Summary
of Evaluation Reports from Peer Review of the
MFE Chamber Technologies Program

July 30, 2001

Review Meeting Date/Location: April 26, 2001
University of California, Los Angeles

Review Panel Members: Leslie Bromberg, MIT
Grant Logan, LLNL/LBNL
Ken Schultz, GA (Chairman)
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Summary Preparation: Sam Berk, DOE

Review Panel Guidelines: See Attachment 1

Evaluation Criteria: See Attachment 2

Review Meeting Agenda: See Attachment 3

Review Panel Findings and Recommendations: See Attachment 4

Terminology:

The panel was asked to use the following terminology in making evaluations:

Term	Meaning	Related Score	Related Grade
Excellent/ Outstanding	Among the best of programs; truly outstanding; quality and progress is in the top 10% of comparable programs	3.5 - 4.0	A
Very good	Very strong program; quality and progress is in the upper 1/3 of comparable programs; no notable deficiencies	2.5 - 3.4	B
Good	Sound program; quality and progress is in the middle 1/3 of comparable programs; any notable deficiencies are minor with clear pathways to resolution	1.5 - 2.4	C
Marginal	Much of program is good, but there are notable deficiencies that cannot be considered minor and may not be easily resolvable; quality and progress is in the lower 1/3 of comparable programs	.5 - 1.4	D
Unsatisfactory	Program has significant deficiencies that are not clearly resolvable	0 - .4	E or F

Executive Summary

This document summarizes the evaluation reports submitted independently by each member of the review panel.

For the evaluation criterion of **Quality of Science and Technology**, review panel evaluations were consistent with an overall rating of **very good to excellent**.

For the evaluation criterion of **Productivity and Progress,** review panel evaluations were consistent with an overall rating of **very good.**

For the evaluation criterion of **Relevance and Impact**, review panel evaluations were consistent with an overall rating of **very good.**

The following are excerpts from comments made by the reviewers:

> "… very high scientific quality, the researchers are first rate and enthusiastic about their work, and the program is logical and integrated within itself."
>
> "…a high quality research program and it scores well against the peer review evaluation criteria. They are doing excellent science."
>
> "The scientific output of this program is outstanding, particularly when one considers its limited resources and the short time it has been in existence."
>
> "… forcefully lead and dynamic. It has a strong presence in the world fusion program and the international scientific community."
>
> "...the program makes excellent use of the capabilities and expertise from a large number of organizations."

The reviewers expressed a number of concerns about the program and made recommendations to address their concerns. These are noted in the text that follows and are listed in Attachment 4.

The concern most frequently expressed was the need for closer coordination with related activities of the broader Fusion Program, most notably plasma physics activities on MHD effects, the ARIES work on attractive design spaces for fusion energy systems, and Plasma Facing Component (PFC) program work on high surface heat flux systems.

Other concerns expressed by more than one reviewer were (a) the need for adequate experimental verification and benchmarking of computational models and (b) the justification for high power density chamber concepts to achieve optimal fusion energy system performance and trade-offs of benefits from these concepts versus their associated costs and risks.

The following recommendations from one of the panel members were directed specifically at DOE and will be addressed by DOE separately from the panel's finding and recommendations listed in Attachment 4:

> Given the difficulty of reviewing the program without complete information on related activities in PFC and fusion materials programs and the considerable overlap and interaction between APEX, ALPS, and fusion materials research, "Take a more integrated approach to MFE Chamber R&D and in its peer review." However, in contrast to this recommendation, another panel member commented that "DOE, the VLT management, and the MFE Chamber group should be commended for the relatively high degree of integration and cross-fertilization between the programs."
>
> Given the cross-fertilization and synergy between MFE and IFE chamber concepts and modeling, "encourage joint/coordinated MFE/IFE chamber technical progress meetings at least once a year."

