Presentation at PFC Group Annual Meeting
20-22 June 2012 - PPPL

Status Report on
Sandia Plasma Materials Test Facility (PMTF) and Actions after Li Fire on 26 Aug 2011

Richard Nygren and 01658 Team
Sandia National Laboratories, Albuquerque, New Mexico, USA

- **Overview of PMTF and Li Fire**
- **Comments on Lessons Being Learned**
- **Current status**
- **Approach for lithium safety awareness** *(separate presentation)*

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.

Magnetic Fusion at Sandia

Collaborations with Japan, China, Korea, India

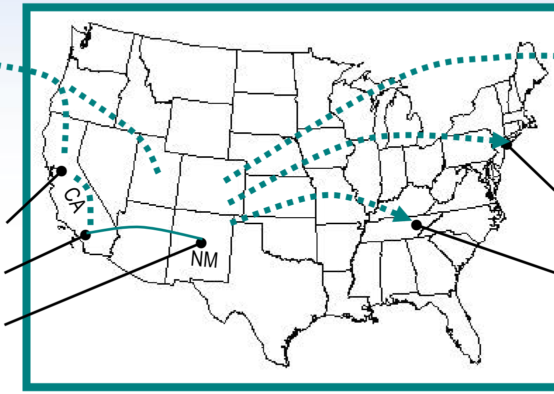
IPO, CEA France

Other EU collaborations

Livermore

La Jolla

Albuquerque



NSTX, PPPL

IP-ORNL

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California Lab.

- **Physical & Eng. Sci.**
  - **Analytical Mat. Sci.**
    Tom Felter, Mgr.
    - PSI experiments
    - DiMES collaborations
    - joining metallurgy
    - DIII-D Edge Probes
    - Jon Watkins - @DIII-D

Livermore, CA

Science & Technology

- **Phys., Chem. & Nano Sci.**
  - **Rad.-Solid Int.**
    Ion Beam Lab (IBL)
    Jon Buester
    - PSI experiments
    - PSI collaborations
- **Pulsed Power "Z" *(ICF)***
  - **Fusion Technology**
    Larry Schneider, Acting Mgr.
    - ITER FW R&D/Design
    - NSTX Liquid Li Divertor
    - **Other:** W armor, He-cooled PFCs
    - Jon Watkins

Albuquerque, NM

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Overview of PMTF and Li Fire

high visibility – potential for injury

NNSA (site & HQ/Safety), DOE (FES, SC, Safety, Enforcement)

