R&D NEEDS AND APPROACH TO MEASURE PROGRESS FOR LIQUID METAL BLANKETS AND SYSTEMS ON THE PATHWAY FROM PRESENT EXPERIMENTAL FACILITIES TO FNSF

S. Smolentsev,[a] * M. Abdou,[a] N. B. Morley,[a] S. Malang,[b] C. Kessel[c]

[a] *University of California, Los Angeles, USA; *sergey@fusion.ucla.edu*
[b] *Consultant, Fliederweg 3, D 76351 Linkenheim-Hochstetten, Germany*
[c] *Princeton Plasma Physics Laboratory, USA*

The paper describes research needs in primary R&D areas for the family of dual-coolant lead-lithium (DCLL) blankets. Associated key scaling parameters are introduced and evaluated under conditions of FNSF, ITER and DEMO and also for the existing non-fusion MHD facilities, using the MaPLE loop at UCLA as an example. Comparisons among these parameters are recommended for measuring the R&D progress on the pathway from the present experimental facilities to FNSF. Possible experiments both in the existing facilities and FNSF are discussed along with the flow diagnostics.

I. INTRODUCTION

A Fusion Nuclear Science Facility (FNSF) has been recognized in the US fusion community as a necessary facility to resolve the critical technology issues of in-vessel components prior to the construction of a DEMO reactor.[1] The primary mission of FNSF as defined in the earlier comprehensive studies since the 1980's (Ref. 1) is to provide the prototypical fusion nuclear environment in which the fusion nuclear components and materials can be tested and developed. Several FNSF designs were proposed under different names and further evaluated in the US (Refs. 2-6) and China.[7] One promising FNSF strategy is to have a base breeding blanket system along with specially designed port-based test blanket modules (TBMs). Both the base blanket and the TBMs should be based upon DEMO relevant blanket designs and materials, and both will have testing missions. However, the TBMs can be designed for more aggressive experiments with high performance parameters. The data obtained from testing both the base blanket and TBMs can be used to design next base blankets, while the TBMs themselves can serve as forerunners for more advanced base blankets. It is important to provide stepwise testing of the blankets, starting from more conventional designs limited to lower temperatures and stresses, and finally arriving at the blanket versions comparable in performance with the DEMO blanket.

Of the liquid metal (LM) blanket concepts, the dual-coolant lead-lithium (DCLL) blanket,[8] utilizing eutectic alloy PbLi as breeder and coolant, is both potentially attractive and the near term option.[9,10] An advanced self-cooled PbLi blanket (SCLL), which uses SiC as a structural material is potentially attractive but SiC material with required mechanical, electrical, hermetic and thermophysical properties[11] will likely not be available in the FNSF timeframe. In this paper, the main emphasis is on the DCLL blanket concept. With DCLL, which is based on well-characterized reduced activation ferritic/martensitic (RAFM) steel as a structural material and SiC as a non-structural functional material, it is possible to achieve high thermal blanket efficiency of 45%. In the proposed stepwise approach, a low-temperature (LT) DCLL (Ref. 12) can be used as a first-step base blanket, while more advanced high-temperature (HT) DCLL (Ref. 13) as a TBM.

This paper identifies the key R&D areas and research needs related to the use of PbLi as a breeder and coolant for the family of DCLL blankets. These R&D areas are: (1) LM MHD and heat transfer, (2) MHD corrosion of RAFM steel and deposition of corrosion products, (3) specific effects associated with the use of a SiC flow channel insert (FCI), and (4) tritium transport. One way to measure research progress in these areas on the path from the present experimental facilities to FNSF is by engineering scaling. In this paper the engineering scaling parameters are derived for present experimental facilities and then for ITER, FNSF and DEMO blankets. Comparisons among the base scaling parameters are necessary to understand if blankets in these devices act alike and what meaningful tests and experiments can be done to better understand complex flow physics associated with MHD/heat & mass transfer of LM breeders and eventually to design blankets. Given this understanding, the possible MHD/Thermofluids experiments in FNSF TBMs and required flow diagnostics are discussed.

