMo LEU, Backup: U_3Si_2 27 % U-235
- In support of future nuclear power, Gen3+ & Gen4
- Dedicated for material/fuel irradiation and testing
- Other applications envisaged (isotope production)
- International consortium



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Presentation of experimental capacity

In reflector

Up to 5.5 10^{14} n/cm².s

~20 fixed positions

(Φ100mm ; 1 position Φ200mm)

and 6 displacement systems

~20 simultaneous experiments

In core

Up to 5.5 10^{14} n/cm².s > 1 MeV

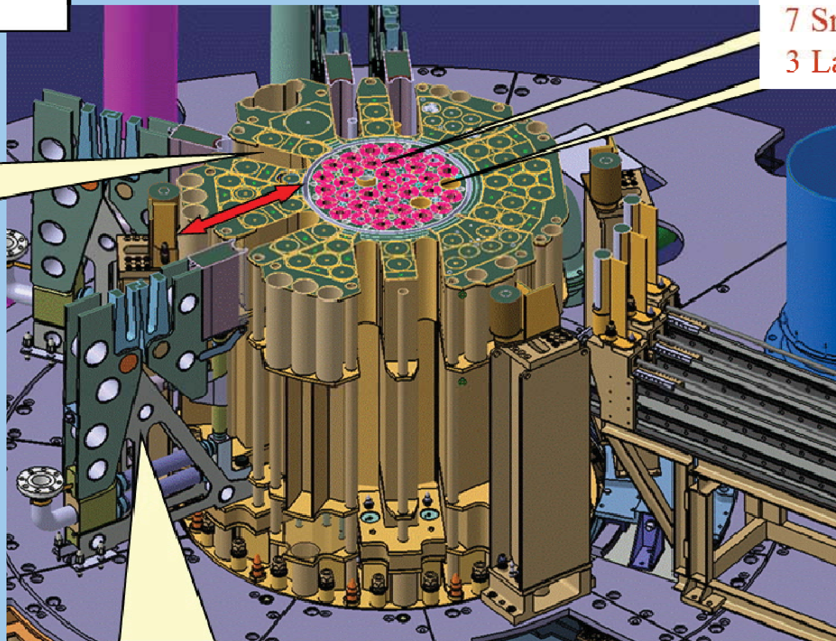
Up to 10^{15} n/cm².s > 0.1 MeV

7 Small locations (Φ~ 32 mm)

3 Large locations (Φ~ 80 mm)

Fuel studies: up to 600 W/cm with a 1% ^{235}U PWR rod

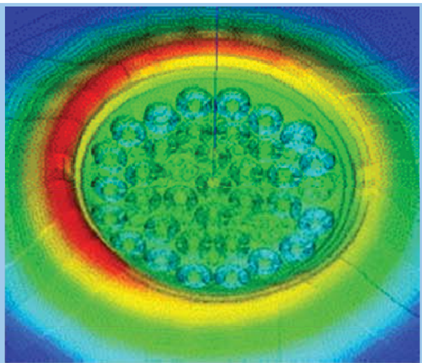
Material ageing (low ageing rate)



Fuel experiment (fast neutron flux)

Material ageing (up to 16 dpa/y)

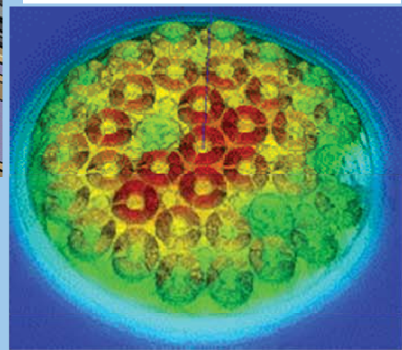
Thermal neutron flux



Displacement systems:

