

## Progress and Status of Fusion Technology and Materials Research in China

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**Abstract.** Fusion technology and materials research in China was included in the National High Technology Project during 1986–2000. Since 2000, the National Natural Science Foundation Committee, the State Development Planning Commission, and the Ministry of Science and Technology have supported this field of research. The research program has covered the topics of tritium engineering, plasma facing materials and structural materials. The Southwestern Institute of Physics has been a leading institute in this research program in the last 15 years in China, and over ten universities and institutes have joined the program.

### 1. Introduction

In China, fusion research was included in the National High Technology Project during 1986–2000. Since 2000, the National Natural Science Foundation Committee (NNSFC), the State Development Planning Commission (SDPC), and the Ministry of Science and Technology (MOST) have supported fusion research. The research program on fusion technology and materials has covered the topics of tritium engineering (in the first years only), liquid metal magnetohydrodynamics (MHD), plasma facing materials (PFMs) and structural materials. The Southwestern Institute of Physics (SWIP) has been a coordinating institute in this research program in the last 15 years in China, and over ten universities and institutes have joined the program.

There are two concepts for the blanket in Chinese fusion reactor design, namely a liquid metal breeder blanket and a solid breeder blanket. For tritium engineering, tritium production and release in-pile using  $\gamma$ -LiAlO<sub>2</sub> ceramic spheres was performed [1–3].

For the liquid metal blanket, the Liquid Metal Experimental Loop (LMEL) was built in 1992, and many experimental results have been obtained.

The fusion materials R&D effort in China is focused on low activation alloys such as Fe-Cr-Mn(W,V), V-Cr-Ti and SiC/SiC composites, carbon based materials and high Z materials, such as multielement doped graphite, W coating and W/Cu alloy components. Functionally graded materials (FGMs) of W/Cu have also been developed [4–6].

### 2. Fusion Technology Research

Tritium production and release was performed in-pile at the China In-pile Tritium Production (CITP) facility. The specimen box, which contained ten hollow cylinders of  $\gamma$ -LiAlO<sub>2</sub> ceramic, was located in the activity zone of a fission reactor. The tritium was blown by helium gas with 0.1% hydrogen. Increases in tritium release related to the breeder temperature are given in Fig. 1, and it can be seen that the tritium rockets by more than one order of magnitude at 400°C (see Fig. 1 below).

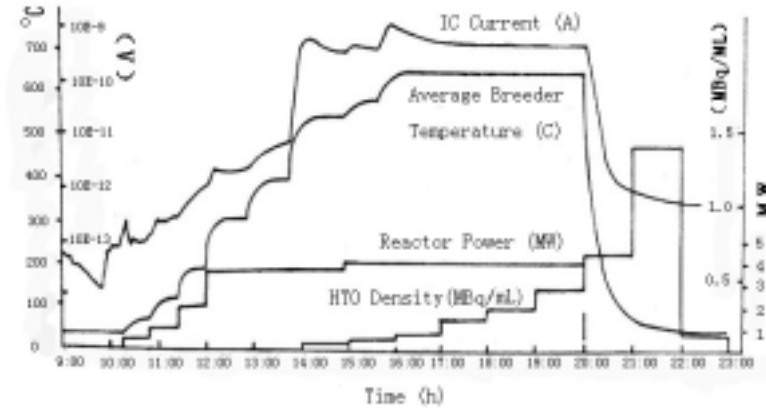


FIG. 1. Results of tritium production and release in-pile at CITP.

Many films have been developed, such as palladium,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiN}+\text{TiC}$ ,  $\text{TiN}+\text{TiC}+\text{TiN}$  and  $\text{TiN}+\text{TiC}+\text{SiO}_2$  on 316L stainless steel. The experimental results have shown that the permeation rate was lower by 4 to 5 orders of magnitude at 200–500°C and by 3 orders of magnitude at 600°C for  $\text{TiN}+\text{TiC}+\text{TiN}$  film compared with palladium film, and lower by 4 to 6 orders of magnitude at 200–500°C and by 4 orders of magnitude at 600°C for  $\text{TiN}+\text{TiC}+\text{SiO}_2$  film compared with palladium film.