II. KEY R&D AREAS AND R&D NEEDS

II.A. Liquid Metal MHD and Heat Transfer

Beyond the MHD pressure drop and associated flow balancing, there are many important MHD flow phenomena that have not yet been uncovered. Therefore recent studies in the US (Ref. 14) and worldwide[15,16] are focusing more on understanding the detailed structure of MHD flows, including various 3D and unsteady effects associated with flow instabilities, MHD turbulence and

 http://dx.doi.org/10.13182/FST14-919

buoyancy-driven convection. These complex MHD flow processes can affect transport properties of MHD flows in drastic ways and have a significant impact on DCLL blanket operation and performance. In spite of advances to our knowledge of blanket flows in the recent past, the MHD thermofluids phenomena in blanket-relevant conditions are not yet fully characterized. For example, LM MHD flows are closely coupled with heat transfer due to buoyancy effects, which may lead to stagnant or even reverse flow zones. Understanding and predicting these effects requires much better knowledge of MHD flows compared to relatively simple pressure drop predictions.

II.B. MHD Flow Induced Corrosion and Redeposition

Implementation of RAFM steels and PbLi in blanket applications still requires material compatibility studies related to physical/chemical interactions in the RAFM-PbLi system. First of all, the mass loss caused by the flow-induced corrosion of the steel walls at temperatures in the range 450-550°C needs to be characterized. Present PbLi blanket studies limit the maximum wall thinning to 20 μm/yr that corresponds to the maximum wall temperature at the interface with the liquid metal in the hot leg of about 470°C. These limits were derived in the past in the US in the Blanket Comparison and Selection Study (BCSS) (Ref. 17) but should be reevaluated with updated assumptions and data. Second, along with a possible deterioration of the mechanical integrity of the blanket structure due to the wall thinning at the interface with the flowing PbLi, another serious concern is the transport of activated corrosion products and their precipitation in the cold section of the loop that may require an effective cleanup system as proposed in Ref. 18. Third, an important modeling parameter, the saturation concentration of iron in PbLi, needs further evaluations as the existing correlations demonstrate scattering of several orders of magnitude. Fourth, many physical effects on corrosion/deposition processes in the presence of a magnetic field have not been characterized yet, such as Q2D MHD turbulence, multi-material interactions (e.g. due to presence of SiC), and magnetic and temperature field gradients. Also, the corrosion processes can be altered by irradiation effects and due to impurities in PbLi.

II.C. Specific Effects Associated with the Use of an FCI

For the SiC FCI material, the goal is low thermal conductivity of 1-2 W/m-K and low electrical conductivity of about 1 S/m for the inboard DCLL blanket. Higher electrical conductivities of about 50 S/m are allowed for lower magnetic field outboard blanket modules. When using such FCI materials compared to bare ducts, the MHD pressure drop reduction by a factor of 50-100 is expected in poloidal flows. For the assessment of MHD impacts on the flowing PbLi it is important to know the electrical, mechanical and thermophysical properties of the FCI in realistic operating conditions. This includes, for example, changes in electrical conductivity by a strong ionizing gamma-field and also due to neutron fluxes, which are known to modify the electrical properties of SiC composites very significantly, resulting in much lower room temperature conductivity and a steeper temperature dependency. The important considerations, which still require more analysis include: effectiveness of FCI as electric/thermal insulator, MHD flows in the thin gap between the FCI and the RAFM wall, impact of the joint region between two FCI segments on the MHD pressure drop and tritium transport, effects of the FCI on heat and mass transfer, and FCI flows in abnormal conditions (e.g. FCI cracking or PbLi infiltration in the bulk FCI material).

II.D. Tritium Transport

In the DCLL blanket, tritium losses from the PbLi into the helium coolant may occur when the LM breeder is moving in the poloidal ducts. Quantitative analysis of the mass transfer processes associated with the tritium transport in the breeder as well as tritium diffusion through the structural and functional materials are important for two main reasons. The first is that there can be a substantial difficulty in extracting tritium from high temperature, high pressure helium coolant. The second is that radioactive tritium can make its way from the helium stream into the environment leading to serious safety concerns. Current studies suggest that efficient tritium extraction from the He-coolant is still necessary to meet the limit on tritium release to the environment of 1 g/yr as established in safety studies. Thus, the R&D for tritium transport in the blanket should be closely coupled with the analysis of the tritium extraction schemes such as the vacuum permeator.

