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Post-test examination of a Li-Ta heat pipe exposed to H plasma in Magnum PSI

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ABSTRACT

The authors exposed a radiatively cooled, Li-filled tantalum (Ta) heat pipe (HP) to a H plasma in Magnum PSI continuously for ˜2 h. We kept the overall heat load on the inclined HP constant and varied the tilt to give peak heat fluxes of ˜7.5–13 MW/m^2. The peak temperature reached ˜1250 °C. This paper describes the post-test analysis and discusses Li HPs with materials other than Ta for fusion. A companion paper describes the experiment.

1. Introduction

A heat pipe (HP) transports heat from its evaporator to its condenser. The choices of liquids and jacket materials enable a wide range of operating temperatures and uses. Lithium (Li) has the highest performance at temperatures of 1000–1400 °C and requires refractory metals.

We believe work HPs for fusion is incomplete. This motivated an experiment to expose a high-performance (Li) HP to a hydrogen plasma and magnetic field. Our objective was a low-cost experiment to generate interest and investment to further develop HPs for fusion, and this has happened. The work is a collaboration by Sandia National Laboratories, Aavid-Thermacore Inc. (ATI), the Culham Centre for Fusion Energy (CCFE) and the Dutch Institute for Fundamental Energy Research (DIFFER). As an expedient start, Sandia purchased an existing Tantalum (Ta) Li HP from ATI, who retrofitted a high performance porous sintered niobium (Nb) wick. Fig. 1 shows the HP. Table 1 gives details.

A companion paper [1] has details of the test, photos, and background about HPs and their constraints, e.g., liquid metal magnetohydrodynamics [2] acts like a drag force on the return flow of liquid metal from the condenser to the evaporator. Another paper describes the near infra-red thermography (NIRT) measurements [3].

The paper's last sections continue our discussion of HP applications. This includes the array concept in Ref [1] with the ends of the HPs heated and HPs heated on the side (as in this test) as well as our strategy for future R&D.

The Li leak that ended the test was not unexpected. Ta is not a likely choice for fusion applications. The discussion recommends materials for further R&D. The next sections describe the leak and our post-test analysis.

2. Experiment

We exposed this HP to fusion relevant conditions (H plasma in a magnetic field) in DIFFER's linear plasma source Magnum PSI [4,5]. We kept the overall heat load on the inclined HP constant for ˜2 h and varied the tilt to get peak heat fluxes > 10 MW m^2. At the 30° tilt, the HP operated at ˜1250 °C peak in the saddle-shaped heated zone on the tubular wall of the HP and ˜1000 °C in the condenser's highly radiating zone. The plasma was steady throughout the test, but the power profiles were narrower than originally anticipated [1]. The NIRT indicated a hot

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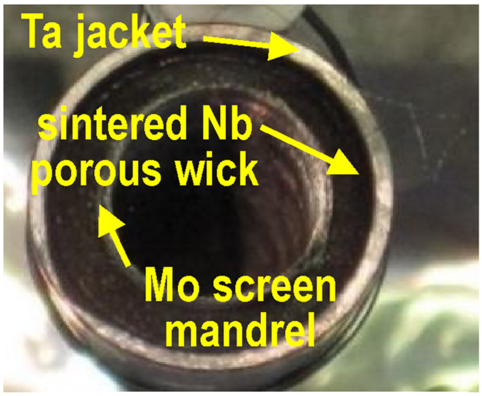

Fig. 1. Li-Ta HP before end cap weld.

Table 1
Ta/Li heat pipe construction.

Component	Material	Dimensions
Jacket, pebble-milled surface	Ta	OD ID L (mm) 17 15.6 197 0.7 emissivity
Sintered wick	Nb particles	ID 0.088-0.25 mm 55% porosity
Screen	Mo mesh	0.15 mm grid
End caps	C-103 Nb alloy	6mm thick
Fill tube	Nb (1%Zr)	
Working fluid	Li	˜5g

spot close to the location where the axis of the H column intercepted the HP later leaked Li.

We stopped after a major Li leak occurred near that spot. A Li nodule formed (6 mm dia. ˜0.06 g) and a coating covered half of the area wetted by the beam. It was discernible in the video monitor even while the HP was radiating strongly (white hot) with the plasma present. Li then formed wing-like structures below the nodule, Li blobs trickled away from the primary leak site, thickened and then spread to form the thin dark grey coating that covered most of the prior plasma footprint on the HP. Table 2 gives the time history.

