Summary of Topic-1
Fusion Power Extraction and Tritium Fuel Cycle

Mohamed Abdou
with Takeo Muroga and Neil Morley

1st IAEA DEMO Workshop
UCLA, Los Angeles, CA, USA
October, 2012
Topic 1: Fusion Power Extraction and Tritium Fuel Cycle

- What choices are available for material, coolant, breeder, configuration and design concepts for fusion nuclear components worldwide (focus on power extraction and tritium fuel cycle)?
- What are the key fusion nuclear science and technology (FNST) issues and challenges?
- What issues can be resolved in non-fusion facilities?
- What issues require experiments in integrated fusion nuclear environment?
- What laboratory facilities need to be upgraded or constructed in the next 10 years?
- What are the major parameters and features required in a next step fusion nuclear facility to resolve the FNST issues and develop fusion nuclear components?
- What is the role of ITER TBM?
- What are the stages of experiments and development of FNST in a fusion nuclear facility?
- What strategies can be adopted for design, construction and operation of next step fusion nuclear facility(ies) to address the challenges of RAMI and limited availability of external tritium supply?
FW/Blanket concepts for fusion power extraction and tritium production

- EU: HCLL, HCPB, WCLL, DCLL
- US: DCLL (HCCB)
- KO: HCCB (LL)  CH: HCLL, DCLL, HCCB
- IN: LCCB (HCCB)

Examples from EU, IN, US
Many “Concepts” discussed -- but technologies, issues and therefore R&D and facilities strongly overlap

Two classes of concepts:
Liquid Breeder and Ceramic Breeder (using RAFS in common)

Both classes have feasibility issues and selection can not be made prior to testing in the fusion environment

Variations within class have much less impact on the necessary R&D
R&D on Blanket/FW and Tritium for DEMO

- Extensive programs for the design, analysis, and qualification of the components are needed which requires a number of testing facilities.
- EU described a significant R&D program
  - Spanning all concepts and coolant types including extensive RAFM, instrumentation, modeling
  - Driven by risk and mitigation analysis, TRL, Eurofer code qualification, ITER and DEMO safety
- IN as well described activities including RAFM/ODS, Pb-Li/LiTiO3, coating, In-RAFM: optimization of W and Ta level
- CN described an ambitious program plan including facilities and integrated modeling
- Other parties R&D was not described in detail in presentations in this workshop
Fusion development strategies / DEMO

- **EU, KO** propose DEMO construction in 2030s,
  - Operation in not too far future in order to keep relevancy in domestic energy programs (programmatic/political motivation)
  - Initial phase of DEMO used for testing materials and blanket components
- **US, IN, CH, RF** propose a strategy with Fusion Nuclear Facility for testing in-vessel components
  - Recognition that *experiments in the fusion environment are needed* to show *scientific and engineering feasibility* and perform long *engineering development/reliability growth* phase prior to DEMO
  - US has no official schedule for FNSF or DEMO
  - IN has SST-2 (FNSF role) project start in 2027 and DEMO project start in 2037
  - CN’s has CFETR in mid 2020’s (FNSF role, but also tests of fusion-fusion hybrids)
  - **All options recognize importance of using small power devices to deal with issue of limited external tritium availability**
- **EU and JAPAN** do not have Fusion Nuclear Facility for component tests in their roadmap, IFMIF taking a key function for obtaining necessary materials data for DEMO
  - However, specification of IFMIF depends on the DEMO definition.
DEMO DEVELOPMENT TIME PLAN

- Pre-conceptual design (2011-14) ↔ PPPT
- Design and R&D – CDA (2014-20)
- Design and R&D – EDA (2020-30)
- Construction (2030-40)
What should be the next step for MFR in China?

