R&D Activities for the Laser Inertial Fusion Energy (LIFE) Engine

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The LIFE vision is to provide a carbon-free, scalable, baseload option for electrical generation

- Leverages multi-decade investments in NIF and Mercury lasers
- Capitalizes upon recent advances in low-cost, high-power diode technology
- Exploits the ICF point neutron source to enable system modularity and separability
- High neutron fluxes enable specialized missions:
  - Destruction of excess weapons materials
  - Disposition of spent nuclear fuel from existing LWRs
- Inherent separability enables a rapid development path
LIFE is, at the core, a fully functioning pure fusion engine for fusion-based energy missions.

We purposefully designed LIFE to function/operate at the 1st wall conditions and fusion confinement (\(\rho R\)) required for a pure fusion system.
LIFE naturally divides into fusion and fission systems

The Fusion Engine
- 100 MWth X-rays/ions
- 35 MJ (Gain 25) with LIFE-relevant targets
- 30¢ targets @ 5-15 Hz
- Beam propagation
- Molten salt: coolant and T source
- Manage fusion environment: 1st wall (5-7 yrs) Chamber clearing, Final optic, ...

The Fission Engine
- 400 MW neutrons
- 40 Tons DU in Pebbles
- 2600 MWth
- Passive Safety
- > 99% burn without reprocessing

Fission blanket gain

Tritium management

Maintain constant power

Inject, track & engage

Inject, track & engage
Different LIFE blankets provide unique Pure Fusion and Once-Through Closed fuel cycle energy systems

1st Wall modules contain fusion, multiplies and moderates neutrons

LIFE blankets options

- Li-based coolant for pure fusion energy and T for other LIFE missions

- Coolant with natural U, DU or Th pebbles for sustainable, once-through closed fuel cycle energy (goal > 99% burn-up)

- Coolant with fertile or fissile pebbles for once-through closed fuel cycle energy while burning SNM and LWR waste (goal > 99% burn-up)
  - WG-Pu, HEU
  - TRU or TRU+FP from SNF
  - SNF (without reprocessing)

A fully functioning laser-driven inertial fusion engine is required for LIFE
The LIFE engine starts with ICF targets injected into a chamber @ 10-15 Hz
For the Pure Fusion LIFE system, a 30 MW, 0.53 μm laser (~ 2 MJ @ ~15 Hz) is focused on the target producing ~ 1600 MW of fusion.

A pure fusion blanket gain of 1.35, a 13% efficient DPSSL and a 55-60% thermal to electric conversion efficiency provides 1 GWe.
For the hybrid LIFE systems, a 15-20 MW laser (~ 1.4 MJ @ 10-15 Hz) is focused on the target producing ~ 500 MW of fusion.

One of the many individual laser beams providing ~ 1.4 MJ of 0.35 μm @ 15 Hz
DU loaded pebbles, a Be blanket and flibe coolant provide the fission gain and tritium for the fusion targets.

Molten salt (flibe) coolant also provides the tritium for the fusion fuel.

40 Tons U, DU, Th, or SNF (without reprocessing).

Be layer to multiply and moderate the neutrons.

~ 500 MW fusion

~ 4.5 m

~ 1.4 MJ @ 15 Hz

40 tons of fertile fuel could provide 2500-3000 MWth for ~ 50 yrs.
The external neutrons allows us to burn the fuel to very high FIMA (goal > 99%) in one step.

- 40 Tons U, DU, Th, or SNF (without reprocessing)
- Molten salt (flibe) coolant also provides the tritium for the fusion fuel
- Be layer to multiply and moderate the neutrons
- High Burn-up (Goal 99%)
- Waste Disposal
- 50 years later

And provides a once-through, closed nuclear fuel cycle system that could also burn SNM and PuMA from SNF.
A LIFE hybrid engine would provide decades of steady-power from 40 MT of depleted uranium.