The same panel member made the following additional recommendation to DOE, but another panel member expressed disagreement with the recommendation:

> "Moderately boost support for liquid wall R&D for MFE and IFE, to improve staffing and diagnostics for the experiments, even if this has to come at the expense of a small part of PFC/solid wall R&D, to achieve a proper balance of risk mitigation and benefit to fusion." The panel member who disagreed with this recommendation noted that "The liquid wall idea is an innovative concept that has a lot of interest and some exciting potential if it could be implemented. It should be pursued. However is also has a lot of risk. We cannot cannibalize the PFC-solid wall area to enhance liquid wall work."

Summary of Panel Member Evaluation Reports

Quality of Science and Technology

Overall:

Review panel evaluations were consistent with an overall rating of **very good to excellent,** with panel members making comments such as "the program is doing very good quality science" and "the quality of science in the MFE chamber work is excellent".

Validity of scientific methods and approaches:

The reviewers indicated **very good to excellent**. Reviewers noted the impressive progress in theory and analytical models for chamber phenomena and the initiation of experiments to test and guide the development of models. A reviewer commented that "the research approaches are very innovative and creative, with appropriate emphasis on coupling of simulation codes and small-scale experiments." More than one reviewer stressed the need for substantially increased experimental verification and benchmarking of models. In one case, there was a strong concern about the imbalance between

modeling and experiment (see Finding #1 in Attachment 4), to the point that continued over emphasis of modeling and under emphasis of experiments could potentially compromise the quality of the science. The reviewer commented "There is a lot of theory and modeling in liquid walls, but it is not supported with an appropriate level of experimental work. This will be true even when the planned experiments come on line." The reviewer noted in particular the limited plans for experiments addressing some key issues of MHD effects and experiments in the area of liquid wall interactions with the plasma, suggesting a well-diagnosed set of experiments to provide basic data for models.

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

The reviewers indicated **very good to excellent**. Reviewers commented on the impressive use of the latest computer codes and simulation tools and on the development of new computational tools, such as those to model liquid metal wall MHD flows. A reviewer strongly approved of the approach taken to begin with relatively simple experiments to validate separate-effects phenomena models in the codes, before entering into more complex studies of interactive phenomena. One reviewer commented that "the number and variety of planned diagnostics in support of the upcoming experiments are adequate, but could be improved for enhanced scientific productivity." (see Finding #2)

Creativity, innovation, and originality in addressing technical problems:

The reviewers indicated **very good to excellent**. One reviewer noted the effective use of using recycled equipment and the innovative ideas that have allowed excellent science at reasonable cost. Another reviewers noted that the entire field of research on liquid walls was highly innovative and is spawning ground for many innovative ideas, although experimental verification remains a key to validation of the ideas.

Quality and completeness of documentation and reporting:

The reviewers uniformly indicated **excellent,** with such comments as "absolutely first rate", "the technical archives available on the UCLA web pages are first rate", and "documentation, with over 100 journal publications in the last four years, is excellent."

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

The reviewers generally indicated at **good to very good,** with one indicating **excellent.** A reviewer commented on the impact the program has had on the fusion community, given the "large number of experimental groups considering the use of liquid walls". Also, the "number of visiting scientists to this program attests to the accomplishments of this group." The large number of invited papers and awards by group members were seen as an indication of the "high caliber of the team". One reviewer expressed the concern that "by focusing their efforts on liquid walls for MFE and on heat fluxes and power densities higher than are expected to be needed by main line fusion concepts, the program has become a bit insular." (see Finding #3)

Productivity and Progress

Overall:

Review panel evaluations were consistent with an overall rating of **very good ,** with panel members noting that the program has "a steady stream of innovative ideas and advanced modeling efforts,", " an enviable record of international cooperation and cost-effective experiments", and "a well-deserved international reputation for high quality, innovative work." It was also noted that "the level of international cooperation is excellent".

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

The reviewers generally indicated **very good**. The reviewers noted "a steady stream of research papers on new analytical methods" and "a steady stream of innovative ideas and advanced modeling efforts."

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

The reviewers uniformly indicated **excellent,** with such comments as "the team has maintained an enviable record of international cooperation and cost-effective experiments", "they have assembled a highly qualified team that takes advantage of a diverse range of skills", "this group has made the most of the available resources", "a healthy visiting scientist activity…has given this program a well-deserved international reputation for high quality, innovative work." and "very effective use of resources in both domestic and international programs."