1st IAEA-DEMO Program workshop
Range of key parameters and several design versions of CFETR are under comparison (China)

\[ B_t = 4.5-5.0 \, T \]
\[ R_0 = 5.5-5.7 \]
\[ b/a \sim 1.8 \]
\[ a = 1.6 \]
\[ \delta \sim 0.5 \]
\[ I_p = 7.5-10 \, \text{MA} \]
\[ \beta_N = \sim 2 \]
\[ P_{ad} \sim 100 \, \text{MW} \]
Materials/Blanket Roadmap for Japan and EU (scientists’ point of view)

Discussed and agreed in IFMIF Specification Working Group
Reported by Garin (Ibarra) in SOFT-26 (2010)
Agreement on need for FW/Blanket testing in the fusion environment

• Despite differences in names and size of devices, there is strong recognition of the essential need of component testing in the fusion environment
  – Performance verification, model validation, tritium self-sufficiency, reliability growth
• Vision of multiple phases/stages of component testing with progressively higher fluence
  – 20 dpa, 50 dpa... Stages in both EU/IN/K DEMOs
  – 10 dpa, 20 dpa ... Stages in US FSNF
  – Can goal of MTBF > 40 MTTR be achieved? What is the impact on achievable dpa?
    – What is ultimate lifetime? Is 50 dpa/500 appm He sufficiently attractive?
    – What is the down/lag time between learning from one stage and implementing improvements in following stage (or leap-frog stages?)

• Although EU and Japan do not have FNSF, they also recognize that the nuclear component tests makes the present DEMO roadmap more robust, and have intention to join the research by collaboration if available.
Uncertainties, concerns about devices for testing FW/Blanket components

• Questions about licensing
  – Experimental nuclear components with VV and extensions as primary containment barrier? ITER-method
  – Regulatory authorities should be engaged in process to inform them about unique fusion challenges
  – What are the necessary multi-effect test facilities prior to fusion environment testing?

• Early stage tokamak DEMOs will still have plasma disruptions
  – how to deal with this in FW/Blanket tests
  – How to combine mitigation solutions and engineering/design solutions

• FW heat/particle flux
  – Do we know the non-uniformity and peaking or is the assumption of a uniform 0.5 MW/m2 a valid one
FNST Studies Developed a **PROCESS** for Technical Planning Using Rollback from Power Plants/DEMO and Analogy to Other Technologies

NUCLEAR FUSION, Vol.27, No.4 (1987)

**EXPERIMENT PLANNING**
*Is a Key Element of Technology Development*

- Proposed Application of a Scientific Principle
- Conceptual Designs
- **Experiment Planning**
  - promising design concepts
  - test plan
- **R & D Implementation**
  - Commercial Product

**FINESSE PROCESS** For Experiment Planning

Vision for Power Plants
- promising designs

- Characterize Issues
- Quantify Experimental Needs
- Evaluate Facilities
  - Existing
  - New
- Develop Test Plan
  - Role, Timing, Features of Major Experiments, Facilities

- Considered issues before experiments and experiments before facilities
- The idea of FNSF emerged from the last step of “Develop Test Plan”

M. Abdou  FNST Studies Perspective FNST/PFC/Materials Mtg. Aug 2-6
Neill Taylor Safety Lessons Summary

- Lessons may be learned from the experience of safety and licensing of ITER, but there are important differences between ITER and DEMO.
- Some aspects of fusion power plant safety have been well-addressed in earlier studies. Others remain important issues, including:
  - fire and explosion risks (particularly in fuel cycle)
  - in-vessel H and H/dust explosion risks
  - tritium issues, particularly normal operation effluents
  - occupational radiation exposure
  - practical radioactive waste management
  - tokamak erosion dust
- Some of these are influenced by fundamental design choices (e.g. materials, coolant)
  - safety must be taken into consideration from the start
In-vessel components role as confinement barrier (from Neill Taylor)

• Strategy should be decided early
  – Will VV provide confinement barrier (as in ITER)?
  – Will in-vessel components be considered experimental with no safety function (as in ITER), OR will they have safety function (unlike ITER)?
Role of TBM in these strategies

• What is the role of ITER-TBM in programs
  – Break-in to fusion environment testing in a manageable way, instrumentation development
  – First integrated fusion environment testing to compare with models and partially validate separate effects science/designs
  – Anchor blanket and materials development to reality (fabrication, licensing, safety)

• Why is US not doing TBM?
  – Complex government issues related more to ITER than TBM
  – Emphasis on science and not engineering development in US program

• What is the need for TBM on development plan timing
  – Are early DEMO down select decisions and engineering designs being made prior to ITER-TBM information (the same question applies to DT burning plasma physics testing)?
  – What is the impact of further delays in ITER schedule on DEMO plans?
Role of Multi-effect Facilities relative to TBM