Thermal power and content of fertile and fissile material as a function of time for an optimized LIFE engine loaded with 40 tons of DU, driven by 500 MW of fusion. (Performance would be similar for natural U or non-reprocessed SNF)

Level of LIFE fuel burn-up (FIMA) will be a trade-off between economic and proliferation constraints.
LIFE fuel burn-up can be adjusted as desired

Remaining quantities of actinides for an initial load of 40 tons of DU as a fraction of burn-up (FIMA)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>90%</th>
<th>95%</th>
<th>99%</th>
<th>99.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>8.4 kg</td>
<td>6.2 kg</td>
<td>35 g</td>
<td>190 mg</td>
</tr>
<tr>
<td>$^{237}\text{Np}$</td>
<td>9.1 kg</td>
<td>6.5 kg</td>
<td>479 g</td>
<td>44 g</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>496 kg</td>
<td>314 kg</td>
<td>6.4 kg</td>
<td>1.0 kg</td>
</tr>
<tr>
<td>$^{241}\text{Am}$</td>
<td>121 g</td>
<td>47 g</td>
<td>11 g</td>
<td>320 mg</td>
</tr>
<tr>
<td>$^{246}\text{Cm}$</td>
<td>137 kg</td>
<td>145 kg</td>
<td>101 kg</td>
<td>57 kg</td>
</tr>
</tbody>
</table>

• 40 tons of depleted uranium becomes essentially 40 tons of fission products

With > 99 % burn-up, LIFE produces > 30 X less high level waste per GWe than once-through LWRs and has insignificant quantities of actinides per MT IHM at end of operation
Improved performance is realized by segmenting the blanket and extending the lifetime

- Different blanket regions (e.g. front, middle, back) experience different neutron fluxes

- When the front region is fully burned, successive layers are promoted and new fuel is added to the back

- Full power mode can be extended indefinitely
Segmented blankets for DU, Nat U and SNF can be operated as long as desired

- Different blanket regions (e.g., front, middle, back) experience different neutron fluxes
- When the front region is fully burned, successive layers are promoted, and new fuel is added to the back
- Full power mode can be extended indefinitely
Recent work has emphasized plant footprint, modularity and rapid construction & maintenance schedules.

- Modular (advanced architecture) lasers that could be factory built
- Separate first wall & blanket modules for rapid & independent replacement
Next-generation laser technology could result in a very compact LIFE engine.
A modular chamber design enables rapid first wall replacement
Pure fusion and hybrid LIFE engines have (by design) the same 1st wall design and 1st wall neutron loading.

LIFE systems producing 1 GW$_e$ @ 15 Hz
1st wall W-coated ODS-FS or SiC

Gain 10 SNM or TRU
220 MW$_{fusion}$
$R_{chmbr}$ 1.7 m
Neutron 5 MW/m$^2$
4.8 μg/cc Xe/Kr

Gain 5 DU or SNF
450 MW$_{fusion}$
$R_{chmbr}$ 2.4 m
Neutron 5 MW/m$^2$
3.3 μg/cc Xe/Kr

Pure Fusion 1700 MW$_{fusion}$
$R_{chmbr}$ 4.4 m
Neutron 5 MW/m$^2$
1.7 μg/cc Xe/Kr

All require a fully functioning fusion engine. The difference is in the driver/fusion MJ, $R_{chamber}$, gas fill and blanket configuration.
LIFE power flow for a hotspot pure fusion system