A reviewer noted that given the many experiments just beginning, "rapid scientific progress can be expected once these experiments get underway". This reviewer suggested that "the resources are spread a bit too thin given the level of funding, and so the work on EVOLVE might be delayed in order to boost productivity of the other areas." Similarly, another reviewer noted that sub-marginal APEX funding has been spread too thin, trying to address too many concepts for which critical data may not be available to assess adequately. This reviewer recommended that concepts with very limited supporting data bases, like EVOLVE, "should be put on hold unless critical data can become available." (see Finding #4)

Rate of progress toward resolving scientific issues and technical problems:

The reviewers indicated **good to very good.** While one reviewer noted "steady progress on the analytically challenging problem of multi-dimensional liquid metal flows in magnetic fields" and another noted the good progress made in theory and modeling to develop predictive capabilities, there remains the need for supporting progress in experimental validation (see Finding #1). Another reviewer remarked that liquid wall research "has been divided into a relatively large number of simpler problems, handled with different tools. One difficulty with this approach is that some of the critical issues

of some of the leading candidates have not been analyzed. One of such issues is the calculations of the pumping power, especially for the case of conductive liquids, going through the large field gradient at the location near the toroidal field coils. Other issues have to do with transients (startup) and interaction with halo and eddy currents." Noting that "the team has partially evaluated a large number of options, with good progress in some of them", this reviewer recommended that the team "concentrate on a smaller number of options, and analyze them more thoroughly." (See Finding #5)

Effectiveness of teaming domestically and internationally for information transfer and synergistic problem-solving:

The reviewers indicated **very good to excellent,** with such comments as "the level of international cooperation is excellent" and "the program is set up for a virtually seamless transfer of information between the domestic and international partners". A reviewer commented that "integration into the chamber program of results from other elements of the MFE program appears to need improvement, however, as high power density regimes being pursued appear to less interest internationally." (see Finding #6)

Relevance and Impact

Overall:

Review panel evaluations were consistent with an overall rating of **very good ,** with panel members noting that the program has substantial strengths with respect to influences on fusion research, to connections with and leadership in international fusion programs, to peer-reviewed publications, and to educational benefits. A reviewer remarked that "They have earned this reputation by virtue of their well laid out program with precise objectives, their first rate, cutting edge advances in liquid wall modeling, their large archival publications, and their ability to attract researchers from around the world."

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

The reviewers indicated **good to very good.** In one reviewer's opinion, "…they have asked all the right questions and have embarked on a path to answer them", noting that "This is the hallmark of a methodical, well-constructed program."

A reviewer expressed the concern that, since the program is focused on liquid walls concepts at high heat fluxes and power densities with the high magnetic fields associated with tokamaks, the program "is of limited relevance to the needs of the Fusion Program." The reviewer remarked that "high power density/high magnetic field regimes appears to be somewhat outside the area of primary interest for the MFE program. While the excellent science being done will have broad applicability, the program would probably be more effective if it focused its interests closer to the main line. The MFE Chamber Technologies program is clearly doing the science right. It is less clear that it is doing the right science." (see Finding #3). This reviewer observed that ARIES studies have indicated tokamaks may optimize at lower wall loads than are the goals for APEX chamber concepts, recommending that the program maintain closer ties to the ARIES

power plant studies and PFC program efforts that are addressing questions and issues related to MFE chamber technologies. (see Finding #7).

Another reviewer commented that "…while liquid walls could allow for significantly higher wall loading, and hence lead to more efficient, compact and cost effective power plants" there is a need to better understand trade-offs, such as "Does the added expense of safely and efficiently transporting liquid metal cause more headaches than it alleviates?, How resilient are liquid walls to disruptions?, Can a liquid wall divertor handle a load that maximizes its potential?, and What, in fact, is the overall efficiency gained by going to liquid walls?" Noting that the program has concentrated on developing innovative solutions, the reviewer recommended that in coming years the program more carefully evaluate whether or not the solutions lead to something that is more efficient, compact, and cost effective (see Finding #8). This reviewer also recommended adding a systems designer and another plasma physicist to APEX Steering Committee, noting that the committee has one plasma physicist, but would benefit from another specializing in a different area, and that there are currently no systems designers on the team. The reviewer indicated that such additions are needed to provide adequate feedback and guidance for this research from throughout the fusion community (see Finding #9).

