LIFE – Laser Inertial Fusion Energy based systems for electricity production and waste burning

March 10, 2009

Erik Storm

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
One of LIFE’s goals is to provide an option for a once-through closed nuclear fuel cycle.

Inertial fusion target chamber surrounded by mission specific blankets.

Laser: 1.4 MJ 350 nm 10-15 Hz

Heat exchange system and balance of plant.

Space for target factory.

LIFE could provide the bridge from today’s nuclear power to a pure fusion option later in this century.
The energy picture is not sustainable when we factor in future changes in global standard of living.

Today ~ 18% of the population uses ~ 55% of world’s TWe.

Source: Pasternak, “Global Energy Futures and Human Development: A Framework for Analysis”
We will see significant increase in electricity demand as the rest of the world moves up the economic ladder.

Source: Pasternak, “Global Energy Futures and Human Development: A Framework for Analysis”
The implications are rather serious

Even by ~ 2050, NEW capacity would be ~ 1.5 X existing

A Business as Usual approach is obviously not acceptable
The situation in the US is equally serious: Demand could reach 1 TWe by 2050 and 2 TWe by 2100.
A significant increase in nuclear is a logical conclusion –
But at 1 TWe, this would require 1 Yucca Mountain ~ every 3-4 years
We need to close the nuclear fuel cycle
LIFE – one of our goals is to provide an option to close the nuclear fuel cycle

Requirements

Front end
- No enrichment
- Sustainable fuel supply

Back end
- No reprocessing
- No weapons attractive quantities of actinides in the spent fuel
- Minimize requirements for geologic disposition

The system must also be safe and economically competitive
- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm
192 Main Laser Beams Operationally Qualified September 24, 2008

World’s Highest Energy Laser – 4.2 MJ
NIF is not only complete
NIF is operational

1.1 MJ/3w from 96 beams delivered to TTC 3:15 AM March 10, 2009

Target shots start in June, and the Ignition Campaign this fall
Heaters

Thermal sensors

Silicon arms

Heater

10 mm
NIF will execute four major ignition campaigns in the next four years

<table>
<thead>
<tr>
<th>FY2009</th>
<th>FY2010</th>
<th>FY2011</th>
<th>FY2012</th>
</tr>
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<tbody>
<tr>
<td>NIF CD-4</td>
<td>Drive</td>
<td>Tuning</td>
<td></td>
</tr>
<tr>
<td>Campaign 1</td>
<td></td>
<td>Layered THD implosions</td>
<td>1st DT ignition implosions</td>
</tr>
<tr>
<td>Campaign 2</td>
<td></td>
<td></td>
<td>2nd DT ignition implosions</td>
</tr>
<tr>
<td>Campaign 3</td>
<td></td>
<td></td>
<td>3rd DT ignition implosions</td>
</tr>
<tr>
<td>Ignition Platform</td>
<td></td>
<td></td>
<td>Ready</td>
</tr>
</tbody>
</table>
Ignition and gain on NIF will be a transforming event, and will focus the world’s attention on the possibility of an inertial fusion energy option.

But NIF/NIC gains will not be adequate for an inertial fusion energy system.
Pure IFE could be realized with NIF-like lasers, NIF-like targets and chambers ~ ½ the size of NIF

But IFE with 3-4 MJ lasers systems are unlikely to be economically attractive
With Fast Ignition, more attractive IFE systems are possible

![Graph showing laser energy vs. fusion yield](image)

- **125 MJ @ ~ 15 Hz; 1 GWe, 4.5 m chamber**
- **250 MJ @ ~ 10 Hz; 1 Gw, 5.5 m chamber**

**Hot Spot Ignition with NIF illumination**

**Demonstrated NIF energy**

**Low incidence angle FI**

**NIC 2010-2011**

- **25-40 MJ, Gain 15-25**

**We will resolve the physics issues of FI by early 2012/2013**
The challenge is to find a fusion option that would work with NIF/NIC performance.

We believe LIFE is such an option.
LIFE goal: Provide a sustainable, once-through closed nuclear fuel cycle energy option

• LIFE uses fusion neutrons to drive a subcritical fertile/fissile fuel blanket and provide a once-through closed nuclear fuel cycle

• The science and technology “building blocks” for a NIF-based LIFE system are logical and credible extensions of NIF, ignition on NIF and ongoing developments in the world nuclear power industry

• The inherent separability of LIFE, would allow a NIF-based LIFE system to be piloted by 2020-2025
The idea of a fusion-fission hybrid was first proposed more than 50 years ago.