Laser
4.2 MJ @ 10 Hz
10% $\eta$

42 MW laser

$G_{\text{fusion}} = 53$

2209 MW fusion

$G_{\text{fission}} = 1.35$

2982 MW thermal

Power Cycle
$\eta = 49\%$

411 MWe
(31% recirc)

1455 MWe

1527 MWth

Process heat

44 MWe

1000 MWe

Pumps / aux. power

To grid

1000 MWe

To grid
The copious neutrons provided by the fusion source enable fission hybrids as well.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LIFE Pure Fusion</th>
<th>LIFE Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion power (MW)</td>
<td>1700</td>
<td>350-500</td>
</tr>
<tr>
<td>Fusion yield (MJ)</td>
<td>50-200</td>
<td>35-75</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>5-15</td>
<td>5-15</td>
</tr>
<tr>
<td>Neutron wall loading (MW/m²)</td>
<td>2-4</td>
<td>3-5</td>
</tr>
<tr>
<td>Laser energy (MJ)</td>
<td>1.0-2.5</td>
<td>0.5-1.4</td>
</tr>
<tr>
<td>Laser wavelength (nm)</td>
<td>351 or 532</td>
<td>351</td>
</tr>
<tr>
<td>Chamber radius (m)</td>
<td>3-5</td>
<td>2-4</td>
</tr>
<tr>
<td>First wall</td>
<td>W on ODS-FS or SiC</td>
<td>W on ODS-FS or SiC</td>
</tr>
<tr>
<td>First wall protection</td>
<td>Xe/Kr at 4 μg/cc</td>
<td>Xe/Kr at 4 μg/cc</td>
</tr>
<tr>
<td>Tritium breeder</td>
<td>Molten salt or oxide</td>
<td>Molten salt</td>
</tr>
<tr>
<td>Coolant</td>
<td>Molten salt or He</td>
<td>Molten salt</td>
</tr>
</tbody>
</table>
LIFE power flow for a hotspot DU-fueled hybrid system

Laser
1.86 MJ @ 10 Hz
10% $\eta$

18.6 MW laser

G$_{\text{fusion}}$ = 27

510 MW fusion

2690 MW thermal

G$_{\text{fission}}$ = 5.4

Power Cycle
$\eta$ = 46%

1234 MWe

1456 MWth

Process heat

196 MWe
(19% recirc)

37 MWe

1000 MWe

Pumps / aux. power

To grid
LIFE does face some technical and scientific challenges

Low cost
1 - 2.5 MJ DPSSL
@ 10-15 Hz ~ 15%
with high availability

Target production
~ 30¢ each @ 10-15 Hz
Injection and engagement

ICF performance
10-120 MJ with LIFE relevant targets

Manage fusion environment:
1st wall
Beam propagation
Chamber clearing

Fission Engine:
T management,
Passive safety,
Maintain constant power,
and High burn-up of fuel

LIFE divides naturally into a Fusion and Fission engine
The fusion engine further divides into four separate and distinct subsystems
**LIFE** science and technology issues:
Managing fusion environment and 1st Wall

- **Low cost**
  - 1 - 2.5 MJ DPSSL
  - @ 10-15 Hz ~ 15%
  - with high availability

- **Target production**
  - ~ 30¢ each @ 10-15 Hz
  - Injection and engagement

- **ICF performance**
  - 10-120 MJ with LIFE relevant targets

- **Manage fusion environment:**
  - 1st wall Beam propagation Chamber clearing

- **Fission Engine:**
  - T management, Passive safety, Maintain constant power, and High burn-up of fuel
Top-level design choices flow down from requirements on driver, chamber protection and targets

Driver

Chamber Protection

Targets

Heavy Ions → Gas → Direct Drive

Pulsed Power → Thin Liquid → Indirect Drive

Lasers → Thick Liquid

Direct-drive targets are thermally fragile and require low gas pressures
Results in large chamber radius and low flux on fission fuel
Direct drive ignition is not currently planned
Top-level design choices flow down from requirements on driver, chamber protection and targets.

Heavy ions and pulsed power optimize to large fusion yields.

Results in either large chamber radius or thick liquid wall → low flux on fission fuel.

Can recover fission gain with thick blanket, but full burn up takes more than a century.
Top-level design choices flow down from requirements on driver, chamber protection and targets

- **Driver**
- **Chamber Protection**
- **Targets**

Heavy Ions → Gas → Direct Drive

Pulsed Power → Thin Liquid → Indirect Drive

Lasers → Thick Liquid

**Indirect-drive targets are thermally robust and enable ~ 100× more chamber gas**

**Small chamber radius provides high neutron flux on fission fuel**

**Indirect-drive targets will be demonstrated on the NIF**
Thermal robustness of indirect-drive targets allow use of chamber fill gas and compact chambers

- First wall is ODS-FS or SiC over-coated with 500 μm W
- X-rays from target pre-ionize gas near target and causes partial laser absorption by inverse bremsstrahlung
- Gas stops all ions (~ 4MJ) and ~ 90% of 4.5 MJ of x-rays
- Absorbed energy is re-radiated over 100’s μsec
- Experiments and modeling at LLNL, UCSD and UW for ~ 1800 K pulses

Xenon densities of ~4 μg/cc reduce the thermal pulse to <1000 K
A significant beam propagation effort is still needed

What is beam loss for hotspot ignition hohlraums (285 eV)?