Relative to APEX work on advanced dry wall concepts, noting that "there is certainly some exciting science being pursued here", a reviewer commented that "it is little disturbing to see that dry-wall concepts seem to be coming to a stop. The reason for this is that it looks like there has been a conscious effort to stop studying a concept because it has become hard, in order to pursue more 'exciting' untried things. This type of thinking may be great for science, but it is lousy for progressing towards the stated mission…" The reviewer recommended that "there should be some modest level of effort looking at both innovative dry wall concepts and more advanced wall materials", noting that EVOLVE is doing the former, but the later appears to be ignored. The reviewer also recommends "re-evaluating previous work and establish the genealogy of the present limitations. For example, is the 5% limit on the swelling rate someone's preconceived notion of what is allowable because they think things just eventually won't fit, or is this the result of a substantial and fundamental degradation of the material strength?" The reviewer noted the very small amount of funding being applied toward this type of work and asked if this represented an imbalance in the resources for APEX (see Finding #10).

Another reviewer commented that "The chosen embodiment of the solid walls, using tungsten alloys at very elevated temperatures, is the weakest part of the MFE Chamber program. Although the work was very innovative, the resulting designs were very unnecessarily aggressive and 'kludgy'. The perceived difficulties of the approach need to be justified in view of the marginal improvement of increased conversion efficiency of the fusion power." (See Finding #11)

<u>Influence on progress in fusion research and establishment of fusion energy scientific foundations:</u>

The reviewers uniformly indicated **very good**. A reviewer commented on the program's relevance to success of the MFE science effort, noting the program's "…many fundamental contributions to the fields of thermo hydraulics, turbulence, and especially in magnetohydrodynamics of conducting condensed phase fluids and the interaction of a

free liquid surface with nearby plasmas." In remarking that the program is vital to developing the basis for attractive fusion energy, this reviewer noted that the program "is very innovative and high leverage to the prospects of achieving high power density MFE systems." Another reviewer commented that "scientific methodologies being developed will provide an excellent basis for analysis of liquid metal blankets of all kinds." Another reviewers remarked that while "the promise of liquid wall is high", much more work is needed and "the group is making good progress toward getting there, as indicated not only by their high quality work but by the fact that they have clearly garnered the attention of the mainstream community."

Use of research results in both domestic and international fusion programs:

The reviewers generally indicated **very good,** noting domestically the ties that are being forged with the plasma MHD community and related Plasma Facing Components efforts and internationally the strong coupling to the world wide fusion effort, especially with related work in Japan. A reviewer commented that the APEX team approach of bringing in many diverse skills from the larger fusion community "ensures that this group is using the results of work done elsewhere." Another commented that "The program has been only partially successful in educating the fusion community, in particular the physicists, on their work. Further work needs to be done to reach a broader audience.." (see Finding #12)

Influence on scientific communities and other elements of domestic and international fusion programs:

The reviewers indicated **good to very good.** A reviewer commented that the program has given the fusion community an opportunity to consider liquid wall concepts and, even if it is shown that thick liquid walls are not attractive for MFE power plants, "this conclusion will be valuable to the fusion community, and the methods and data developed will be valuable for other applications such as plasma facing components, contained liquid blankets, and IFE chambers." Another reviewer commented that "It is obvious that this work is influencing some of the thinking in the fusion community" noting that several large scale magnetic fusion experiments are evaluating the use of liquid walls in various forms.

Contributions to other scientific and technical fields:

The reviewers indicated **good to very good.** A reviewer commented that the methods and data being developed "…should be of value to a variety of technical areas where flow control of conducting fluids in magnetic fields is important" such as "MHD power generation, re-entry vehicles and hypersonic aircraft, and advanced combustion research. Another reviewer remarked that "the behavior of liquid should be of interest to several scientific disciplines, including injection modeling, atmospheric effects, ocean waves, tidal forces, crystal growth, and aerodynamics."