A review of MHD studies for liquid-metal blankets performed in the US and worldwide in the recent past and a complete reference list can be found in Refs. 15 and 16. As examples of more current studies we can refer to experimental investigations of MHD pressure drop reduction in PbLi flows using MaPLE facility at University of California, Los Angeles[19] as well as theoretical studies of MHD instabilities and Q2D turbulence,[20] mixed-convection flows,[21] tritium transport[22,23] and MHD flow induced corrosion in the RAFM-PbLi system.[24]

III. ENGINEERING SCALING

It is important that any proposed experiments can demonstrate similarity in the key physical phenomena associated with MHD, heat & mass transfer processes in the flowing liquid metal. One approach to ensure such similarity involves dimensionless parameters that represent ratios between different physical mechanisms or forces acting on the flowing liquid. Such parameters are the hydrodynamic *Reynolds number Re* (ratio of inertia to viscous forces), *Hartmann number Ha* (Hartmann squared is the ratio of electromagnetic to viscous forces), *interaction parameter N* (ratio of electromagnetic to inertia force) and *Grashof number Gr* (approximates ratio of buoyancy to viscous force). These parameters can be used to characterize MHD effects and also play a major role in heat and mass transfer processes in the blanket, which are coupled with the MHD flow. These parameters can also serve as a metrics to measure the R&D progress on the pathway from the present experimental facilities to FNSF and eventually to the DEMO plant. Each blanket component (e.g. manifolds, inlet/outlet pipes, poloidal ducts, etc.) can be characterized with its own sub-set of the parameters. In this study, the parameters were evaluated for poloidal ducts, which typically occupy more than 90% of the total DCLL blanket space. Table I summarizes both the dimensional (mean bulk velocity U_0, duct half-width L, applied magnetic field B_0) and the dimensionless parameters defined as $Re = U_0 L/\nu$, $Ha = B_0 L\sqrt{\sigma/\nu\rho}$, $Gr = g\beta\Delta T L^3/\nu^2$, and $N = Ha^2/Re$. Here, ρ, ν and σ are the fluid density, kinematic viscosity and electrical conductivity correspondingly, and g is the acceleration due to gravity.

The DCLL DEMO design used here as a basis for evaluation of the dimensionless parameters was proposed in Ref. 26 and further elaborated in the course of the ITER TBM studies in the US (Refs. 27 and 28). The main goal of this DEMO design was to assure that the test results of the selected ITER-TBM first wall and blanket can be extrapolated to conditions of a high performance tokamak reactor. The proposed DCLL blanket in this DEMO study is a poloidally segmented two-pass blanket. In the outboard region, the PbLi inlet and outlet temperatures in the blanket are 460 and 700°C, respectively. The 8 MPa helium cools the first wall, and all the RAFM structures. The helium inlet and outlet temperatures are 300 and 480°C, respectively. Concentric pipes are used for both PbLi and helium coolants circulating in and out of the blanket module. The peak neutron wall loading is 3.72 MW/m^2 at the outboard and the average chamber neutron wall loading is 2.13 MW/m^2. When calculating the parameters for the FNSF blanket, a generic toroidal facility was assumed with an outboard magnetic field of 4 T and the average neutron wall load (NWL) of 1 MW/m^2. As an example of the non-fusion experimental facility we consider the MaPLE (Magnetohydrodynamic PbLi Experiment) loop (Fig. 1) at the University of California, Los Angeles.[19] This facility uses PbLi as a working fluid, and allows for up to 1.8 T magnetic field, which is uniform in the work space of 80cm x 15cm x 15cm, maximum pressure head of 0.15 MPa and maximum PbLi flow rate of ~40 L/min (without a magnetic field). At this moment the facility does not have heat transfer experiments but the estimates show that with simple loop modifications the maximum achievable Grashof number (based on the differential heating temperature scale ΔT) will be of the order 10^7. This value is consistent with earlier experimental efforts[25] on natural-convection flows in a magnetic field where the maximum *Gr* number was 1.5×10^8. Other existing experimental MHD facilities used in fusion-relevant studies, for example MEKKA at FzK, Germany and MHD loops at IPUL, Latvia (Ref. 16), have capabilities similar to MaPLE.

