MFE Chamber

Summary and Closing Remarks

Presented by: Mohamed Abdou

For the MFE Chamber Community

Presented to:

Chamber Technology Peer Review

UCLA, Los Angeles – April 26, 2001

MFE Chamber Responsiveness to Peer Review Evaluation Criteria

- **Each presentation showed many examples of responsiveness to the Evaluation Criteria**

- **The MFE Chamber Community has prepared an extensive summary document that provides many specific examples of how well the criteria are met under each and every subcategory of the criteria.**

  [The document is provided in the handout]

- **This presentation will provide only quick reference to some examples given in the presentations and in the Criteria Summary document**

MFE Chamber Summary for Peer Review Criteria

[Cover Page for the Document in the Handout]

Prepared by

Mohamed Abdou (UCLA)
Bob Kaita (PPPL)
Mike Kotschenreuther (UT)
Kathy McCarthy (INEEL)
Neil Morley (UCLA)
Brad Nelson (ORNL)
Richard Nygren (SNL)
David Petti (INEEL)
Tom Rognlien (LLNL)
Mohamed Sawan (UW)
Dai-Kai Sze (ANL)
Mike Ulrickson (SNL)
Clement Wong (GA)
Alice Ying (UCLA)
Steve Zinkle (ORNL)

Peer Review Meeting at UCLA
Los Angeles, CA
April 26, 2001

I. Quality of Science and Technology

(some examples)

♦ Validity of scientific methods and approaches

➢ **The MFE Chamber research approach emphasizes:**

- **innovative concepts**
- **understanding and advancing the underlying engineering sciences**
- **creative solutions to physics and practical engineering problems**
- **partnership with the physics community and other elements of the technology program**
- **interactions with scientific and technological fields outside fusion**

This approach:

- **serves well the science and energy goals of the fusion program**
- **is effective in making progress on plasma physics devices in the near-term**
- **is improving the long-term vision for attractive fusion energy systems.**

♦ Validity of scientific methods and approaches (cont'd)

- **A variety of tools have been developed for analyzing liquid surfaces in fusion devices. Data from experiments on devices like PISCES (UCSD), M-TOR, FLIHY (UCLA), DPE (SNL), are being used to validate the models.**

- **Impurity intrusion from the wall to the core was calibrated with hydrogen and carbon impurity transport measured in DIII-D.**

- **Utilized the latest theoretical understanding of plasma equilibrium and resistive wall modes in the development of plasma WALLCODE and proposing stabilization schemes with liquid metal walls.**

- **A special task was dedicated to addressing the practical engineering problems associated with liquid walls for fusion systems.**

- **Exploration of innovative solid wall concepts that could extend operation to high power density and high thermal efficiency.**

- **Etc. (see handout for complete list)**

♦ Effectiveness in using state-of-the-art analytical and experimental tools

- **The current effort takes advantage of and builds on state-of-the-art analytical and experimental tools and in some cases has extended the state-of-the-art.**

- **Vast improvements in predictive capability of free surface, turbulent, MHD flows and interfacial transport for liquid walls and divertors have been achieved by utilizing and extending the state of the art tools in CFD as well as developing our own unique capabilities where none have existed previously.**

  - **For example, FLOW-3D MHD code used to identify flow stability under various field configurations was developed by modifying a commercially available state-of-the-art non-MHD CFD code to take into account the effects of the induced field and MHD drag in certain cases.**

- **FLIHY was constructed as a flexible facility that serves many needs for free-surface flows using the best available experimental techniques.**

- **M-TOR facility and experiments will extend the state-of-the-art in experimental exploration of MHD effects of multi-component magnetic fields and gradients as well as effects of applied electric currents.**

- **Effectiveness in using state-of-the-art analytical and experimental tools (continued)**

  - **State-of-the-art diagnostics for non-invasive flow characterization in our experimental effort including ultrasound and scattered laser techniques.**