Publications in peer-reviewed journals:

The reviewers uniformly indicated **excellent**, with comments about the program such as "… a strong academic base and maintains a high level of publications in peer-reviewed

journals" and "a very impressive publication list…this is a very prolific group, and should be commended for their achievements in this area."

Educational benefits, such as effectiveness of attracting and training students to become future fusion scientists and engineers:

The reviewers indicated **very good to excellent.** A reviewer commented "UCLA has done an excellent job of getting students involved with this research." Another remarked that the program has "…provided valuable opportunities for graduate and undergraduate education." Others commented that "the educational component is very high for a program of this size" and "The program has been very effective in attracting and educating large number of students."

Transfer of knowledge and technology developments to industry:

The reviewers generally indicated **good,** noting that the work effort is too new to have made significant transfers to industry and that the restructuring of the Fusion Program has led to a significantly diminished industry role. A reviewer commented that "Within these constraints, the MFE Chamber Technology program has been fully willing to involve industry, primarily through cooperation with SBIR grants".

Stature and leadership in domestic and international communities:

The reviewers uniformly indicated **excellent**, with comments such as "…a forceful and dynamic leader in Prof. Abdou. He has established and maintains a strong presence in the world fusion community" and "this program is recognized by the international and domestic fusion community as being the leader in liquid wall research. They have earned this reputation by virtue of their well laid out program with precise objectives, their first rate, cutting edge advances in liquid wall modeling, their large archival publications, and their ability to attract researchers from around the world."

Attachment 1:
Guidelines for Review Panel

Chairman: The review panel chairman serves to keep the panel focused on their mission and generally presides over the review panel proceedings. In particular, the chairman keeps the panel focused on the review scope, which is scientific and technical quality and progress of ongoing R&D activities.

Consensus: While panel members should not attempt to reach consensus views during or after the meeting, they are free to discuss among themselves any matters for the purpose of exchanging information and points of view.

Conflict of Interest: Under any circumstances that a panel members feels that his association with a particular aspects of the PFC program is so close as to prevent him from providing a fair and impartial evaluation, he should not engage in discussions at the meeting on this aspect of PFC program. In addition, the panel member should not comment on this aspect of the PFC program in preparing his evaluation report.

Panel Reporting: Each panel member will prepare and send to DOE a written report that evaluates the PFC program relative to the major categories of the general evaluation criteria (Quality of Science and Technology, Productivity and Progress, and Relevance and Impact).

Evaluation Summary: Based on the evaluation reports from panel members, DOE will prepare an evaluation summary, which will be distributed to the panel, OFES management, the PFC program community, and the VLT Director and senior leaders. If the evaluation reports identify problems areas in the scientific and technical quality and progress of PFC program R&D activities, the deficiencies will be noted and DOE will work with the VLT Director and the PFC community to develop corrective action plans.

Attachment 2:
Evaluation Criteria

Quality of Science and Technology

- Validity of scientific methods and approaches
- Effectiveness in using state-of-the-art analytical and experimental tools
- Creativity, innovation, and originality in addressing technical problems
- Quality and completeness of documentation and reporting
- Recognition of research accomplishments by peers, scientific communities, and professional societies (e.g., citations and awards)

Productivity and Progress

- Sustained achievement in advancing knowledge and in developing new technologies that advance research capabilities and reduce research costs
- Efficiency and effectiveness of using available research resources, both domestically and internationally
- Rate of progress toward resolving scientific issues and technical problems
- Effectiveness of teaming domestically and internationally for information transfer and synergistic problem-solving

Relevance and Impact

- Relevance of research activities to scientific goals for the program element
- Influence on progress in fusion research and establishment of fusion energy scientific foundations
- Use of research results in both domestic and international fusion programs
- Influence on scientific communities and other elements of domestic and international fusion programs
- Contributions to other scientific and technical fields
- Publications in peer-reviewed journals
- Educational benefits, such as effectiveness of attracting and training students to become future fusion scientists and engineers
- Transfer of knowledge and technology developments to industry
- Stature and leadership in domestic and international communities

