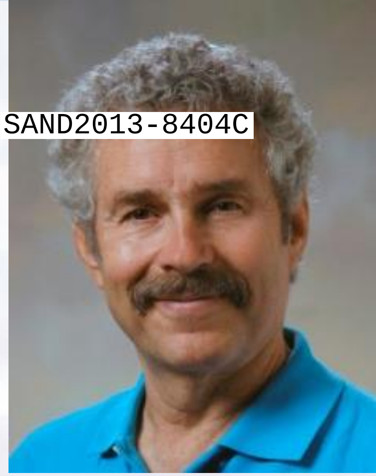
Introduction - Presenter
Richard Nygren



- **Hanford Engineering and Development Lab** — radiation damage, **LMFBRs**, fusion and FMIT*
  **Fusion Materials Test Facility, not built, precursor to IFMIF*
- **Oak Ridge Nat. Lab** — materials in Fusion Engineering Device
- **Argonne Nat. Lab** — Director, FW-Blanket-Shield Program
- **DOE/FES** — Spec. Ass't. to AD US Fusion Program
- **UCLA** — Plasma materials interactions (PISCES now at UCSD)

- **Sandia National Laboratories** (since 1989)

  Distinguished Member Technical Staff (DMTS)

  ***TEXTOR** He pumping, **Tore Supra** water-cooled pump limiter, **ITER, NSTX-U** liquid Li PFCs, **DIII-D** power handling (thermal modeling)*

  Former Manager, Fusion Technology Dept.

  High heat flux testing; water, He, liquid metal coolants; ITER R&D; Liquid Lithium Divertor for NSTX

Special Session VIII on
Lithium Safety and Handling

Richard Nygren, Organizer
Sandia National Laboratories, Albuquerque, New Mexico, USA

- **Welcome – Benvenuti in Frascati**
- **Hello - Ciao bella**
  [no, I do not speak Italian but my mother-in-law is a paisan.]
- **Introduction**
  - Agenda
- **Presentations on Li Safety and Awareness by Nygren and by Dr. Eichi Wakai**

We need to handle Li and Li alloys safely.

R&D on Li PFCs and Pb-Li blankets is increasing.

US: R&D with Li free surfaces (open to vacuum) or with Pb-Li

- **PPPL**
  - **System for EAST/HT-7 by Zakharov***
  - **Injection of liquid Li into CDX-U: stir Li in LTX with e-beam (Majeski*).**
  - **NSTX-U options for a Li surface replenished from a reservoir.**
  - **Circulating Li loop in lab using a clever EM pump [Jaworski* et al]**
- **University of Illinois**
  - **System for EAST/HT-7 by Ruzic and Currelli* et al.**
  - **LIMITs* (EM + thermoelectric drive)**
  - **Wetting experiments; plasma shielding**
- **UCLA Pb-Li loop**

*papers at ISLA2013

Other notes

We must consider liquid metal embrittlement or LME in Li systems and should investigate LME as an issue of potential high consequence. Pb-Li may not be as chemically active, but LME may still be a concern.

Let us not create lithium paranoia. Let us understand and clarify to others which safety hazards are specific to Li and which are more general, e.g., for dust, thin films, aerosols, etc.

Our institutions have various rules and practices. We can exchange information and help ourselves achieve a standard of "best practices."

Agenda

- **Introduction** — Richard Nygren
- **Comments on Li Safety** — Richard Nygren, Eichi Wakai
- **Forum A: Li handling in labs** — Introduction/Nygren

Panel:		
	Eichi Wakai	JAEA-IFMIF-EVEDA
	Leonid Zakharov	PPPL
	Ming-ju Ni	CAS University Beijing
	I. Lyublinski or A. Vertkov	Efremov
	Thomas Lin	ARL Penn State University

Forum B: Li in fusion experiments — Introduction/Nygren

Panel:		
	Giuseppi Mazzitelli	ENEA Frascati
	Masa Ono	PPPL
	Jiansheng Hu and J.G. Li	IPP-CAS Hefei
	Paco Tabares	CIEMAT
	A. Vertkov or Lazarev	Efremov
	Tazhibayeva	NTSC Kazahkstan

- **Formation of a work group** — Nygren

Agenda

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- **Formation of a work group** — Nygren

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 CO2. 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