  - **Computer codes used in the equilibrium and stability of plasma in the presence of liquid walls are "state-of-the-art" (e. g., Tokamak Simulation Code (TSC) for dynamic modeling of plasma equilibrium, Princeton Equilibrium and Stability Code (PEST) for ideal MHD stability, and WALLCODE at the University of Texas/Institute for Fusion Studies (UT/IFS) for resistive MHD stability).**

  - **The Pro-Engineer 3-D CAD system is used for the configuration studies and addressing design integration issues.**

  - **State-of-the-art nuclear and safety data and codes. Deep understanding and skillful use of these codes resulted in accurate treatment of bremsstrahlung radiation attenuation, which was found to be very important in predicting surface temperatures of liquid walls.**

Creativity, Innovation, and Originality

- **The fundamental approach has been to foster an environment conducive to innovation**

- **Creativity, innovation, and originality are evident at several levels:**

  a) **Innovative concepts (CLIFF, MP, EMR, EVOLVE, etc.)**

  b) **New candidate materials (SnLi, Sn, W)**

  c) **Novel solutions to design problems (many presented)**

  d) **Creative approaches to modeling and experiments**

  e) **"Creative Synergism": for example, schemes to improve physics performance using clever engineering solutions (e.g. liquid metal conducting shell for plasma stabilization, liquid lithium surface for particle pumping and improved global confinement)**

Progress toward Practical and Attractive Liquid Walls: Many Creative Innovations

The APEX Approach to Problems

- Understand problems and underlying phenomena and science

- Search for Innovative Solutions: Our job is "to make things work"

- Modeling, analysis, and experiments to test and improve solutions

Examples of Creative Innovations

- **New fluid candidates with low-vapor pressure at high temperatures (SnLi, Sn)**
- **"Surface Renewal": New schemes to promote controlled surface mixing and wave formation to reduce surface thermal boundary layer resistance**
- **Flow tailoring schemes to "control" flow around "penetrations"**
- **Two-stream flows to resolve conflicting requirements of "low surface temperature" and "high exit bulk temperature"**
- **Toroidal Flow ("Soaker Hose") concept to reduce MHD effects**
- **Novel schemes for electromagnetic flow control**
- **Creative design with over laid inlet streams to shield nozzles from line-of-sight**
- **Innovative design of "bag concept" with "flexible" SiC fabric structure**

♦ Quality and completeness of documentation and reporting

- **In the past five years: [See List of publications]**
  - **130 Scholarly Journal Papers**
  - **120 Papers/Presentations in Conferences and Symposia**
  - **25 reports.**
- **A comprehensive APEX interim report (>600pages) was published.**
- **A dedicated APEX website was established, and kept up to date.**
- **Regularly scheduled physical and electronic meetings with good community participation.**
- **Invited and contributed papers have been presented in all relevant domestic and international fusion conferences and symposia (e.g. ISFNT, ICFRM, ANS Topical, IEEE, IAEA, CBBI, etc.).**
- **Papers were contributed to technical conferences outside fusion (e.g. PAMIR-MHD, ASME, ISEM, International Conference of Fluid Mechanics).**

- **Recognition of research accomplishments by peers, scientific communities, and professional societies**

  - **Both NSTX and Alcator C-Mod have invited proposals on the use of liquid surfaces for particle control.**

  - **Important evidence of recognition by peers is the gradual acceptance of liquid wall research as promising for fusion experiments and reactors. This can be seen from the increase in publications and from participation at workshops.**

    e.g. -First International Symposium on "Free Surface", May 10-11 in Japan
    -Mini-Conference on LWs in APS, October 2000
    -Plasma-Surface Interactions US-J Workshops

  - **Japanese universities are providing us funding for 6 years starting April 2001 to participate in our thermofluid and pebble bed thermomechanics chamber research.**

  - **FZK (Germany), JAERI, and CFETP (Canada) sent their favorite pebble bed ceramic materials for thermomechanics testing at UCLA.**

