SAND2011-4284 C

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SCIENCE IN FUSION TECHNOLOGY

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This paper presents examples from work in developing the technology needed for fusion. The purpose is to illustrate how our research ranges from very basic investigations to more directed applications. The paper draws primarily from work by others on the critical goals of extracting heat in a useful way from a fusion reactor and producing and handling tritium as a self-sufficient fuel.

I. INTRODUCTION

Fusion is moving into a new era. ITER [1] and NIF (National Ignition Facility) [2] are to produce plasmas in which deuterium and tritium fuel burn under conditions relevant for fusion reactors. But neither will have a self-sustaining tritium fuel cycle nor use high-temperature coolants and harvest energy. These functions of fusion nuclear technology are significant future challenges.

The following paragraphs give a cursory history of development in fusion technology. Figure 1 is a sketch of a quarter of a tokamak fusion reactor and a cutaway view with some basic components that surround the plasma. Figure 2 indentifies their basic functions.

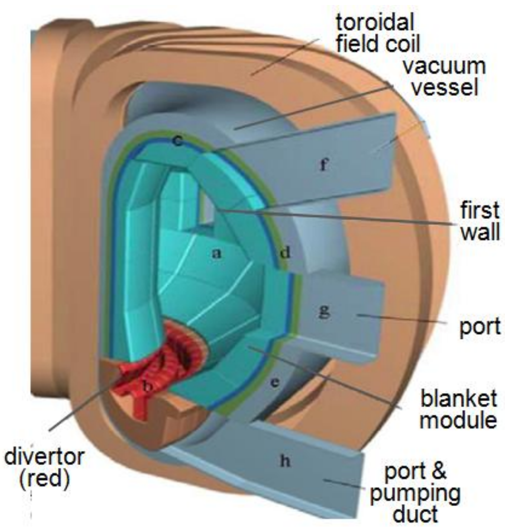

Figure 1. Cross section showing some components typical of a magnetic fusion DEMO reactor.

[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

1970-1990 – The power into plasmas and length of plasma confinement increase. Power handling and the effects of atoms coming back into the plasma from the walls become important. Basic issues of power generation and harvesting, tritium self-sufficiency and damage to materials are investigated in design studies and limited experiments are done.[3-6]

1990-2010 – Confinement experiments have high power plasmas and effects of plasma edge are more important. There is progress in alternative confinement systems, e.g. spherical torus and helical systems.[7,8] ITER, now being constructed, followed US planning for a Fusion Engineering Device and then the international INTOR study.[9] Our earlier still relatively small US program on fusion nuclear technology for a DEMO is now mostly subsumed into the support program for ITER.

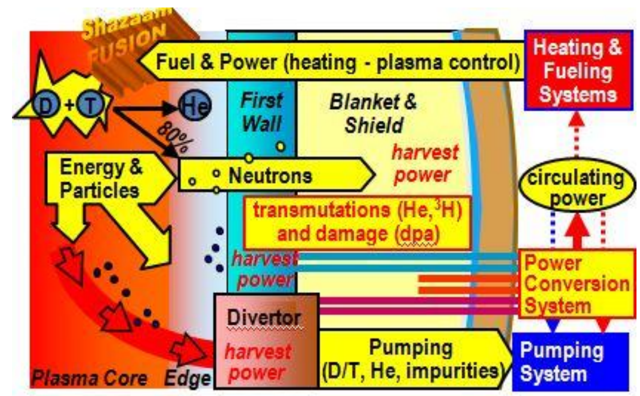

Figure 2. Cross section of DEMO from plasma outward.

II. WHAT DO WE MEAN BY "TECHNOLOGY?"

We in the US fusion program have straddled the fence on whether fusion is a science program or an energy program. Implicitly it is both. We have named research *fusion technolo*gy for the end product, but this is a misnomer and a clearer name is fusion nuclear science. We are investigating as yet poorly understood physical phenomena to increase our basic understanding. Let me now offer two basic points for this paper.