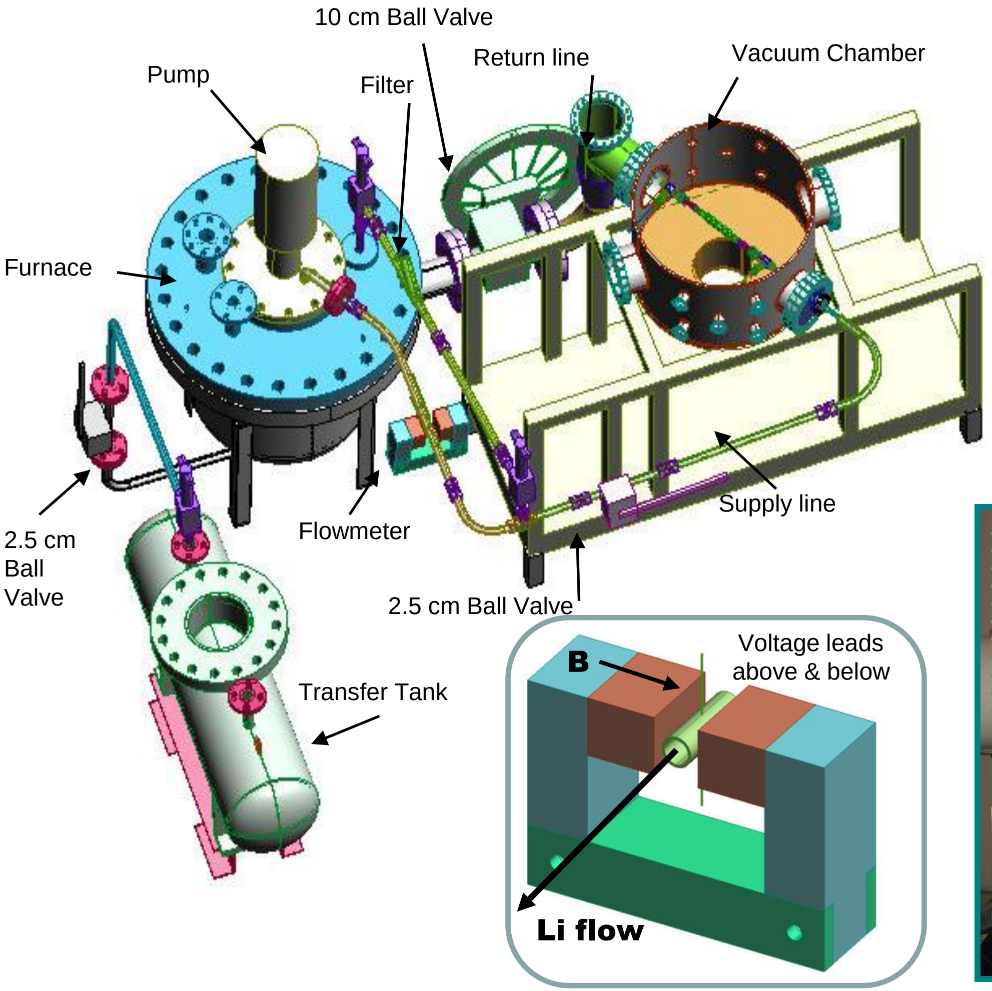
Sequence after fire on August 26, 2011

- PMTF isolated; access limited.
  Li-related work halted. EB1200 chamber interior still not cleaned.
- VP formed Accident Investigation Team; report issued. (Dec.)
- Separate SNL team investigated and prepared Occurrence Report and Corrective Action Plan (released in March).
- Sandia extensively identified activities needed for safe future operation and prepared plan (cost/schedule) for recovery of PMTF.
- FES decided to support SNL program but not fund PMTF. (April)
- Sandia is reviewing possibilities to operate PMTF as a Sandia, rather than FES, facility.
  "Work-for-others" business model is very difficult without major sponsor.

LIMITS Layout for first use in 2003

LIMITS is a lithium loop in the Plasma Materials Test Facility at Sandia.

The sketch below shows LIMITS configured to test a Li jet flowing across a vacuum chamber previously used with our small e-beam.



- lithium furnace (kettle) with rotary pump
- heated piping
- heated transfer casks
- nozzle and flow collector (for the NSTX test)

We use an argon glove box to transfer Li in an inert atmosphere.

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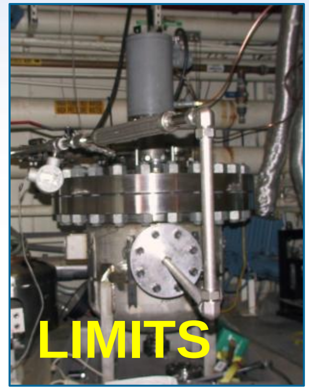
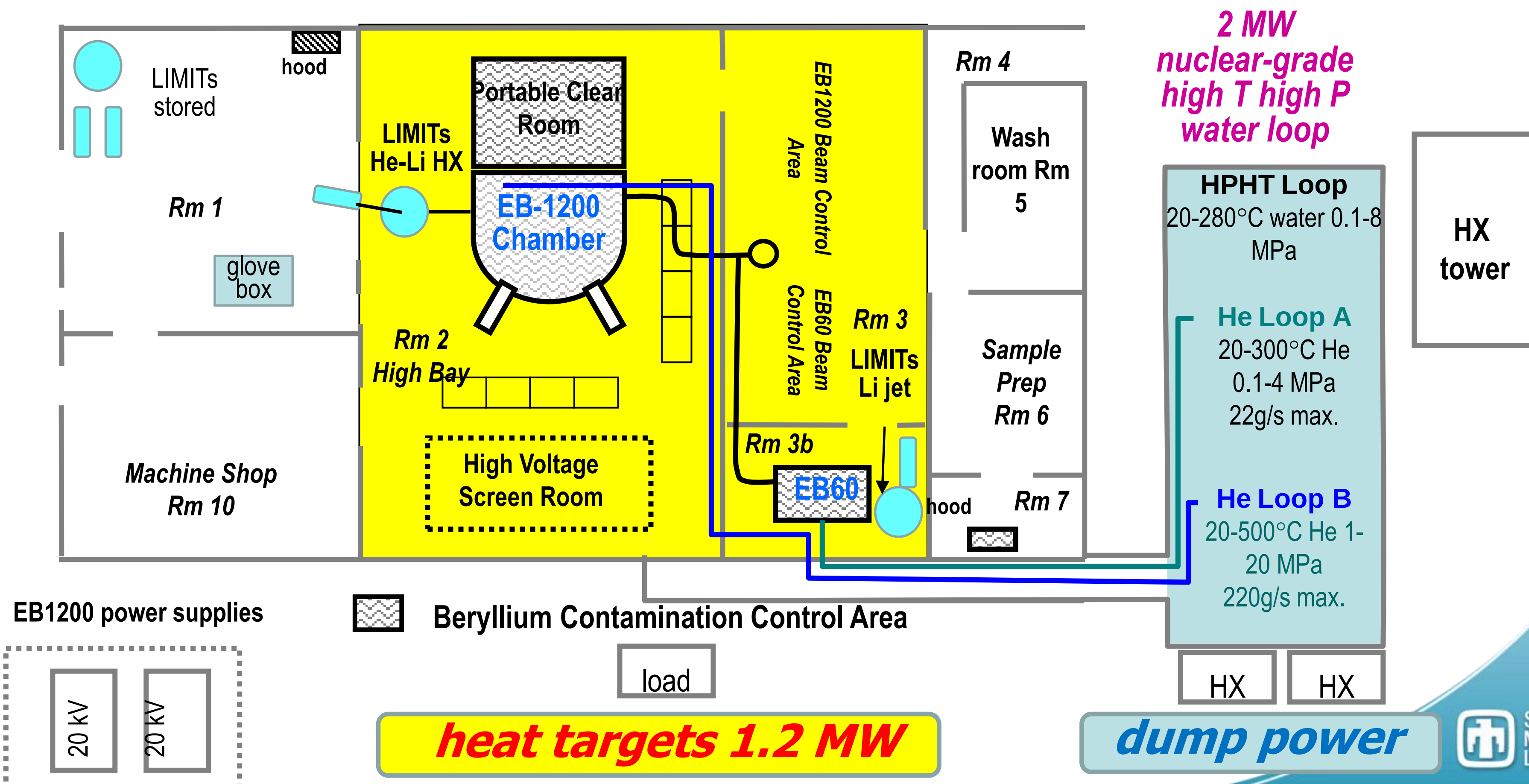
PMTF Layout
(Plasma Materials Test Facility)