- Adjust the fissile power
- Study transients

Fast neutron flux



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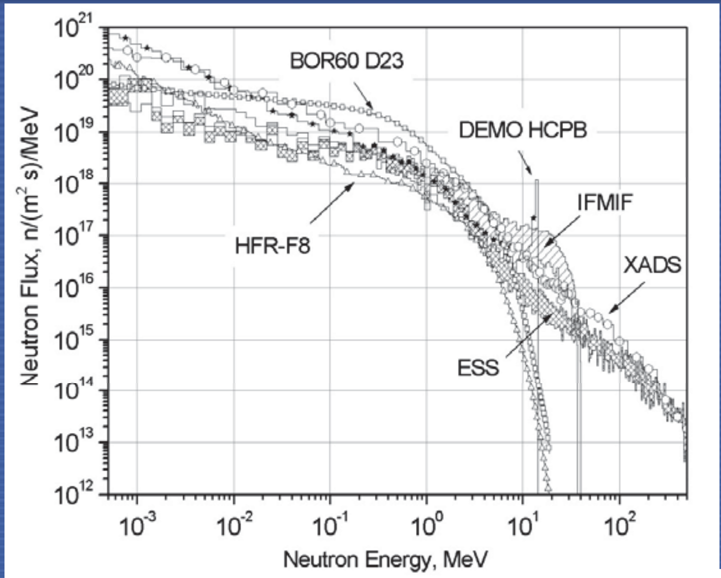
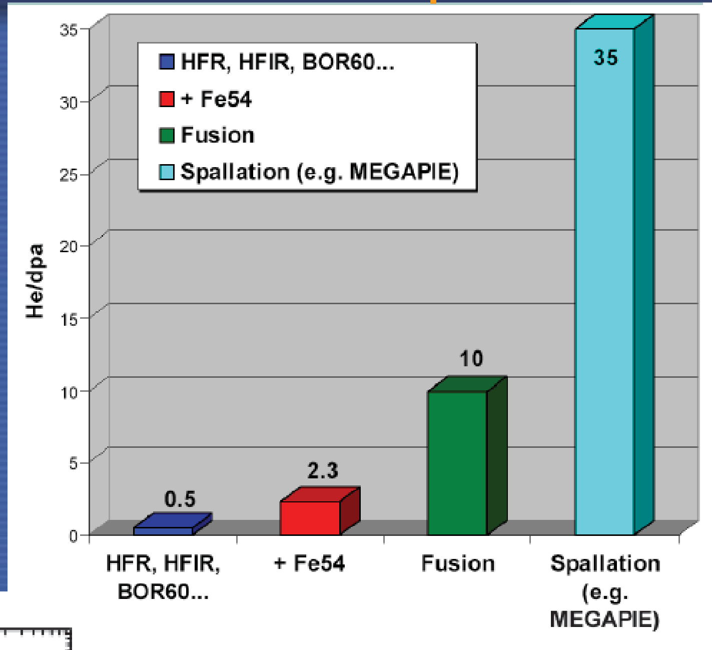
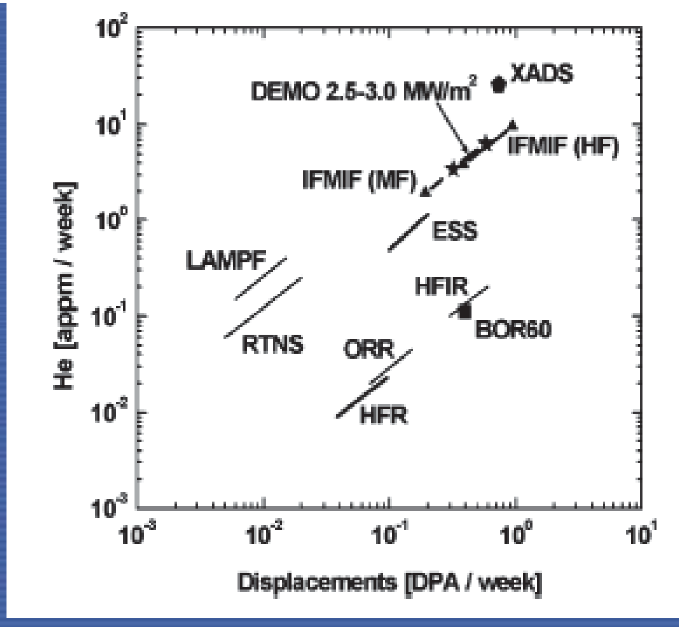
Need of Specific Material Irradiation Devices for Fusion