### 3. Research on Liquid Metal MHD Effects

For the investigation of liquid metal MHD effects in the case of an off-normal reactor shutdown, a simulation experiment was performed. The MHD pressure drop, mean velocity and magnetic field were measured after a sudden turn-off of the magnet power supply (with the electromagnetic pump power supply still on). The results show that the MHD pressure drop is about 25% higher in a quickly changing magnetic field than in a steady magnetic field.

The velocity distributions on the center plane of the cross-section of rectangular and circular ducts have been measured. For a rectangular duct, the velocity in the boundary layer is 6 times higher than that in the core region. For a circular duct, the velocity in the boundary layer is 2 times higher than that in the core region. Both boundary velocity and core velocity increase with the increase of the Hartmann number  $M$ , whereas according to theoretical expectations, the core velocity would decrease with the increase of the Hartmann number, and jet flow would not occur in the boundary layer in a circular pipe. The two-dimensional MHD pressure drop factor  $\Delta P_{2-D}$  due to velocity distribution is obtained from experimental data and theoretical analysis, and can be expressed as:

$$\Delta P_{2-D} = K_{2-D}(0.018 - M^{-1/2}) \sigma_f V_0 B_0^2 L_0 \phi \quad (1)$$

where  $K_{2-D}=b/a$ , and  $b$  and  $a$  are the lengths of the long and the short sides of the duct cross-section, respectively.  $\sigma_f$  and  $\sigma_w$  are the flow conductivity and the channel wall conductivity, respectively, and  $\phi$  is the wall conductance ratio.

For three-dimensional MHD manifold effects upstream and downstream, the results show that velocity distribution is affected by the manifold only in a half-area of the cross-section of the pipe in the downstream case and in the whole cross-section area of the pipe in the upstream case. The three-dimensional MHD pressure drop due to the manifold is also different for the two cases.  $\Delta P_{3-D}$  can be expressed as:

$$\Delta P_{3-D} = \beta \sigma_f a_1 V_0 B_0^2 \phi_1^{1/2} \quad (2)$$

$$\phi_1 = \sigma_w t_{w1} / (\sigma_f a_1) \quad (3)$$

$$\beta = 1.43 \times 10^{-4} M a_1 / a_0 \quad \text{for the upstream case} \quad (4)$$

$$\beta = 1.1 \times 10^{-4} M a_1 / a_0 \quad \text{for the downstream case} \quad (5)$$

where  $a_0$  and  $a_1$  are the main pipe and the bypass pipe radius, respectively.

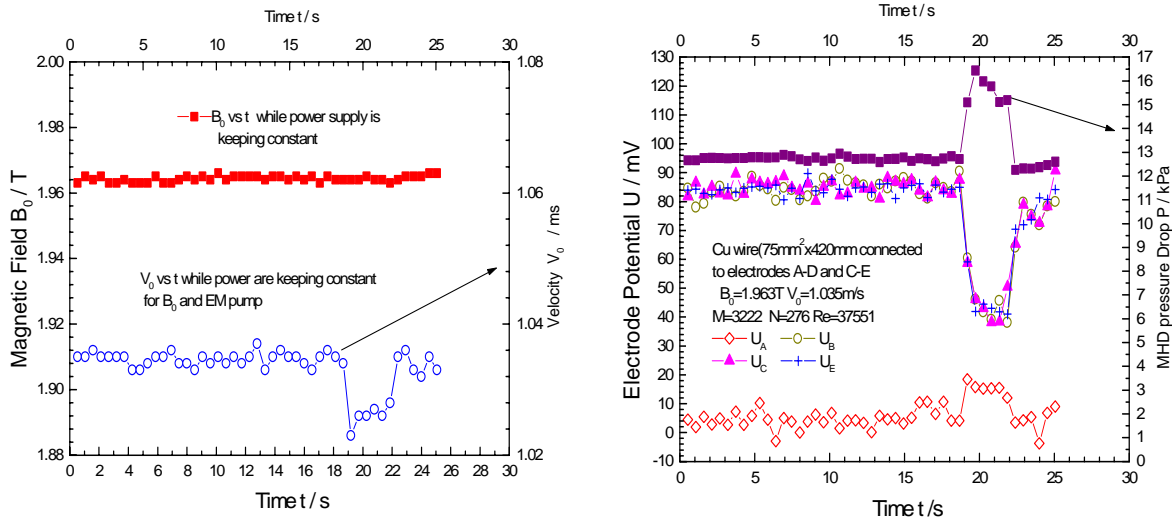


FIG. 2. Time dependence of magnetic field, velocity, surface electrical potential and MHD pressure drop with all external conditions fixed.