First, for some, the term "technology" implies that significant research and development (R&D) are not required, or at most, development will be straightforward engineering. As noted above, our use of the term in fusion does not carry this meaning. This distinction of what is technology is more than semantic quibbling. The mindsets of decision makers profoundly affect how they view the fusion program and interpret needs for development. It is important that we articulate our research needs clearly to others outside the fusion program.

Second, before we can deliver the technologies to enable fusion, our understanding should be good enough to predict how the nuclear subsystems will handle the awesome power from the plasma, extract useful heat, and produce and handle tritium in a self sufficient-fuel cycle. Our research on such systems is still at a fairly basic level, and much of it has a strong science component. To show this I take examples from the three areas below.

Materials science - Understanding the evolution of materials damaged by neutrons and how the properties change is critical. Modeling of these interactions at the nano-scale can guide research and the design of materials.

Surface science - How surfaces bombarded by ions evolve over time is an area of interest and concern and has provided surprises, e.g., the growth of tungsten fuzz.

Thermal fluids - To utilize flowing liquid metals to breed tritium or to extract heat, we must understand how magneto-hydrodynamic effects dominate flow. We know the basic principles but cannot yet predict flow patterns in complex geometries. For helium cooling, we can better exploit a novel porous structure in the cooling channels to enhance heat transfer, due to a recent breakthrough in computational fluid dynamic modeling.

III. NEUTRON DAMAGE TO MATERIALS

At the atomic level, the regular array of atoms in the crystalline lattice has many types of defects [2], and irradiation by neutrons creates many more. With increasing exposure (neutron fluence), the continuing evolution of a metal's microstructure as these defects interact can degrade the metal's properties. Radiation embrittlement is an example. Metals are malleable when numerous dislocations moving through an atomic lattice make incremental bits of shear displacement that on the macroscopic level accomplishes the change in shape as when a nail bends. Defects from irradiation can hinder the motion of dislocations and cause embrittlement.

We would like to be able to predict the effects of radiation damage to the end-of-life of a component and to identify or develop materials that resist degradation. To do such development by trial and error is very expensive and time consuming. We would have to irradiate many variants of the materials of interest at many temperatures, then test them and move forward incrementally based on the results. Another concern is that damage mechanisms from the higher energy neutrons in a fusion reactor differ from those in fission reactors where we would do testing. A big difference is the large amount of helium as a transmutation product in the fusion environment. We have studied the issues in such testing and development extensively [4,5,10]. Our hope is that insights from sophisticated modeling of materials that has blossomed with advances in computer power will lead us to smarter selections of the materials and a shorter more efficient path for development and testing.

Scientists can create molecular dynamics models in simple materials that simulate, at least for short times, the the creation of vacancies and interstitial and how these move and interact with other features. Such modeling can give insights into how to make materials stronger at high temperatures. For example, at high temperatures metals deform slowly at stresses below their yield stress in a process called creep. Nanoparticles of silicon carbide in a ferritic steel increase its creep strength and make possible its use at higher operating temperatures.

Modeling of ferritic steels hardened with nano-particles is of interest for nuclear fission and fusion and with much more R&D in the former. US work for fusion includes efforts by Kurtz [11] and Odette [12] and Zinkle [13]. (Ref. 13 is an excellent overview of materials for fission and fusion.) Figure 3 (from Ref. 12) shows several types of defect damage from irradiation as well as how nanoparticles, voids and dislocations have associated as the microstructure evolves during neutron irradiation.