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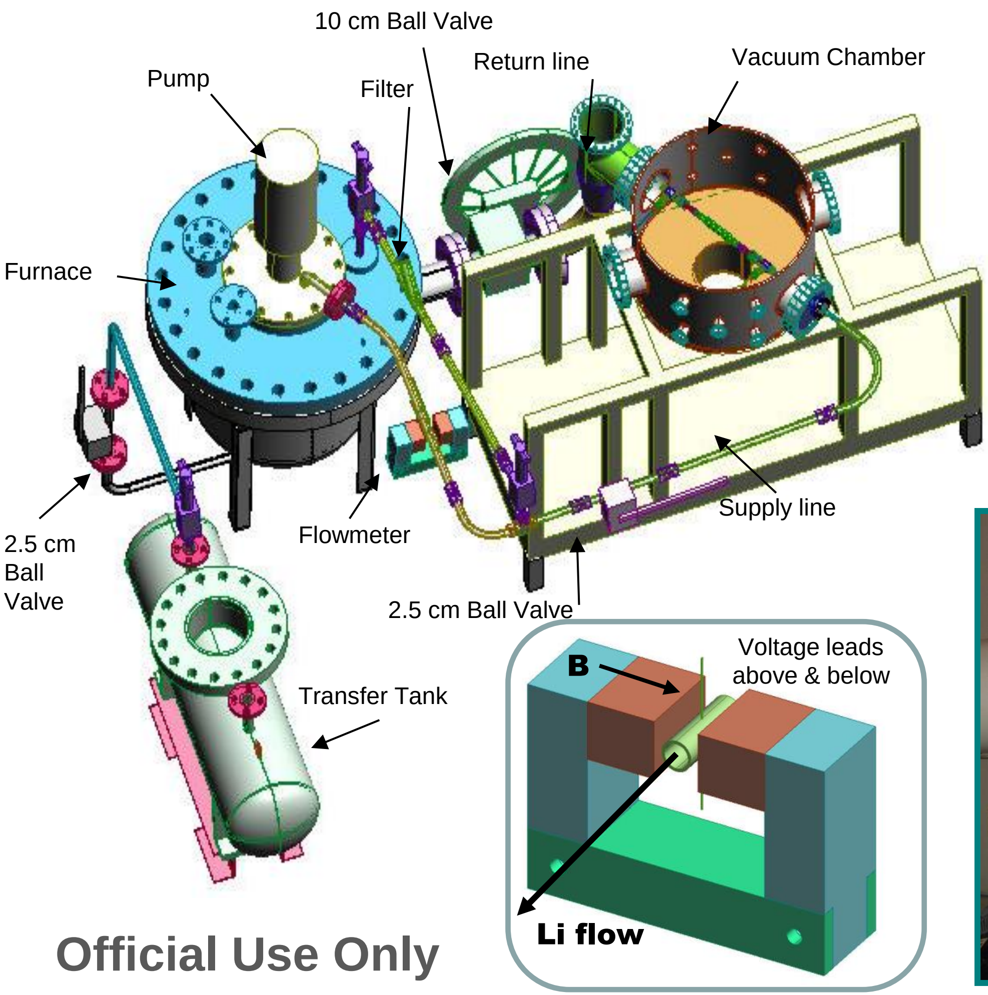
LIMITS Layout for first use in 2003