- Multi-effect proposed by US (some misunderstanding of proposed role)
  - Bred tritium extraction from PbLi: PbLi Loop to unit cell in fission or neutron source. TBM scale
    - Investigate PbLi tritium extraction and chemistry control in steady state with irradiation products (not studying breeding or breeding ratio itself)
    - Investigate irradiation effects on transport of tritium and corrosion in unit cell
  - FW/Blanket thermomechanics: PbLi and He coolant loops to prototypic modules with simulated heat/mechanical/electromagnetic loads – TBM scales
    - Investigate reliability and thermomechanical behavior of FW/B mockups in steady state
- ITER-TBM
  - Bring the thermal/nuclear/EM/mechanical effects together in integrated environment.
  - Near prototypic fusion flux and spectrum, magnetic field structure
  - But not steady state, pulsed loading leading to cyclic effects, more difficulty in instrumentation
Generic overview of fusion fuel cycle mass and energy flows
Summary on Tritium Processing

- Key performance requirements were identified for:
  - Tritium purification/recycle and detritiation
  - Tritium breeding and tritium extraction
- A development progression to DEMO for each area was identified in terms of:
  - Qualitative/quantitative requirements
  - TRLs
- Key facilities that could bridge the gaps are:
  - ITER-TBM (planned): Small-scale, integrated tritium breeding and extraction development (with neutrons) in a fusion prototypic environment
  - Tritium Breeding and Extraction Facility (TBEF): Small-scale, integrated tritium breeding and extraction development (with neutrons) in a dedicated, flexible facility
  - Fuel Cycle Development Facility (FCDF): Medium-scale, integrated “tritium” purification/recycle and “detritiation” development in a non-tritium facility
- Development is needed at:
  - TRL 1-4: Proof-of-concept
  - TRL 5-6: Testing in a relevant environment
Gap analysis, major themes in Tritium Processing

• Tritium extraction from PbLi blanket
  – Fundamental experiments are needed.
  – No proof-of-concept experiments have been performed. Full experiments will require neutron irradiation.
  – ITER TBM is planned and complimentary work is needed
  – A large body of work will be required to field a functioning, full breeder blanket on FNSF.

• Tritium purification and recycle
  – Proof-of-concept work has been performed, but now this must progress to the next level. ITER will make significant contributions.
  – New technologies will be needed due to impractical scale-ups and to accommodate tritium breeding.

• Safety
  – Scaling containment/detritiation systems to the next level is proving difficult and expensive.
  – Containment in the extreme DT fusion environment will reveal issues that must be addressed.
**Modelling Issues**

### General Objectives
- to exploit the experiments of TBSs in ITER
- to support the design extrapolation to DEMO breeding blankets

### Scope
- **Scope of the R&D activities on TT modelling tools:**
  To put in place all those activities necessary to have available a robust and accurate tritium transport modelling tool potentially able to predict the tritium concentration in any point of the system and at any time.
- **When available?**
  Before the beginning of the DT phase

---

**Exp. database consolidation** → **Development/integration + pre-validation** → **Validation against DT-phase experiments in ITER**
Discussion Topic – Suggestions on how to better work together

• Countries agree on and take major facilities necessary for fusion development beyond ITER, avoid drifting, waiting in the program where little gets done
• Countries will NOT ever have unified roadmap and development plans, but they can support or present a unified consensus on major facility needs
• Define / divide common work needed in the next 5 years to advance fusion technology development
• Define / catalog existing facilities, what capabilities exist? What is still needed?
  – EU has many facilities, some under-utilized. What are the capabilities that already exist?
• People/expertise are also valuable resources that can be better shared
• EU discusses a small D-D Divertor Test Tokamak, US discusses a small FNSF (CTF) prior to DEMO. Can/should these be a unified facility?
  – Operation in 2020s as plasma/thermal/EM test using H/D, Refitting and operation in 2030s as DT nuclear test facility
List of possible experiments: electromagnetics, neutronics, tritium generation/extraction, MHD, corrosion, etc.

Preliminary work-plan aimed at filling the gap between the present R&D level and the required one defined.

Experimental campaigns undergoing in several EU laboratories.

