Challenges for Materials Development for Advanced Fission, Fusion, and Hybrid Reactors: The Critical Role of Ion Beams

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Executive Summary

- Ion-beam materials research can accelerate the development of two critical materials areas for nuclear energy
  - The development of radiation tolerant materials is the big scientific/technical goal that is specific to the success of sustainable nuclear energy
  - Similarly, the development of high and ultra-high burn-up fuels is critical to the development of advanced fission and FFH systems

- Energy independence and the reduction of global warming will be realized as a result of nuclear energy being a significant part of the global strategic energy plan
  - The long time (~20 years) for materials development, testing, licensing, and insertion is a scientific and technological challenge if not an imperative.

Radiation tolerance and high burn-up are science challenges with strong technological implications.
Energy needs, and sustainable and safe development for state sovereignty

- Access to energy is essential to quality of life
- A meaningful target that accounts for footprint, materials availability, and energy storage capabilities requires a balanced portfolio of fossil fuel, renewable sources, and nuclear.

Why nuclear?

- Nuclear energy accounts for 17% of the energy portfolio worldwide.
- Besides a fourth generation of fission reactors in the planning, a nuclear renaissance is shaping up with recent advanced fission and fusion/fission reactor concepts.

Access to energy is essential to quality of life: 80% of the world’s population of over 6 billion people is below 0.8 on the U.N. Human Development Index (HDI). (Source: UN Development Program; McFarlane 2006).
New generations of nuclear power reactors will require high burn-up fuels long in-core life times and radiation tolerant materials

During the last 60 years very slow improvement in burn-up (BU)

Despite >50 years of fission reactor R&D we still do not have all the science-based tools that we need for advanced nuclear energy
Oxide Dispersed Strengthened Steel— a Candidate Material:  
A model system for radiation tolerance

What refinements or general principles can we discover that will improve ODS’ mechanical and rad tolerant properties?
High and ultra-high burn-up nuclear fuels will play an essential role in the future of sustainable nuclear fission energy.

Long-term goals: uranium economy, waste minimization, fission economy, and proposals for hybrid fusion/fission reactor concepts.

One of the broad objectives is a solution to the “3R” problem: Repository-Recycling-Reprocessing.
Hybrids can work, and for less demanding fusion conditions:
1987 US Academy of Science study

<table>
<thead>
<tr>
<th>Technology</th>
<th>Plasma Power Gain, Q</th>
<th>Neutron Wall Loading, W (MW/m²)</th>
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</thead>
<tbody>
<tr>
<td>Pure fusion</td>
<td>15 to 25</td>
<td>3 to 5</td>
</tr>
<tr>
<td>Fission-suppressed hybrid</td>
<td>10 to 15</td>
<td>2 to 3</td>
</tr>
<tr>
<td>Fast-fission fuel-producing hybrid (with some power output)</td>
<td>5</td>
<td>1 to 1.5</td>
</tr>
<tr>
<td>Fast-fission power-only hybrid</td>
<td>3</td>
<td>1</td>
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R. Moir, Third Fusion-Fission Hybrid Workshop, Univ of MD, March 2009
There are numerous technological challenges for the Laser Initiated Fusion Energy (LIFE) Fission Hybrid

- Target injection, survival of cryo fuel, tracking and laser intercept
- Manage fusion environment: A threat to final optics, 1st wall, beam propagation, chamber clearing
- Low cost NIF-energy level Dpoul @ 10-15 Hz 10-15% with high availability
- 1st wall survive 5 to 7 years from fusion neutron, x-rays and ions
- High burn-up of fuel (goal is > 99%) without reprocessing
- Robust Hot spot yield w/LIFE-relevant targets

E. Storm, Third Fusion-Fission Hybrid Workshop, Univ of MD, March 2009
There is no fertile fuel form capable of 99% FIMA

EXECUTION PLAN – CHALLENGES
- Fuel stability in an evolving chemistry (fission products)
- Accommodation of fission gases
- High irradiation resistance (hence low swelling)
- Fuel-cladding bond (to maximize conductivity)
- Protection against fuel-cladding interaction
- Environment-friendly fabrication process and low fabrication cost
- Closure of the fuel cycle / Waste form and disposition