- Difference in neutron spectra



- Difference in He/dpa ratio





Combined/comprehensive approach is needed →

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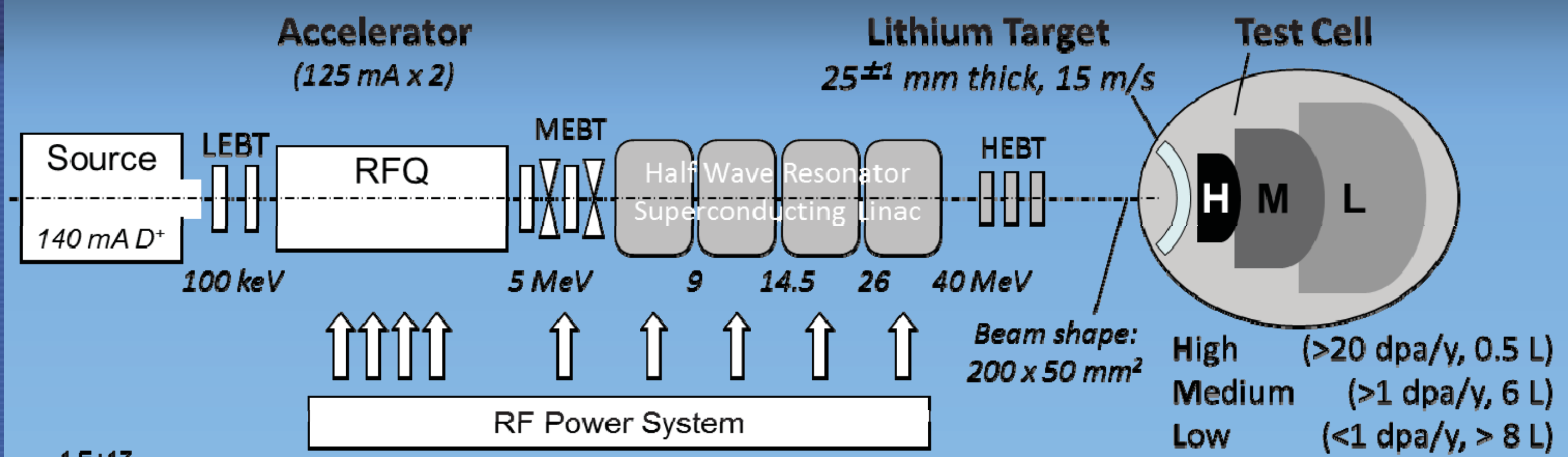
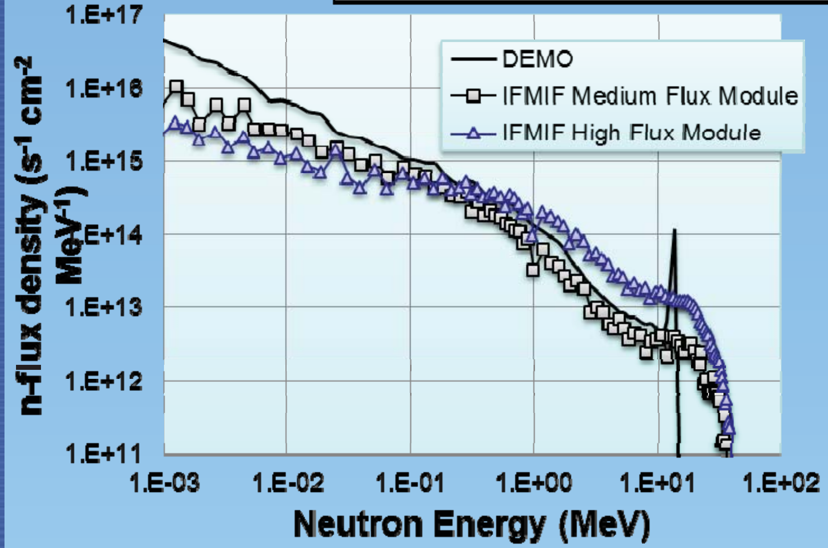
Before International Fusion Material Irradiation Facility (IFMIF) is available