We believe LIFE is an idea whose time has come.
LIFE starts with a 15-20 MW laser (NIF-like 1.4 MJ @ 10 - 15 Hz)
NIF-like targets are injected at 10-15 Hz providing 350-500 MW of fusion.

15-20 MW Laser

~ 1.4 MJ @ 10-15 Hz
Fertile or fissile fuel, flibe coolant and a Be blanket provide the fission gain and tritium for the fusion targets.

40 tons of fertile fuel could provide 2000-5000 MWth for 50 yrs (7 MT of fissile fuel for ~ 7 years)
The external neutrons allows us to burn the fuel to very high FIMA (goal > 99%) in one step.

- 40 Tons U, DU, Th, SNF (7 Tons Pu, HEU)
- Molten salt (flibe) coolant also provides the tritium for the fusion fuel
- 15-20 MW Laser
- ~ 1.4 MJ @ 10-15 Hz
- 350-500 MW fusion
- ICF Targets @ 10-15 Hz Gain 25-30
- High Burn-up (Goal 99%)
- Fission Products
- 50 years later (7 years for Pu)
- 2000-5000 MWth
- Fission Gain 4-10
- Be layer to multiply and moderate the neutrons
- Waste Disposal
LIFE uses a point source of inertial fusion neutrons to drive a sub-critical fissile fuel blanket.

- 15-20 MW Laser
- ~ 1.4 MJ @ 10-15 Hz
- 5 m
- 350-500 MW fusion
- ICF Targets @ 10-15 Hz Gain 25-30
- High Burn-up (Goal 99%)
- Be layer to multiply and moderate the neutrons
- Molten salt (flibe) coolant also provides the tritium for the fusion fuel
- Fission Gain 4-10
- 2000-5000 MWth
- 50 years later (7 years for Pu)
- 40 Tons U, DU, Th, SNF (7 Tons Pu, HEU)

LIFE would provide a once-through, closed nuclear fuel cycle.
LIFE provides decades of steady-power from a depleted uranium fuel loading

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

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>Burn-up</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>1.6 kg</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>3300 kg</td>
</tr>
<tr>
<td>$^{237}$Np</td>
<td>5.4 kg</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>210 kg</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>10 kg</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>4.2 kg</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>150 kg</td>
</tr>
</tbody>
</table>

- 40 tons of depleted uranium can become nearly 40 tons of fission products

With > 99% burn-up, LIFE produces up to 20 X less high level waste per GWe than once-through LWRs and has insignificant quantities of actinides 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

Segmented blankets would enable fuel burn-up to be tuned as desired
Segmented blankets 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
LIFE can burn excess plutonium in a high-gain blanket

- System fueled with 7 MT of weapons grade plutonium (WG-Pu)
  - Or 7 MT of PuMA from processed spent nuclear fuel

- Fuel (whether in “TRISO”-like loaded or Solid Hollow Core Pebbles) blended 80% ZrC + 20% Pu
  - Also loaded with 400 wppm boron as burnable poison

- Fusion power is 375 MW (25 MJ @ 15 Hz) Flat top thermal power is 3000 MW --- Blanket gain of 8

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### Pu blanket is driven by 375 MW of fusion

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Initial mass</th>
<th>Final mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$Pu</td>
<td>6.56 tons</td>
<td>1.3 mg</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>406 kg</td>
<td>&lt;1 μg</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>9.1 kg</td>
<td>1.2 mg</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>1.4 kg</td>
<td>&lt;1 μg</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>15.4 kg</td>
<td>&lt;1 μg</td>
</tr>
<tr>
<td>Total actinides</td>
<td>6.99 tons</td>
<td>2.83 kg (2.04 kg $^{246}$Cm)</td>
</tr>
</tbody>
</table>
LIFE offers key benefits relative to other nuclear systems

• LIFE would be a unique fusion-fission system:
  — Operates with a variety of different fuels
    – Depleted or Natural uranium, SNF, Excess weapons material, Thorium
  — No enrichment and no reprocessing
  — No weapons attractive materials at start or end of operation
    minimizes proliferation concerns
  — Deeply sub-critical at all times and passive removal of decay heat
    makes it inherently safe