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

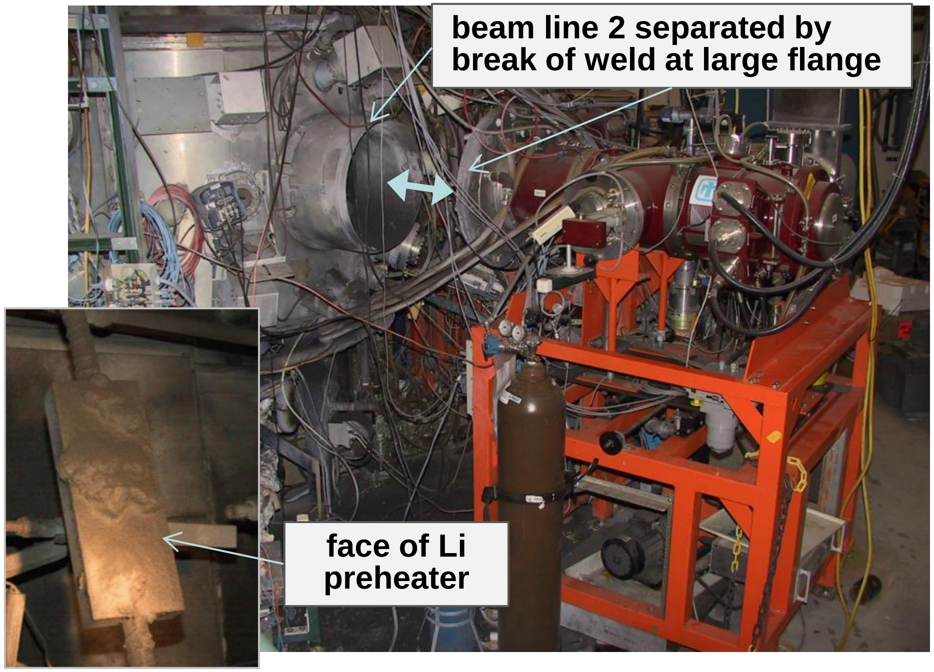
- nozzle and flow collector (for the NSTX test)

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

Official Use Only

Li Fire in Aug 2011 - Observations

- **Lab space - 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*
  - *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**

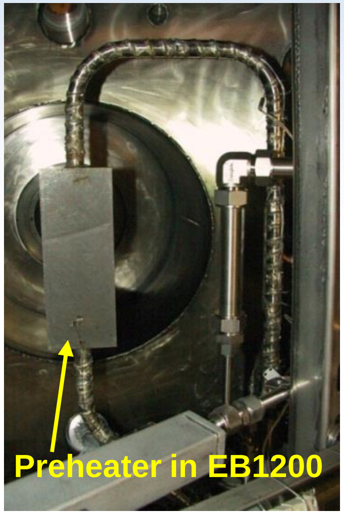


- **Very high visibility (DOE Secretary)**
  Investigation, Corrective Actions, Office of Enforcement
- **No serious injury (but potential)**
- **Problematic work documents**
- **Material failure**
  - *1018 steel (recommended in literature)*
  - *failed rapidly, low system pressure (~8 psi)*
  - *stress ⇒ 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)*

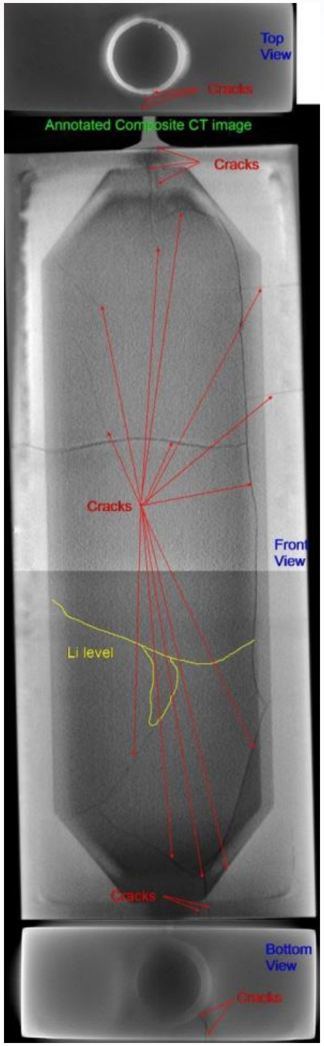
⇨ ***Lack of defense-in-depth (safety)***

****ICFRM16 paper - failure of Li preheater and some implications***

Evaluation of Li preheater



- **Failure sequence** (conclusions from evaluation)
  - During pre-test checkout prior to e-beam operation, differential gas pressure (LIMITS pump off) 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 stress-induced 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.



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But the Li fire happened.

What were some contributing factors?

What did we learn?

