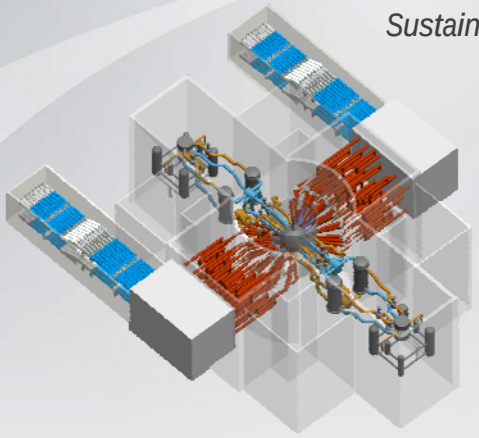
Laser Inertial Confinement Fusion-Fission Energy

Sustainable, carbon free energy for the planet

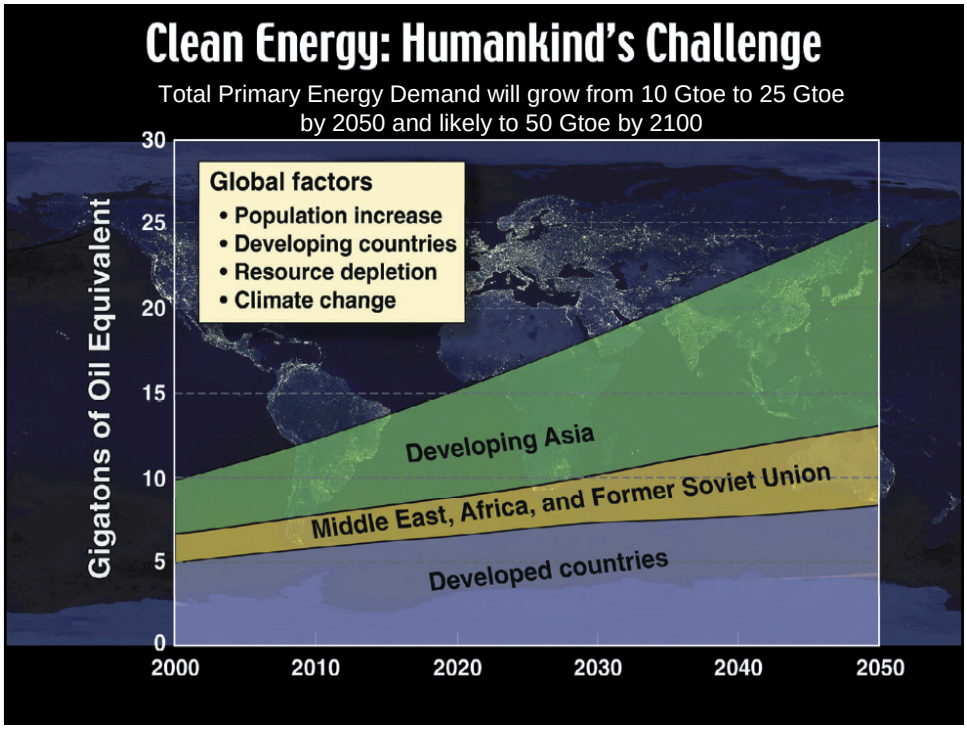


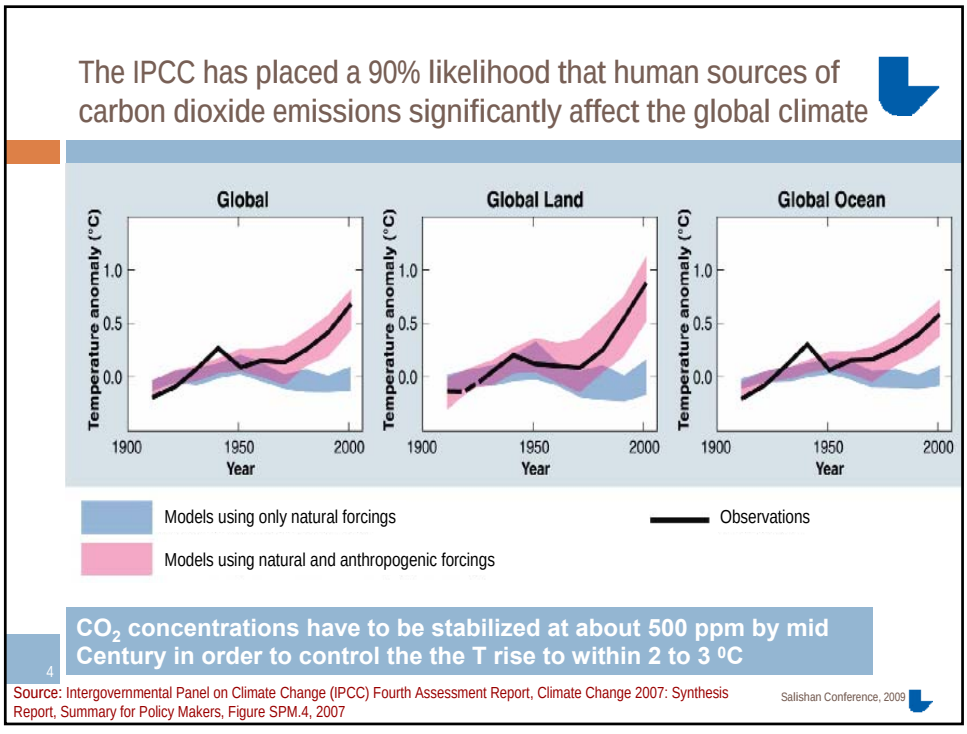
Salishan Conference
April 28, 2009

Tomás Díaz de la Rubia
Laboratory Chief R&D Officer
Lawrence Livermore National Laboratory

A few factoids related to energy and carbon

- Today, fossil fuels account for 80% of global energy demand
  - One swimming pool per second of oil consumed worldwide
  - 50% of electricity production in the U.S. is from coal
  - China is building 1 new coal-fired power plant every 4.5 days
- Human CO_2 emissions into the atmosphere amount to approx. 27 $GtCO_2/yr$
  - Current CO_2 concentration is about 380 ppm; approximately 100 ppm more than pre-industrial levels, and continues to rise
  - According to the ice core data, this already exceeds by far the natural range over the last 650,000 years (180 – 300 ppm)
- Carbon-free nuclear energy accounts for 16% of worldwide electricity production and represents 21% in the U.S.
- Only 0.4% of total global energy demand is met by solar, wind or geothermal energy