Locations of LIMITS for various experiments

- furnace with pump
- transfer tank



Bldg 6530



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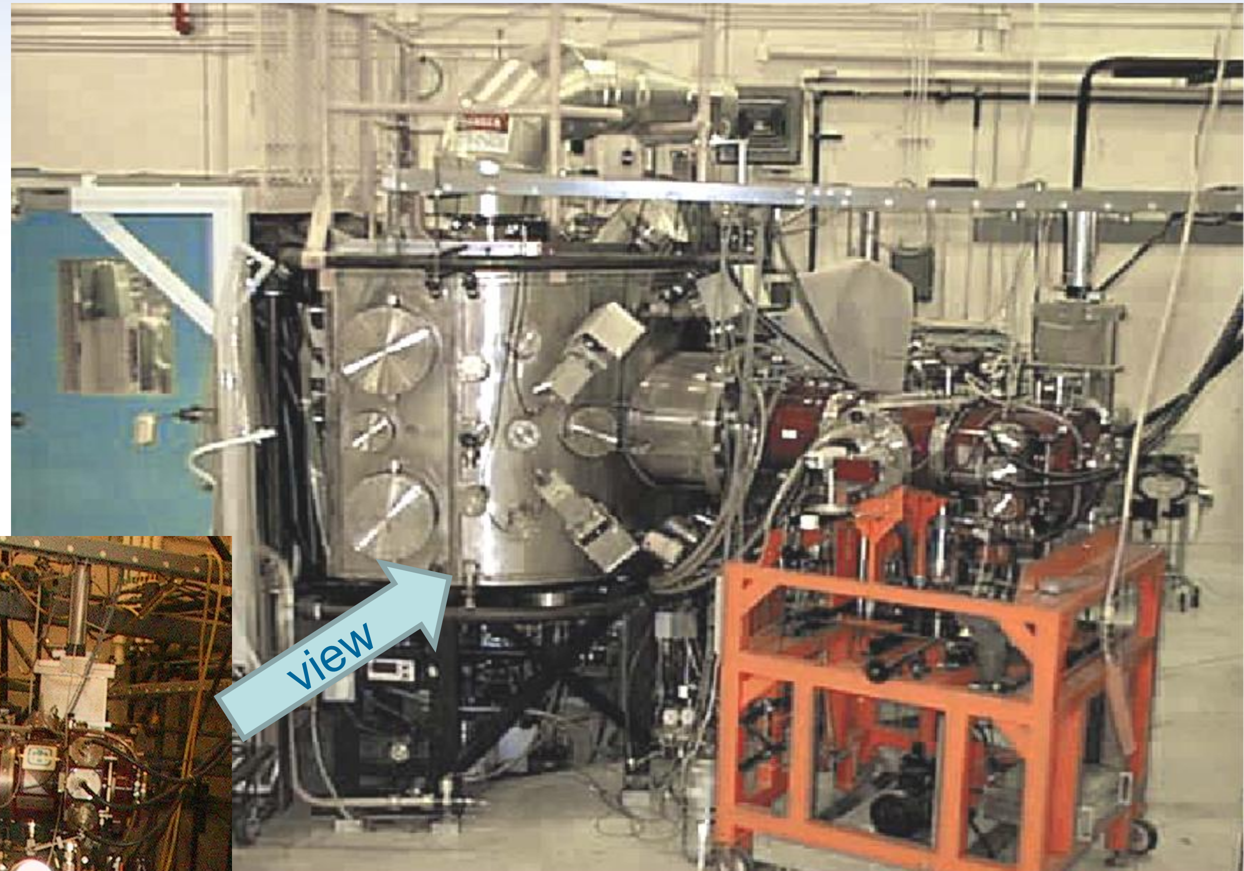
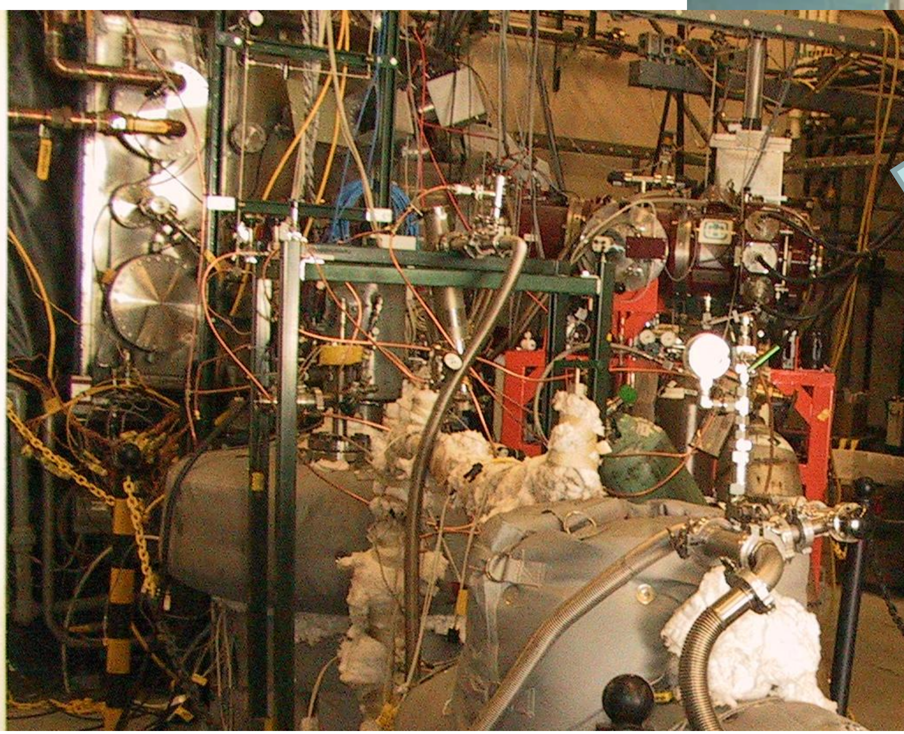
EB1200 Chamber & Beam Line 2