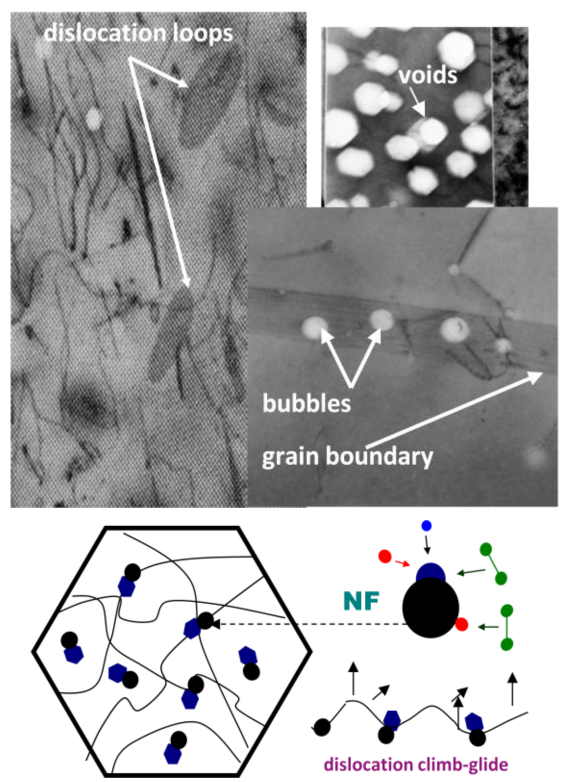

Figure 3. Micrograph, ferritic steel hardened with a nanodispersion of TiC_2 particles; (below) diagram of interactions of dislocations and nanoparticles.

[2] Point defects: vacancy (site without atom), interstitial (atom between normal atomic sites). Dislocation (edge of a plane of atoms inserted between planes). The arrangements of the atomic lattices do not match across a stacking fault or grain boundary.

While there are limitations in what this type of modeling can predict, it is the state-of-the-art in materials science and being applied in fusion to guide us toward productive directions for materials development.

IV. EVOLUTION OF MATERIALS/SURFACES

Plasma facing components (PFCs) must survive in a challenging environment with high temperature, high heat loads, strong gradients in temperature and intense bombardment from energetic particles. The operation of magnetic fusion systems with long pulses and actively cooled PFCs is in its infancy. ITER will have the first PFCs in a fusion nuclear system, but its low coolant temperature and applications differ from a reactor, where tungsten and high temperature helium are frequently cited as the plasma facing material and coolant of choice [14].

At surfaces adjacent to the plasma, ions (and energetic neutrals) penetrate and produce defects that can trap implanted hydrogen and helium. The sputtering of atoms and implantation of ions typically do not depend on temperature, but the processes that trap atoms depend on diffusion and are highly dependent on temperature.

Our next example is the growth of a low-density fuzz (Fig. 4) on the surface of tungsten bombarded with helium at levels of helium influx and temperatures of tungsten that are relevant for a PFC in a reactor. Researchers using the linear plasma sources PISCES at the University of California, San Diego and NAGDIS-II at Nagoya University first observed this unexpected feature [15,16].

How the fuzz grows is not yet understood. Again, modeling with molecular dynamics as well as ab initio calculations can give some insight. The early ongoing work noted here [17] and only recently presented is complemented by other computational modeling. Figure 5 is a snapshot at one point in time of a simulation that shows vacancies and He atoms clustering together and forming a structure that grows. The structure in Figure 5 looks very much like a precursor to some eruption that will break through the surface and move helium upward from its former subsurface positions.

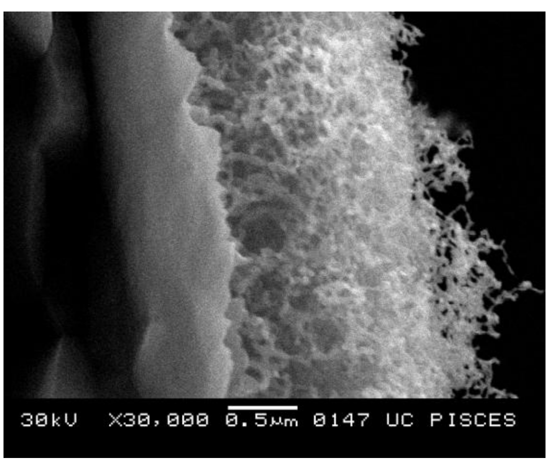

Figure 4. Tungsten tendrils created with a He plasma, He energy of 25eV, 1200 K, 4290 s, 2x1026 He+/m2 (courtesy of UCSD Jacobs Mechanical and Aerospace Engineering Dept.)