After the dark grey coating had formed, the well-resolved live image of the 2nd IR camera showed Li flow from what appeared to be a transverse crack as indicated by the curved and white arrows in Fig. 2. This light grey coating wetted an area ˜30 mm^2 and thickened with a slight bulge. The description here is a recollection of the live image. The IR camera had stopped recording before this time, and the flow was not visible in the video cam.

Fig. 2 was taken on a workbench while the HP was briefly exposed to air. The nodule and light grey coating were shiny at first. Then, slowly, oxidation began to reveal the grain boundaries, which are apparent in the images. The smaller coating also flowed over the dark grey coating. Both have closed perimeters and overlay the dark grey coating. So, we presume the same process formed these as formed the light grey coating. Adjacent to the nodule are the dark fans of a leaf-like structure.

Table 2
Leak Timetable.

0 s	plasma color changes	175	bright spots (reflections) indicate bulging (more Li)
29	very strong radiation	216	flow spreads down HP
49	oscillations on video	240	flow on video cam stops
109	nodule visible	???	light grey coating forms
130	new shape by nodule	254	tilt HP to horizontal
163	Li flows from primary leak over small area		

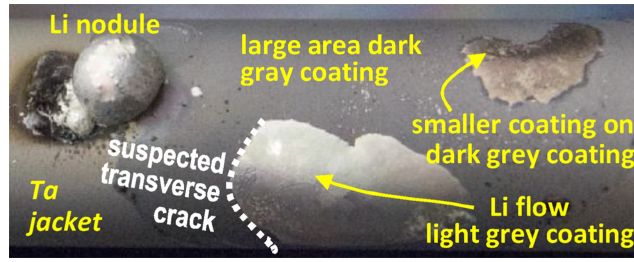

Fig. 2. Li-Ta HP just after removal from Magnum PSI.

3. Post-test analysis

After the post-test inspection, the HP was sealed in a bag with an argon atmosphere and later shipped to Sandia to examine the Ta jacket at the primary (pinhole) leak site and to verify the apparent crack. Potential failure mechanisms of interest were (1) damage or metallurgical anomalies, and (2) liquid metal or H embrittlement.

3.1. Preparation

At Sandia, the HP was cut up in an argon glove box. Fig. 3a, taken in the glove box, shows a cut piece with the Li coatings and the Li-containing wick visible. Scrapings from the Li coatings were bagged under argon for high resolution x-ray diffraction analysis (XRD).

Cleaning of Li can be a problem, so we give details. Li was cleaned from cut pieces with water inside a fume hood. This is a strong exothermic reaction (73.2 kJ/g).

Each cut piece was held in a cage of perforated SS to contain any ejected debris and placed in a “pickle jar” that held ˜3 liters of water. This 1-gallon plastic jar, an approved Haz-Waste container, sat in a catch basin to collect any splashed cleaning solution. The ˜15-mm-long cut portion had ˜1 g of Li. The cleaning released ˜2 liters of H_2 (1 atm) and the cleaning bath rose in temperature of by ˜13 °C (estimations). The used cleaning solution had a measured pH of 14 and required Haz-Waste disposal.

3.2. Metallographic analysis

Fig. 3b shows the pinhole failure site of the primary Li leak. Splashed and mounded material overlaid the tube surface. The mounded surfaces (at A and C, Fig. 3b) were ˜40 μ above the tube wall. The shoulder (B) of the deep hole was ˜250 μ below the tube prior surface. Material to the left of the hole had melted and cracked.

The large grains in Fig. 3c indicate recrystallization. In places a single grain spanned the Ta wall thickness.

An SEM exam of the surface under the light grey and dark grey coatings (Fig. 3d), revealed a few small holes but no large crack at the site shown in Fig. 1. The surface under the coatings was like the other side of the pipe which was had been hot but not but not exposed to plasma.

Fig. 4 shows element maps of surfaces at the primary leak site. Oxygen (O) and sodium (Na) were significant. Only a single small blob of ejected carbon (C) or a carbide was found, so C was not widespread.

3.3. X-ray diffraction (XRD) analysis of coatings

Scrapings were transferred to the XRD chamber for analysis. Fig. 5 shows XRD spectra of the nodule and coatings on the Li-Ta HP.