It is obvious that the existing experimental facilities do not allow for high enough Hartmann numbers and are limited in heating conditions. As a matter of fact, at present there are no practical solutions for volumetric heating in non-fusion experimental facilities. FNSF, as a fusion machine, will allow for both volumetric and surface heating, but the flow parameters in FNSF are still lower compared to the DEMO blanket. This is especially apparent from the comparison for the Grashof number, which is a few orders of magnitude lower in FNSF. The direct consequence is that in the FNSF blanket flows, the important buoyancy-driven effects can be significantly lower compared to those in the DEMO blanket

TABLE I. Characteristic Values of the Dimensionless MHD Flow Parameters for the Existing Experimental Facilities (MaPLE) and DCLL Blanket under Different Conditions

Machine or Facility	ITER TBM	DEMO	DEMO	FNSF	MaPLE
Location	Outboard	Outboard	Inboard	Base blanket	-
B_0, **T**	4	4	10	4	1.8
L, **m**	0.1	0.1	0.1	0.1	0.04
U_0, **m/s**	0.04	0.07	0.15	0.05-0.1	0.15
NWL, MW/m^2 (average)	0.78	2.13	1.33	1.0	-
Ha	6.5 x 10^3	1.2x10^4	3.0x10^4	6.5x10^3	1.2x10^3 (max)
Re	3.0 x 10^4	6.0x10^4	1.2x10^5	(3-8)x10^4	4.5x10^4 (max)
N	1.4 x 10^3	2.4x10^3	7.5x10^3	(0.7-1.5)x10^3	up to 10^4
Gr	7.0 x 10^9	2.0x10^{12}	1.6x10^{12}	1.0x10^{10}	up to 10^7
Reference	Ref. 26	Ref. 26	Ref. 27	-	Ref. 19

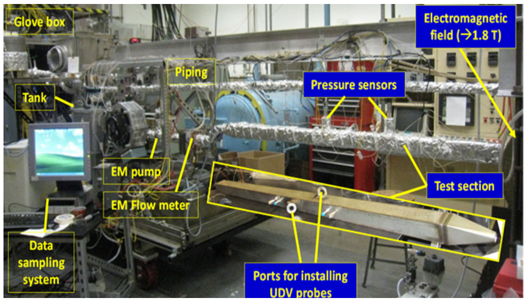

Fig. 1. Current view of the MaPLE loop at UCLA. This non-fusion facility is used for both testing MHD flows and studies of flow-material interactions in PbLi in a magnetic field.

However, unlike the base blanket, the TBMs in FNSF can be designed for higher temperatures and stresses and then more aggressive testing performed to better approach DEMO blanket conditions.

IV. SUGGESTED EXPERIMENTS in FNSF

As mentioned earlier in the paper, TBMs in FNSF would allow an aggressive experimental program to prepare for the next-step base blankets and to approach DEMO blanket conditions as close as possible. An experimental TBM can be designed for higher thermal and/or mechanical stresses using, for example, a thicker RAFM wall and a thick FCI. Another useful feature, which can be incorporated in the TBM design, is a larger blanket size *L,* through which a higher Grashof number can be achieved, as this parameter depends on the blanket size as L^3. In the experiments, the thermal and hydraulic blanket responses will be measured in normal and abnormal-like operating conditions. There are just a few experimental parameters that can be actively varied, including the inlet temperature and the flow rate of both PbLi and He flows. Of them, the PbLi flow rate seems to be the most important parameter as changing it can simulate flow conditions from HCLL (helium-cooled lead-lithium) to HT DCLL and even SCLL blankets. When planning the experiments, it is important to perform careful pre-experimental analysis to assure meaningful results. The experiments will require various flow diagnostics. The optimal goal is to provide measurement tools for local and integral field parameters, including detailed temperature and velocity distributions. At present such tools, especially those for PbLi flow velocimetry, are limited due to high temperatures and aggressive nature of PbLi. Although a research on implementation of ultrasonic velocimetry is in progress,[29] its applicability to MHD PbLi flows is still questionable even in the lab conditions. Other necessary measurement techniques, such as temperature measurements using thermocouples and electric potential measurements using potential probes, are perhaps less problematic. It appears that the use of thermocouples is not limited by the neutron irradiation conditions as thermocouples have been widely used in fission reactors. However, taking into account corrosive nature of PbLi and neutron enviroment it is uncertain that thermocouples and electric potential sensors can be used directly in the flowing PbLi over a long run. However, placing them on the solid walls or embedding them in the FCI structure will allow for important information about temperature, electric current and even velocity distribution. Such information can be used as indication of any blanket failure, to characterize the MHD pressure drop and to make conclusions about FCI performance as electrical and thermal insulator. Post-experiment examination of the RAFM structures and FCIs can also be used to infer effects of corrosion and heat transfer averaged over the exposure time.

High temperature/high ΔT experiments. In these experiments, the flow rate is reduced from the nominal value to achieve higher PbLi exit temperatures and higher bulk temperature difference between the flow outlet and inlet.