Typical reactions

$^{7}Li(d,2n)^{7}Be$

$^{6}Li(d,n)^{7}Be$

$^{6}Li(n,T)^{4}He$

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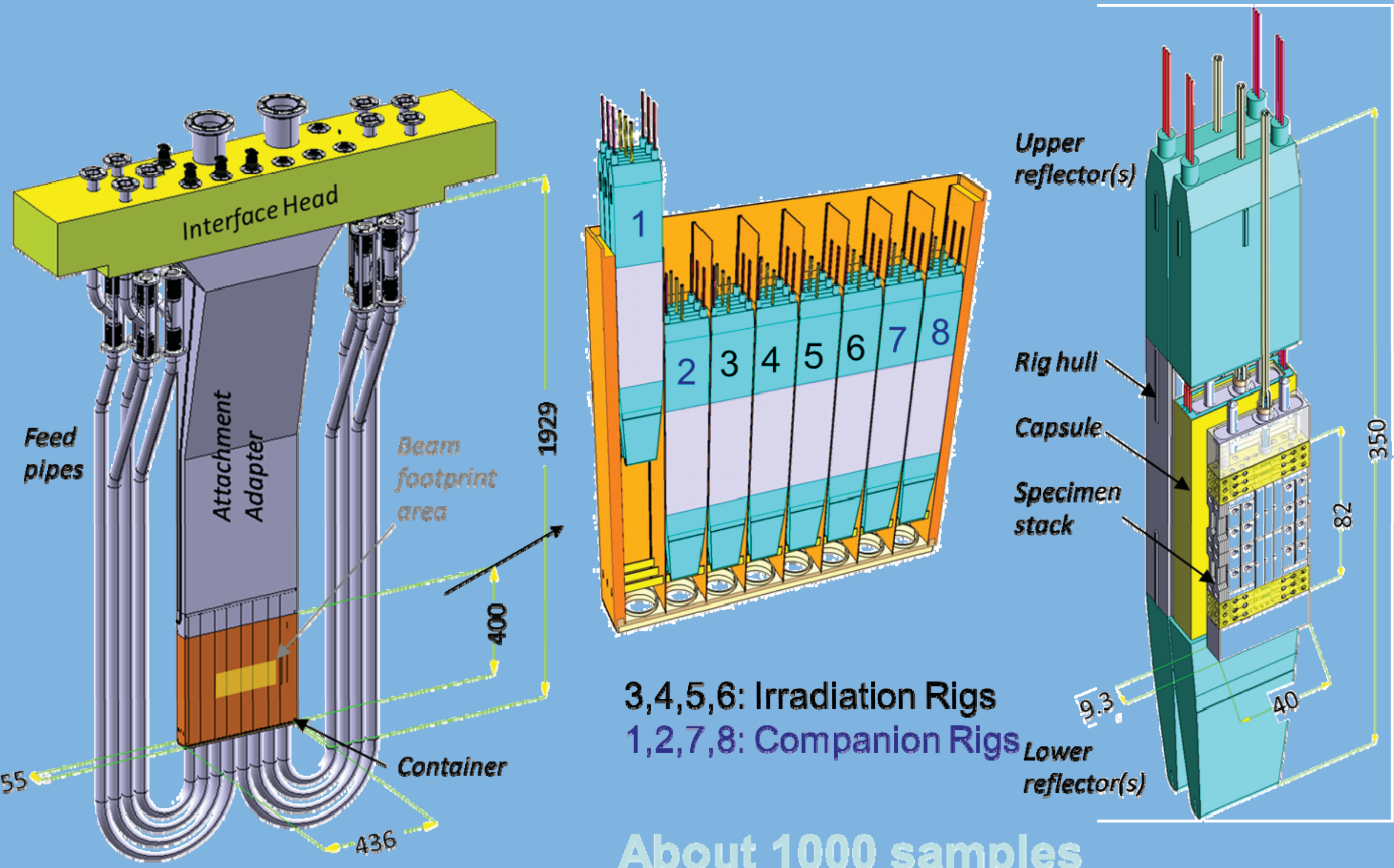
High Flux Test Module current design