With respect to the effects of insulator coating imperfections, new phenomena were observed of surface (side-wall electrical potential) and bulk (MHD pressure drop and velocity) instabilities. The results show that surface electrical potential  $U$  and MHD pressure drop  $\Delta P$  exhibit *non-monotonic* behavior with increasing  $V_0$ , while magnetic field  $B_0$  is held constant, and while all external experimental conditions are fixed (see Fig. 2 above). These results are also important for device designs with liquid-metal-free surfaces.

## 4. Fusion Materials Research

### 4.1. Structural Materials

For structural materials R&D, CHT-9, CHT-7, Fe-(12-15)Cr-(15-30)Mn, ODS 13Cr-MoTi+Y<sub>2</sub>O<sub>3</sub> and V-alloys (a 5 kg ingot of V-4Ti-4Cr was produced at SWIP in June 2002, see Fig. 3 below) have been developed. For SiC/SiC<sub>w</sub> research, a small piece of SiC/SiC<sub>w</sub> was produced with hot pressure sintering to investigate the possibility of producing high density SiC through the reaction of silicon and carbon under lower temperature and lower pressure. Some SiC/SiC<sub>w</sub> samples were obtained with a density of 2.6 g/cm<sup>3</sup> (81% TD) and thermal conductivity of 7 W/m.K under sintering conditions of 1700°C and 40 MPa.

The effects of carbon are being studied in Fe-Cr-Mn(W,V) alloys. The results indicate that the strength is lower for low carbon (0.26% C) than for high carbon (0.34% C) alloys, and that the tensile strength and synthesis properties are better for low carbon (0.26% C) than for high carbon (0.34% C) alloys. For 0.26–0.29% carbon alloys, the grain size is small and the phase is stable. For W and V modified alloys, swelling and segregation properties are being investigated during 1.3 MeV electron irradiation. The swelling rate was 0.3% (8–15% for 316L) and the total segregation was 3% (8–12% for 316L) after a dose of up to 15 dpa. Part of

the  $\gamma$ -phases were changed to  $\alpha$ -phases during irradiation, which improved the alloys' resistance to swelling.

For V4Cr4Ti, V3TiAlSi, V4Ti, V4Ti3Al and V4TiSi alloys, oxidation experiments were performed at elevated temperatures of from 400 to 600°C in air (Case I) and in a flowing argon gas with  $5.1 \times 10^{-3}$  to  $9.1 \times 10^{-3}$  torr O<sub>2</sub> (Case II). The oxides formed were mainly V<sub>2</sub>O<sub>5</sub> for Case I and V<sub>2</sub>O<sub>4</sub> for Case II. All showed a parabolic weight increase, indicative of a diffusion controlled oxidation process.

All vanadium alloys in the present study showed great sensitivity to hydrogen embrittlement. V4Ti and V4TiSi alloys showed higher resistance to hydrogen embrittlement than the other alloys. Their tensile elongation kept in the range of 6–11% even when the hydrogen content reached 113 wppm, while that for other alloys was ~2.5%.

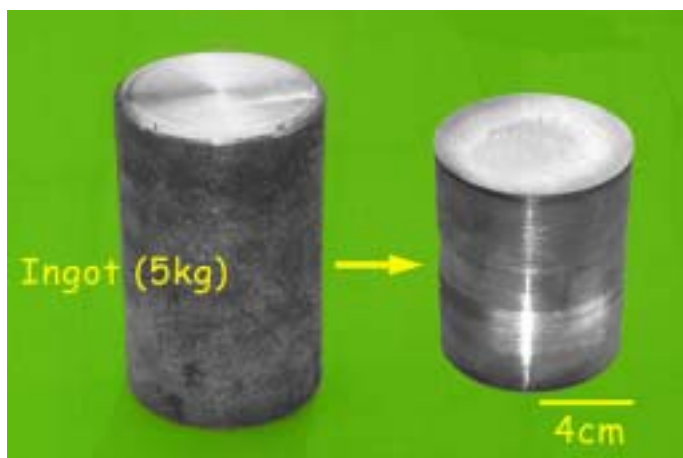


FIG. 3. Vanadium alloy (V-4Ti-4Cr) developed at SWIP in China.