High pressure drop experiments. In these experiments, the flow rate is increased to increase the pressure drop. This will cause nearly proportional reduction in the temperature at the blanket exit. Because of this reason, experiments where high ΔT and high pressure drop are achieved at the same time do not seem to be possible.

Experiments with a reversed flow. As recommended in Ref. 14, the flow in the front duct facing the plasma side in the normal operating scenarios should be upward to reduce the risk of reverse flow zones near the "hot|" wall that may appear due to a strong effect of buoyancy forces. In the proposed experiments, the flow in the front duct could be intentionally changed to downward to simulate conditions that will result in locally reverse flows.

Heat transfer experiments. In these experiments, which can be performed in the D-D phase (no volumetric heating), the inlet He and the inlet PbLi temperatures are changed to provide a higher temperature difference between the two fluids, leading possibly to the temperature drop across the FCI of more than 200 K.

"Failed" FCI experiments. The goal of these experiments is to evaluate possible consequences of abnormal blanket scenarios when the FCI is miss-functioning because of cracks or/and liquid metal ingress. The behavior of such "failed" FCIs should be mimicked somehow, for example, by using loosely connected FCI segments.

V. NEAR-TERM EXPERIMENTS AND FACILITY UPGRADES

The near-term R&D studies have to be performed in the existing non-fusion facilities. We can refer to the already mentioned MaPLE loop at UCLA as an example of the facilities for MHD thermofluids studies. These near-term activities in MaPLE are suggested for a 10-year period starting from now. At the end of this period, a larger step should be taken from MaPLE towards a new experimental blanket facility that will extend present MHD thermofluid studies to more integrated tests at higher operating parameters. This 10-year period can be subdivided into three phases. In Phase I (Year 1-3), single effect MHD experiments are performed in a magnetic field ~ 2 T. An example of such experiments is the rectangular duct flow with an insulating FCI. Various FCI materials and shapes can be tested, including foam-based SiC, SiC/SiC composites and a sandwich (steel-alumina-steel) FCI. In Phase II (Year 3-6), the main research focus will be on multiple MHD/heat & mass transfer effects, for example, MHD flow induced corrosion and mixed convection flows. These experiments will require MaPLE upgrades, such as tilting the magnet to the vertical position and adding the high-temperature leg at ~ 550°C. In Phase III (Year 6-10), the magnet system should be replaced with a larger and stronger magnet to provide a ~ 5 T magnetic field in a uniform field region of ~ 1.5 m x 0.3 m x 0.3 m. With this upgrade, either blanket mockups of 1/4 to 1/2 size or full-size blanket components can be tested.

VI. CONCLUSIONS

R&D needs for DCLL blankets have been summarized in the four key areas. An engineering scaling-based approach has been proposed to measure progress for LM blankets and systems on the pathway from present experimental facilities to FNSF. Key scaling parameters have been evaluated and compared for non-fusion facilities, ITER, FNSF and DEMO. A set of experiments in FNSF has been proposed for port-based TBMs. Experiments have been proposed in a non-fusion facility MaPLE and FNSF.

ACKNOWLEDGMENTS

This work was performed with support from the US Department of Energy, Office of Fusion Energy Sciences, under Grant No. DE-FG02-86ER52123.