3,4,5,6: Irradiation Rigs

1,2,7,8: Companion Rigs

About 1000 samples

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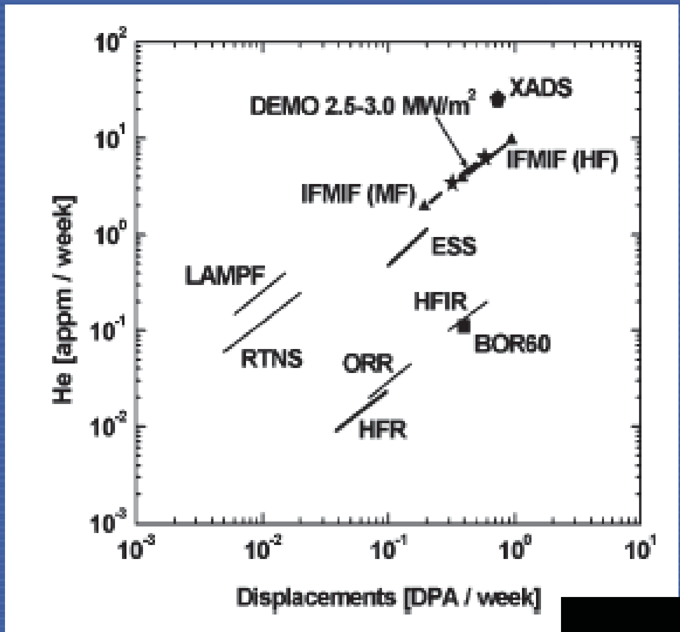
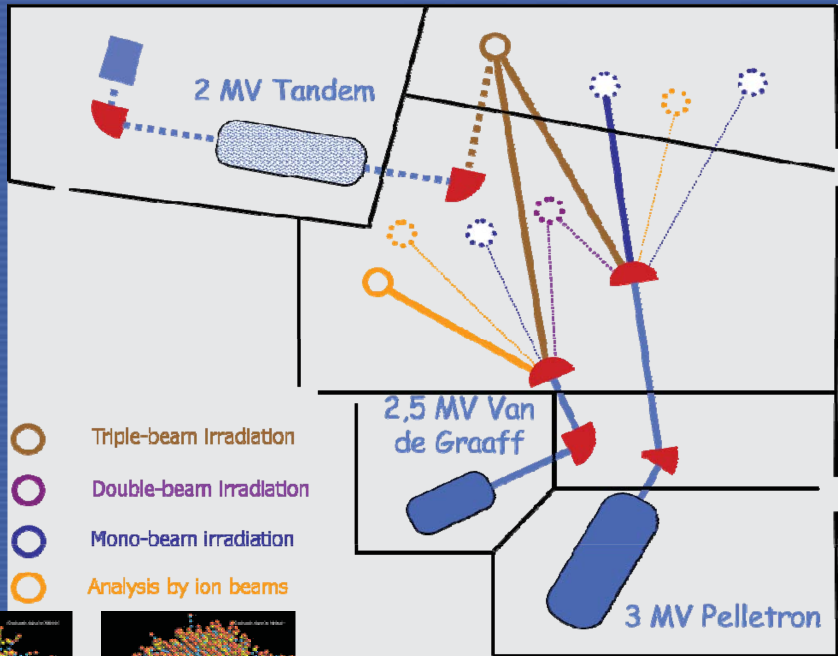
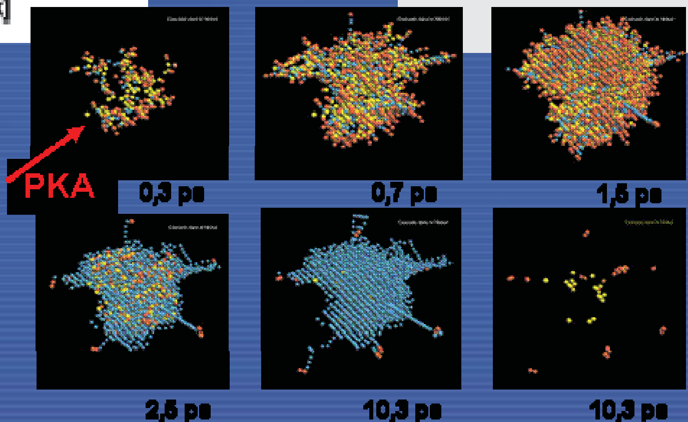
Combined/comprehensive multi-disciplinary approach