♦ Recognition of research accomplishments (cont'd)

- **Outstanding scientists from outside fusion (e.g. Dhir, Kunugi, Satake, Kim, Banerjee) attracted to contribute to our high quality, challenging research (at no cost to us).**

- **Tens of visiting scientists, engineers, and university professors from J, EU, RF, PRC came to the US to participate in chamber research for extended periods.**

- **Researchers gave more than 50 invited papers and seminars in the past 5 years at domestic and international conferences.**

- **Research performers are of very high caliber, which is demonstrated by the large number of awards and recognition from domestic and international organizations and professional societies.**

- **Leadership of important international studies, e.g. IEA-HVPNS, ITER Technology Testing.**

II. Productivity and Progress

(Some Examples)

- **Sustained achievement in advancing knowledge and in developing new technologies that advance research capabilities and reduce research costs**

  - **Dramatic increase in predictive capabilities for free surface MHD flows with and without turbulence. These include, for example,**

    a) **extending DNS, the most computationally challenging CFD method, to treat free-surface MHD flows**

    b) **formulation of physics-based mathematical models and numerical schemes for use in RANS**

    c) **extending a commercial 3-D fluid dynamics code to treat MHD in free-surface flows**

    d) **development of several versions of reduced dimensional (1.5-2.5D) MHD codes that have yielded significant results**

  - **New capability to experimentally simulate and diagnose liquid wall phenomena. The M-TOR and FLIHY facilities were constructed and several experimental techniques developed.**

  - **Assessment of the edge-plasma characteristics and its ability to shield wall impurities for a number of liquids and device configurations.**

♦ Sustained achievement in advancing knowledge (cont'd)

- **Fusion Technology based on liquid walls might be more resistant to disruptions, eliminate the first wall thermomechanical problems, reduce the structural material problems to a tractable level, and reduce the R&D costs.**
- **Completed the evaluation of W-alloy blanket concepts with high pressure helium cooling and the innovative concept of cooling by vaporizing lithium.**
- **Quantification of heat transfer degradation in the near-surface region due to free surface effects and MHD effects on turbulence.**
- **Development of a new resistive MHD code (WALLCODE) to predict the effects of flowing liquid metals on plasma confinement and stability.**
- **Development of a discrete numerical simulation code to provide details of the thermomechanical state and to quantify the effective thermal-mechanical properties of blanket pebble beds.**
- **Etc.**

- **Efficiency and effectiveness of using available research resources, both domestically and internationally**

  - **Investigations of MHD free surface flow characteristics and plasma liquid surface interactions have drawn extensively on existing codes and internationally recognized expertise.**

  - **The M-TOR facility is made up of existing (RECYCLED) components from MIT, PPPL, and UCLA. The FLIHY facility is utilizing expensive diagnostics already available from SNL, UCLA and Tohoku University.**

  - **We made use of the accumulated knowledge from the US and EU experts and programs, and with cross-fertilization with our Japanese colleagues through workshops and their frequent participation in APEX meetings.**

  - **Materials, instrumentation, and test articles for both thermofluid and pebble bed research were provided by Japanese universities, JAERI, and Europe.**

  - **Data acquisition system with internet-based remote viewing and control capability has been established (e.g. UCLA-JAERI) and proved effective in reducing cost and travel.**

- **Rate of progress toward resolving scientific issues and technical problems**

  - **A real hallmark is a dedication to actually solving problems rather than simply raising technical issues.**
  - **Exceptional rate of progress:**

    In a little over three years:

    1) evaluated numerous design ideas, configurations, and material choices
    2) many innovative solutions proposed and analyzed
    3) identified promising concepts; effort proceeded to "concept exploration"
    4) achieved excellent rate of progress on modeling, experiments, analysis and innovation

  - **Several potential choices exist now for FW/blanket systems that can handle peak power densities of 10 MW/m^2, and peak surface heat flux of 2 MW/m^2, which is substantial progress.**