REFERENCES

1. M. ABDOU, S. BERK, A. YING, M. PENG, S. MALANG, E. PROUST et. al., “Results of an International Study on a High-Volume Plasma-Based Neutron Source for Fusion Blanket Development,” Fusion Technol., 29, 1 (1996); http://dx.doi.org/10.13182/FST96-3.
2. E. T. CHENG, R. J. CERBONE, I. N. SVIATOSLAVSKY, L. D. GALAMBOS, Y.-K. M. PENG, “Study of a Spherical Torus Based Volumetric Neutron Source for Nuclear Technology Testing and Development,” *Fusion Eng. Des*., **48**, 299 (2000); http://dx.doi.org/10.1016/S0920-3796(00)00165-4.
3. Y.-K. M. PENG, P. J. FOGARTY, T.W. BURGESS, D. J. STRICKLER, B. E. NELSON, J. TSAI et al., “A Component Test Facility Based on the Spherical Tokamak,” *Plasma Phys. Control. Fusion*, **47**, B263 (2005); http://dx.doi.org/10.1088/0741-3335/47/12B/S20.
4. V. S. CHAN, R. D. STAMBAUGH, A. M. GAROFALO, J. CANIK, J. E. KINSEY, J. M. PARK et al., “A Fusion Development Facility on the Critical Path to Fusion Energy,” *Nucl. Fusion*, **51**, 083019 (2011); http://dx.doi.org/10.1088/0029-5515/51/8/083019 .
5. J. E. MENARD, L. BROMBERG, T. BROWN, T. BURGESS, D. DIX, L. EL-GUEBALY et al., “Prospects for Pilot Plants Based on the Tokamak, Spherical Tokamak and Stellarator,” *Nucl. Fusion*, **51**, 103014 (2011); http://dx.doi.org/10.1088/0029-5515/51/10/103014.
6. T. BROWN, J. MENARD, P. TITUS, A. ZOLFAGHARI, L. EL. GUEBALY, L. MYNSBERGE, “Progress in Developing the STFNSF Configuration,” *Proc. 25th Symposium on Fusion Engineering*, San Francisco, June 10-14, 2013; http://dx.doi.org/10.1109/SOFE.2013.6635333.
7. Y. T. SONG, S. T. WU, J. G. LI, B. N. WAN, Y. X. WAN, P. FU et al., “Concept Design of CFETR Tokamak Machine,” *Proc. 25th Symposium on Fusion Engineering,* San Francisco, June 10-14, 2013; http://dx.doi.org/10.1109/sofe.2013.6635362.
8. S. MALANG, M. TILLACK, C. P. C. WONG, N. MORLEY, S. SMOLENTSEV, “Development of the Lead Lithium (DCLL) Blanket Concept,” *Fusion Sci. Technol.,* **60 (1)**, 249 (2011); http://dx.doi.org/10.13182/FST10-212.
9. C. P. C. WONG, M. ABDOU, M. DAGHER, Y. KATOH, R. J. KURTZ, S. MALANG et al., “An Overview of the US DCLL ITER-TBM Program,” *Fusion Eng. Des*., **85**, 1129 (2010); http://dx.doi.org/10.1016/j.fusengdes.2010.02.021.
10. A. R. RAFFRAY, L. El-GUEBALY, S. MALANG, X. R. WANG, L. BROMBERG, T. IHLI et al., “Engineering Design and Analysis of the ARIES-CS Power Plant,” *Fusion Sci. Technol*., **54**, 725 (2008); http://dx.doi.org/10.13182/FST08-4.
11. S. SHARAFAT, A. AOYAMA, N. MORLEY, S. SMOLENTSEV, Y. KATOH, B. WILLIAMS et al., “Development Status of a SiC-Foam Based Flow Channel Insert for a U.S.-ITER DCLL TBM,” *Fusion Sci. Technol*., **56**, 883 (2009); http://dx.doi.org/10.13182/FST09-7.
12. S. MALANG, K. SCHLEISIEK (Editors), “Dual Coolant Blanket Concept,” Kernforschugszentrum Karlsruhe, Karlsruhe, Germany, KfK 5424 (1994).
13. M. S. TILLACK, S. MALANG, “High performance PbLi blanket,” *Proc. 17th IEE/NPSS Symposium*

on Fusion Engineering, San Diego, California, Oct. 6-10, 1997, **2**, 1000 (1997); http://dx.doi.org/10.1109/FUSION.1997.687793.

