Status of IFE S&E Activities in the US


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Aknowledgements:

• HAPL team:
  – DoD/DoE Labs: NRL, LLNL, SNL, LANL, ORNL, PPPL, ANL, INEL
  – University: University of California San Diego, University of Wisconsin, University of California Los Angeles, and University of Rochester

• Z-IFE team:
  – DoD/DoE Labs: SNL, LLNL, LANL, NRL, LBNL
  – Industry: GA, ATK-MRC, SAIC, Omicron
  – Collaborating Institutions in Russia: Kurchatov Institute (Moscow), Institute for High Current Electronics (Tomsk)

• Fusion Safety Program at Idaho National Laboratory
Outline

• Introduction

• Overview of IFE S&E:
  – HAPL program
  – Z-IFE
  – The role of NIF

• Conclusions

• Future directions for IFE S&E
S&E considerations are critical for the success of IFE

- IFE has both *radiological and toxicological hazards*:
  - Tritium fuel, activated structural material, activated dust, activated coolants or coolant impurities, and activated gases
  - Chemically toxic materials (i.e.: Hg, Pb)
- **Energy sources** that can mobilize these hazardous materials include:
  - chemical energy, decay heat, pressure energy and radiation
- In the US, current IFE S&E activities are focused on these programs:
  - The *High Average Power Laser* (HAPL) Program for the development of a dry-wall, laser-driven IFE power plant
  - The *Z-IFE* Program for the production of an economically-attractive power plant using high-yield z-pinch-driven targets
In the recent years there has been great progress in IFE S&E

• In order to maximize the S&E advantages of IFE, accident consequences must be addressed realistically

• Led by LLNL, we have developed an updated methodology for IFE safety analysis, that was applied to various IFE designs and a target fabrication facility

• This work have allowed for a better understanding of the S&E issues associated with emerging design concepts in the IFE community

• The ultimate goal is to maximize the attractiveness of IFE as a safe and environmentally clean source of energy
SET OF COMPUTER CODES AND LIBRARIES

TART input:
- Model geometry, materials

TART: photon/neutron transport
- Photon/neutron energy deposition, path-lengths

TARTCHECK:
- Verification of TART geometry

ACAB input:
- Irradiation history, neutron flux, materials, output options

ACAB: activation calculations
- Radioactive inventory, afterheat, etc

TARTREAD

ENDL:
- Cross-section library

FENDL/A-2.0:
- Cross-section library

FENDL/D-2.0:
- Decay library

CHEMCON input:
- Geometry, energy source term

CHEMCON:
- Heat transfer

Time-temperature history

MELCOR input:
- Geometry, radioactive source term

MELCOR:
- Thermal-hydraulics

Radioactivity release fraction

DCF library

OFF-SITE DOSES

TART input for γ-ray transport

= input file
= FORTRAN code
= Data library
= Output data
US IFE programs are paying close attention to S&E aspects

• The US HAPL program is carrying out a coordinated effort to develop IFE based on lasers, direct-drive targets and a dry wall chamber
  – a conceptual blanket has been proposed based on a self-cooled liquid lithium blanket with ferritic steel F82H as structural material
  – assessments are being developed to assess potential Li hazards and optimize the S&E characteristics of the HAPL chamber

• A Z-IFE conceptual design has been proposed with a repetitive target insertion in a thick liquid wall chamber
  – target attached to the end of a Recyclable Transmission Line (RTL) that is inserted at the top of the chamber for each shot (0.1 Hz)
  – RTL material choice is critical from S&E point of view
S&E activities in support of the HAPL Program

• Dominant issue in accident scenario with Li chemical reactions is mobilization of tritium and activated structural materials

• We have completed preliminary S&E assessment for the HAPL design, including:
  – neutronics and activation assessments
  – assessment of LOFA and passive decay heat removal capability
  – simulation of Li spill with air ingress and consequent fire

Schematic of HAPL chamber using self-cooled liquid Li blanket
HAPL S&E: Loss of flow accident

- We have used the heat transfer code CHEMCON to simulate a loss of flow accident and assess dissipation of afterheat during the accident.