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Comments on Lithium Safety Awareness

From ICFRM 16 paper: Nygren et al, **Failure of a Lithium-filled Target and Some Implications for Fusion Components**

- We anticipate component failures .. test targets to failure.
- **<u>mindset</u>** .. leak .. dribble of lithium .. freeze on colder components, .. or plug itself .. rise in the pressure in the chamber .. shut down
- **<u>Surprise</u>** .. lithium squeezed through thin cracks .. streams reached the vessel wall .. up the beam line of one e-beams
- We .. considered many ..failure modes .. but ..not ..rapid failure of the preheater due to LME (liquid meal embrittlement) nor .. formation of strong lithium jets from very fine cracks and the combination of these as even remotely likely possibilities.
- *Our preparation included a literature search (next slide)*
- History now demonstrates **<u>these were indeed possible</u>** and with an **<u>impact of high consequence</u>**.
- Although no one was injured .. .. **<u>potential for serious injury</u>**

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Comments on Lithium Safety Awareness

From ICFRM 16 paper: Nygren et al, **Failure of a Lithium-filled Target and Some Implications for Fusion Components**

Literature on Lithium Containment

Initially we had expected
(a) stresses in the lithium preheater to be quite low, and
(b) that mild steels were the appropriate containment material.

Many published studies.. corrosion or dissolution of mild or ferritic steels .. literature on liquid metal embrittlement (LME) ..many examples, ..

conclusions and recommendations .. [NOT] uniform nor clear.

Below are several excerpts.

(early paper) "In general, only low-carbon steel….is desirable materials of construction for molten lithium"

many like that above, but some with notes of caution

(more recent) "Ferritic steels… Lithium: the compatibility .. good enough. The susceptibility to LME will be very high"

LME of ferritic steels and of pure Fe (Armco iron) can be extreme, large reductions in ductility can occur

from studies of long term exposure of mild steels to liquid Li, a spheroidization heat treatment that converts pearlite to carbides will reduce corrosion through the dissolution of pearlite

Comments on Lithium Safety Awareness

Defense in Depth: Safety is a Design Requirement

- **Lithium Safety Awareness Briefing**
- **Engineering Management Plan**

Engineered Safety Approach (lab start or restart)
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 …**

important detail

- **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 …

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Thank you - Our next speaker is Dr. Wakai

IFMIF/EVEDA
Lab at O-arai site
Japan Atomic Energy Agency

- **Presentations on Li Safety and Awareness** by Nygren and **by <u>Dr. Eichi Wakai (JAEA)</u>**

  Leader, IFMIF Irradiation and Test Facilities Development Group

Agenda

- **Introduction** — Richard Nygren
- **Comments on Li Safety** — Richard Nygren, Eichi Wakai
- **Forum A: Li handling in labs** — Introduction/Nygren

  Panel:

Eichi Wakai	JAEA-IFMIF-EVEDA
Leonid Zakharov	PPPL
Ming-ju Ni	CAS University Beijing
I. Lyublinski or A. Vertkov	Efremov
Thomas Lin	ARL Penn State University

- **Forum B: Li in fusion experiments** — Introduction/Nygren

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Jiansheng Hu and J.G. Li	IPP-CAS Hefei
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- **Formation of a work group** — Nygren

Forum A: Li handling in labs - Introduction

PANEL

Eichi Wakai
JAEA-IFMIF-EVEDA
previous presentation

Leonid Zakharov
PPPL

Ming-ju Ni
CAS University Beijing

Lyublinski/Vertkov
Efremov

Thomas Lin
ARL Penn State U.

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LiWall Fusion: no alternative, no other option

Leonid E. Zakharov
Princeton University, PPPL, MS-27 PO Box 451, Princeton NJ 08540
zakharov@pppl.gov

1. Introduction.
Putting aside politics and propaganda, it is clear that the present approach to fusion does not lead to "harvesting" fusion energy. Moreover it cannot even resolve the plasma physics part of the problem. Exhausted at the level of TFTR and JET, which showed fusion power but did not reach the promised $Q_{DT} = 1$, it resulted in stagnation of the program, which is now gradually falling into degradation. ITER, which is presented as a last step before putting fusion power to the grid, could very well be the last magnetic fusion experiment. Developed without having a single essential plasma physics problem solved, it cannot fulfill the claims of the fusion proponents. More likely, it will completely discredit fusion as a valuable physics idea.