Do atoms in excited states behave differently?

Would a different fill gas and/or hohlraum material matter?

How do we validate these calculations?

How much density variation and turbulence is acceptable?

Do we really understand SRS, SBS & filamentation?

What do residual plasma and/or debris will be acceptable?

How are short pulses affected by residual plasma/debris?

Will aerosols and/or molecular clusters degrade the beam?

Is B-integral a problem for short pulses?
Chamber clearing analyses raise many scientific questions

- What are the “equilibrium” conditions after many shots?
- What is the temporal/spatial chamber gas state (T, ρ, composition, ionization)?
- How long do gradients persist in the gas?
- What is the physical/chemical state of the debris, and when/where could aerosols form?
- Do blast/shock waves transport chamber gas up the beamtubes, and what impact is there on the final optics?
- How is mixing affected by chamber geometry and gas temperature and density?
- Is mixing of vent/fill gases desirable, or should cold/clean gas avenues be created to protect the target and laser path?
Tackling these questions will require an integrated and iterative approach.

What are chamber conditions at time of next shot?

What does chamber environment do to propagating laser beam?

How does the propagating beam change the local chamber environment?

Are beam loss and/or degradation acceptable?

How can vent/fill be designed to optimize conditions for next shot?

BUCKY
Lasnex
Hydra
Miranda

Rad-hydro
CFD
Aerosols
Experiments

Hydra
F3d
VBL

Experiments & Modeling

Experiments & Modeling

Experiments
The dynamic chamber systems effort includes both modeling and scaled experiments

- Modeling will include simulations related to opacities, rad-hydro, computational fluid dynamics, and beam propagation. Key issues are residual debris fraction and plasma densities, gas temperature, turbulence and mixing.

- Scaled plasmas will be generated using OSL and/or Jupiter: generation and decay of Xe and Xe/Pb plasmas with and without gas venting and/or backfill; opportunity to bring in secondary laser pulse after arbitrary delay.
ODS-Ferritic Steel is a good baseline material for LIFE 1st wall

1st wall in a LIFE system sees a neutron load of ~ 35 dpa/yr

ODS steel tested in BOR-60 sodium-cooled fast flux reactor (> 85 dpa) - (85 dpa would give a 1st wall lifetime of ~ 3 years)

Ion beam irradiation at 500 °C project to 150 dpa, (1st wall lifetime of ~ 5 years)
LIFE science and technology issues: Fuels and fission engine systems optimization

Maintain constant power output

T management

Goal of 99% burn-up of fuel without reprocessing

Chemistry control on flibe

Molten salt fuel

Be processing

Passive Safety

Ongoing developments in the world nuclear power industry give us confidence that these challenges are tractable
Beryllium multiplication and moderation enables rapid production of fissile material.

Neutrons are multiplied via $^9$Be(n,2n) reactions.

Beryllium produces ~1.8 neutrons for every fusion neutron.

10 cm of Be considerably softens the neutron spectrum.

More thermal neutrons are available to produce tritium and fissile material.
LIFE uses $^6$Li as a burnable poison to control the thermal power and produce tritium.

A flat power curve is desirable.

