Comments on Demo designs and issues

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General Comments regarding the Path to Demo

• Don’t over-constrain DEMO mission
  • Feasibility vs. attractiveness (cost, ES&H, etc.)
  • A fusion nuclear science facility would be highly valuable for addressing multiple-effects issues (TRL 5-7)

• If burning plasma is not achieved, then fusion nuclear technology research is unnecessary
  • However, based on current timelines (e.g., ITER), critical path items for DEMO are mainly associated with fusion technology issues (PFCs, etc.)

• Near-term R&D should focus on critical-path issues
  • Especially low-TRL (i.e., low-cost) issues
Timeline of some key events for nuclear energy and materials and computational science

1940
CP-1
Graphite reactor

1950
1st stellarator & Tokamak

1960
Shippingport

1970
Tokamak era begins

1980
Nuclear >10% US electricity

1990
JET: Q=0.65, 0.5s

2000
NIF

2010
ITER

Development of Mat. Sci. as an academic discipline

1st MD simulation of radiation damage
(500 atoms, 1 min. time step)

1 Gflops achieved; high performance computing centers established

multimillion atom MD simulations
(~1 fs time step)

S.J. Zinkle, Fusion Sci. & Technol. 64 (2013) 55
Technology Readiness Level: Assessment of Functional Maturity

Mankins, 2009

Zinkle, Federici, Kessel, Konishi, Muroga & Snead, ICFRM-16, Beijing, 2013
The Technology Readiness Level of Fusion Materials was Evaluated by Experts at ICFRM-15

All evaluated materials are at a relatively low TRL~3

H. Tanegawa (JAEA), S. Zinkle (ORNL), A. Kimura (Kyoto U.), R. Shinaivski (Hyper-Therm), M. Rieth (KIT), E. Diegele (F4E), L. Snead (ORNL)

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“Concept development” | “Proof of principle” | “Proof of performance”

M. Tillack et al., ICFRM-15, Charleston, SC, 2011
A Visual Flow of Materials Research and Facilities to Accomplish that Research in Preparation for a Fusion Nuclear Science Facility FNSF (early DEMO)

2014

single-few effects

- Tritium: $25-30M
- Fusion neutrons: $10-50M
- Plasma-material: $20M
- Liquid metals: $10-20M

Aggregate of smaller materials-focused facilities addressing 4 major areas and costing ~ $65-120 M

2024

maximum integration

- Fusion/fission integrated assemblies: $60 M
- Non-nuclear integrated components: $30M

Integrated PFCs on tokamaks $10-20M

2034

Individual- or multiple-effect test facilities addressing blanket, divertor, and special components in non-nuclear or nuclear environments, costing ~$100 M

Early DD phase of FNSF

Zinkle, Federici, Kessel, Konishi, Muroga & Snead, ICFRM-16, Beijing, 2013
Outstanding Challenges

• Still a divergence of opinions on how to bridge the gaps to fusion power plants
• However, there are outstanding issues common to any next major facility after ITER, whether a DEMO, a Pilot Plant or a FNSF/CTF:

Key Design Drivers/ Areas where advances are needed:

- Handling of heat exhaust (divertor and first wall)
- Tritium breeding + electricity production ⇒ mature Balance of Plant
- Structural and PFC materials
- Maintenance scheme ⇒ plant architecture
- Operating plasma scenario ⇒ CD requirements

Zinkle, Federici, Kessel, Konishi, Muroga & Snead, ICFRM-16, Beijing, 2013
Overview of Defect Microstructures in Irradiated Materials

- SFT, Dislocation loops
- Bubbles, voids, precipitates, solute segregation
- Amorphization (intermetallics & ceramics)
- Network dislocations
- Grain boundary helium cavities

Stage I

Stage III

Stage V

Irradiation Temperature ($T/T_M$)
Effect of initial sink strength on radiation hardening of ferritic/martensitic steels (fission neutrons ~300°C)

H retention increases dramatically in the presence of cavity formation

3 to 5x increase in retained hydrogen when cavities are present, even with 2-3x reduction in neutron fluence exposure

500-700 appm H (few cavities) 1700-3700 appm H (rad.-induced cavities present)

Retained H level is ~100x higher than expected from Sievert’s law solubilities

Baffle-former bolt removed from Tihange-1 (Belgium) pressurized water reactor Type 316 austenitic stainless steel