♦ Rate of progress toward resolving scientific issues…(cont'd)

- **Exceptional rate of progress in advancing "liquid walls" from a vague "idea" to a most promising concept. All key issues ranging from plasma-liquid interactions to fluid dynamics to practical engineering were identified and analyzed; and many innovative solutions to resolve them were proposed and analyzed.**

- **The Liquid Surface Module idea was discussed with NSTX in August 2000 and a detailed proposal was presented to the NSTX Research Forum in January 2001.**

- **Construction of the M-TOR facility was completed within a year.**

- **New resistive MHD code (WALLCODE) nearly complete after about a year of effort.**

- **In three years, we completed and documented the evaluation of two solid wall W-alloy designs (one with helium cooling, and the other, EVOLVE, is with lithium vaporization) and are in the process of working on the design windows of a SiC/SiC LiPb-cooled concept.**

- **Effectiveness of teaming domestically and internationally for information transfer and synergistic problem-solving**
  - **APEX is effectively organized as a team with researchers from 13 universities and laboratories.**
  - **Partnerships with the physics community (e.g. NSTX, C-Mod, and PPPL) and with other technology programs (PFC, materials, safety, tritium, and ARIES).**
  - **Effective interactions between IFE, MFE, and IFMIF on LWs.**
  - **EU scientist (Malang) contributed to the foundations for the innovative EVOLVE concept. Barleon, FZK, contributed.**
  - **A formal teaming arrangement with Japanese universities and MONBUSHO on thermofluids and pebble bed ceramics/SiC thermomechanics has been established through the JUPITER-II program.**
  - **The pebble bed thermomechanics research is part of IEA collaboration.**
  - **Very effective partnership with several Japanese professors (e.g. Kunugi, Satake) for joint collaboration on DNS and RANS CFD development with applications to fusion and other fields (e.g. global warming).**

III. Relevance and Impact

(some examples)

♦ Relevance of research activities to scientific goals for the program element

- **Current MFE research effort is essential to realizing FESAC/IPP Goal G-4 "Enabling Technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy…" and the sub-goal, G-4.3 (Section 3.4.3 in IPP) for the Chamber Technology, "Demonstrate the scientific feasibility of innovative plasma chamber technologies for magnetic fusion energy…"**

- **We are aiming at identifying high performance innovative fusion chamber concepts that will help enhance the attractiveness of fusion as an energy source (improving plasma performance, higher power density and operating temperature capabilities, simpler technological and materials constraints, etc.)**

- **Demonstration of particle control using a liquid lithium free surface module in a fusion plasma experimental device could lead to improvement of plasma global confinement and performance.**

- **Our effort on the practical engineering problems associated with the implementation of liquid surfaces, is what "grounds" the APEX vision and links the scientific goals to a practical embodiment of selected liquid surface concepts and thus a practical end product for the fusion program.**

- **The research is greatly extending the engineering science knowledge base for chamber technology.**

♦ Influence on progress in fusion research and establishment of fusion energy scientific foundations

- **Development path toward liquid wall reactors would favorably influence not only the technology of the FW, divertor, and blanket but also the plasma stability and confinement, plasma-wall interactions, particle and power handling and power density.**
- **The possibility of providing FW/blanket systems that can achieve much higher power densities than have previously been considered practical will enhance the development of more aggressive alternate confinement and reactor concepts like the advanced tokamak, the spherical tokamak, and other toroidal confinement schemes, all of which would benefit from higher power density capability.**
- **The substantial relief of the thermomechanical loading on the first wall through removal of the surface heat flux by flowing liquids will make structural material problems more tractable.**
- **Edge-plasma results used for assessing new materials for walls and analyzing experiments such as DIII-D DiMES and CDX-U, and proposed Li module for NSTX.**
- **Science base provided in several areas, such as free surface MHD flows with and without turbulence, two phase MHD flow and pebble bed thermal-physical-mechanical properties.**