• Simple technological solutions
  — Low-yield
  — Dry wall
  — Fast development path
  — Makes its own fuel (fusion & fission)
  — Incinerates its own actinide waste

We believe the S&T for a NIF-based LIFE system are logical and credible extensions of NIF, NIC and ongoing developments in the world nuclear power industry
LIFE goal: Provide a sustainable, once-through closed nuclear fuel cycle energy option

- LIFE uses fusion neutrons to drive a subcritical fertile/fissile fuel blanket and provide a once-through closed nuclear fuel cycle

- The science and technology “building blocks” for a NIF-based LIFE system are logical and credible extensions of NIF, ignition on NIF and ongoing developments in the world nuclear power industry

- The inherent separability of LIFE, would allow a NIF-based LIFE system to be piloted by 2020-2025
A NIF-based LIFE engine comprises a NIF-like laser system, a NIF-level point source of neutrons and a subcritical fission blanket and builds on ongoing developments in the world nuclear power industry.
The Baseline, NIF-based LIFE faces technical and scientific challenges

- 350-500 MW fusion ICF Targets @ 10-15 Hz Gain 25-30
- Robust Hot Spot yield w/LIFE-relevant targets
- Manage fusion environment: A threat to final optics, 1st wall, beam propagation, chamber clearing, etc.
- Target production at 15 Hz @ ~ 30¢ each
- Low cost NIF-energy level DPSSL @ 10-15 Hz 10-15% with high availability
- 1st wall survive 5 to 7 years from fusion neutron, x-rays and ions
- High burn-up of fuel (goal is > 99%) without reprocessing
LIFE divides naturally into a Fusion and Fission engine with different and distinct challenges.

The Fusion Engine:
- 1.4 MJ laser ~ 15 Hz (High availability)
- Flibe: coolant and T source
- Manage fusion environment: 1st wall (5-7 yrs), beam propagation, chamber clearing, - -
- 30¢ targets @ 15 Hz
- 35 MJ (Gain 25) with LIFE relevant targets
- 100 MWth X-rays/ions
- Flibe: coolant and T source

The Fission Engine:
- 40 Tons DU in Pebbles
- 400 MW neutrons
- Maintain constant power
- Fission blanket gain
- 2600 MWth
- High burn-up (goal > 99%)
- No reprocessing
- Passive Safety
- Tritium management

Inject, track intercept

Be for neutron multiplication

In the Fusion Engine:
- 35 MJ (Gain 25) with LIFE relevant targets
- 100 MWth X-rays/ions
- 30¢ targets @ 15 Hz
The fusion engine further divides into four separate and distinct subsystems

The 1.4 MJ laser which will consist of ~160 LIFElet “building blocks”

The fusion target chamber

Manage fusion environment:
1st wall (5-7 yrs) beam propagation, chamber clearing, - -

ICF performance

35 MJ (Gain 25) with LIFE relevant targets will be done on NIF

We believe the S&T building blocks for NIF-based LIFE are credible extensions of NIF/NIC and ongoing developments in the world nuclear power industry.
We have identified S&T development paths:

**Fusion yield**

- Robust Hot Spot yield w/LIFE-relevant targets
- Target production at 15 Hz @ ~ 30¢ each
- Manage fusion environment: A threat to final optics, 1st wall, beam propagation, chamber clearing, - -
- 1st wall survive 5 to 7 years from fusion neutron, x-rays and ions
- High burn-up of fuel (goal is > 99%) without reprocessing
- Low cost NIF-energy level DPSSL @ 10-15 Hz 10-15% with high availability
- Target injection, survival of cryo fuel, tracking and laser intercept
- 350-500 MW fusion
- ICF Targets @ 10-15 Hz Gain 25-30
- Fusion yield
NIF target yields are enabling for LIFE and will be demonstrated with NIC

NIF Hot-spot Ignition Campaign will start in 2010

- Target, cryo technologies and diagnostics have been developed
- The scientific basis for HIS targets has been extensively developed

We anticipate LIFE-level yields by 2012 and with LIFE type targets by 2013
We have identified S&T development paths:

**Fusion laser**

- We have identified S&T development paths:
  - Fusion laser

- **350-500 MW** fusion ICF Targets @ 10-15 Hz
  - Gain 25-30
  - 1st wall survive 5 to 7 years from fusion neutron, x-rays and ions

- Robust Hot Spot yield w/LIFE-relevant targets

- Target production at 15 Hz @ ~ 30¢ each

- Manage fusion environment:
  - A threat to final optics, 1st wall, beam propagation, chamber clearing, - -

- Low cost NIF-energy level DPSSL @ 10-15 Hz 10-15% with high availability

- 1st wall survive 5 to 7 years from fusion neutron, x-rays and ions

- High burn-up of fuel (goal is > 99%) without reprocessing
The LIFE laser is a logical extension of the NIF laser

- Repetition frequency $10^{-4}$ Hz
- Electrical efficiency 1%

- Repetition frequency 13 Hz
- Electrical efficiency >10%

- Fluence is identical
- He cooling enables average power
- Diode pumping enable efficiency
The LIFE laser 100 KW “building block” is a NIF-like beamline producing 7 kJ at ~ 15 Hz

Efficient high power laser diodes and high flow rate He cooling allows this NIF-like beamlet to operate at 15 Hz
Laser diodes and He gas cooling enable a NIF-like architecture to meet LIFE high rep rate high efficiency requirements.

High Power Diode Arrays

- 100 kW peak power

High Speed Gas Cooling

- 3 W/cm² cooling (average)

These technologies have been developed as part of the Mercury Project.
We have identified S&T development paths:
Fusion targets

- **Fusion targets**
  - 350-500 MW fusion
  - ICF Targets @ 10-15 Hz
    - Gain 25-30
  - 1st wall 5 to 7 years life
    - Fusion neutron
    - X-ray / ion thermal load

- **Target production at 15 Hz @ ~ 30¢ each**

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

- **Robust Hot Spot yield w/LIFE-relevant targets**

- **Low cost laser**
  - 1.4 MJ @ 10-15 Hz
  - 10-15% efficiency
  - High availability

- **Target injection**
  - Tracking
  - Laser intercept

- **Low cost laser**
  - 1.4 MJ @ 10-15 Hz
  - 10-15% efficiency
  - High availability
System and economic criteria for LIFE targets are more stringent than NIF

<table>
<thead>
<tr>
<th></th>
<th>NIF</th>
<th>LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep-rate</td>
<td>$&lt;10^{-5}$ Hz</td>
<td>10 - 15 Hz</td>
</tr>
<tr>
<td>Cost</td>
<td>$\sim$100,000</td>
<td>$\sim$0.2 - $0.4</td>
</tr>
<tr>
<td>Waste stream</td>
<td>$&lt; 1$ gm</td>
<td>$10^6$ gm/year</td>
</tr>
<tr>
<td>Chamber placement</td>
<td>$\sim 10$ $\mu$m$^3$</td>
<td>$\sim 1 - 5$ mm$^3$</td>
</tr>
<tr>
<td>Chamber impact- mass/ shot</td>
<td>gm</td>
<td>100 mg</td>
</tr>
<tr>
<td>Number/year</td>
<td>100</td>
<td>$6 \times 10^8$</td>
</tr>
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</table>
The material costs are low

<table>
<thead>
<tr>
<th>Item</th>
<th>Material</th>
<th>Cost ($)</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hohlraum/cone</td>
<td>Pb</td>
<td>&lt; $0.01</td>
<td>Deep-draw</td>
</tr>
<tr>
<td>Capsule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ablator</td>
<td>CH</td>
<td>$0.000003</td>
<td>Micro-encapsulation</td>
</tr>
<tr>
<td>Foam</td>
<td>CH</td>
<td>$0.00007</td>
<td>CO₂ extraction</td>
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<tr>
<td>DT</td>
<td></td>
<td>$0.00001 (D)</td>
<td>Permeation</td>
</tr>
<tr>
<td>Total costs</td>
<td></td>
<td>$0.01</td>
<td></td>
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Total estimated target material cost = $0.01

Target cost will be in production processes
Costs are in mass-production at high precision

