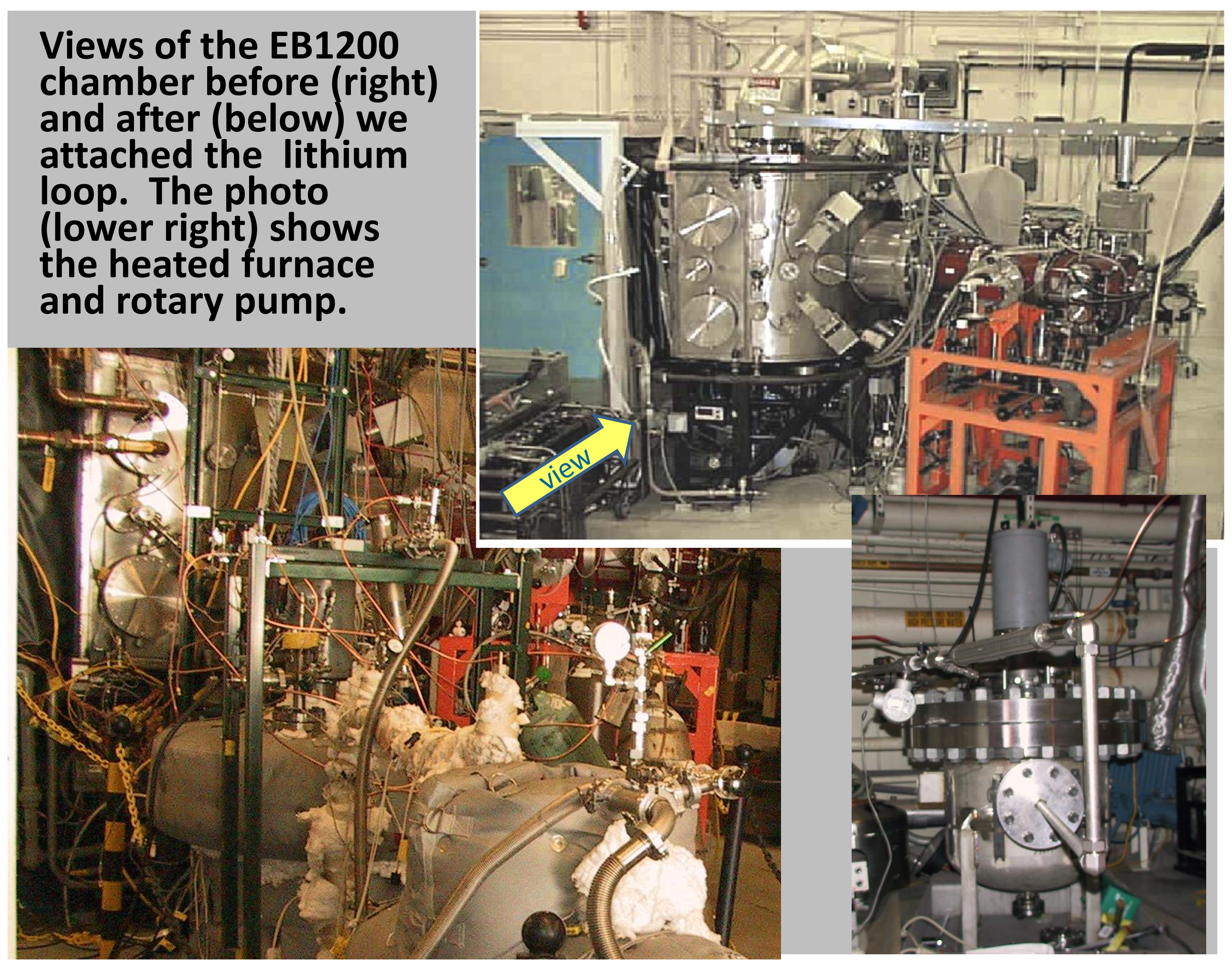
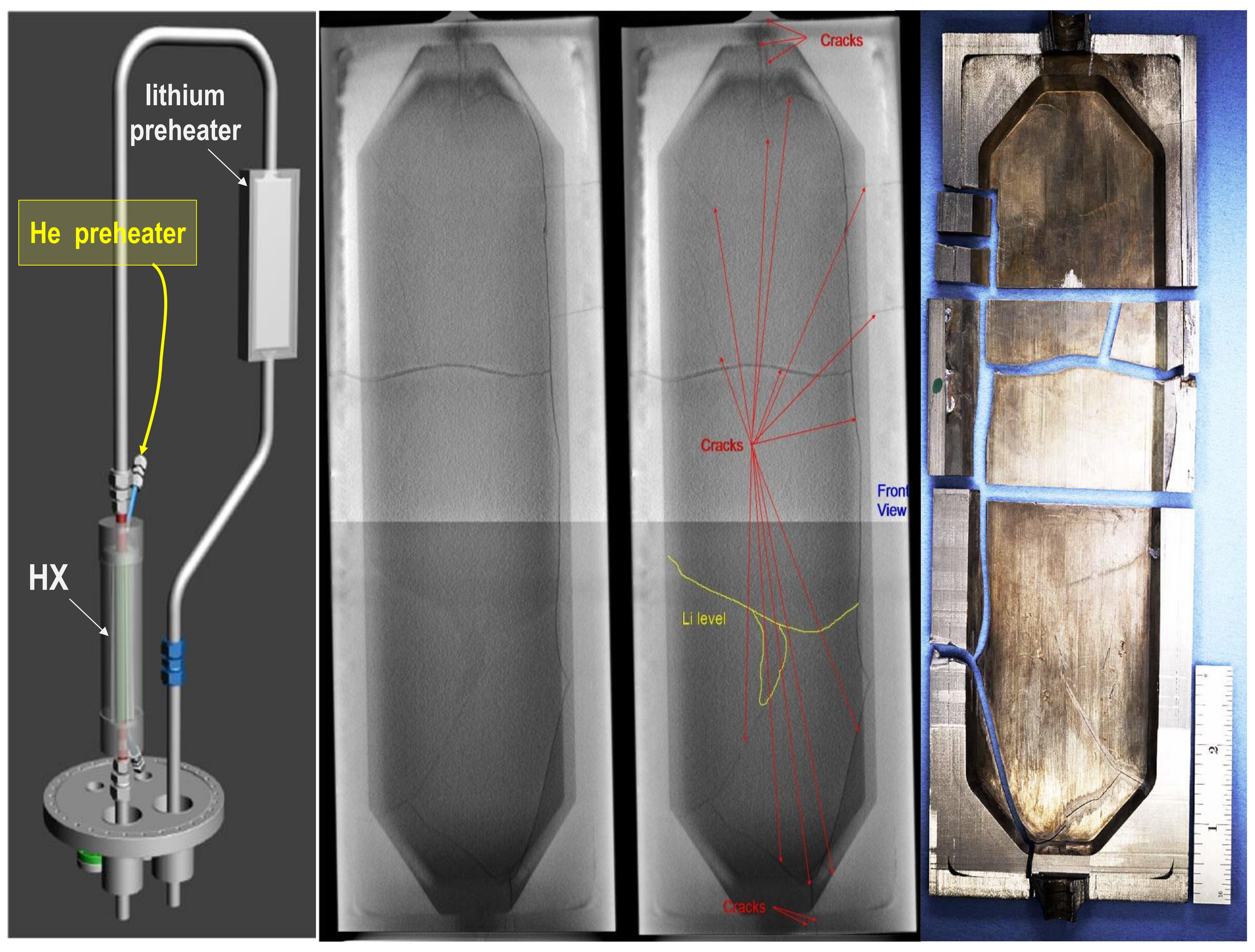
SAND2014-18086D