♦ Use of research results in domestic/international fusion programs

- **A Liquid Surface could be a profound change in handling particle control and high heat loads in existing and planned fusion devices.**

- **The US has established leadership in the world program on innovative chamber concepts. Other countries are being greatly influenced by the US effort (evidence from new collaboration requests, substantial participation in APEX meetings, HPD workshops, etc.)**

- **The US Physics community has taken great interest in liquid wall ideas and the potential for improved plasma confinement and stability. (Examples: SNOWMASS, APS Mini-conference on LWs, DIII-D/CDX-U experiments, NSTX test module, etc.)**

- **General edge-plasma modeling has strong international impact.**

- **MHD code development will provide useful tools for use in domestic and international fusion programs and potentially a commercial product for outside applications.**

- **JUPITER-II is clear evidence of the benefits to the Japanese.**

- **A credible "vision of fusion" is likely to be a strong influence worldwide.**

- **The solid wall evaluation will have an impact on the fusion materials program through the enhancement of effort on development of high temperature refractory alloys.**

♦ Contributions to other scientific and technical fields

- **Properties of liquid metals in the vicinity of a hot plasma, their behavior in various magnetic geometries, and their influence on MHD modes have possible interest in astrophysics and areas of engineering that involve MHD effects in liquid conductors.**

- **The work on code development, liquid surface modeling and experiments is of interest to other fields such as environmental science, oceanography, LM melt control and casting, boundary layer control on aircraft and ocean vessels, crystal growth, etc.**

- **Methods developed for free-surface interfacial transport are used in analyzing the CO_2 "missing sink" problem in the global warming field.**

- The importance of liquid wall science to other scientific pursuits and applications were detailed in a presentation by M. Abdou, entitled "Moving Beyond Prediction to Control: Free Surface, Turbulence, and Magnetohydrodynamic Interactions and Effects on Flow Control and Interfacial Transport". This presentation given on March 13, 2001 in the Fusion Science Seminar at Gaithersburg, MD, is posted on the APEX website.

- See Appendix to Overview in handout and on website.

- **Educational benefits, such as effectiveness of attracting and training students to become future fusion scientists and engineers**
  - **Over 30 graduate students received their MS and Ph.D in the chamber area over the past 10 years.**
  - **Many of the students who were trained in the US Chamber research program have become leaders in many areas of fusion and outside fusion. For example, the leaders of US Safety Program, European PFC Program, and Korean KSTAR Chamber Division are graduates of the UCLA Chamber Program. Several graduates have also become faculty members of universities. Some of the graduates are leading programs outside fusion in major organizations such as Boeing, Raytheon, and Northrop-Grumman.**
  - **Over 40 scientists from universities and research organizations in Japan, Europe, China and Russia came to the US over the past 10 years for training in the US Chamber Research program. Many of these became distinguished university professors and leaders of programs in their own home institutions.**
  - **More than 20 students are currently participating in MFE Chamber Technology Research.**

♦ Stature and leadership in domestic and international communities

- ➢ **The US Chamber Technology Program is recognized internationally for leadership on exploring innovative concepts, advancing the underlying engineering sciences, analysis, and technical planning.**

- ➢ **The work is managed and performed by well-recognized researchers who have leading roles in other domestic and international programs.**

- ➢ **Examples of leadership in the world program:**

  - **The largest percentage of invited papers in international conferences such as ISFNT**
  - **The large number of world researchers who come to the US for training**
  - **Japan providing funds under JUPITER-II**
  - **Leadership of important international studies and projects such as IEA-HVPNS, ITER Technology Testing**
  - **Leadership in establishing ISFNT**
  - **Members of US chamber research community serve on lead positions, e.g. Editors of International Scholarly Journals, Chair of the International Standing Committee for Fusion Nuclear Technology, etc.**