- PbLi loop at IPUL for corrosion experiments.
- The MEKKA facility at KIT NaK loop for MHD experiments.
- The HEBLO/HETRA facility at KIT for investigation of heat removal from the FW.
- The CASPER facility at KIT tritium laboratory (tritium accountancy).
- The TRIEX loop at ENEA for the development of the TEU.
- The DIADEMO facility in CEA for thermomechanical testing of subcomponents.
- The HeFus3/EBTTF Facility in ENEA for thermomechanical testing of full-scale TBM mock-ups.
General Comments on Today’s Presentations

- In general speakers addressed what we are doing today
- However, no speaker addressed a complete program
  - What are the major issues that we need to work on that we are not currently working on?
  - What data is needed for in-vessel components in order to design, construct, license and operate a successful DEMO?
  - What degree of confidence can we get from the sum of the current world program in the performance and the operating parameter of DEMO? How far are we from DEMO?

Proposal for this discussion session

- Participants make comments or ask questions on what they heard today?
  - Please avoid focusing on narrow issues but instead on broader challenges that can impact the necessary outstanding R&D and the main elements of the roadmap to DEMO
My own observation is that the following questions need a clearer articulation

- Can you really go from ITER to DEMO without FNSF?
- How do we get data on failure modes and rates without integrated component testing?
- With all these plans for DEMO, where will the start-up Tritium inventory (~10 kg/DEMO) come from?
- How are we really going to demonstrate Tritium self Sufficiency given that it depends on so many physics and technology parameters?
- Should the next fusion nuclear facility be a large size / large power device?
Summary of Talks

The following is brief points from each presenter
Presentations – Monday, Topic 1

Morley - Nuclear and non-nuclear testing and facilities for power extraction and fuel cycle
- Science based research steps,
- Basic, for separate effects e.g. mixed convection Pb-Li flow tests and analysis
- Multiple effects including some integrated tests, e.g. HFIR/ATR with tritium extraction or corrosion loop
- Integrated tests in TBM and FNSF
- International collaboration can be enhanced for step 1 and 2.

Ricapito - Current European activities and R&D needs for power extraction and fuel cycle
- Minimum requirement TBR for tritium self-sufficiency ~1.15
- Uncertainty of TBR estimate by MCNP ~10%
- TBM will suggests optimum T control condition (temperature and environment (H2 addition etc)
- TBR requirements depends on doubling time, T fractional burn-up, reserve time, processing and inventory
Presentations – Monday, Topic 1

**Wilms** - Tritium handling technology roadmap
- Gas analysis has been made
- Necessary facilities in addition to TBM
- TBEF (nuclear, tritium extraction and control)
- FCDF (non nuclear, tritium exhaust processing innovation)
- Followed by FNSF (full integration) toward DEMO

**Muroga** - Materials development roadmap and test facilities
- Japanese and EU roadmap for materials development
- IFMIF as a key facility for materials qualification for DEMO licensing
- Role of spallation and fission neutrons – desirable, but not essential
- Role of VNS, potential strengthening of the materials development scenario
**Presentations – Monday, Topic 1**

**Wirth** (presented by Muroga) - Nuclear and non nuclear testing and facilities needs for material development
- PSI, radiation effects and blanket issues
- Fission-fusion similarity and difference in radiation environments
- Database maturity analyses
- Non nuclear tests needs as high T thermomechanical, PWI, corrosion and structural integrity tests
- Nuclear tests needs as neutron irradiation and tritium related issues

**Taylor** - Safety issues for fusion nuclear facilities and lessons learned from **ITER**
- Difference in safety issued for ITER and DEMO
- Accident analysis, materials activation, normal T release, dust issues
- Fukushima effects
- Combined events, beyond design basis, hydrogen explosion
Presentations – Monday, Topic 1

Kumar - Indian DEMO blanket activities and blanket materials readiness
  • ITER, SST-2 and DEMO
  • SST-2 : materials and component tests
  • RAFM/ODS, Pb-Li/LiTIO3, coating
  • In-RAFM : optimization of W and Ta level

Li Puma - Design and development of DEMO blanket concepts in Europe
  • HCLL and HCPB for TBM
  • WCLL as a backup option
  • Early DEMO roadmap
  • Phase I 20 dpa (first wall) 5 dpa (divertor)
  • Phase II 50 dpa