Clean Energy: Humankind's Challenge
Total Primary Energy Demand will grow from 10 Gtoe to 25 Gtoe by 2050 and likely to 50 Gtoe by 2100
Global factors
• Population increase
• Developing countries
• Resource depletion
• Climate change
Gigatons of Oil Equivalent
30
25
20
15
10
5
0
2000
2010
2020
2030
2040
2050
Developing Asia
Middle East, Africa, and Former Soviet Union
Developed countries


The IPCC has placed a 90% likelihood that human sources of carbon dioxide emissions significantly affect the global climate
Global
Global Land
Global Ocean
Temperature anomaly (°C)
1.0
0.5
0.0
1900
1950
2000
Year
Models using only natural forcings
Models using natural and anthropogenic forcings
Observations
CO2 concentrations have to be stabilized at about 500 ppm by mid Century in order to control the the T rise to within 2 to 3 ºC
4
Source: Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, Climate Change 2007: Synthesis Report, Summary for Policy Makers, Figure SPM.4, 2007
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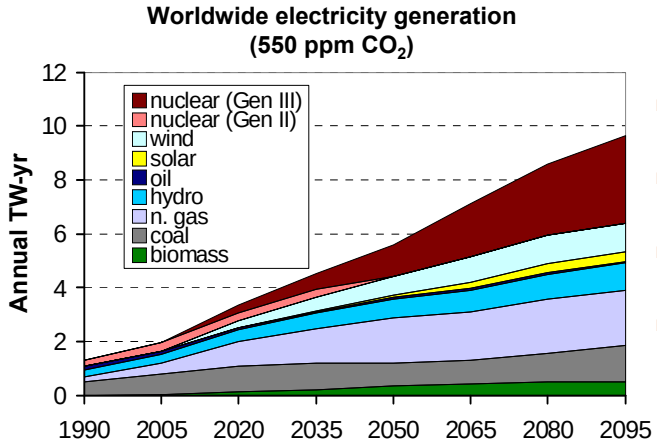
Reducing emissions by 50% (of today's level) by 2050 stabilizes CO_2 at 450 – 550 ppm but represents a tough challenge*