BASICS OF FUSION-FISSION RESEARCH FACILITY (FFRF) AS A FUSION NEUTRON SOURCE

Leonid E. Zakharov

Princeton University, Princeton Plasma Physics Laboratory, MS-27, P.O.Box 451, Princeton, New Jersey 08543
zakharov@pppl.gov

System for EAST/HT-7 by Zakharov*

Forum A: Li handling in labs - Introduction

October 10, 2013:

Session III. Special Liquid Lithium Session: [9:00 – 10:20] [Chair: F.L. Tabarès]

9:00 – 9:30 Y. Hirooka: Hydrogen Recycling over liquid lithium under steady state plasma bombardment

9:30 – 09:50 A. B. Martin-Rojo: Studies of H retention and LiH formation in laboratory experiments

09:50 – 10:10 X. Cao: H_2 plasma interacting with lithium

PANEL

Eichi Wakai
JAEA-IFMIF-EVEDA

Leonid Zakharov
PPPL

Ming-ju Ni
CAS University Beijing

Lyublinski/Vertkov
Efremov

Thomas Lin
ARL Penn State U.

- China has a national research project on liquid lithium walls
- Safety is one of the key issues.
- Several key investigators are attendign ISLA2013
  - Dr. Xuewu CAO, Shanghai Jiaotong Univ
  - Dr. Jiansheng HU, ASIPP
  - Dr. Fujun GOU, Sichuan Univ
  - , Mingjiu

Dear Richard,

Thank you for sending me invitation letter.

In my group, three persons, Ms. Lili Tong(lltong@sjtu.edu.cn), You(youximing1989@163.com) and I will attend the special se Safety.

Best regards,

Xuewu CAO

Forum A: Li handling in labs - Introduction

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JAEA-IFMIF-EVEDA

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    - with: Ms. Lili Tong and Mr. Ximing You
  - Dr. Jiansheng HU, ASIPP
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Forum A: Li handling in labs - Introduction

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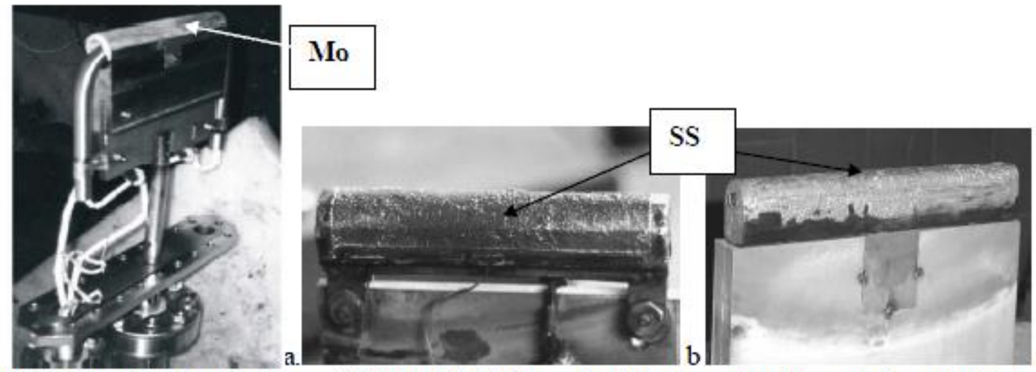

FIG. 1. Liquid lithium limiters of T-11M with CPS based on Mo (a) and stainless steel meshes(b c)

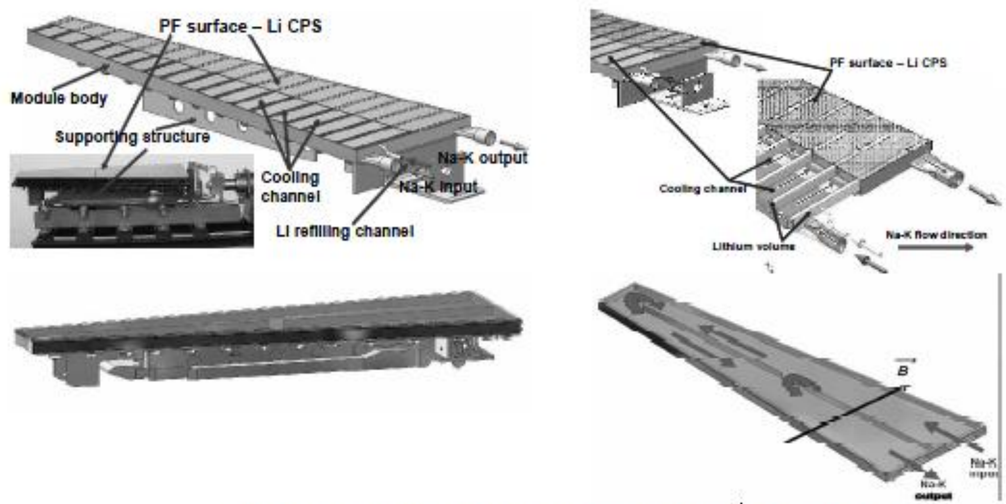

FIG. 8. Design of the lithium in-vessel element of KTM divertor

Development and Experimental Study of Lithium Based Plasma Facing Elements for Fusion Reactor Application