Strong (200) and (211) lines indicate that the nodule was metallic (amorphous) lithium. The coatings contained crystalline material. The dark grey coating was composed of LiOH and Li3N, as was the black deposit below the nodule. The latter had trace amounts of an unidentified phase. The light grey coating was predominantly LiOH. The Discussion Section explains how this coating formed.

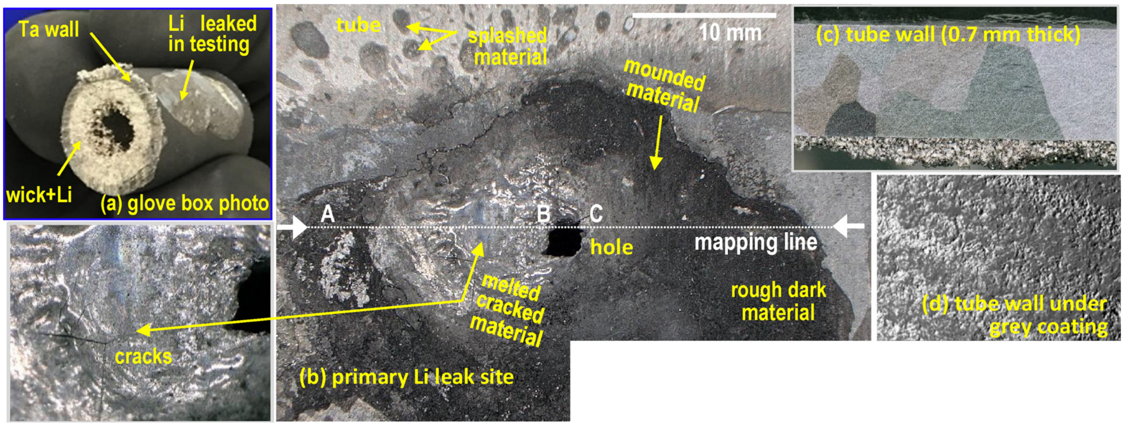

Fig. 3. (a) glove box photo, coatings, no nodule; (b) primary Li leak site, 0.2 x 0.3 mm hole; (c) Microstructure of 0.7-mm-thick Ta wall; (d) Ta tube surface under grey coatings.

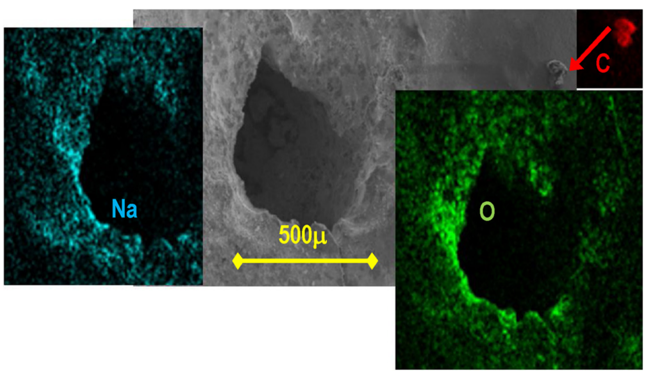

Fig. 4. SEM photo of pinhole leak site and elemental maps of surface impurities.

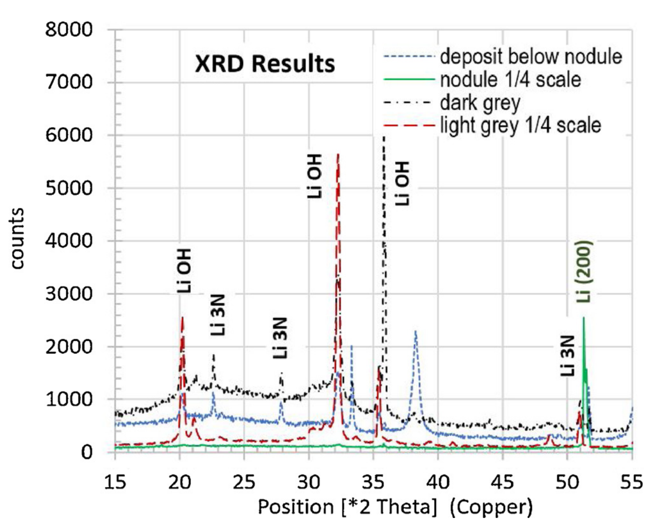

Fig. 5. XRD results for the Li nodule and coatings.