**Baseline design: RAF at 545 C, 5 Hz**

- *Decay heat rapidly transfers through radiation to cooler structures (confinement building)*

- In case of enhanced design (with ODS steel) the starting temperatures are higher but same trend can be observed.

**FW temperature evolution: baseline vs enhanced design, at 5 and 10 Hz**

- In case of 10 Hz operation, increased afterheat results in slower transfer, but also passive removal due to radiation.
HAPL S&E: Li spill and fire

- Used modified MELCOR code version (INL) to predict the consequences of lithium accidents: major Li spill (300 tonnes) with simultaneous air ingress

- **FW temperature peaks at ~ 800K and gradually decreases**

- However, tritium inventory in coolant is mobilized and available for release

- **Need to minimize tritium inventory in Li**, possible approaches may include:
  - gas recovery, getters, cold trap, molten salt, permeation

Temperature evolution during Li fire
S&E activities in support of Z-IFE

- We have performed 3D neutronics analyses for Z-IFE
- Determined key nuclear parameters (TBR, energy deposition) for a thick-liquid-wall chamber
- Determined radiation dose (dpa/y) to chamber wall
  - Effect of jet configuration
- Completed scoping study for recyclable transmission line (RTL) materials
  - Waste disposal rating
  - Contact dose rate
Z-IFE RTL waste disposal rating study: Goal is WDR < 1

Weekly recycling rating

Daily recycling rating

WDR > 10
1 < WDR < 10
0.1 < WDR < 1
0.01 < WDR < 0.1
WDR < 0.01
Not studied
Z-IFE RTL contact dose rate study:
Goal is <114 Gy/h (3.0E7 Gy in 30 fpy)
Can the Z-IFE RTL materials be cleared?

- The use of a Clearance Index (CI) allows us to understand if the material could be released from regulatory control
- CI < 1 indicates that the material could be released

* This assumes weekly recycling of material

<table>
<thead>
<tr>
<th>Material</th>
<th>Clearance Index @ 3y cooling</th>
<th>Dominating Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>5.72E+06</td>
<td>Mn-54, Fe-55, Co-60</td>
</tr>
<tr>
<td>Mylar</td>
<td>1.31</td>
<td>Be-10, C-14</td>
</tr>
<tr>
<td>Flibe</td>
<td>0.081 (~ 1 @ 3d)</td>
<td>Be-10, C-14</td>
</tr>
</tbody>
</table>
The role of NIF on IFE S&E

• During peak operations, **NIF** will produce fusion yields of 1200 MJ/y
• With up to $4.3 \times 10^{20}$ D-T neutrons produced per year, neutron activation is significant within the Target Bay
• The DOE has committed to maintaining the total dose equivalent (dose) $\leq 10$ person-rem/y
• The facility must be capable of operation with individual doses $\leq 500$ mrem/y (1/10 of the 10CFR835 limit as per the LLNL Health and Safety Manual)
• The ALARA principle is applied to all doses
• *Neutronics and activation calculations are essential for determination of shielding requirements and appropriate planning of NIF operations and worker activities*
Neutronics and safety studies are needed for NIF

- The main **safety** concerns in NIF are related to worker doses:
  - Prompt doses within and outside the facility
  - Neutron-induced reactions produce radioactive material
- We are performing neutronics and activation calculations NIF in order to estimate worker doses and control frequency/duration of maintenance activities
- The results from our calculations are critical for:
  - Material selection
  - Shielding design
With the current methods, analyzed NIF FOAs

- 1 TART run with ~300 zones
- 53 TARTREAD runs
- 53 ACAB runs
- 53 TABLES runs
- ~6 nuclides of interest per zone
- 334 TART runs*
- 31 GTALLY runs

*Note: Short-lived radionuclides ignored. Would need ~600 runs if included.
S&E activities in support of NIF

• Although not an IFE program, NIF will be crucial for the development of IFE by demonstrating ignition in the laboratory.