Conclusions

• In order to progress from ITER to DEMO, a dedicated intermediate-step fusion nuclear science facility is anticipated to be important to address integrated-effects phenomena (TRL~5-7).
  • ITER and mid-scale facilities are expected to provide necessary but insufficient fusion nuclear science information to enable high confidence in the optimized design for DEMO
  • A detailed US fusion energy roadmap (at least at the level of detail as other international roadmaps) needs to be jointly developed by DOE-FES and the research community
• The specific objectives and concept for FNSF need to be established
  • Key questions to address include whether FNSF needs to be a prototypic design for DEMO (versus a non-prototypic magnetic configuration simply used for component testing)
• The time to initiate community discussions on FNSF is now
The development of fission energy faced numerous technological barriers (e.g., Zr alloy cladding)

- 1950: US annual production of Zr was ~200 lbs (~10^6 lbs/yr needed by late 1950s); $240/lb cost was ~30x higher than economical limit

- “At the time of this decision there was no assured source of Zr, no estimate of how much would be needed, no certainty that any known or conceivable process could produce the required amount, and no specifications for the nuclear, mechanical, or corrosion qualities the metal had to possess.” (Nautilus launched Jan. 17, 1955 using Zry2 cladding that was first specified in Aug. 1952)

H.G. Rickover, History of the development of Zr alloys for use in nuclear reactors, NR:D:1975
Detailed timeline of some key facilities for nuclear energy and materials

- **CP-1**: Graphite reactor
- **CP-5**: Graphite reactor
- **BSR**: Bulk Shielding Reactor
- **MTR**: MTR
- **ETR**: ETR
- **ORR**: OBRR
- **BGRR**: Calder Hill
- **Shippingport**: Obninsk AM-1

### Timeline

- **1942**: Inception of nuclear submarine program
- **1944**: Initiation of design of shielding for nuclear submarines
- **1946**: ORNL becomes the lead institution for naval-reactor shielding
- **1948**: Penetration of neutrons and gamma rays through various materials studied at the Graphite Reactor
- **1950**: BSR went critical
- **1952**: BSR became the Bulk Shielding Reactor
- **1954**: MTR added to broaden the usability of the BSR
- **1956**: Forcel-cooling system added to the BSR

### Key Events

- **1946**: E.P. Wigner published his first radiation damage paper in *J. Appl. Phys.*

![Fig. 33. Cutaway view of the MTR. (Courtesy of Idaho National Laboratory)](image)

![Fig. 34. The MTR in operation. (Courtesy of Idaho National Laboratory)](image)

**Fig. 37.** The BSR in its “swimming pool.”

![Fig. 37. The BSR in its “swimming pool.” (ORNL Photo 4117-96)](image)

**Fig. 38.** The BSR became useful for a wider variety of experiments including studies of the effects of radiation on materials.

**Fig. 39.** In a change from the MTR, the control rods entered from below, making the fuel elements easily accessible from above, and the upper grid plate was split in an arrangement that permitted leaving experiments in place during refueling.
Several materials-tritium issues require additional investigation

• Identification of a robust, efficient and economic method for extraction of tritium from high temperature coolants
  – Large number of potential tritium blanket systems is both advantageous and a hindrance

• Current materials science strategies to develop radiation-resistant materials may (or may not) lead to dramatically enhanced tritium retention in the fusion blanket
  – Fission power reactors (typical annual T\textsubscript{2} discharges of 100-800 Ci/GW\textsubscript{e}; ~10% of production) are drawing increasing scrutiny
  – A 1 GW\textsubscript{e} fusion plant will produce ~10\textsuperscript{9} Ci/yr; typical assumed releases are ~0.3 to 1x10\textsuperscript{5}Ci/yr (<0.01% of production)
  – Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure
  – Tritium trapping efficacy of precipitates and nanoscale solute clusters (blanket & piping) is poorly understood from a fundamental perspective
Comments on fission vs. fusion energy development

• Fission Q=1 was much easier to experimentally achieve
  – Hence, numerous Demo fission reactors could be quickly built in the 1950s to
    explore multiple-effect physics and engineering issues

• Global political environment in 1950s and 1960s was favorable for
  fission energy research (national security impact)
  – Lack of long-term (and well-funded) energy strategies in many countries is an
    impediment to progress

• Much more aggressive approach to rapidly obtaining results at all costs
  in 1950s & 1960s (different ES&H attitudes)

• There was a dynamic, (over?)aggressive champion for US fission
  energy R&D during its formative years

• Is fusion sometimes caught up in the pursuit of the optimal answer,
  when an inelegant placeholder solution might suffice?