Estimated production costs based on typical factory

<table>
<thead>
<tr>
<th>Item</th>
<th>Number</th>
<th>Cost/year ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating personnel</td>
<td>69 people at $300K/yr</td>
<td>21</td>
</tr>
<tr>
<td>Capital depreciation</td>
<td>$200,000,000 typical factory/5 years</td>
<td>40</td>
</tr>
<tr>
<td>Maintenance</td>
<td>5% cost of equipment</td>
<td>10</td>
</tr>
<tr>
<td>Electricity</td>
<td>Factory typical</td>
<td>8</td>
</tr>
<tr>
<td>Total factory cost/yr</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>Production cost per target</td>
<td>631 million/year (20 Hz operation)</td>
<td>$0.13</td>
</tr>
<tr>
<td>Target material cost (Pb)</td>
<td></td>
<td>$0.01</td>
</tr>
<tr>
<td>Target material recycle costs</td>
<td></td>
<td>$0.10</td>
</tr>
<tr>
<td>Total target cost</td>
<td></td>
<td>$0.24</td>
</tr>
</tbody>
</table>

Together with GA we are developing a research plan for target fabrication to meet cost/precision objectives
Bullets are an interesting comparison, as they are multi-component, multi materials, that tolerate high acceleration and high velocity. However, LIFE targets with ~2 mg/cc foam filled Pb hohlraums, Cryo-DT in ~2 mg/cc carbon foams CH shells and µm precision assembly will clearly require significant development.
Injection demonstration at GA to simulate the full length of a LIFE fueling system have demonstrated many objectives:

- Injection at 6 Hz (burst mode) 400 m/sec to 200 µm demonstrated
- Additional R&D needed for Cryogenic targets and >10 Hz
We have identified S&T development paths:
Managing fusion environment and 1st Wall

Target production at 15 Hz @ ~ 30¢ each

Low cost NIF-energy level DPSSL @ 10-15 Hz 10-15% with high availability

Robust Hot Spot yield w/LIFE-relevant targets

Target injection, survival of cryo fuel, tracking and laser intercept

Manage fusion environment: A threat to final optics, 1st wall, beam propagation, chamber clearing, - -

1st wall survive 5 to 7 years from fusion neutron, x-rays and ions

High burn-up of fuel (goal is > 99%) without reprocessing

350-500 MW fusion

ICF Targets @ 10-15 Hz Gain 25-30
Thermal robustness of indirect-drive targets allow use of chamber fill gas and compact chambers

- First wall is oxide dispersion strengthened ferritic steel 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
ODS-Ferritic Steel is a good baseline material for LIFE 1st wall.

ODS steel tested in BOR-60 sodium-cooled fast flux reactor (> 85 dpa)
Ion beam irradiation at 500 °C project to 150 dpa, (1st wall lifetime of ~ 5 years)
We have identified S&T development paths: Fuels and fission engine systems optimization

- Maintain constant power output
- Goal of 99% burn-up of fuel without reprocessing
- Molten salt fuel
- Be processing
- Passive Safety
- Chemistry control on flibe
- T management

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 $^9\text{Be}(n,2n)$ 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.
LIFE could potentially use a variety of fuels

- Enhanced TRISO for WG-Pu and HEU

- Solid hollow core and Encapsulated powder pebbles for fertile fuels (DU, Nat U, Th and SNF)
Molten salt fuel is an attractive option for burning fertile fuels

- Radiation damage to fuel is a non-issue
- Rare earth elements removed to avoid precipitation (on-line processing)
- Plutonium maintained below solubility limit → can adjust Th/U ratio to control [Pu]_{max}
- Blanket gain of 6-10× possible with on-line refueling
LIFE goal: Provide a sustainable, once-through closed nuclear fuel cycle energy option

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• The inherent separability of LIFE, would allow a NIF-based LIFE system to be piloted by 2020-2025
There are three phases that lead to commercial power from the NIF-based LIFE

2014

LIFE Technology Development Program (TDP)

Demonstrate LIFE fusion performance on the National Ignition Facility (NIF)
Establish and validate LIFE-ITDF technologies
(Ignition will be demonstrated by the separately funded National Ignition Campaign)