• In addition, NIF will provide data that can benchmark and improve the predictive capability of various neutronics and safety computer codes that will be needed to design future IFE power plants.

• A growing effort will be devoted towards the development of integrated radiation safety assessments for NIF during the next few years: IFE should benefit from this (i.e, CAD-to-MCNP conversion tools).

CAD (left) to TART (right) conversion for NIF target positioner clam-shell.
Conclusions (I)

- *In the past few years, safety analyses have matured significantly:* the behavior of IFE systems with respect to public safety is better understood than ever before based on safety analysis.

- The use of lithium as both the breeder and coolant can simplify the HAPL chamber design which may result in higher reliability.

- However, careful design must be utilized to decrease the risk from a Li spill, i.e.: cover gas, avoid water use, segmented Li inventory, multiple containment, minimized T inventory in coolant.

- S&E assessments for **Z-IFE chamber** using thick liquid wall of flibe has been completed:
  - Fe and Flibe, the two top candidates for the RTL meet waste disposal and contact dose rate criteria.
  - If Flibe can be used as an RTL material, it could be released from regulatory control with as little as 3 days of cooling.
Conclusions (II)

- Although not an IFE program, **NIF** will be crucial for the development of IFE by *demonstrating ignition* in the laboratory.

- IFE should benefit from the developments due to the growing interest on **NIF radiation safety** (integrated tools, CAD-to-neutronics conversion, etc).

- NIF will provide data that can benchmark and improve the predictive capability of various *neutronics and safety computer codes* that will be needed to design future IFE power plants.
Future directions in IFE safety

• *Probabilistic safety assessment* is growing in importance for fusion, ITER licensing decisions will set a regulatory precedent for future fusion power plants

• *Chemical safety analyses* are becoming more important in IFE as more chemically toxic materials are used

• *Radioactive waste* issues continue to be a concern; more work should be devoted to the minimization of waste volumes and the definition of clearance of materials for recycling or for free release

• More work should be devoted to the understanding of *occupational safety*

• *Safety codes* will require updating for future IFE designs to account for new materials, updated mobilization and radiological data
Back up
Effect of array configuration in Z-IFE chamber

Reference case

Enhanced venting case

Jets

Chamber wall

![Graph showing neutron dose (Gy/y) vs. angle (degrees)]

Neutron dose (Gy/y)

Angle (degrees)
Benchmarking of our codes and methods

- The RTNS-I facility at UC Berkeley was used to benchmark ACAB calculations
- We have irradiated samples of NIF concrete
- Excellent agreement between calculations and experiments has been observed
- The same reaction $[^{27}\text{Al}(n,\alpha)^{24}\text{Na}]$ is important for FOA results

Exposure rates measured from a concrete sample irradiated for 1 hour in RTNS-I.

![Graph showing exposure rates over time](image-url)
NIF is a crucial step in the quest for inertial fusion energy

Level of development steps

Fusion energy development (Phase III)
Cost goal <2B

Performance extension (Phase II)
$80–120M/yr

Proof of principle (Phase I)
~$50M/yr

IF Demo

Results from ETF (100–300MW) provide design basis for DEMO with economic competitiveness and attractive ES&H characteristics

Supporting power technologies for the Demo

Design basis for ETF from NIF and IRE program on driver chamber and targets.
- Economic attractiveness is plausible

National Ignition Facility – NIF – and ignition program (Separately DOE/DP funded)

Integrated Research Experiments(s) – IRE – (Laser and/or ions)

Advanced driver and target R&D

Supporting technology R&D

- Design basis for IRE established
- Scaled experiments on chamber, target fab, and injection provide technically plausible path to IFE

Target design & technology R&D

Krypton Fluoride Laser

Diode-Pumped Solid-State Lasers

Ion Beams