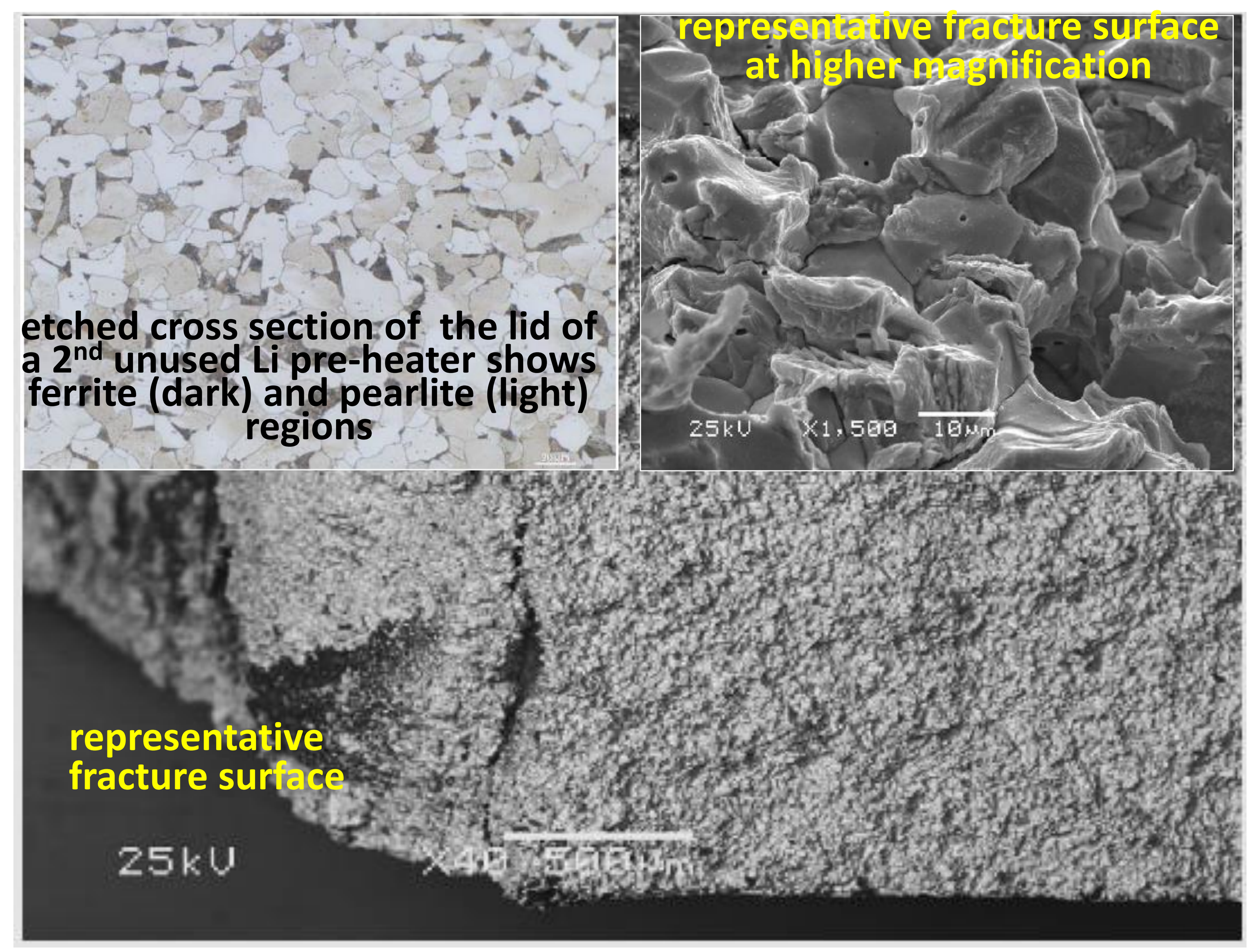
Exceptional service in the national interest