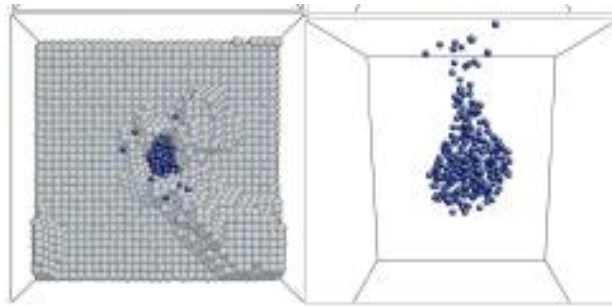

Figure 5. Snapshot form modeling of the coalescence of vacancies and He atoms and growth after 115 ps.

V. LIQUID SURFACES AND LIQUID METAL MHD

Several design studies have investigated flowing liquids as the plasma facing surface for the first wall or divertor in a fusion reactor [18-21, Ref. 18 cites many early papers.] Since lithium is used to breed tritium fuel, lithium and lithium-containing liquid metals in breeding blankets are a natural choice. For liquid metal blankets in magnetic fusion devices, the strong magnetic fields dominate the flow and affect the heat transfer due to the liquid metal magneto-hydrodynamic (LMMHD) effects. (The other class of blankets uses solid breeders such as lithium silicate and lithium titanate.)

We know the basic principles for LMMHD (in Maxwell's equations) and the implicit limitations, and analytical solutions were found for simple configurations such as straight pipes or bends [18]. But only in the last decade have the increased computational capability, utilizing such features as adaptive meshes and very fast solvers, enabled researchers to make headway in modeling flow in more complex shapes. The application to fusion, led in the US by UCLA with collaborators in several other countries, has uncovered very interesting features of MHD-controlled flow [22-24] .

Well known effects in LMMHD are: (1) turbulence is suppressed, and (2) fast flowing jets form at the sides of a channel (see Fig. 6) and dominate the mass flow. Since the pressure drop would be much too high for fast flow in large channels in a fusion breeding blanket, designs with moderate flow rates have evolved, such as that for the dual coolant lithium lead blanket favored by the US [25]. Very slow flow between the side jets would cause a large rise in temperature from prolonged nuclear heating, but this problem can be mitigated by another fascinating phenomenon revealed in this modeling, i.e., two dimensional quasi-turbulence where eddies form with their axes of rotation along the magnetic field. Figure 6 shows a model rendering of the 2-D turbulence and compares the rise in temperature when the slower flow in the central section is either laminar or has 2-D turbulence.

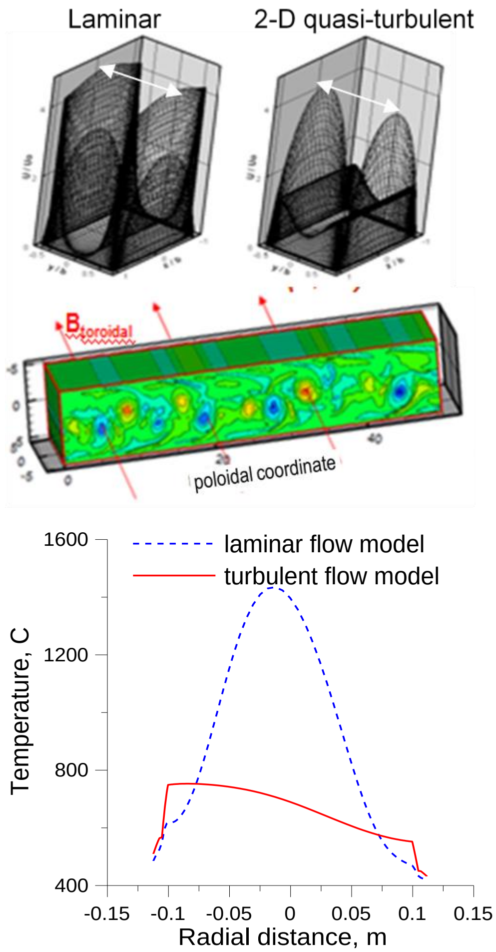

Figure 5. (top) Flow distributions; (center) 2-D quasi-turbulence; (bottom) temperature profiles across channel (lateral direction of arrows in top figure).