prior to setup with LIMITS (below)

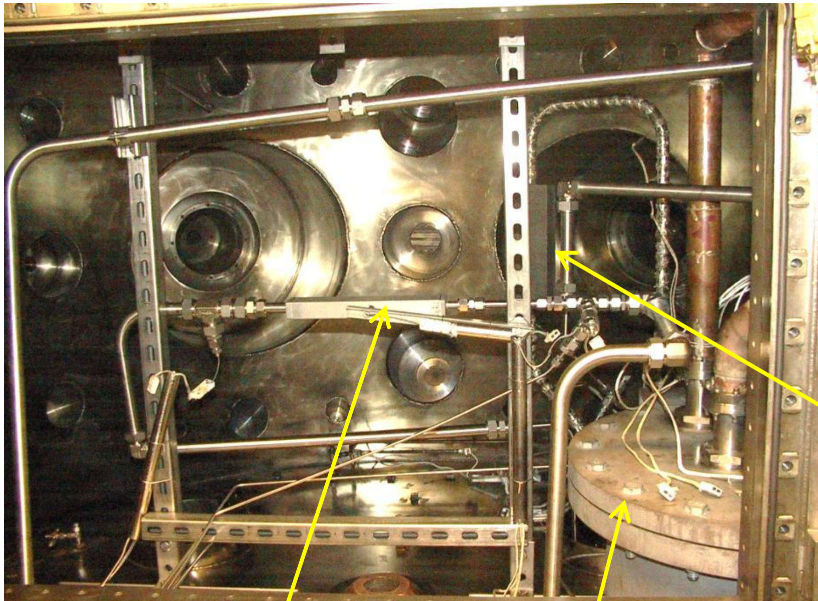


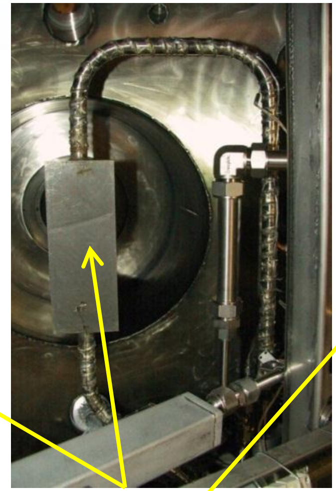


View over LIMITS with chamber (left) and beam line 2 in background

Setup in EB1200 for Li-He HX Experiment

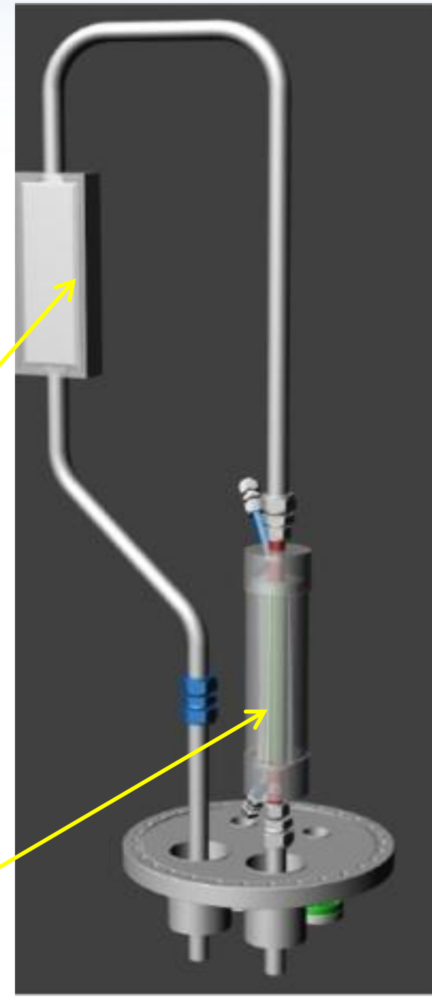
Installation photos from door of EB1200