2018

LIFE Integrated Pilot and Prototype (IPP) --- Phase I

Full Scale Laser Plant, with subscale, Integrated Technology Demonstration of LIFE’s fusion facilities operated in burst mode (15 Hz for minutes)
Demonstrate molten salt system and tritium recovery
Fuel blanket pebble injection (without fissile fuel), flow and extraction
Materials test facility at full neutron, ion and x-ray fluences

2022

LIFE Integrated Pilot and Prototype (IPP) --- Phase II

Full scale 500 MW fusion facility with partial fission blanket operating at plant performance specifications for a total of 350 MW of electric power
Full life test of structural and fuel materials for licensing of commercial plant

2030-2035 Commercial power on the grid

Demonstrate LIFE fusion performance on the National Ignition Facility (NIF)
Establish and validate LIFE-ITDF technologies
(Ignition will be demonstrated by the separately funded National Ignition Campaign)
There are three phases that lead to commercial power from the NIF-based LIFE

**2030-2035 Commercial power on the grid**

**LIFE Integrated Pilot and Prototype (IPP) --- Phase I**
- Full Scale Laser Plant, with subscale, Integrated Technology Demonstration of LIFE's fusion facilities operated in burst mode (15 Hz for minutes)
- Demonstrate molten salt system and tritium recovery
- Fuel blanket pebble injection (without fissile fuel), flow and extraction
- Materials test facility at full neutron, ion and x-ray fluences

**LIFE Integrated Pilot and Prototype (IPP) --- Phase II**
- Full scale 500 MW fusion facility with partial fission blanket operating at plant performance specifications for a total of 350 MW of electric power
- Full life test of structural and fuel materials for licensing of commercial plant

**LIFE Technology Development Program (TDP)**
- Demonstrate LIFE fusion performance on the National Ignition Facility (NIF)
- Establish and validate LIFE-ITDF technologies
  (Ignition will be demonstrated by the separately funded National Ignition Campaign)

The separability of ICF and LIFE makes such a rapid demonstration path possible.
LIFE could begin to provide electricity by the mid 2030’s and one-half of expected U.S. baseload demand by ~ 2100

Scenario for 1 Tw from LIFE engines burning DU and/or SNF (50% of projected U.S. electricity demand in 2100)
We believe that a NIF-based LIFE with “today’s technology” is credible and meets LIFE goals

• NIF-like lasers
  — APG-1 glass; He cooling; high power edge emitting diodes

• NIC-like targets
  — Hot spot ignition; 25-40 MJ @ 1-1.4 MJ

• Target production, injection and engagement
  — Studies and scaled experiments at GA

• Fusion environment, 1st wall and final optics
  — Xe-filled, compact chambers; ODS-FS 1st wall
  — Thin Fresnel fused silica lens – self annealing color centers

• High burn-up Fuels
  — SHC pebbles provide options for high burn-up
  — Molten salt – radiation damage not an issue
And LIFE can only get better:  
By the time of a LIFE Pilot/Integrated Test Facility

- Next generation NIF-like lasers  
  - Y-SFAP; He cooling; VCSEL diodes  
    - 3x fewer diodes; lower cost

- Fast Ignition targets  
  - Fast Ignition; 25-40 MJ @ 0.5-0.6 MJ and 0.53 µm  
    - Lower cost lasers, lower operating costs

- Target production, injection and engagement  
  - Studies and scaled experiments at GA

- Fusion environment, 1st wall with improved materials  
  - Radiation resistant materials; Higher temp 800 vs 700 C  
    - 1st wall last 10 yrs; Thermal to electric eff 43% - 52 %

- High burn-up Fuels  
  - Radiation resistant materials  
    - Improved blanket gain and > 99.9% FIMA for all fuel forms in solid pebbles
We believe that LIFE could provide the bridge to the future

Global Factors
• Population increase
• Developing countries
• Resource depletion
• Climate change

This challenge must be met and solved in the next 10-15 years … Not 50 years from now
Neutron power flow for DU case at time of peak $^{239}$Pu (~10 years); TBR = 1.09

<table>
<thead>
<tr>
<th>Source</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion</td>
<td>500</td>
</tr>
<tr>
<td>Beryllium</td>
<td>-20</td>
</tr>
<tr>
<td>Tritium prod.</td>
<td>129</td>
</tr>
<tr>
<td>Fuel prod.</td>
<td>171</td>
</tr>
<tr>
<td>Fission</td>
<td>1983</td>
</tr>
<tr>
<td>Incineration</td>
<td>-87</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2676</strong></td>
</tr>
</tbody>
</table>