Systems achieving 90%+ balance of plant utilization may be possible through tritium management.
The neutron spectrum varies considerably in the different regions of a LIFE engine

![Graph showing neutron flux vs. neutron energy with different regions labeled: 2.5-4 dpa/y, 10 dpa/y, and 35 dpa/y. The legend includes symbols for Target surface, First wall, Beryllium, and Fuel.]
LIFE could potentially use a variety of fuels

- Enhanced TRISO for WG-Pu and HEU

- Solid hollow core and Encapsulated powder pebbles for Fissile fuels (WG-Pu, TRU) or fertile fuels (DU, Nat U, Th and SNF)
Modular chambers significantly eases plant construction and maintenance.
The separability of ICF and LIFE makes a rapid demonstration path possible

Low cost
1 - 2.5 MJ DPSSL
@ 10-15 Hz ~ 15%
with high availability

Target production
~ 30¢ each @ 10-15 Hz
Injection and engagement

Manage fusion environment:
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Chamber clearing

ICF performance
10-120 MJ with LIFE
relevant targets

Fission Engine:
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LIFE divides naturally into a Fusion and Fission engine
The fusion engine further divides into four separate and distinct subsystems
NIC and the IFE science and technology roadmap feed into the larger LIFE program plan

<table>
<thead>
<tr>
<th>NIC and the IFE science and technology roadmap feed into the larger LIFE program plan</th>
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<tbody>
<tr>
<td><strong>National Ignition Campaign</strong></td>
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<tr>
<td><strong>Early Technology Evaluations</strong></td>
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<td><strong>LIFE ST&amp;E Roadmap</strong></td>
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<td><strong>Technology Devel. Program</strong></td>
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<td><strong>LIFELET Construction</strong></td>
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<td><strong>Pilot Operations</strong></td>
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<td>Phase 1 Burst Mode</td>
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<td>Phase 2 Steady Ops</td>
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<td>To Commercial</td>
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The inherent separability of many IFE technologies allows rapid development in parallel with NIF/NIC

<table>
<thead>
<tr>
<th>Category</th>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
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<td>Design / Construct / Ops</td>
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<td>Fabrication &amp; Foams</td>
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<td>Design</td>
<td>Construct &amp; Operate</td>
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<td>Systems Analysis, Integrated Laser Modeling, etc.</td>
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</table>
LIFE is, at the core, a pure fusion engine that also provides options for once-through, closed nuclear fuel cycles.

- The science and technology “building blocks” for LIFE are credible extensions of NIF, ignition on NIF and ongoing developments in diode pumped solid state lasers and the world nuclear power industry.

- The inherent separability of LIFE, would allow a 150-200 MW LIFE demonstration fusion engine that could then be scaled to:
  - Offer an early option for GWe level Pure Fusion LIFE systems
  - Provide Once Through, Closed Fuel Cycle options to generate GWe levels of baseload electricity from
    - fertile fuels (DU, Nat U, Th) or
    - by burning SNM and nuclear waste
We are building national team

- UC-Berkeley: neutronics, pebble management, structural materials, safety
- General Atomics: target fabrication, injection, tracking & engagement
- California Institute of Technology: structural materials
- BWXT: fuel fabrication & handling
- University of Wisconsin-Madison: first wall response, chamber clearing
- Los Alamos Nat’l Lab: neutronics, materials science
- University of Nevada-Las Vegas: fuel materials
- UC-San Diego: target injection, chamber dynamics, final optics
- Lawrence Berkeley Nat’l Lab: heavy ions, chamber phenomena, actinide science
- Idaho Nat’l Lab: aerosol formation, molten salts, fuel materials, safety
- Texas A&M: safeguards by design
- University of Rochester / LLE: lasers, target physics
- Oak Ridge Nat’l Lab: structural and fuel materials
- Savannah River Nat’l Lab: tritium handling and storage
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- Savannah River Nat’l Lab: tritium handling and storage

Current LIFE effort supports:
13 graduate students, 2 undergraduates, and 2 postdocs

UC-Berkeley NE265 class (8 students) have taken LIFE hybrids on as a design project with LLNL personnel as guest lecturers.

Current international collaborations include Kyoto University, University of Madrid, and CEA
Recent work has focused on making LIFE smaller and highly modular.

The high degree of separability inherent to IFE translates into a significant development path advantage.

LIFE could be designed as a pure fusion plant or as a hybrid to complete waste-related missions.

We believe a pilot plant could be operational a decade after NIF ignition and that a commercial power plant could be running a decade after that.