- 4000 new nuclear reactors
- CCS effective at $20/MWhr
- 3 Million 1 MW wind turbines
- Four times more hydro power

* Source: International Energy Agency, Energy Technology Perspectives 2008; Executive Summary,

To Paraphrase NY Times Columnist Thomas Friedman …

We have two options:

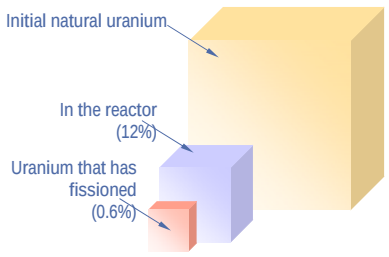
1. *Things are so bad … let's party … or*
2. *"… But we also need to make a few big bets on potential game-changers: systems that could give us abundant, clean, reliable electrons and drive massive innovation in big lasers, materials science, nuclear physics and chemistry that would benefit, energize and renew many U.S. industries". New York Times, Sunday, March 16, 2009*

The revolutionary should be pursued in parallel with the evolutionary

Nuclear power could be used to provide carbon-free energy

+ Positive
  - It contributes no greenhouse emissions
  - Fuel is plentiful and (for now) cheap
  - New reactor designs are safe and economical over time
  - Generates 1000's MW of baseload electric power with 90% capacity factor
- Negative
  - There is no accepted solution to the radioactive waste disposal problem
  - There are nuclear weapons proliferation concerns
  - There is a "residual" fear of radioactivity through the weapons association and things like the Chernobyl accident

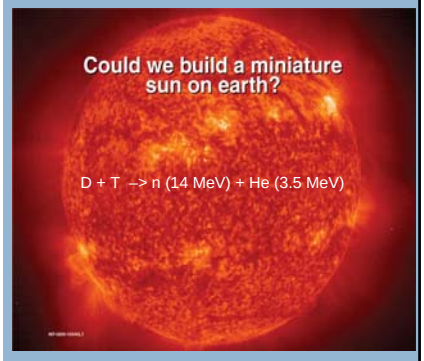
Fraction of uranium in nuclear reactors



Thermal Reactors utilize only a very small fraction (<3%) of the energy content of the fuel. The rest is disposed off as high-level, long-lived nuclear waste