Attachment 3:
Review Meeting Agenda
Thursday, April 26, 2001, UCLA

7:45 a.m.-8:15 a.m.	Continental Breakfast	All (20 min.)
8:15 a.m.-8:25 a.m.	Abdou and Meier	Panel Introduction and Agenda (10 min.)
8:25 a.m.-9:10 a.m.	Abdou (UCLA)	- MFE Chamber Overview (presentation) -(PDF)--(PPT)- - Liquid Wall Science Application in Other Fields (Appendix)-(PDF)--(PPT)- (45 min)
9:10 a..m.-9:30 a.m.	ALL	Discussion (20 min.)
9:30 a.m.-10:10 a.m.	Morley (UCLA) (Task II Group plus JUPITER-II Thermofluids)	Liquid Wall Concepts, Modeling, and Experiments (v. 4-17-01) (40 min.) (PPT) (PDF)
10:10 a..m.-10:30 a.m.	ALL	Discussion (20 min.)
10:30 a..m.-10:45 a.m.	ALL	Coffee Break (15 min.)
10:45 a.m.-11:15 a.m.	Kaita (PPPL) Kaita/Rognlien/Kotschenreuther and Tasks A, B, V Groups	Plasma-Liquid (Surface and Bulk) Interactions and Plasma Stabilization (4-13-01) (30 min.)
11:15 a..m.-11:30 a.m.	ALL	Discussion (15 min.)
11:30 a.m.-11:50 a.m.	Ulrickson (SNL) (Ulrickson/Ying/Kaita, Task I and ALIST interface)	Exploration of Options for Testing Liquid Wall in Plasma Devices (e.g. NSTX) (4-20-01) (20 min.)
11:50 a.m.-12:00 noon	ALL	Discussion (10 min.)
12:00 noon-1:00 p.m.	ALL	Lunch (60 min.)
1:00 p.m.-1:30 p.m.	Nelson (ORNL) (Sze/Nelson/Nygren and Task III and D Group)	Engineering Issues of Liquid Walls (4-17-01) Movie 1 Movie 2 Movie 3 (4-5-01) (30 min)
1:30 p.m.-1:45 p.m.	ALL	Discussion (15 min.)
1:45 p.m.-2:15 p.m.	Wong (GA) (Wong/Malang/Sawan and Task IV and D Group)	Exploration of Innovative Advanced Solid Wall Concepts (4-11-01..3pm) (30 min.)
2:15 p.m.-2:30 p.m.	ALL	Discussion (15 min.)
2:30 p.m.-2:45 p.m.	Ghoniem (UCLA) (Zinkle/Sharafat/Ghoniem and Task C Group)	Structural Materials (4-18-01) (15 min.)
2:45 p.m.-2:50 p.m.	ALL	Discussion (5 min.)
2:50 p.m.-3:10 p.m.	Ying (UCLA) (UCLA Thermomechanics Group including JUPITER-II)	Material System Thermomechanics Interactions Modeling and Experiments (4-18-01) (20 min.)
3:10 p.m.-3:20 p.m.	ALL	Discussion (10 min.)
3:20 p.m.-3:50 p.m.	Abdou (UCLA) (APEX Team and MFE Chamber Community)	Summary (4-22-01) (30 min.) Evaluation Criteria Document (4-17-01) (30 min.)
3:50 p.m.-4:10 p.m.	ALL	Discussion (20 min.)
4:10 p.m.-4:30 p.m.	ALL	Coffee Break (20 min.)

