ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 201–205

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Experimental study of lithium target under high power load

B.I. Khripunov [a,*], V.B. Petrov [a], V.V. Shapkin [a], A.S. Pleshakov [a], A.S. Rupyshev [a], N.V. Antonov [a], A.M. Litnovsky [a], P.V. Romanov [a], Yu.S. Shpansky [a], V.A. Evtikhin [b], I.E. Lyublinsky [b], A.V. Vertkov [b]

[a] *Nuclear Fusion Institute of Russian Research Center, Kurchatov Institute, Kurchatov Square 1, 123182 Moscow, Russian Federation*

[b] *State Enterprise, Red Star, Moscow, Russian Federation*

Abstract

This paper presents experimental research on simulation of a free liquid lithium surface under high heat flux impact for divertor application. Capillary porous structure (CPS) was taken to form the free liquid metal surface imitating divertor target plate. Experiments were performed in the SPRUT-4 linear plasma device with electron beam as power source. Lithium-filled targets were investigated at 1–50 MW/m^2 heat loads in steady state. Lithium evaporation, energy and mass balance, surface temperature, vapor ionization, lithium plasma parameters and radiation were studied. Detailed thermal analysis was made to study heat flows in the target and their correspondence with experimental observations. Durable operation of the setup was possible in the range 1–20 MW/m^2 without damage of the structure. The relevance of the experimental performance to divertor condition is analyzed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Lithium

1. Introduction

Though lithium was proposed as a plasma-facing material for magnetic fusion devices long ago it has been remaining without essential experimental research and finding rather schematic than practical incarnations [1–3]. A new optional realization of a liquid lithium surface was proposed by the authors [4] for tokamak divertor application. A problem to form a liquid lithium surface so that it could operate in severe conditions of particle bombardment and heat fluxes could be solved by the use of a lithium filled capillary porous structure (CPS) on a plasma facing wall [5,6]. The approach appears attractive for steady-state fusion devices and offers a feasible engineering solution for them.

In this paper we describe the experimental work and present the results of the study carried out in SPRUT-4 linear plasma simulator (NFI RRC Kurchatov Institute) on the formation of liquid lithium surface with capillary porous structure and on its interaction with high power load in steady state condition. Evaporation of lithium, plasma generation, and target thermal response to the heat load are considered. The obtained data are discussed in relation with divertor problem.

2. Experiment description

The main goal of the experiment was to realize a liquid lithium surface with a capillary porous structure, to load it with high power flux in steady state and to study the effect of such interaction and accompanying phenomena. The preference was given to electron beam as the power source. SPRUT-4 plasma device [7] was taken for this purpose. It had a 40 kW electron gun providing the electron beam in a longitudinal magnetic field 0.08–0.85 T at 1–100 MW/m^2 of specific power for heat flux. Lithium had been already used in the machine

---

[*] Corresponding author. Tel.: +7-095 196 7900; fax: +7-095 943 0073.

E-mail address: boris@nfi.kiae.ru (B.I. Khripunov).

PII: S0022-3115(00)00433-5

as working fluid in previous investigations of beam-plasma discharge.

Electron beam passes along magnetic axis through water-cooled condenser and is terminated by the lithium-filled CPS target (Fig. 1). Interaction zone is surrounded by the shield condenser equipped with thermocouples and it has no forced cooling. Pressure was not higher than 1×10^{-5} Torr during experiments in different sections of the chamber.

Electron beam current density was measured at the target position to characterize power load on the receiving surface (Fig. 2) (the power flux values given below should be referred to the plateau of the distribution). The beam power was varied in the range 1–50 MW/m^2 at electron accelerating voltage 1–9 kV and beam currents 0.1–2 A. Transition period needed to achieve a given steady state beam power level did not exceed 20 s while exposure time depended on particular experimental run (from 34 s to 3 h).

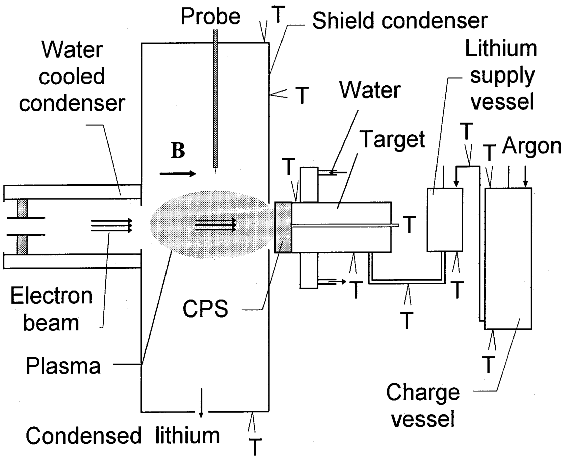

Fig. 1. Target arrangement, interaction zone and lithium supply system (T-thermocouples).