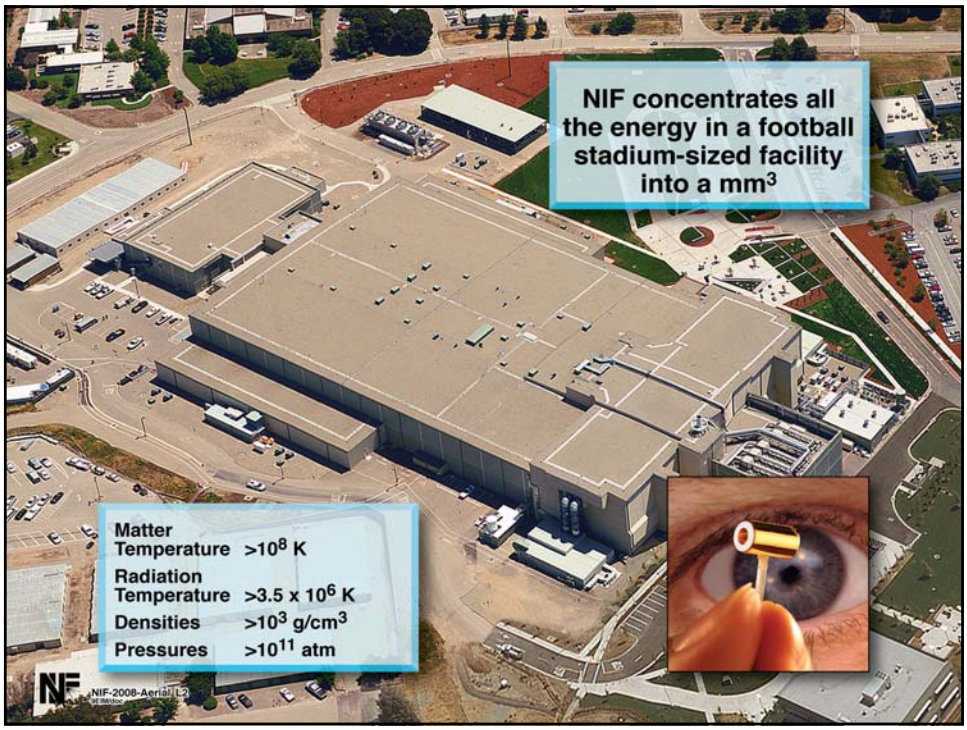
Fusion Energy

+ Positive
  - It contributes no greenhouse emissions
  - Fuel is plentiful and cheap
  - Future reactor designs are safe
  - Produces lots of neutrons
  - Generates 1000's of MW
- Negative
  - There is no "physics" demonstration yet
    - It has been 50 years away. Will it always be 50 years away?
  - The neutrons are not very energetic
  - There are significant engineering and cost concerns associated with generating commercial scale power through pure fusion



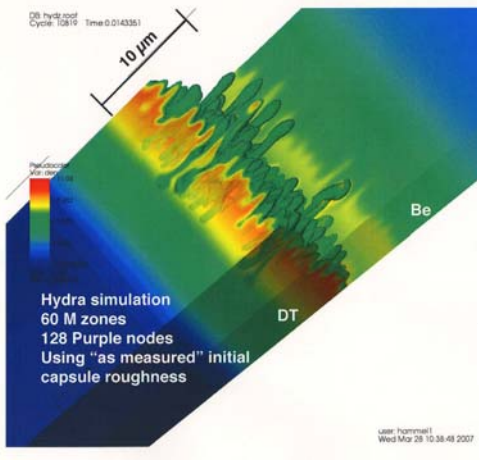
Fusion generates lots of neutrons but is not a very efficient process for generating electricity


National Ignition Facility
February 26, 2009; 2 AM
• 192 Beams delivered to Target Chamber Center

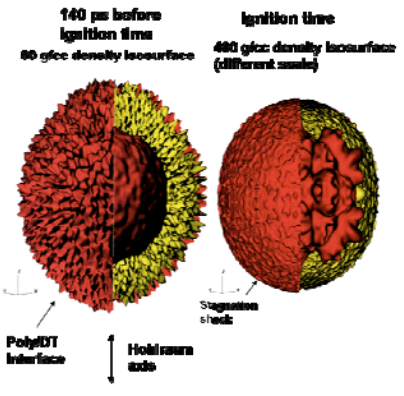

NIF concentrates all the energy in a football stadium-sized facility into a mm3
Matter Temperature >10^8 K
Radiation Temperature >3.5 x 10^6 K
Densities >10^3 g/cm^3
Pressures >10^11 atm
NIF-2008-Aerial-L2

Full 3D calculations of ICF point design are needed to assess sensitivity to perturbations at all wavelengths

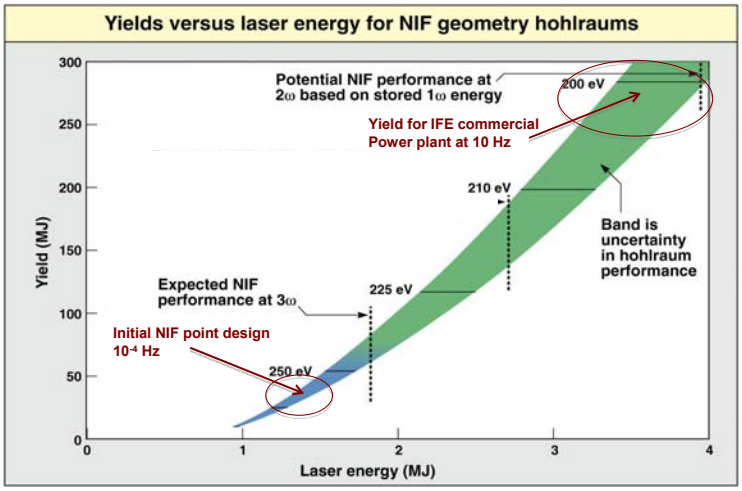
High mode mix at the DT:Be interface as capsule approaches peak V (@14.3 ns)