I.E. Lyublinski 1), A.V. Vertkov 1), V.A. Evtikhin 1), S.V. Mirnov 2), V.B. Lazarev 2), I.L. Tazhibayeva 3), G. Mazzitelli 4), M.L. Apicella 4), F. Tabares 5)

Forum A: Li handling in labs - Introduction

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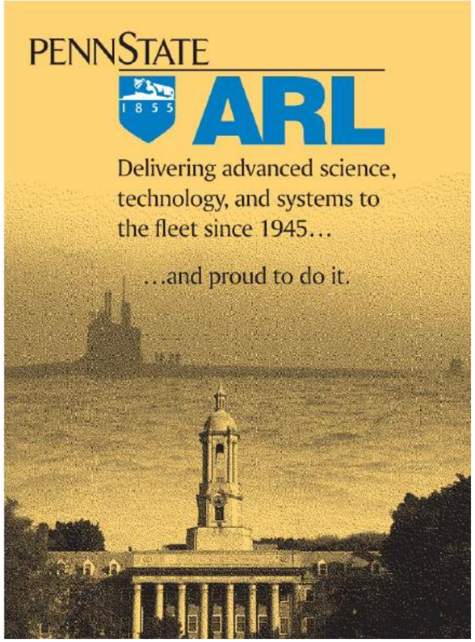
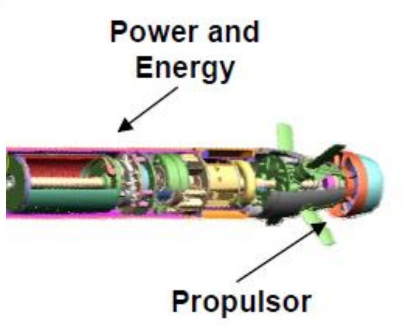


The Applied Research Laboratory is a US facility on the campus of Penn State University



ARL has a lithium loading facility in which liquid lithium flows vertically down from a delivery tank into a propulsion tank that is then sealed.

The facility is open to the atmosphere. A continuously flowing inert cover gas shrouds the area around the liquid Li.

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 can be strong irritant. Disposal cost (hazardous waste water, pH of 14) may be high.

Cleaning in-situ is also possible slowly with water or isopropanol and appropriate PPE.

Vinegar, another cleaning agent (used at PPPL) reacts to give non-caustic solution.

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Lithium Safety: Lab Setting

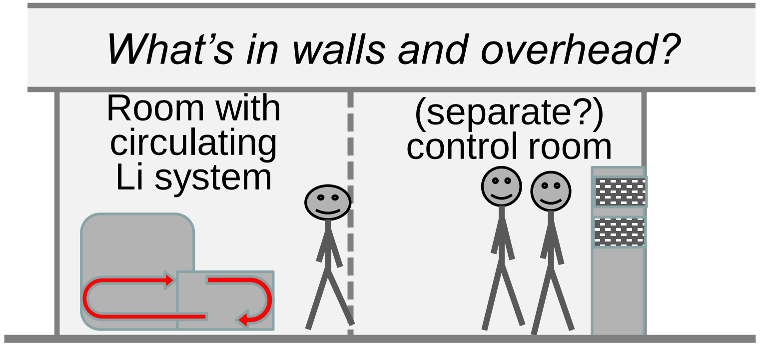
Lithium is implicit with fusion technology.

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
- …
- …

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	A. Vertkov or Lazarev	Efremov
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- **Formation of a work group** — Nygren

Forum A: Li fusion expm'ts - Introduction

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Paco Tabares
CIEMAT

Vertkov/Lazarev
Efremov

Tazhibayeva
NTSC Kazahkstan

(thanks)
Graze mille Jiansheng Hu for these questions:

What effects does Li have on human health, such as nerves? What are measures for protection?

What should the person do in the cases below?

- Li contacts skin.
- Li in vapor or powder is inhaled (lungs)?