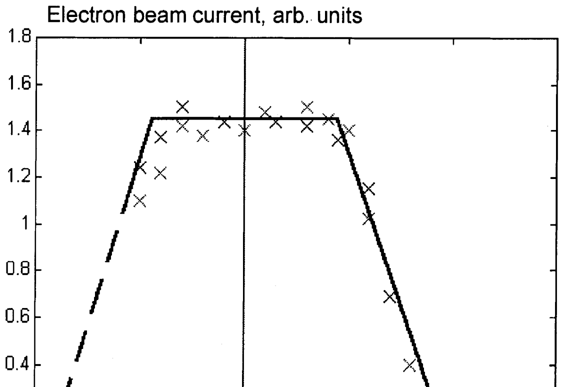

Fig. 2. Electron beam radial profile at the target position.

Different targets were used in the work. Common to all targets was a capillary structure on the receiving face made of a molybdenum mesh ($d = 0.1$ mm, $h = 0.25$ mm) and the presence of a transport part behind it. Target CPS diameter was 40 mm. First targets had no force-cool for residual heat removal so that the temperature was slowly rising during experiments and total exposure time was limited. Presently working is the target shown in Fig. 1 in which a water cooling system is realized attached to the side wall in some distance from the facing plate. Lithium was introduced to the target from a special supply system with total lithium charge 0.8 kg. Thermocouples are installed in all parts of the filling system and in the target itself to monitor temperature regimes during filling operations and during exposure of the target.

Energy load characteristics were determined by taking the initial beam parameters (total current, electron energy) and target current. Shield condenser collected the essential part of evaporated lithium and also served to establish the thermal and mass balance of evaporation process. Lithium plasma was analyzed with Langmuir probe placed in front of the target 6 cm apart at 1.5 cm from the axis. Visual light spectrum was taken with MDR-6 double monochromator. The whole process was registered by video to check the time correlation of the observed picture with power load and with other measured parameters.

3. Experimental results

3.1. Lithium evaporation

Evaluation of the target surface temperature and measurement of lithium mass balance to deduce evaporation rate were of primary interest in the study. For this, experiments were performed to measure temperature in different points of the targets around the hot spot for different power fluxes. Evaluation of the absorbed power fraction for the targets having no water cooling (no thermal stabilization) was made by the analysis of target temperature temporal behavior. The energy removed by evaporated lithium was deduced from the measurement of shield condenser temperature rise in time with the account for its heat capacity and lithium vaporization heat as well as by total amount of lithium collected in the shield condenser. For the water-cooled targets the energy fraction absorbed by target was established by calorimetry. The results of lithium evaporation rate evaluation are summarized in Fig. 3 showing lithium flux from the CPS target as a function of power

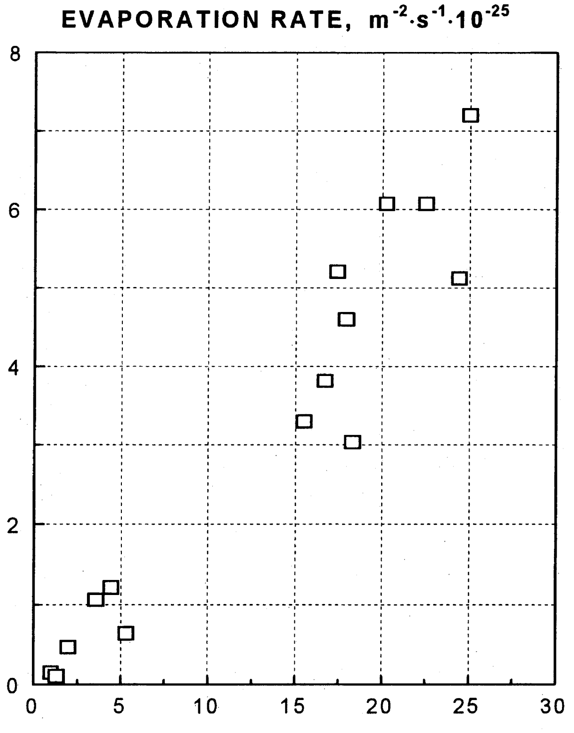

Fig. 3. Lithium flux from CPS target under electron beam power load.

load. The corresponding surface temperature values calculated on the basis of energy and mass balance measurement are given in Fig. 4. For comparison we also plot in Fig. 4 the points of temperature measured directly in the target body (the thermocouple was placed at 20 mm from the hot spot center). The points of temperature measurement correlate with the values deduced from balance and they are about 100°C lower than these. It is explained by the thermocouple position in the target body where temperature gradient occurs.