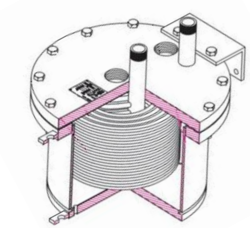
Li preheater

Li-He HX, Mo, obscured by clamp heaters



Lithium portion of test assembly

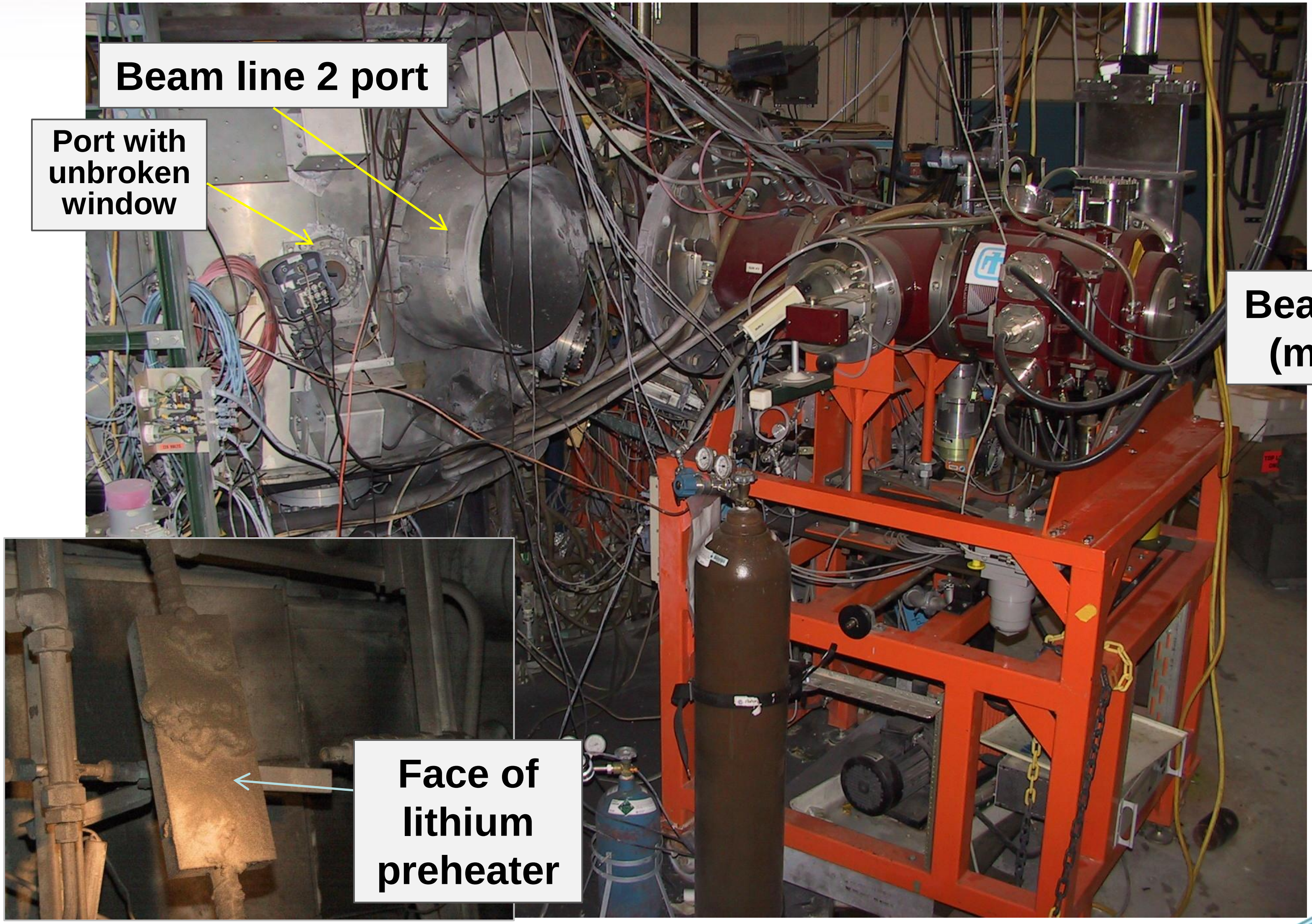
He preheater



He-water HX (cooler)

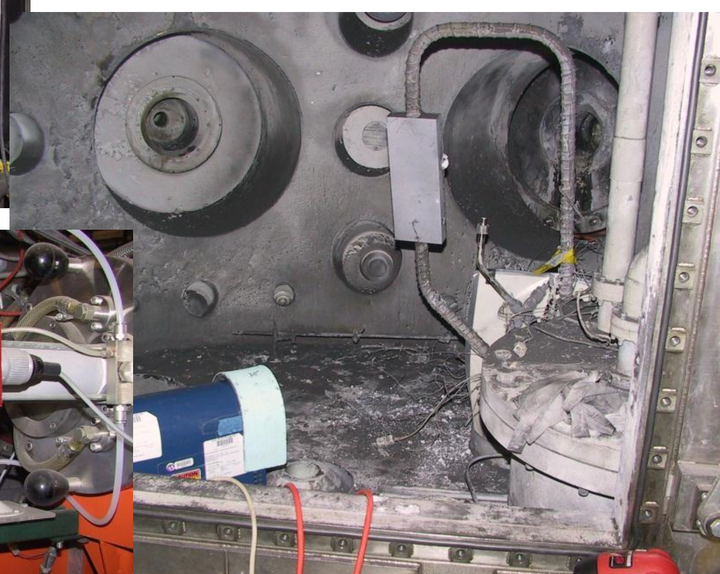
Beam Line 2 Displaced After Fire

Flange separated from port wall.