Sandia National Laboratories



Views of the EB1200 chamber before (right) and after (below) we attached the lithium loop. The photo (lower right) shows the heated furnace and rotary pump.





SOFT Poster
P4.151

Failure of a Lithium-filled Target and Some Implications for Fusion Components

R.E. Nygren, D.L. Youchison, J. R. Michael, J. D. Puskar, T.J. Lutz
Sandia National Laboratories, Albuquerque, New Mexico, USA

As we prepared to test a Li-He heat exchanger, and before we used the electron beams or pressurized the He system, an operator introduced Li at ~400°C, and ~18-20 psi above the chamber vacuum, prematurely into the 1018 steel Li preheater then at only ~200°C. The preheater failed only a few seconds after the Li contacted the previously empty preheater . It then spewed Li into the chamber. We attribute the failure to liquid metal embrittlement. The paper analyzes the preheater and discusses some implications for fusion.

Experimental Arrangement

The CAD drawing (left, center figure) shows part of the test hardware and a flange on the bottom of the vacuum chamber of our large electron beam EB1200 plus the Li preheater and neutron radiographs made before sectioning for metallographic examination.

Ultramet, Inc made the Li-He heat exchanger (HX) and preheater* for testing at Sandia to measure its performance with various flow conditions of Li and He using EB1200's dual electron beams for separate preheating of the He and Li streams. Electrical trace heating on the Li preheater and Li piping was in place to heat them above the melting point of Li to the temperature of the liquid lithium in the adjacent Li loop.

*DOE Small Business Technology Transfer Grant (see www. http://science.energy.gov/sbir/)

Material

The preheater was made of two 1018 steel plates and iron tubes welded in each end that connected to coolant channels machined into the thicker bottom plate. The closure weld was around the perimeter of the thinner top plate.

Metallographic and elemental analyses confirmed the materials were as specified, i.e., 0.15-0.20 C, 0.6-0.9 Mn, 0.15–0.30 Si and bal Fe (wt%) and the microstructure contained the expected ferrite and pearlite regions. (See figure.) The hardness values of the pre-heater body, which averaged 86 HRB for the case and 91 HRB for the lid, indicate the material was in cold rolled or formed.

Literature on Lithium Containment

Initially we had expected mild steels to provide appropriate containment. Many published studies have focused on corrosion or dissolution of mild or ferritic steels by flowing liquid Li, and literature on LME of steels has many examples. But collectively the conclusions and recommendations are by no means uniform and clear.

As we continued, we noticed that for us the more interesting papers were not our primary references (this paper*) and those noted in the search engines we consulted, but rather those cited as references or those in the second level of references.