VI. GAS FLOW IN POROUS MEDIA

The goal of extracting fusion power with high efficiency leads many design concepts for fusion reactors to the use of helium as a coolant coupled to a Brayton cycle for generating electricity.[26] US effort in developing helium-cooled refractory PFCs is divided primarily between design studies and testing. Exploiting the benefits of helium cooling requires us to explore novel concepts that greatly increase the area of the heated surface in contact with the helium. And nearly all the novel concepts tested in the Plasma Materials Test Facility at Sandia were developed by industry with grants from the Small Business Innovative Research program of the US Department of Energy or from Creative Research and Development Agreements also funded by government agencies.

In the examples of research in this section and the next, the progress combines a) computational tools that can solve problems for complex configurations and b) coordinated experiments to benchmark the computations.

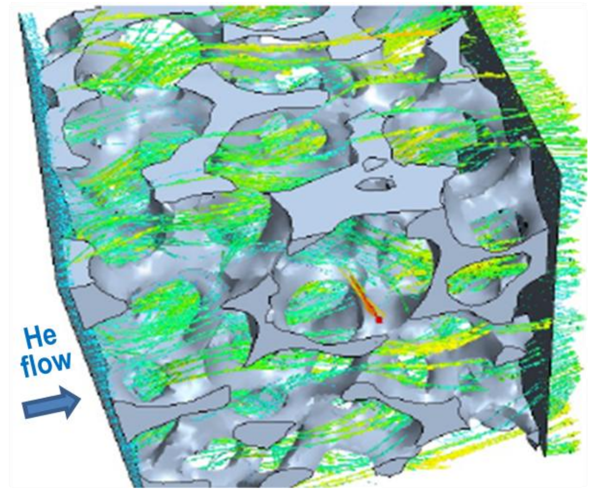

Figure 4. Flow streamlines in 2x2 mm section of model of an irregular porous geometry presented in Ref. 26 that appears elsewhere in this proceedings.

Again the examples push the boundaries in the engineering sciences. Youchison's paper in this conference [27] gives an excellent example of recent work in which state-of-the-art computational fluid dynamics (CFD) is applied to a problem in fusion, specifically how gas flows through a porous media where the solids have irregular shapes. In fusion in the past, finned heat sinks and other enhancements for heat transfer have typically been modeled using an approximation called the Ergun equation [28] that is an averaged model of heat transfer using thermal penetration based on materials properties and a characteristic distance.

Ultramet, Inc (Pacoima, CA) made the porous structure by chemical vapor deposition of molybdenum (could also be tungsten) over a ligamentary precursor of carbon. The application here is a helium-cooled refractory structure with a very open porosity, as compared to a packed bed. The open porosity and connectivity of the ligamentary structure are beneficial for heat transfer but present a formidable challenge for modeling because a true representation has to reproduce the solid mass with fidelity and introduce a dense mesh in the boundary layers around the solid structure so that the flow and shear in the boundary layers can be modeled accurately. Youchison and co-researchers used x-ray micro-tomography to document the shapes and translated the data to a useful format for the solid geometry for the model.

In Figure 7 (taken from Ref. 27) the flow velocities are shown as streamline arrows. This model contains the full fluid physics so that the effect of turbulence on heat transfer and the effect of differential pressures are manifest. One concern with helium coolant is that bypass flow away from hot spots can compromise the effectiveness of the overall heat transfer. This is most obvious in multiple channels where heating from a local hot spot causes a decrease in density of the adjacent helium and slight pressure differential that can retard flow. This in turn leads to even poorer heat transfer locally, unstable flow and the potential threat of burning out the channel. Such flow instability was demonstrated previously in a test with a bypass channel and a heated channel with another type of porous medium [29].