400 MW n
100 MW x-rays & ions

129 MW

-20 MW

171 MW

-87 MW

Power Generation
1983 MW

Waste incineration
LIFE Engine basics – The extra fission gain makes low fusion gains viable

Recirculating fraction < 0.15 even for modest fusion gains of 25

Net Power, $P_e = (1-f) P_{out}$

$G = 100-300$

$f \sim 2.2/(\eta_d G)$

NIF fusion gains alone would require recirculating fractions ~ 60%
LIFE power flow for DU blanket

Laser: 1.4 MJ @ 13.3 Hz, 13% \( \eta \)

\[ G_{\text{fusion}} = 27 \]

19 MW laser \rightarrow 500 MW fusion \rightarrow 2600 MW thermal

\[ G_{\text{fission}} = 5.2 \]

Power Cycle: \( \eta = 43\% \)

144 MWe \rightarrow 1118 MWe \rightarrow 1482 MWth

Pumps / aux. power: 25 MWe, 949 MWe

To grid

Process heat
LIFE power flow for Pu blanket

Laser
1.4 MJ @ 13.3 Hz
13% $\eta$

$G_{\text{fusion}} = 27$

19 MW laser
500 MW fusion
3000 MW thermal

Power Cycle
$\eta = 43$

$G_{\text{fission}} = 6$

144 MWe
1290 MWe
1710 MWth

Process heat

Pumps / aux. power

To grid

1121 MWe
25 MWe
The separability of ICF and LIFE makes a rapid demonstration path possible

• Demonstration of LIFE fusion yield with targets produced with low-cost fabrication technologies that scale to LIFE production quantities will be demonstrated on NIF

• Mass production technologies for the fusion targets at required precision will be done off line

• Target delivery, tracking and engagement and chamber clearing will be demonstrated with surrogate targets and low power lasers in a separate facility

• The technology for the 15-20 MW LIFE diode pumped solid state laser (DPSSL) will be prototyped at the modular level.
  — One LIFE-let ~100 kW is the “building block”

• Management of the fusion environment to demonstrate laser beam propagation, full life-cycle testing of thermal pulsing of 1st wall, and adequate lifetime of final optics will be performed in scaled experiments

• Ion beam-based accelerated testing coupled with multi-scaled modeling will be used to design and validate fuels and structural materials
We are also exploring advanced LIFE concepts. The most promising is Fast Ignition.

Fast ignition targets compress more fuel to ignition conditions with less laser energy, providing higher gain.

Fuel Mass = 0.24 mg
Capsule kinetic energy = 15 kJ

Fuel Mass = 0.9 mg
Capsule kinetic energy = 12.5 kJ

20 MJ of fusion yield for a Gain of 17
90 MJ of fusion yield for a Gain of 112

Hot Spot Ignition fuel assembly

Fast Ignition fuel assembly
Indirect drive Fast Ignition has the potential of being compatible with low incidence angle illumination.

Possible Low Incidence Angle Indirect Drive Fast Ignition Target

- Symmetry requirements relaxed, allows low incidence angle illumination
- Lower drive pressures/Tr, i.e. LPI issues relaxed, allows longer wavelength driver ($2\omega$)
Fast ignition thus offers the possibility of more attractive chamber options and 530 nm compression lasers.
Different targets result in different chamber sizes and plant electric output.

- **37.5 MJ @ 13.3 Hz**
  - 1150 MWe
  - 2.5 m chamber

- **100 MJ @ 10 Hz**
  - 2400 MWe
  - 4 m chamber

- **125 MJ @ 8 Hz**
  - 2330 MWe
  - 4.5 m chamber
  - 530 nm laser

- **37.5 MJ @ 13.3 Hz**
  - 1070 MWe
  - 2.5 m chamber
  - 350 nm laser

**FI systems**
- 20° incidence half angle
- 530 nm compression @ 200 eV
- $E_{\text{ign}} = 150 \text{ kJ @ 1060 nm}$

**HSI Systems with NIF geometry illumination**

**Fission gain** = 6

**Laser efficiency** = 10%

**Thermal-to-electric conversion efficiency** = 43%