Attachment 4:
Review Panel Findings and Recommendations

1	The level of experimental work to support theory and modeling is not adequate. **Recommendation**: Seek opportunities to significantly enhance experimental efforts relative to theory and modeling efforts.
2	Although the number and variety of planned diagnostics in support of the upcoming experiments are adequate, the diagnostics could be improved for enhanced scientific productivity. **Recommendation**: Seek opportunities to improve experiment diagnostics.
3	APEX emphasizes chamber technologies with high power density capabilities, focusing on liquid wall concepts capable of operating at high power density in high magnetic fields associated with leading tokamak power plant configurations. This may make APEX of less relevance to MFE concepts that do not require high power densities for optimal performance and/or have low magnetic fields. APEX needs to reassess goals toward high power density concepts, considering such questions as: (a) are high power densities really needed to achieve attractive tokamak power plants? and (b) can economics/performance of tokamaks be optimized at modest power densities?. Also, is APEX liquid wall work relevant to alternate concept power plants that may operate with modest magnetic fields. **Recommendation**: Reassess APEX goals toward high power density concepts for high magnetic field systems.
4	Since the APEX resources appear to be spread too thin given the total level of funding, work on EVOLVE might be delayed in order to boost productivity of the other areas. **Recommendation**: Consider delaying work on EVOLVE in order to boost productivity of the other areas.
5	Since liquid wall research has been divided into a relatively large number of simpler problems that are handled with different tools, some of the critical issues for leading candidates have not been analyzed. One such issue is calculations of pumping power, especially for the case of conductive liquids going through the large field gradient at the location near the toroidal field coils. Other issues have to do with transients (e.g., startup) and interactions with halo and eddy currents. **Recommendation**: Noting that the team has partially evaluated a large number of liquid wall options, concentrate on a smaller number of options that can be analyzed more thoroughly.
6	There is room for improving integration into the program of results from other elements of MFE programs world-wide, since the high power density regimes being pursued appear to less interest internationally. **Recommendation**: Assess the results from other elements of MFE programs world-wide and, to the extent that high power density regimes are of lesser interest internationally, integrate these results into program strategy and planning.
7	The program needs to coordinate more closely with related fusion program activities, such as plasma physics MHD studies, ARIES studies of attractive design spaces for fusion energy systems, and elements of the PFC program. **Recommendation**: Develop closer ties to related activities in plasma physics research, ARIES power plant studies, and the PFC program that are addressing issues relevant to MFE chamber

	technologies.
8	While liquid walls can potentially lead to more compact and higher power density fusion systems, there is a need to better understand trade-offs of benefits versus associated costs and risks. For example, it is necessary to consider such questions as: (a) does the added expense of safely and efficiently transporting liquid metal cause more headaches than it alleviates?, (b) how resilient are liquid walls to disruptions?, and (c) what is the overall thermal efficiency gained by going to liquid walls?. **Recommendation**: Considering trade-offs of benefits versus associated costs and risks, determine if liquid walls can lead overall to fusion energy systems that are more thermally efficient, reliable, and economical.
9	The APEX Steering Committee could benefit from additional membership that would provide broader feedback and guidance from the fusion community. The committee has one plasma physicist, but would benefit from another specializing in a different area, and that there are currently no systems designers on the APEX team. **Recommendation**: Consider adding a systems designer and another plasma physicist to APEX Steering Committee.
10	Some effort should be maintained on innovative dry wall concepts. Consider redirecting a modest solid wall efforts to support the research needs of more conventional solid wall design concepts that may not have high power density capabilities. Maintain an effort on advanced dry wall materials, re-evaluating previous work and establishing the genealogy of the present limitations. For example, is the 5% limit on the swelling rate a preconceived notion of what is allowable or is this the result of a substantial and fundamental degradation of the material strength? Also, considering the very small amount of funding being applied toward this type of work, determine if there is an imbalance in the resources for APEX. **Recommendation**: Re-evaluate previous work on advanced dry wall materials and assess appropriateness of balance in APEX resources between liquid wall and dry wall research.
11	The use of tungsten alloys in advanced dry wall concepts at very elevated temperatures may result in designs that are unnecessarily aggressive and complicated. The perceived difficulties of the approach need to be justified in view of the marginal improvement of increased thermal efficiency of the fusion power. **Recommendation**: Determine if the benefits of tungsten alloy design concepts outweigh potential negatives, such as design complexity.
12	While the program has been partially successful in educating the fusion community on the results of its work, further effort need to be made toward reaching a broad audience. **Recommendation**: Seek opportunities to further reach broad audiences on communicating the results of program work.