VII. FLUID FLOW IN HYPERVAPORTRONS

The hypervaportron is an efficient heat sink that ITER now uses for portions of its first wall that may receive high (5 MW/m^2) heat loads. The first wall panels comprise a set of fingers (Fig. 8, top), plus a set that extend in the opposite direction from a central manifold.

Water flows across rather than along the ribs on the heated side of the channel. High heat transfer occurs when boiling starts at the base of the groove (mid, Fig. 8.) Bubbles grow, are ejected into the main water flow and collapse, having transferred the heat of vaporization from the base of the groove into the main flow. In sub-cooled regions, the heat transfer is highest at the ends of the ribs.

Figure 8 shows the results of a fluid flow model [29] with full fluid physics for turbulence and phase changes and detailed geometry of the boundary layers in the ribs and grooves. This treatment for the first time accurately predicts the thermal performance of the complex two-phase flow and heat transfer in a hypervaportron, and has accurately predicted the Critical Heat Flux[3] for bench-mark high heat flux tests in which a short section of a hypervaportron finger was heated in the Plasma Materials Test Facility at Sandia. The model also reproduced results for a test of a Russian hypervaportron.

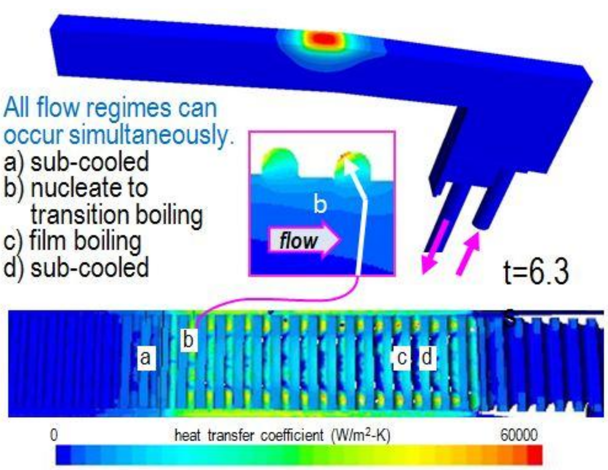

Figure 8. Results of CFD model. (top) Thermal signature (red) in high heat flux test. (mid) X-section with high heat transfer coefficient (HTC) with sub-cooled boiling at base of groove. (lower) Map of HTC.

[3]Above the Critical Heat Flux, excessive boiling creates a vapor barrier that blankets the grooves and ribs. The heat transfer drastically decreases and the metal above overheats and fails.

VIII. FINAL COMMENTS

Our past and current activities to develop nuclear “fusion technology” for a reactor in many cases are at the level of science inquiries to give us basic understanding. The paper has provided examples.

We are very familiar with issues, less with solutions. We have extracted issues from performance requirements in our design studies for reactors, but cannot now predict which concepts for fusion nuclear subsystems will actually work. By contrast, we are learning a tremendous amount in ITER about the level of detailed knowledge needed to build a fusion nuclear device. But as noted previously, ITER has neither a breeding blanket for tritium self sufficiency nor PFCs that will operate the high temperatures needed to harvest useful power.

Development of nuclear technology will likely pace the development of fusion. How do we move forward?

- First we need a credible path that is affordable yet provides sufficient understanding of critical subsystems to confirm a reasonable expectation of success. At present, we are identifying areas where we lack understanding and need basic experiments plus the means (facilities) to conduct the experiments. We also must attract young researchers into the program and, in many cases, also advance the state-of-the-art in science-based engineering.
- Next we will develop detailed knowledge and a predictive capability that enable us to model, design, mock up and test integrated subsystems. These activities give us information such as modes of failure and problematic constraints and trade-offs that arise on the path to a workable component. This stage will also require additional new facilities.

Our goal is sufficient confidence to go forward to the next stage where we build, operate and demonstrate robust nuclear subsystems appropriate for a reactor. “Sufficient confidence” here means that our demonstrated knowledge is compelling for both the investment and the licensing of a fusion device with reactor- relevant nuclear subsystems.

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