#### 4.2. Plasma Facing Materials/Components (PFMs/PFCs)

In China, PFM research focuses on carbon-based materials and high Z materials, such as multielement doped graphite, W coating and W/Cu alloy components. FGMs of W/Cu have also been developed using hot pressing. For W-Cu FGMs, there are five layers from 100% W to 100% Cu. There are cracks in W and W-Cu layers, but not in the W/Cu interface layer, after laser beam bombardment with a surface density on the specimens of  $122.9 \text{ MW m}^{-2}$ , beam sizes of 4 mm and 7.2 mm in diameter, a duration of 4 ms, a frequency of 10 Hz and a total irradiation time of 70 s. W coating on graphite has also been developed, and the adhesion strength is between 34.8 and 67.0 MPa.



FIG. 4. Thermal load test at  $10 \text{ MW m}^{-2}$  electron beam irradiation under 1000 cycles of 20 s duration and 20 s intervals for a W/CuCrZr weld by hot isostatic pressing.

W/CuCrZr components are also being developed in the program. Samples with a diameter of 40 mm were made by hot isostatic pressing under conditions of 150 MPa, 950°C, 2 h, and no cracking was observed in the interface of the W and CuCrZr alloy after a thermal load of 10 MW m<sup>-2</sup> electron beam irradiation for 1000 cycles of 20 s duration and 20 s intervals (see Fig. 4 above).

New types of multielement doped carbon materials (B, Si and Ti doped graphite and C/C composites) have been developed. The results have shown that the chemical sputtering yield is lower by about one order of magnitude, and that TDS and RES rates are lower by about 20% for the new multielement doped materials than for non-doped carbon-based materials. After the specimens were exposed to about 100 plasma discharges, no significant cracking was observed for the multielement doped materials, but for the non-doped materials, there was considerable net cracking. There are also ongoing investigations, both theoretical and experimental, of the key issues of advanced limiter-divertor plasma facing systems (ALPS) and the behavior of free surface jet flow in a non-uniform magnetic field.

## 5. Conclusions

In China the research on fusion technology and materials covers most of the key issues of the field, but it is limited to the laboratory level scale. Low activation alloys and high Z PFMs/PFCs, as well as liquid-metal-free surfaces, will be the focus of upcoming work. A favorable budget for fusion technology and materials research may perhaps be expected in the not too distant future in China.

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## References

- [1] Zengyu XU, Jiming CHEN, Xiang LIU, Fu ZHANG, et al., 15 Year Summary Report on Blanket Technology and Materials of Mixed Fuel Reactor Research Sponsored by National “863” Projects, CNIC-01622 swip-0144, China Nucl. Sci. Technol. Rep. (2002) (in Chinese).
- [2] Benfu HU, H. TAKAHASHI, Damage behavior in an electron/helium dual-beam irradiated Fe-Cr-Mn(W,V) alloy, *J. Nucl. Mater.* **258–263** (1998) 1708.
- [3] Zengyu XU et al., Experimental investigation of magnetohydrodynamic effects caused by a manifold circular pipe, *Fusion Sci. Technol.* **40** 1 (July 2001) 79–85.
- [4] Jiming CHEN, Shaoyu QIU, Lin YANG, Zengyu XU, et al., Effects of oxygen, hydrogen and neutron irradiation on the mechanical properties of several vanadium alloys, *J. Nucl. Mater.* **302** (2002) 135.
- [5] J.P. QIAN, P.Y. LI, L. LU, X. LIU, The behavior of low-Z materials under high heat flux, *J. Nucl. Mater.* **196–198** (1992) 653–657.
- [6] X. LIU, N. YASHIDA, N. NODA, Z. XU, Y. LIU, The erosion and erosion products of tungsten and carbon based materials bombarded by high energy pulse electron beam, PSI-15, 27–31 May 2002, Gifu, Japan.