At the end of the day what counts is thermal conductivity and radiation tolerance of the fuel package.
Capabilities in Japan

D. Hamaguchi et al, First International Workshop on Measuring, Modeling, and Managing Helium-DPA Effects, June 15-17, 2009 Paul Scherrer Institute, Switzerland
Synergy: a general phenomena  Mechanism: the key to understanding

Our strategy → The Mechanism (experiment & theory)

H, He, and DPA's in Fe(Cr)

- TIARA Triple Beam Facility
- Takasaki Ion Accelerators for Advanced Radiation Applications

Formation of a number of cavities

Oxide particle

Helium cavities

20 nm
CEA studies suggest additional mechanism for He management

- Nano-clusters still present after irradiation
- Defocus suggests bubbles (possibly in the particles)
Mimic radiation enhanced diffusion in fuels with “fission product” ion beams at CAMS

10% Burn-up ↔ DPAs

- Typical fission fragment pair
  - 110 MeV Ru
  - 70 MeV Cs

- 170,000 displacements per fission
  - 10% burn-up equivalent to 17,000 DPA
  - 5 days at 6.24E12 particles/s/cm²
  - 17,000 displacements per uranium-atom

Implanted Fission Fragment Ions (from TRIM program)

Estimated displaced atoms

[Graphs showing implanted fission fragment ions and estimated displaced atoms]
High and ultra-high burn-up pose materials challenges for which practical experimental data and technical experience are needed.

**Challenge:** Physics and Chemistry of ultra-high burn-up materials dramatically change as a result of the in-growth of fission products and the appearance of new complex phases.

The changes in fuel chemistry and the high radiation dose both impact the thermal properties and mechanical integrity of the fuel.
Heavy ions in the range of 100 MeV provide an ideal platform for “simulating” actinide fuel evolution due to radiation-driven processes.

SPECIMEN
Heat
Impurities
Fission Products

Fission Product DPAs
and/or
Fission Product Implants
Synthesis of

Near-surface Zone
Simulation Zone for Radiation Dose and FP Implant
Reference Sample
Radiation Damage Zone
Sample Holder Temperature Control
Post Irradiation Examination

U-7Mo/Al

Challenges for Materials Development for Advanced Fission, Fusion, and Hybrid Reactors: The Critical Role of Ion Beams
OUR APPROACH & PROGRESS ON ODS

ODS Nano-dispersoid

Joint ICFRM-14 and IAEA Satellite Meeting on Cross-cutting Issues of Structural Materials for Fusion and Fission Applications

Challenges for Materials Development for Advanced Fission, Fusion, and Hybrid Reactors: The Critical Role of Ion Beams
Our approach to understanding radiation tolerance in ODS steels

- This SI focuses on the ferritic-martensitic oxide dispersed strengthened (ODS) steels which belong to the general class of materials containing insoluble nano-dispersoids. The approach emphasizes accelerated aging and time transcending theory simulation and modeling.

- Experimental accelerated aging
  - Ion-beam irradiations to produce DPAs, and to implant helium and hydrogen
  - Electron microscopy to study the atomistic aspects of radiation damage and accumulation
  - Micro-scale-mechanical testing to connect long-length scale properties to atomistic characterization

We are science focused but with the goal of advancing the technology of nuclear energy materials
**Material synthesis**

**Producing oxygen free Fe(Cr) has been challenging**

Orientation imaging showing full density equiaxed consolidated Fe(Cr) alloy

- SEM image of Cr$_2$O$_3$ entrapped in the consolidated microstructure

**Our collaborations provide high quality technically relevant specimens**

- We have interesting materials with which to go forward.

**MA957 IAEA CRP Round Robin**

**K3 from Professor Kimura’s program**
Material characterization

Atomistic characterization is at the heart of our plan

- We have characterized the microstructure of two ODS alloys; MA957 (Fe-14Cr-0.9Ti-0.3Mo-0.25Y₂O₃) and K3 (16Cr–1.8W–4.6Al–0.3Ti–0.37Y₂O₃). This work is the baseline for both modeling and comparison of irradiated specimens.

We now have an hypothesis about the atomic structure of the dispersoids

- We now know that there is no single type of particle morphology, but rather a variety of particles with varying chemistry, size, and crystal structures. How these features result in radiation tolerance will be revealed by our radiation studies.