High Flux Fast RRs for dpa generation (e.g. BOR60 in Russia)



Multi-ion beams for H, He and FF generation (e.g. JANNUS facility in France)





Use the best physics understanding through complex modelling of occurring phenomena

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Education & training activities: synergetic approach for fission and fusion

The Abdus Salam
International Centre for Theoretical Physics

Joint ICTP/IAEA Advanced Workshop on
Development of Radiation Resistant Materials

20 – 24 April 2009

(Miramare – Trieste, Italy)

The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, in cooperation with the International Atomic Energy Agency (the IAEA), Vienna, Austria, is organizing the Advanced Workshop on Development of Radiation Resistant Materials, to be held at ICTP, Trieste, from 20 to 24 April 2009.

Within the frame of the INPRO and Generation IV initiatives, the next generations of nuclear power reactors are under assessments and in the R&D process. Almost all new reactor concepts are specified by higher efficiency and better utilization of nuclear fuel with minimization of nuclear waste. For the sustainability of the nuclear option, there is currently a renewed interest worldwide in new reactors and closed fuel cycle research and technology development; however, such an approach means that a new class of structural materials with significantly better radiation resistance will have to be introduced. To achieve the high performance parameters, more focused research and testing of new candidate materials are necessary.

The Abdus Salam
International Centre for Theoretical Physics

Joint ICTP/IAEA Advanced Workshop on
Multi-Scale Modelling for Characterization and Basic Understanding of Radiation Damage Mechanisms in Materials

12 – 23 April 2010

Miramare – Trieste, Italy

JRC EUROPEAN COMMISSION — Institute for Energy — IAEA

Joint EC - IAEA Topical Meeting on:

(F1-TR-37435)

Development of new structural materials for advanced fission and fusion reactor systems

hosted by

FUSION FOR ENERGY

ICFRM-14 Sapporo 2009 — IAEA International Atomic Energy Agency, Atoms For Peace

INFORMATION SHEET

ICFRM-14 Satellite meeting in cooperation with the IAEA on

Cross-cutting issues of structural materials for fusion and fission applications

14th International Conference on
Fusion Reactor Materials
(ICFRM-14)

10 - 11 September 2009

More info: www.ictp.it

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Thanks for your attention and...

...I wish you a successful continuation!

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GEN-IV material development

•GIF R&D Outlook for Generation IV Nuclear Energy Systems (2009)

❑ **VHTR unique components** needed, including the RPV, intermediate heat exchangers, and Brayton cycle turbo-machinery. RPV size and thickness being larger than modern boiling water reactor vessels.

❑ **SFR development of advanced structural materials** may allow further design simplification and/or improved reliability (e.g., low thermal expansion structures and greater **resistance to fatigue cracking**). These new structural **materials need to be qualified**, and the potential for higher temperature operation evaluated.

❑**SCWR development of materials and components** will build on (1) evaluation of candidate materials with regard to corrosion and **stress corrosion cracking, strength, embrittlement and creep resistance**, and dimensional and micro-structural stability; (2) the potential for water **chemistry control** to minimize impacts as well as rates of deposition on fuel cladding and turbine blades; and (3) measurement of performance data in an **in-pile loop**.

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GEN-IV material development

- **GFR** many of the **structural materials** and methods could be adopted **from VHTR, including RPV**, hot duct materials, and design approach. RPV is thick martensitic Cr-steel structure, ensuring negligible creep at operating temperature.

- **LFR corrosion** of structural materials in Pb key issue, corrosion of steels depends on the T and (O). In addition, **surface oxidation and erosion** to dissolution of the structural steel (oxidation rate, flow velocity, temperature, and stress conditions). FM and AS compatibility with Pb has been extensively studied and it has been demonstrated that generally below 450°C!, with an adequate oxygen activity in the liquid metal, both types of steels build up an oxide layer which behaves as a corrosion barrier, above 500°C?, corrosion protection through the oxide barrier appears to fail (e.g. T91 and AISI 316).

- **MSR** main steps are the experimental validation of **SM behaviour** (mechanical properties, corrosion), **like Ni-based alloys** including increased T, and the investigation of fission product deposition on structures and embrittlement.

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