How do we minimize circumstances that lead to fires or explosions from Li reactions?

- if there are water leak during lithium experiments?

How to avoid lithium flow out the tank or tubes due to erosion if lithium is overflowed to seals?

How to avoid lithium oxidation or other reactions, such as with N2, CO, during handling?

How to avoid pollution or damage of lithium on other instruments, such as pumps and gauges?

Which kind material is better for fire extinguisher if fire happened?

Forum A: Li fusion expm'ts - Introduction

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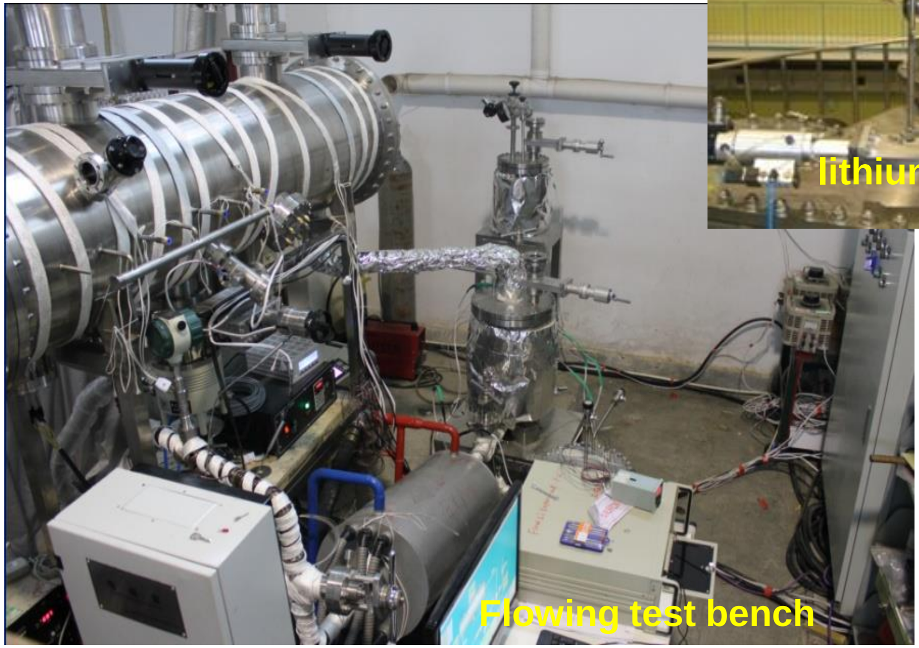
We have tested flowing Li on a test bench and HT-7, and also performed Li coating on EAST.

Lithium systems in ASIPP:

- Lithium ovens
- Lithium powder/pellet injection system
- flowing lithium test bench



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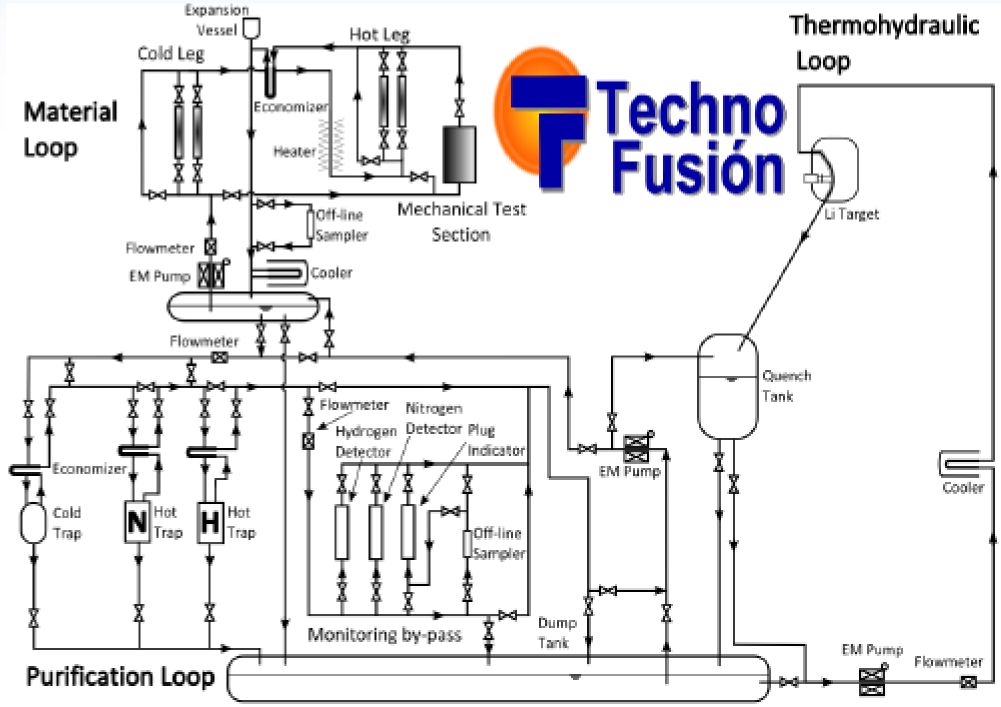