Use of the TITAN microscope will provide key data

- We now have a hypothesis about the atomic structure of the dispersoids.
- Competition between kinetic recrystallization of yittria and thermodynamic driven oxide formation of “getters”

High resolution TEM (HRTEM) images show the existence of facets and ledges at the interfaces between matrix and oxide particle.

Crystal structure of Y₂AlO₅ (YAM)

ODS Nano-dispersoid
Both structure and composition of oxide/matrix interfaces are dependent on the size of $Y_4Al_2O_9$ particles.

This result reveals a relatively faster coarsening rate for incoherent particles due to a higher interfacial energy that could lead to variations of propensity and sink strength for trapping point defects and helium bubbles.

Left: A large particle (> 15 nm): incoherent interface associated with a spherical shell; Right: Small particles (< 10 nm): semi-coherent interfaces associated with facets & ledges.
Nucleation of a $Y_4Al_2O_9$ monoclinic oxide domain in an amorphous $Y_2O_3$ fragment

$$2Y_2O_3 + 2 [Al] + 3 [O] \rightarrow Y_4Al_2O_9$$ during HIPing
Nucleation of a Y₄Al₂O₉ monoclinic oxide grain in an amorphous phase (oxide) domain presumably through the reaction: $[\text{MO}]_{\text{amorph.}} \rightarrow 2\text{Y}_2\text{O}_3 + \text{Al}_2\text{O}_3 \rightarrow \text{Y}_4\text{Al}_2\text{O}_9$ during HIPing.

Crystal structure of Y₄Al₂O₉ (YAM)

$[011]_\alpha // [432]_{\text{YAM}}$
The existence of facets, ledges, and amorphous remnants (marked by red arrows) at the oxide/matrix interface.
Crystallization of amorphous phase (oxide) domain results in the formation of double $Y_4Al_2O_9$ domains within an oxide particle.
Facets, ledges, and amorphous remnants (marked by red arrows) can be found at the oxide (domain II)/matrix interface.

$$[011]_\alpha/[221]_\Pi$$
Microanalysis of the chemical composition of oxide/matrix interfaces is conducted by J. Aguiar and N. Browning using the state-of-art TEM: TITAN.

Normalized EELS Line Scan of an ODS Particle

20 nm

ODS particle

Energy (eV)

Counts

Right

Left

Ti O Y

1

2

3

4

5
Three types of mechanical measurements are planned

Manufacturing micro-specimens is the key

- Tensile specimens will be irradiated and mechanically tested to correlate mechanical properties with atomic changes
  - Spark cutting
  - Laser trimming
  - Focused ion beam shaping

Advanced dislocation and molecular dynamics modeling

The role of cell size is critical in interpreting micromechanical experiments
Technical Approach 4a

Preparing micro-Tensile Test Specimens (TTS) for irradiation studies

Evolution of EDM process to fabricate the conventional TTS to the miniaturized, up to the micro-sized specimen geometry

FIBing (ion milling) - Ultimate fabrication stage for the micro-TTS to target thickness at the inner gage section along with the removal of surface and microstructural HAZ bulk damage caused by EDM

Mechanical properties obtained by Instron’s Microtester 5848 and Nanolndentation to correlate mechanical behavior with atomic changes

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Thickness of a disk slice in 1 mm

Thru FIBing process, the target Inner-gage thickness will be 0.0004” = 10 um

Data before and after the irradiation Modulus, Yield Strength, Ultimate Tensile Strength, and Hardness, etc.,
CONCLUSION

**Ion-beam irradiations: mechanism, saturation, & synergy**

**Sequential irradiations at LLNL FN Tandem**

- The LLNL FN-Tandem electrostatic accelerator has unique features that make it ideal for both simultaneous and sequential irradiations

**Synergy and saturation are key scientific questions**

- Complex synergies have been reported in vanadium and in Fe(Cr) alloys

**Di- and tri-beam irradiations at CEA Saclay JANNuS**

- Our first dual beam experiments were performed 26th July to 8th August, 2009

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**N. Sekimura et. al. J Nuc Mats 283-287 20**


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Thank you for your attention