Li preheater & Li-He HX – radiograph/remove

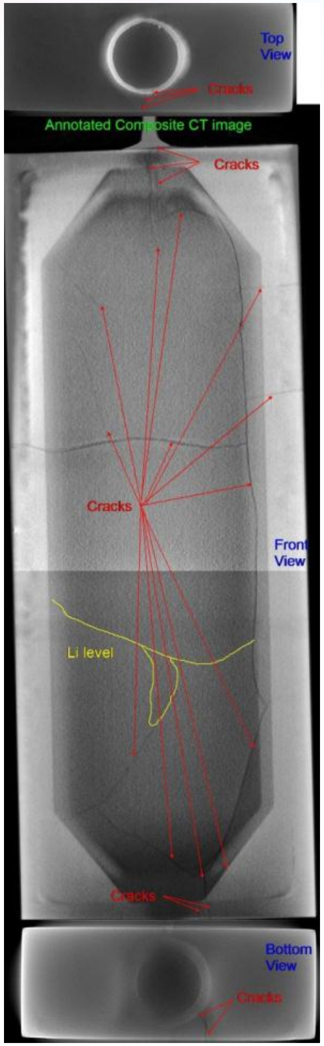
EB1200 chamber

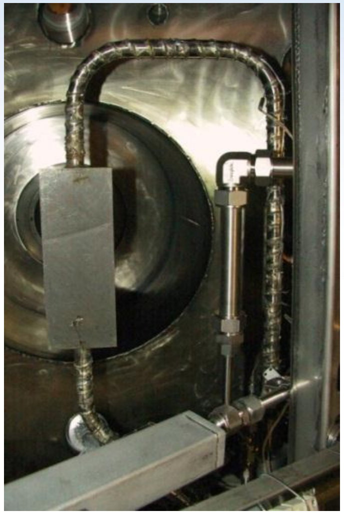


Li-He HX

Li pre-heater

Evaluation of Li preheater





- **Failure sequence** (conclusions from evaluation)
  - During pre-test checkout prior to e-beam operation, differential gas pressure (<u>LIMITS pump off</u>) moved Li at ~400°C from LIMITS into the Li preheater which was at ~200°C which induced some thermal stress.
  - The 1018 steel cover plate 6-mm thick cracked rapidly (seconds) due to <u>stress-induced</u> liquid metal embrittlement.
  - Li at ~8-12 psia streamed into the EB1200 chamber and reached the alumina insulator in beam 2.
  - Molten Li attacked the alumina (exothermic). Holes or cracks released water and propylene glycol that cause further exothermic reaction, produced hydrogen and the fire.
- **Evidence**
  - Radiography showed numerous cracks.
  - SEM examination showed brittle fracture patterns with strong directional features for crack propagation.

Overview of PMTF and Li Fire
Status of Sandia HHF Program

Sandia FES-funded program overall

- Activities continue with Ion Beam Lab (Wampler).
- Activities continue with CA Group (Watkins, Buchenauer, Kolasinksi +).

Sandia activities in Fusion Technology Dept.

- Dennis Youchison and Mike Ulrickson continue in their activities for ITER and work with SBIRs (without testing in FY2012).
- Larry Schneider is Acting Manager. Richard Nygren stepped down (April) and continues in programmatic role and as a senior researcher.
- Sandia is evaluating options for continued use of PMTF as Sandia (Work-for-Others) facility outside of FES base program.

We will explore <u>new roles</u> in collaborative efforts to use and share our expertise in experimental programs.

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We have experience with liquid Li.

2nd International Symposium on Lithium Applications for Fusion Devices

Observations on the LIMITs Lithium Furnace and Rotary Pump

Jimmie M. McDonald, T. J. Lutz and R.E Nygren

[1]Sandia National Laboratories*, Albuquerque, New Mexico, USA

Abstract: LIMITs is a lithium loop in the Plasma Materials Test Facility at Sandia National Laboratories. The full system comprises a lithium furnace, heated piping, heated transfer casks, and an argon glove box for transferring lithium in an inert atmosphere. Lithium was pumped using a mechanical impellor and housing at the bottom of the furnace rather than an external mechanical or an electro-magnetic pump. The impellor received from the vendor of the LIMITS furnace did not work, and Sandia rebuilt the impellor to make LIMITS operational. Sandia used LIMITs initially for flow experiments to support the studies of a flowing lithium wall module in NSTX and later for high heat flux experiments with lithium-cooled targets. During this operation, we had some concerns that the impellor on the pump (or its housing) had suffered some damage, but had to mothball the loop four years ago. We recently reopened the furnace to clean and inspect the components. This paper describes our experience in cleaning and dismantling this system and the observations on the pump and other hardware.

FED 72 (2004) 83-92

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

Liquid metal integrated test system (LIMITS)

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Available online 12 September 2004

Abstract

This paper describes the liquid metal integrated test system (LIMITS) at Sandia National Laboratories[1]. This system was designed to study the flow of molten metals and salts in a vacuum as a preliminary study for flowing liquid surfaces inside of magnetic fusion reactors. The system consists of a heated furnace with attached centrifugal pump, a vacuum chamber, and a transfer chamber for storage and addition of fresh material. Diagnostics include an electromagnetic flow meter, a high temperature pressure transducer, and an electronic level meter. Many ports in the vacuum chamber allow testing the thermal behavior of the flowing liquids heated with an electron beam or study of the effect of a magnetic field on motion of the liquid. Some preliminary tests have been performed to determine the effect of a static magnetic field on stream flow from a nozzle.