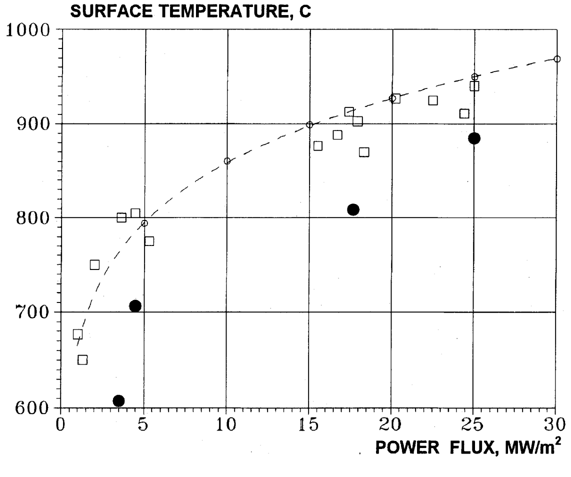

Fig. 4. Surface temperature of the target ((•): measurement at 20 mm from heated area center, (□): evaluated by balance, (dashed curve): calculation).

A detailed heat transfer analysis of the target response to power load has been undertaken to understand the process better. Shown in Fig. 5 are calculated temperature fields in the target (without external thermal stabilization) for 20 MW/m^2 for different moments from the exposure start. Dashed curve shows maximal calculated temperature in the hot spot after 100 s from the power start.

Realization of a steady operation of the liquid lithium target under high power electron beam load with continuous evaporation of lithium from the surface is thought to be the main achievement of the study. Durable operation was demonstrated for the targets without forced cooling at 1–5 MW/m^2 for 1000 s, at 15–20 MW/m^2 for 100 s and 3–5 s excursions were made to 45–50 MW/m^2. Several targets were damaged by the beam. Complete loss of lithium at the surface

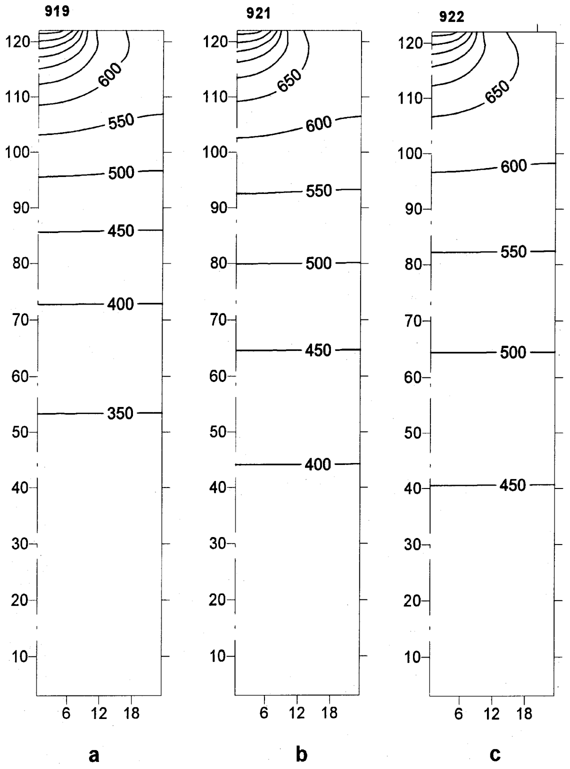

Fig. 5. Temperature field in the target without external cooling at 20 MW/m^2: (a) 100 s, (b) 200 s, (c) 300 s after start correspondingly. Temperature is shown in °C, target dimensions in mm, left side is target axis. Maximal temperatures are shown at the hot spot.

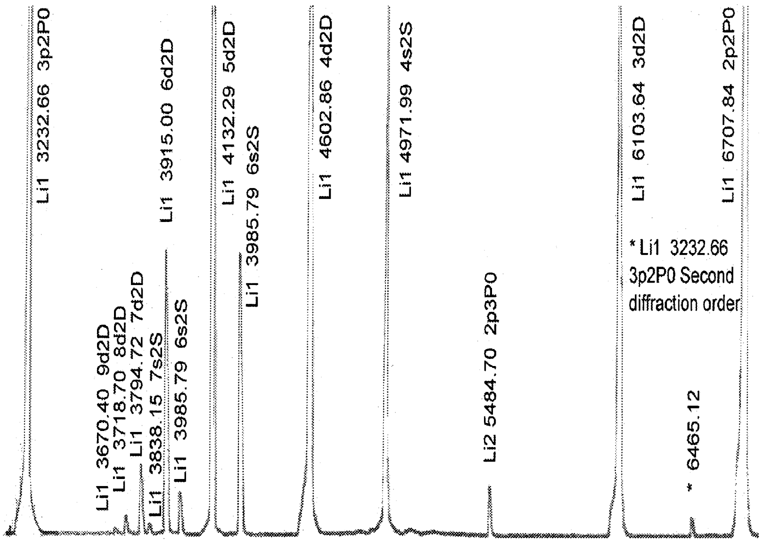

Fig. 6. Light emission spectrum of lithium plasma at the CPS target.