3.4. *Thermal stresses and mechanical testing*

We analysed stresses for a stress state that would promote cracking if the Ta jacket had become embrittled (our hypothesis for the presumed crack). We assumed testing to 1400 °C at ATI had annealed the Ta but produced no bending stresses (symmetrical heating) and only unrelaxed through-wall strains during cooling would leave residual stresses. In Magnum PSI, the mounting and minimal pressure difference caused no significant stress.

Heating the saddle-shape area superimposed: a biaxial compression overall, stress gradients through the heated wall, mild compression at the back (opposite the heated zone) and tension in the sides. Even within 2 h, Ta's primary creep transient at 800 °C [5] is high enough to relax these stresses. After the heating stopped, the previously heated region with stresses relaxed would shrink and go into tension, which could enable cracking.

While the stress state for possible crack formation was confirmed, no cracks were found, and neither H nor Li embrittled the Ta. Also, a longitudinal sliver that lay under the grey coatings was cut from the Ta wall, bent 180° into a hairpin shape and showed no visible cracking.

4. Discussion

We conclude that the Ta jacket was not embrittled, but rather that the dark grey coating was brittle and cracked. Li under the dark grey coating flowed through that crack to form the light grey coating. This is consistent with items 1–4 below. The Li flowing from an apparent crack to form the light grey coating was a compelling image.

1 The hot areas of the heat pipe were radiating, the HP was still operating and rapidly cooling the hot zone, and most of the heat pipe was below 800 °C.
2 The light grey coating formed after the HP had cooled for at least 3 min after the plasma was shut off.
3 The post-test analysis did not find additional leak sites in the Ta jacket beyond the primary leak site.
4 A coating of Li3N would solidify at 813 °C and compress during cooling since its thermal expansion is ˜2.5 times that for Ta [6,7].

Nor did we find evidence of any leak beyond the primary leak site. The following conditions made this a likely failure site: single grains spanned the wall; this site reached highest temperature; the HP contained Li3N and other impurities to promote corrosion. The following observations indicate the Li3N came from the HP, rather as a nitride formed after Magnum-PSI was vented. The coating's dark shade was evident when the light grey coating formed, and when we removed the lid from the chamber and observed the HP still under a blanket of argon. At that time, the smaller coating was still shiny.

The source of N is not clear. Some contaminants, e.g., Na, were present. The HP's complex history of being stored for 20 years and then refitted with the multiple materials for the brazed porous wick brazed and cage provide opportunity for multiple materials interactions.

In their early work on corrosion of Ta-Li HPs, Quartier and Busse found grain growth at 1600 °C, as we did. They also noted removal of any oxide and corrosion in the hot zone related to formation of a liquid Li-O-Y-Ta phase.

5. Future work

Porous wicks that transport liquid Li back to the evaporator give higher performance than rails, groves or other flow channels. In future we wish to develop new Li HPs with porous wicks and materials and configurations more appropriate for fusion. Our strategy is as follows.

1 Use commercially available high temperature jacket materials that can provide a long operating life and that ATI can load and seal.
2 Develop a simpler porous wick. Explore options for Additive Manufacturing and electrical insulation.
3 Demonstrate HP operation at 1.5 kW and 2.5 T in the upgraded Magnum-PSI; improve the test diagnostics.
4 Use a water-cooled sleeve to collect heat radiated from the condenser.
5 Operate a HP in a high power long pulse tokamak.

5.1. Heat pipe materials

Their high performance along with the temperature range for operation is why Li is the likely working fluid for HPs in PF-Cs. Many DEMO designs specify tungsten (W) as the plasma facing material in the divertor, as does ITER. Li and W are compatible. However, Li heat pipes maximize their heat transport when the evaporator operates > 1400 °C where pure W would recrystallize.

In our next step, we must balance high performance above 1400 °C against the jacket's resistance to recyrstallization and degradation. To avoid a materials R&D project with new W-based materials, we are looking at commercial materials, such as grain-stabilized W-Re alloys. Another option is the Nb alloy C103 used in aerospace applications. ATI can apply a silicide coating that hermetically seals the surface and has made a large non-circular C103 HP by AM.