3D simlations of RT growth of surface perturbations



Ultimately, fusion yields well in excess of 250 MJ may be possible on NIF



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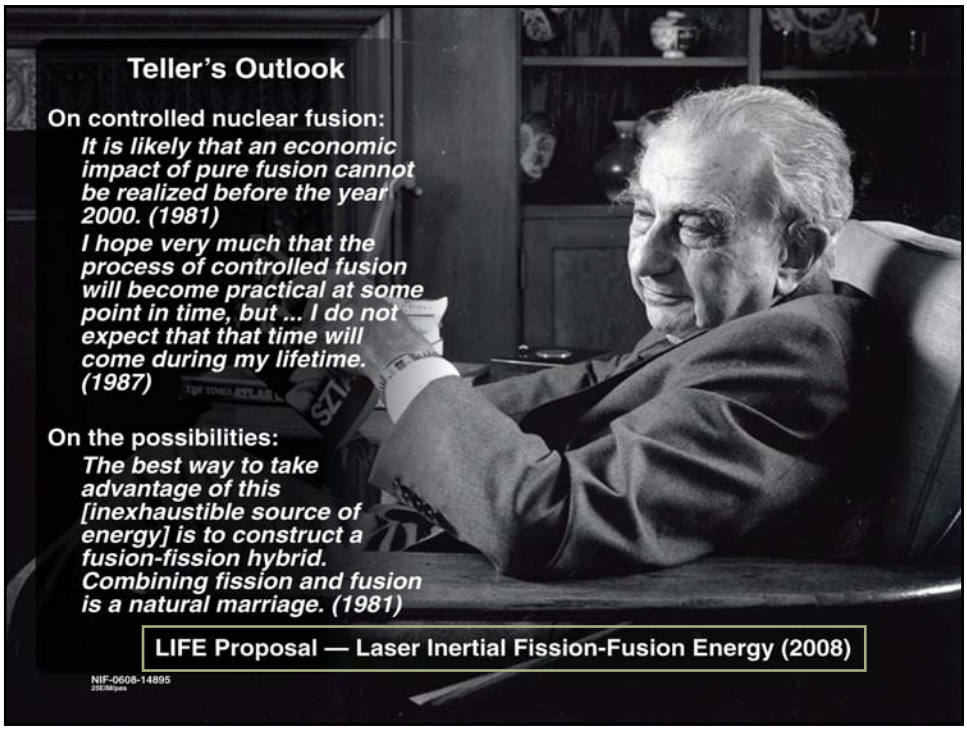
NIF-0107-13186

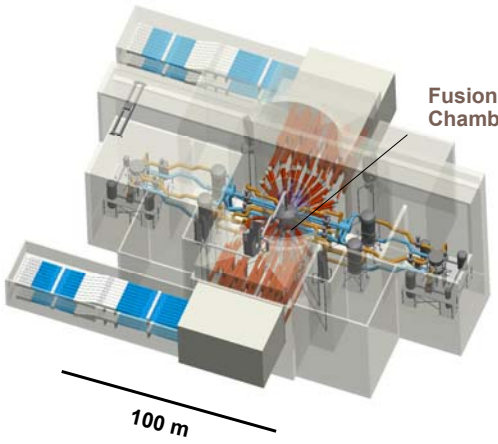


Why are fusion-fission hybrids interesting?

- Combine a copious source of neutrons (fusion) with a plentiful source of energy (fission)
- Promise of thousands of MWe from a modest fusion source
- Subcritical (safe) fission system
- No need for enriched fission fuel
- Promise of no need for spent fuel reprocessing
- Promise of 99%+ utilization of energy content of fission fuel
- Promise of greatly reduced volumes of spent nuclear fuel