We have experience with liquid Li.

Loading Lithium

We remove lithium ingots from their containers and load them into a transfer cask in our in our argon glove box. The glove box has a small crane to assist the operator in lifting and placing the top flange cover on the cask.

The cask, under argon cover gas, is then connected to the furnace and LIMITS piping and the system is evacuated. The lithium in the transfer cask is melted and transferred to the hot furnace by gas pressure.

Lithium Fires

One of our "lessons learned" occurred after we had inadvertently left in place a copper gasket that had been used in leak testing the system. With the system hot, lithium dissolved a portion of the copper gasket, leaked into the insulation and caused a small lithium fire.

With our lab staff, the planning and procedures included Lithex on hand for fire suppression and related training of our lab staff. However, we learned that the site-wide emergency response scenarios were geared for fires and radiation, but their preparation had not included training for lithium fires.

Our event resulted in extended training with site response personnel at an outdoor burn pad used for fire suppression training Sandia.

We performed and filmed a demonstration of the correct techniques for suppression as well as the effects of incorrect procedures such as use of water or CO_2. This film was presented at PPPL at the ALPS meeting in November 2002 and also shared with others.

Valve after fire with Li and Lithex and insulation stripped.

We also worked with the site response team to increase the understanding of the response needed for a lithium fire, which includes how the fire itself is suppressed, equipment shut down, personnel evacuated and examined for exposure to vapor, etc.

We now require an independent safety inspection by a technical person no involved in performing the experiment. Their concern is only safety with out regard to the experimental schedule.

We here acknowledge Tina Tanaka-Martin and Ken Troncosa, both now retired from Sandia, who were instrumental in the development and operation of LIMITS, and also Mike Ulrickson, who was then manager of the Fusion Technologies Department and initiated the lithium experimental program at Sandia as part of APEX with the lithium jet experiment shown in this poster as the initial objective .

T.J. Tanaka, F.J. Bauer, T.J. Lutz, J.M. McDonald, R.E. Nygren, K.P. Troncosa, M.A. Ulrickson, D.L. Youchison, Liquid metal integrated test system (LIMITS), Fusion Eng. Des. 72 (1–3) (2004) 223–244.

J.M. McDonald, T.J. Lutz, D.L. Youchison, F.J. Bauer, K.P. Troncosa, R.E. Nygren, The Sandia Plasma

From "LIMITs Experience" poster at 2nd Int. Workshop on Lithium Applications, PPPL, Apr 2011

But the Li fire happened.
What were some contributing factors?
More in the presentation on
Li Safety Awareness

Overview of Issues:
Lithium Safety Awareness

Larry Schneider, Richard Nygren and 01658 Team
Sandia National Laboratories, Albuquerque, New Mexico, USA

1. Incident (Li Fire) on 26 Aug 2011 and Investigation
2. Experience and complacency
3. Defense in depth – engineered safety
4. Some specific issues with lithium

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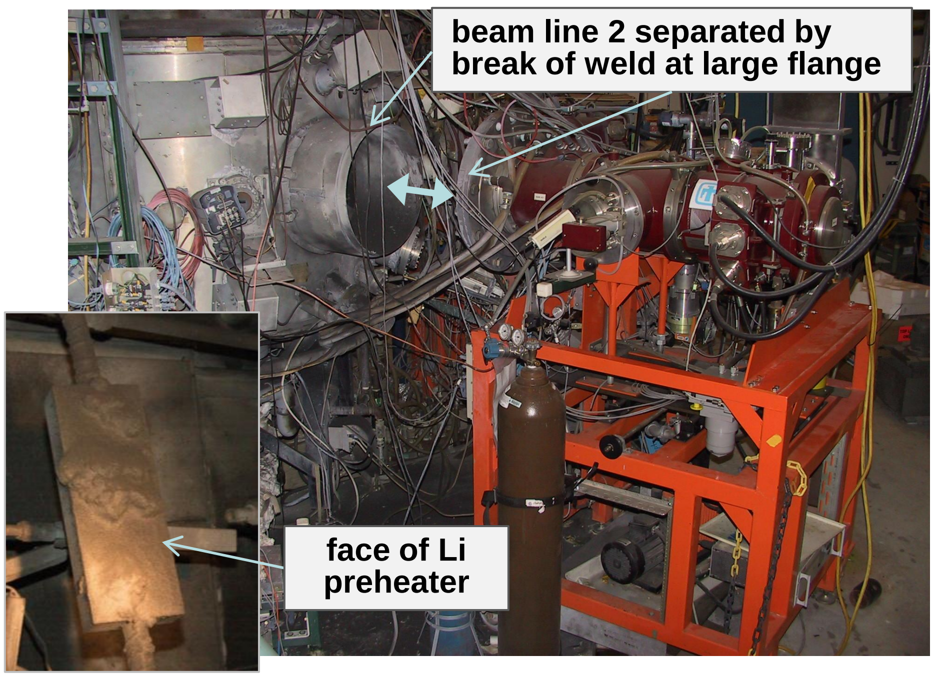
Incident (Li Fire) Aug 2011, Investigation