5.2. HP configurations

Liquid metal HPs can transport high heat loads very effectively without the complication of direct contact of liquid Li by the plasma. Many approaches are possible. Fig. 6 shows a HP array proposed in Ref [1]. The HPs radiate heat to the loose-fitting sleeve of a secondary heat sink. This concept may enable simpler remote maintenance since the heat sink and HP have no mechanical bond to sever.

While the local heat removal can be quite high, the averaged surface heat load and thermal stresses determine the effectiveness of the HPs. For the evaporator area projected on the surface of the array in Fig. 6, an aerial fraction of 40% is reasonable after allowing for clearance between the HP heads, etc. So, without including radiation losses from the head, the heat flux where evaporation occurs will be ˜2.5 times the array's average heat flux, and the edge-to-center temperature gradient in the top of the HP will be a significant source of thermal stresses.

The side of the HP can also be the collector surface, as in our DIFFER test. Imagine a divertor with an array of fingers (e.g., WEST or ITER), each being the flattened wall of a loop[2] HP. The flattened wall would maximize the surface contacting the plasma. Rounded rather than square corners would reduce the stresses. The estimated aerial evaporator fraction in this configuration is ˜65%.

HPs can transport heat (vapor) over long distances and curved paths. A sleeve-array could be far from the heated area, and its cross-sectional shape can change along this path to the accommodate design needs in the application. Also, the condenser should not contact the sleeve. A lower condenser temperature reduces the HP's performance.

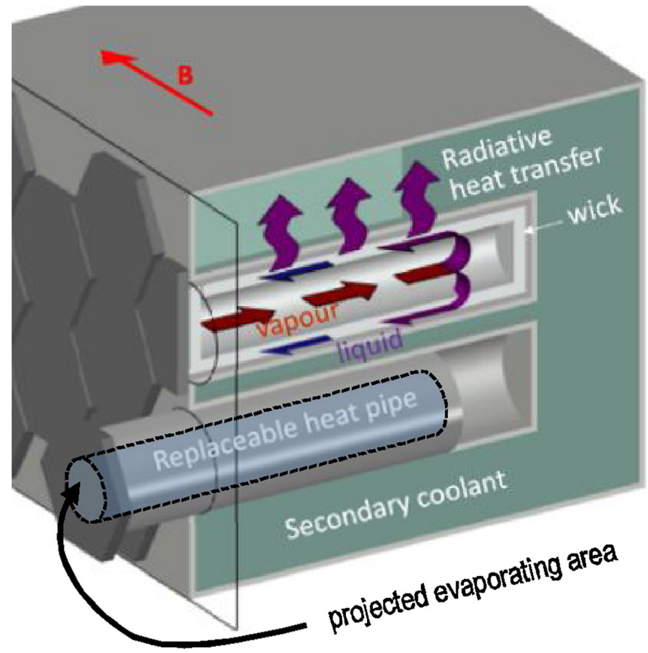

Fig. 6. HP with condenser radiating inside sleeve [Ref. 1].

5.3. Heat pipe capabilities

The heat loads in our test were modest compared to the capability of Li HPs. ATI performance curves show input power of ˜2800 kW at 1400 °C for an emissivity of 0.5. In this regime the HP is nearly isothermal and radiates strongly along its entire length. The HP in our DIFFER test received about ¼ this power and only the center region radiated strongly.

Radiatively coupled HPs (e.g., condenser-in-sleeve) eliminate a joined vacuum boundary with a secondary heat exchanger. This is very attractive for remote maintenance, particularly for divertors and other special components that need interim replacement, e.g., shielding for RF launching structures.

5.4. Concluding comments

We developed the DIFFER experiment because we believe the exploration of HPs for fusion is incomplete. Liquid metal HPs can transport high heat loads very effectively without the complication of direct plasma contact with liquid Li. Many configurations are possible. These include designs in which radiative heat transfer from HPs to loose fitting sleeves of heat sinks without any mechanical attachment to the HPs may simplify remote maintenance.

HP technology also has its constraints. Liquid metal magneto-hydrodynamics act like a drag force on the return flow of liquid metal from the condenser to the evaporator [3,8]. Our strategy includes testing at higher fields in a long pulse fusion experiment to evaluate the magnitude of these effects.

The challenge of developing fusion includes advancements in fusion nuclear technology. Power exhaust and the tritium breeding cycle are two important areas where much work is needed, particularly where innovations can simplify or improve fusion designs. We believe HPs may provide useful innovations for fusion and merit further study. We plan to continue our investigations as funding permits.

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