appeared to be the reason of these damages at power levels $\geqslant 5$ MW/m^2 [4]. Really steady state regimes were obtained by using water cooled target that had special liquid lithium supply system capable to ensure durable operation at high mass flow rate (as measured in maximum 0.2–0.3 g/s). Three-hour experiment was performed with the target up to date.

3.2. Plasma generation

Plasma was observed to appear in front of the target at all studied power loads except the lowest (<1 MW/m^2). Plasma column was attached to the hot spot and it spread along magnetic field depending on power characteristics. The reason of plasma generation is a beam-plasma discharge that has been experimentally studied by the authors for a long time and in lithium, in particular [7].

Plasma parameters have been evaluated with a single Langmuir probe to study the importance of the plasma in particle and power balance. In the 1–25 MW/m^2 range of heat loads plasma density varied from 4×10^{11} to 10^{14} cm^{-3} [7]. Direct measurements near the target were not possible because of high heat load and destruction of the probe. Lithium vapor density estimated for the above conditions was ranging at the target surface from 10^{15} to 10^{17} cm^{-3}. For plasma density on the axis five times as high as that at the probe position we find ionization degree to be 10^{-3}–10^{-2}. Plasma does not accumulate significant energy and does not disturb balance at low electron temperatures.

A typical visible light emission spectrum of Li plasma in front of the target is shown in Fig. 6. Lithium neutral lines are radiated corresponding to transitions from the excited levels with principal quantum number $n = 2$–9. Li2 ion line at 548.4 nm is explained by the presence of electron beam with keV-range energies. Line intensity analysis gave estimation for plasma electron temperature $\leqslant 1$ eV. No impurity radiation has been detected in the spectra in our study.

4. Discussion

Our thermal process is described by a simple equation: $Q_0 = Q_{\mathrm{vap}} + Q_{\mathrm{t}}$, where $Q_0, Q_{\mathrm{vap}}, Q_{\mathrm{t}}$ are initial beam power, energy loss by evaporation and target heating, correspondingly. Thermal balance was established with an accuracy of 10%. At this level the contribution of plasma and neutral radiation to it has not been found significant. Lithium CPS was shown to remove an important fraction of the coming heat load by evaporation. The data shown in Fig. 3 were used for evaluation of the removed power from CPS by evaporation of lithium. About 50% and less of the coming flux are removed at levels less than 5 MW/m^2, the removed fraction increasing up to 60–70% at 15–20 MW/m^2.

As mentioned above, a capillary target is serviceable if CPS is fed enough with liquid lithium by transport system. Roughly, criterion of the process my be described as follows: $\Delta P = P_{\mathrm{c}} - 1/2P_{\mathrm{s}} > 0$, where P_{c} is the capillary pressure of liquid, and $1/2P_{\mathrm{s}}$ is the saturated vapor reaction pressure. MHD pressure loss and hydrostatic pressure loss are negligible in our case. Relation $\Delta P > 0$ means that there is a pressure difference in the system that pulls liquid towards evaporating surface. Comparison of these factors for our targets is illustrated in Fig. 7 where capillary pressure is $P_{\mathrm{c}} = 2\sigma/R$, $R =$

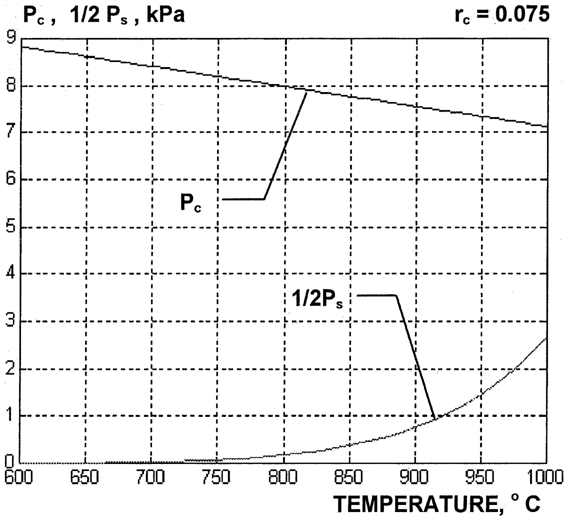

Fig. 7. Target capillary pressure and saturated vapor reaction factor.