Plasma Materials Test Facility (PMTF) Area-III

- **PMTF - high heat flux testing**
  - *60 kW & 1.2 MW e-beams, high-bay*
  - *water, He and Li cooled targets in vacuum*
- **Flowing Li tests, 2002, 2005, 2011**
  - *LIMITs lithium loop with heating, rotary pump*
  - *2011 test of He-Li heat exchanger, 1st time in EB1200*
  - *water & propylene glycol cooling of beam line, vessel and some internal components*
- **Dynamic shock from Li fireball**



- **Very high visibility (DOE Secretary)**
  Investigation, Corrective Actions, Office of Enforcement
- **No serious injury (but potential)**
- **Problematic work documents**
- **Material failure**
  - *1018 steel (recommended in literature)*
  - *failed rapidly, low system pressure (~8 psi)*
  - *thermal stress + liquid metal embrittlement*
- **Design failure**
  - *Low probability accident, high consequence*
  - *Many reasons this would not happen:*
    - *low pressure system*
    - *Li tends to self-plug*
    - *Li has relatively low thermal mass (ρC_p)*
    - *Expectation: freeze (cold surfaces)*
    - *Improbable path for Li into beam line*
  - *Wrong safety basis (He overpressure)*

⇨ ***Lack of defense-in-depth (safety)***

Defense in Depth: Safety is a Design Requirement

Sandia Investigation for Corrective Actions - items

- Lithium Safety Awareness Briefing
- Engineering Management Plan

Engineered Safety Approach (PMTF restart process)

safety basis, analysis, engineering, mitigation, design reviews

- **Define Lab Manager and PI responsibilities (people/roles)**
- **Define "Unacceptable Consequences" definition (Des. Req.)**
- **Develop Engineered Safety Matrix (analysis tool, Des. Reviews)**
- **Others …**

Drill down further

- **Define failure modes**
- **Define analysis requirements**
- **Define controls (engr. & admin.)**
- **Others …**
- **…**
- **Confirm subsystem performance**
- **Design Reviews**

Who - Primary

- Manager & Lab Manager - clear roles & requirements
- Lab staff – detailed knowledge of specific subsystems
- Analytical support – e.g., model of stress on vessels

Who – Secondary

- New "eyes" who know about similar systems
- SME's on safety and operations

How

- Evaluate potential failure modes with attention to:
  - aggregated hazards
  - modes that trigger multiple failures
  - high impact events
- Evaluate consequences
- Develop mitigation
- More …

Lithium Safety Awareness:
Some Issues for Lithium Handling

Basic 1: Very reactive liquid metal; exothermic reaction with water; reacts with C & N; attacks many materials, e.g., dissolves Cu gaskets

Basic 2: Handle in clean vacuum or inert environment, etc.

Basic 3: Pump Li in heated systems with heated piping; plugging arises from contamination and cold spots (flanges = thermal mass)

Basic 4: We clean Li from parts by immersion in a water tank outdoors. This produces H_2 (flammable), vapor (staff may be sensitive), and hazardous waste (water with pH of 14, $$$ for disposal).

Cleaning in-situ is also possible slowly with water or iso-propanol and appropriate PPE. Vinegar is another cleaning agent. It reacts to give non-caustic solution (used at PPPL).

Careful: A literature search confirmed 1018 steel as a good choice, e.g., applications with vats of molten lithium and some where 1018 separated Li from water. A more detailed search, several layers below primary references, found the potential for <u>rapid liquid metal embrittlement</u> under <u>thermal stress</u> (some data classified).

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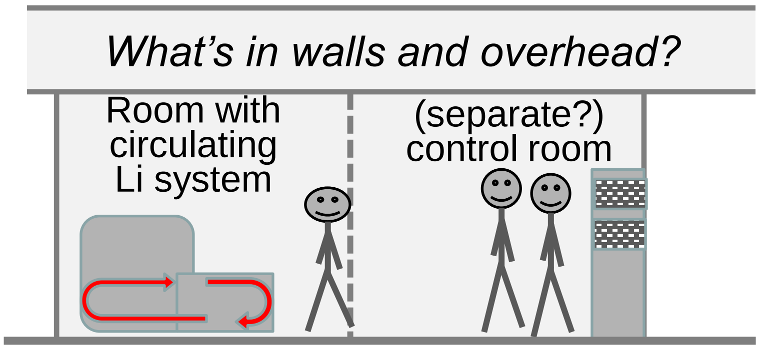
Lithium Safety Awareness:

Lithium is implicit with fusion technology.
FES needs a Li Safety Awareness Program.
Sandia and PPPL are discussing such a program.

Starting Point (consider requirements/implications):
Design a lab with Li flowing for days rather than just minutes.

What system?
- Vac vessel, pump, room …

Who can run it?
- Students
- Technologists
- Minimum number of staff
- Unmanned at night?



What is the safety basis?
- Unacceptable consequences: serious injury, damage level for equipment, ..
- Responsibilities
- Design evaluations and review, checkout, confirmation of safety basis
- Provisions for safe unmanned shutdown in case of accident

- Compliance: National Fire Protection Agency regulations recently changed, ***NFPA 484 Standards for Combustible Metals***
- Events that trigger multiple failures
- Emergency Response
- …
- …

Thank you

E N D