*primary references
P. J. L. Fernandes et al., Failure by liquid metal induced embrittlement, *Eng. Failure Analysis,* 1 (1994) 51-63.
D. L. Olson, D. K. Matlock, The essential chemical and physical properties of ferrous alloys needed for the containment of liquid lithium, *Energy*, 3 (1978) 315-323.
H. C. Meyer, Some practical aspects of handling lithium metal, Handling and Uses of Alkali Metals, Ch2, 1957.
A. Kimura et al., Ferritic steel-blanket systems integration R&D-compatibility assessment, FED 81 (2006) 909-16
O. K. Chopra and P. F. Tortorelli, Compatibility of materials for use in liquid-metal blankets of fusion reactors, *Journal of Nuclear Materials*, 122-123 (1984) 1201-12.
R. C. Anderson, Investigation of a lithium electrolytic cell failure, Oak Ridge, 1977
G. Nicaise, A. Legris, J.B. Vogt, J. Foct, Embrittlement of the martensitic steel 91 tested in liquid lead, JNM 296 (2001) 256-64
A. Legris, G. Nicaise, J.B. Vogt, J. Foct, Liquid metal embrittlement of the martensitic steel 91: influence of the chemical composition of the liquid metal. Experiments and electronic structure calculations, JNM 301 (2002) 70-76
H. Glasbrenner, F. Groschel, T. Kirchner, Tensile tests on MANET II steel in circulating Pb-Bi eutectic, JNM 318 (2003) 333-8

Liquid Metal Embrittlement

The major points in this paper are:

- Unexpected rapid brittle failure occurred in a mild steel (with ferritic structure) exposed to liquid Li;
- We attribute the failure to LME (liquid metal embrittlement). In LME, stress enables wetting and separation at the crack tip that results in rapid crack growth at comparatively low stress.
- We (fusioneers) need to understand where LME can occur. Here are some basic considerations.
  - The stresses for crack propagation can be significantly below the yield for the material.
  - The wetting and reduction in ductility needed to start a crack can enable it to grow rapidly.
  - If minor constituents on grain boundaries or in the liquid metal are important in the chemistry of wetting, the situation is more complicated.
  - In many configurations, as a crack grows the stress intensity at the crack tip increases as the load redistributes in the remaining X-section.
  - How will degradation due to neutrons, corrosion, etc. affect the potential for LME.

Understanding LME is challenging because in part it depends on environmental factors, e.g., wetting at the crack tip, the chemistry that can promote this and the stress state in this location.

For our case, we believe thermal stresses arising from the temperature difference between the Li at ~400°C and preheater initially at ~200°C, plus any residual stresses from fabrication, and adequate wetting by Li, were sufficient to promote LME.

Our further purposes with this paper are:

- Recommend study of LME for Li and Pb-Li systems in the R&D on materials for PFCs and blankets.
- Increase awareness* of issues for safe Li handling.

* R. Nygren has started an informal international working group on this topic**. Please contact him for details. renygre@sandia.gov

** activity noted in G. Mazzatelli et al., Summary of the 3rd International Symposium on Lithium Application in Fusion, Nuclear Fusion (2014, to be published)

Fracture Surfaces

The macroscopic features of the fracture surfaces (rather flat surface and no shear lips, larger micrograph above) indicate a large reduction in ductility in the 1018 steel. The micrograph at higher magnification shows the intergranular nature of the fracture.

Observations of cracks – ductile/brittle

In typical ductile tensile failures, the fracture follows zones within the grains where the material has started to pull apart on a fine scale in an array of micro-voids that coalesce. The dimpled features in the resulting surface show local ductile movement of material. (In typical fatigue cracks, striations mark the crack extension on each step.)

In contrast, the fracture surfaces of the failed Li preheater (where not obscured by reaction products) exhibited intergranular failure, i.e., the fracture path followed grain boundaries and seldom propagated into the interior of grains. Whereas in typical 1018 failures, the fracture surfaces are more ductile in appearance and more deformation is observed.

In brittle failure of the type observed for the lithium preheater, the crack growth proceeds primarily along the surfaces of grain boundaries, and a pattern of chevron-like features indicates the direction of the crack growth.

Perspectives

We had experience with liquid Li. We had moved hot Li from transfer casks, charged our Li loop, and shot a stream of Li in vacuum through a strong magnetic field that simulated the divertor of NSTX.

For the experiment with the Li-He heat exchanger, we considered many possible failure modes but did not regard either the rapid failure of the preheater due to LME nor the formation of strong Li jets from very fine cracks and the combination of these as even remotely likely possibilities.

However, history now demonstrates these outcomes were indeed possible and had potential impact with HIGH CONSEQUENCE. Although no one was injured in this event, there was the potential for serious injury from the energetic deflagration triggered by the preheater failure.

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
SAND No. 2011-XXXXP