14. S. SMOLENTSEV, R. MOREAU, M. ABDOU, "Characterization of Key Magnetohydrodynamic Phenomena in PbLi Flows for the US DCLL Blanket," *Fusion Eng. Des.*, **83**, 771 (2008); http://dx.doi.org/10.1016/j.fusengdes.2008.07.023.
15. S. SMOLENTSEV, R. MOREAU, L. BÜHLER, C. MISTRANGELO, "MHD Thermofluid Issues of Liquid-Metal Blankets: Phenomena and Advances," *Fusion Eng. Des.*, **85**, 1196 (2010); http://dx.doi.org/10.1016/j.fusengdes.2010.02.038.
16. L. BÜHLER, C. MISTRANGELO, J. KONYS, R. BHATTACHARYAY, Q. HUANG, D. OBUKHOV et al., "Facilities, Testing Program and Modeling Needs for Studying Liquid Metal Magnetohydrodynamic Flows in Fusion Blankets," *Fusion Eng. Des.*, In Press (2015); http://dx.doi.org/10.1016/j.fusengdes.2014.03.078.
17. D. L. SMITH, C. C. BAKER, D.-K. SZE, G. D. MORGAN, M. A. ABDOU, S. J. PIET et al., "Overview of the Blanket Comparison and Selection Study," *Fusion Technol.*, **8**, 10 (1985); http://dx.doi.org/10.13182/FST85-4.
18. S. MALANG, I. N. SVIATOSLAVSKY, "Corrosion Product Cleanup System for a Liquid Metal Cooled Fusion Power Reactor Blanket," *Trans. American Nuclear Soc.*, **46**, 289 (1984) .
19. S. SMOLENTSEV, F.-C. LI, N. MORLEY, Y. UEKI, M. ABDOU, T. SKETCHLEY, "Construction and Initial Operation of MHD PbLi Facility at UCLA," *Fusion Eng. Des.*, **88**, 317 (2013); http://dx.doi.org/10.1016/j.fusengdes.2013.03.018 .
20. S. SMOLENTSEV, N. VETCHA, R. MOREAU, "Study of Instabilities and Transitions for a Family of Quasi-Two-Dimensional Magnetohydrodynamic Flows Based on a Parametric Model," *Phys. Fluids*, **24**, 024101 (2012); http://dx.doi.org/10.1063/1.3680864.
21. N. VETCHA, S. SMOLENTSEV, M. ABDOU, R. MOREAU, "Study of Instabilities and Quasi-Two-Dimensional Turbulence in Volumetrically Heated MHD Flows in a Vertical Rectangular Duct," *Phys. Fluids,* **25**,024102 (2013); http://dx.doi.org/10.1063/1.4791605.
22. M. J. PATTISON, S. SMOLENTSEV, R. MUNIPALLI, M. ADDOU, "Tritium Transport in Poloidal Flows of a DCLL Blanket," *Fusion Sci. Technol.*, **60** **(2)**, 809 (2011); http://dx.doi.org/10.13182/FST10-309.
23. H. ZHANG, A. YING, M. ABDOU, "Impact of Pressure Equalization Slot in Flow Channel Insert on Tritium Transport in DCLL-Type Poloidal Duct," *Fusion Sci. Technol.*, **64**, 651 (2013); http://dx.doi.org/10.13182/FST12-579.
24. S. SMOLENTSEV, S. SAEIDI, S. MALANG, M. ABDOU, "Numerical Study of Corrosion of Ferritic/Martensitic Steels in the Flowing PbLi with and without a Magnetic Field," *J. Nuclear Materials*, **432**, 294 (2013); http://dx.doi.org/10.1016/j.jnucmat.2012.08.027.
25. G. AUTHIÉ, T. TAGAWA, R. MOREAU, "Buoyant Flow in Long Vertical Enclosures in the Presence of a Strong Horizontal Magnetic Field. Part 2. Finite Enclosures," *European J. Mech. B/Fluids,* **22**, 203 (2003); http://dx.doi.org/10.1016/S0997-7546(03)00024-4.
26. C. P. C. WONG, S. MALANG, M. SAWAN, M. DAGHER, S. SMOLENTSEV B. MERRILL et. al., "An Overview of Dual Coolant Pb-17Li Breeder First Wall and Blanket Concept Development for the US ITER-TBM Design," *Fusion Eng. Des.*, **81**, 461 (2006); http://dx.doi.org/10.1016/j.fusengdes.2005.05.012.
27. S. SMOLENTSEV, C. WONG, S. MALANG, M. DAGHER, M. ABDOU, "MHD Considerations for the DCLL Inboard Blanket and Access Ducts," *Fusion Eng. Des.*, **85**, 1007 (2010); http://dx.doi.org/10.1016/j.fusengdes.2009.12.005.
28. S. SMOLENTSEV, N. B. MORLEY, C. WONG, M. ABDOU, "MHD and Heat Transfer Considerations for the US DCLL Blanket for DEMO and ITER TBM," *Fusion Eng. Des.*, **83**, 1788 (2008); http://dx.doi.org/10.1016/j.fusengdes.2008.04.002.
29. S. SMOLENTSEV, T. KUNUGI, K. MESSADEK, T. YOKOMINE, J. YOUNG, K. YUKI et al., "Status of TITAN Task 1-3 Flow Control and Thermofluid Modeling," *Fusion Eng. Des.*, **87**, 777 (2012); http://dx.doi.org/10.1016/j.fusengdes.2012.02.027.