$r/\cos\theta$. It is seen that the pressure difference is rather high in the working temperature range and the target should be serviceable.

It was shown in the study that liquid lithium structure successfully withstands rather high power loads in durable operation at levels needed for such reactors as ITER and for further steps. Our experiments show significant lithium flow generated by the target surface at heat fluxes interesting for reactors. At 20 $\mathrm{MW/m^2}$ lithium influx is about 6×10^{25} $\mathrm{m^{-2}\ s^{-1}}$ (0.6 $\mathrm{kg/m^2}$ s). If we take a divertor plate area for ITER-size reactor $S_d = 2\pi R\Delta \cong 5\ \mathrm{m}^2$ ($R = 8$ m, $\Delta = 0.1$ m) then total amount of lithium flowing to divertor region will be $\Gamma_{\mathrm{Li}} = 3 \times 10^{26}\ \mathrm{s}^{-1}$. Penetration of this lithium to reactor core should be limited at a certain level not to quench DT reactions. 1D calculations of tolerable Li impurity level in the core and of Li flux through separatrix [8] show that the limit Li flux from SOL to the core achieves 6×10^{20} $\mathrm{m^{-2}\ s^{-1}}$ for the above reactor dimensions (lithium ion concentration in the core may be more than 13%). This means that total flow through separatrix area $S_{\mathrm{sep}} = 40aRk = 1.5 \times 10^3\ \mathrm{m}^2$ is $\Gamma_{\mathrm{sep}} = 9 \times 10^{23}\ \mathrm{s}^{-1}$. This acceptable value is much lower than the above lithium flow to divertor and reduction factor should be $\Gamma_{\mathrm{Li}}/\Gamma_{\mathrm{sep}} = 3 \times 10^2$. Therefore, operation of the reactor would be possible if injected lithium is efficiently removed in the divertor region. 2D calculation modeling [9] has shown that lithium concentration falls considerably upstream in the SOL from the divertor volume towards X-point and the symmetry plane so that maximal Li^{+3} concentration there is about 10^{10} cm^{-3} thus giving reduction of lithium density from divertor plate to symmetry plane high enough to meet the above Γ_{sep} value. Lithium ions and neutrals escaping the SOL are readily condensed at the walls at temperatures not higher than 350°C. Liquid lithium capillary structures could be also used for this purpose.

5. Conclusion

Liquid lithium capillary target has been investigated under high power electron beam load in steady-state on linear magnetic simulator machine SPRUT-4 for divertor application in the range 1–50 $\mathrm{MW/m^2}$. Evaporation of lithium from the target was found to be essential and it was evaluated experimentally on the basis of mass and heat balance analysis. Durable operation of so formed liquid lithium surface under heat load was realized.

Temperature field in the target has been closely studied. Stabilization of thermal conditions was achieved by water cooling of the target. Capillary structure was shown to have good capacity to support heat loads in the chosen range.

Plasma generation in front of the target was investigated. Lithium plasma was found not to play an important role in energy balance at the experimental conditions.

The results of the study show that if CPS is taken for lithium divertor development, then considerable lithium influx to divertor region will be generated. This puts the problem of the influence on the tokamak main plasma parameters. Application of capillary structures for the receiving plates should be considered as integrated along with condensing wall structures.

References

[1] P. Schiller, Tokamak Concept Innovations, IAEA-TEC-DOC-373, Vienna, IAEA, 1986.
[2] I.R. Kirillov, E.V. Muraviev, Fus. Technol. 1 (1996) 251.
[3] M.A. Abdou, APEX Team, Fus. Eng. Des. 45 (1999) 145.
[4] V.I. Pistunovich et al., J. Nucl. Mater. 233–237 (1996) 650.
[5] N.V. Antonov et al., J. Nucl. Mater. 241–243 (1997) 1190.
[6] V.A. Evtikhin et al. in: Proceedings of the 17th IAEA Fusion Energy Conference, Paper IAEA-CN- 69/FTP/27, 1998.
[7] N.V. Antonov et al., Fus. Energy 3 (1996) 651.
[8] V.I. Pistunovich, D.Yu. Prokhorov, Plasma Phys. Rep. 25 (5), Translated from Fizika Plasmy 25 (5) 476.
[9] Pistunovich et al. J. Nucl. Mater. 248 (1997) 85.