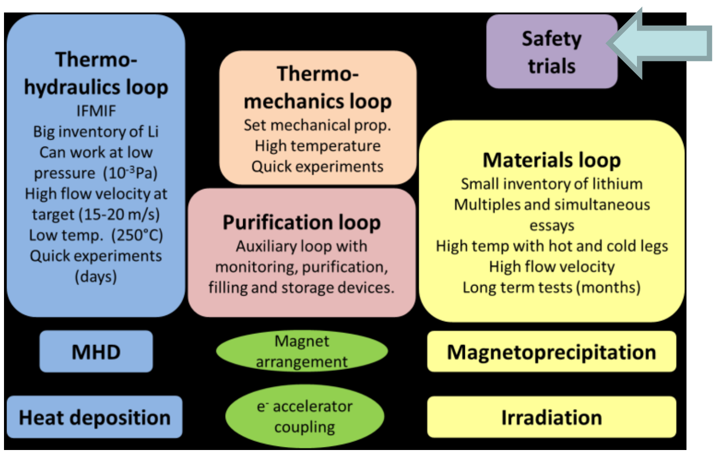

Conceptual design - Li lab, TechnoFusión project

González-del Moral, García-Sanz, Casal, Abánades

Forum A: Li fusion expm'ts - Introduction

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Efremov

Tazhibayeva
NTSC Kazahkstan

Forum A: Li fusion expm'ts - Introduction

PANEL

Giuseppi Mazzitelli
ENEA Frascati

Masa Ono
PPPL

Jiansheng Hu
J.G. Li
CAS IPP Hefei

Paco Tabares
CIEMAT

Vertkov/Lazarev
Efremov

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Lithium Safety: Lab Setting

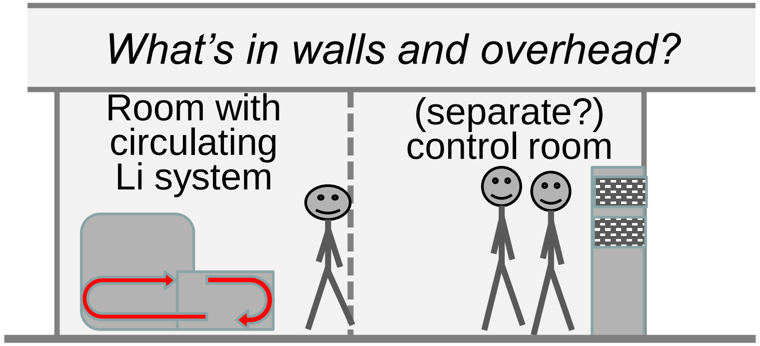
Lithium is implicit with fusion technology.

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
- …
- …

Agenda

- **Introduction** Richard Nygren
- **Comments on Li Safety** Richard Nygren, Eichi Wakai
- **Forum A: Li handling in labs** Introduction/Nygren

Panel:	Eichi Wakai	JAEA-IFMIF-EVEDA
	Leonid Zakharov	PPPL
	Ming-ju Ni	CAS University Beijing
	I. Lyublinski or A. Vertkov	Efremov
	Thomas Lin	ARL Penn State University

- **Forum B: Li in fusion experiments** Introduction/Nygren

Panel:	Giuseppi Mazzitelli	ENEA Frascati
	Masa Ono	PPPL
	Jiansheng Hu and J.G. Li	IPP-CAS Hefei
	Paco Tabares	CIEMAT
	A. Vertkov or Lazarev	Efremov
	Tazhibayeva	NTSC Kazahkstan

- **Formation of a work group** Nygren