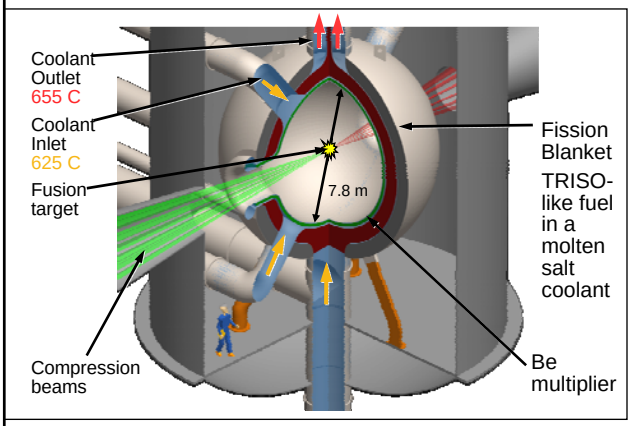
Fusion-Fission offers the promise of once-through, closed nuclear fuel cycle

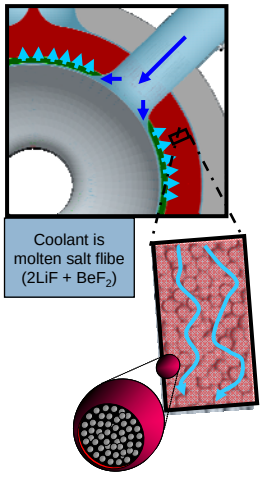
The LIFE vision is to provide the world with sustainable, carbon-free energy via a once-through, closed nuclear fuel cycle

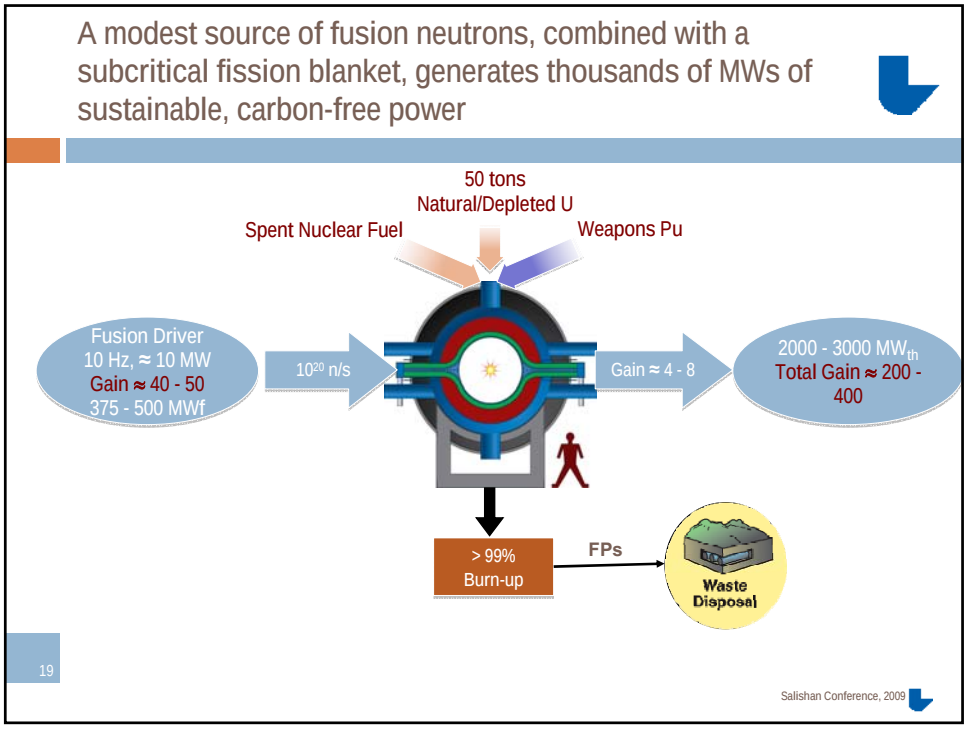


LIFE is a logical and credible extension of NIF, NIC and ongoing developments in the world nuclear power industry

In a fusion-fission LIFE engine, the fusion target is surrounded by a spherical, subcritical fission fuel blanket






A modest source of fusion neutrons, combined with a subcritical fission blanket, generates thousands of MWs of sustainable, carbon-free power
50 tons
Natural/Depleted U
Spent Nuclear Fuel
Weapons Pu
Fusion Driver
10 Hz, ≈ 10 MW
Gain ≈ 40 - 50
375 - 500 MWf
10^20 n/s
Gain ≈ 4 - 8
2000 - 3000 MWth
Total Gain ≈ 200 - 400
> 99%
Burn-up
FPs
Waste
Disposal
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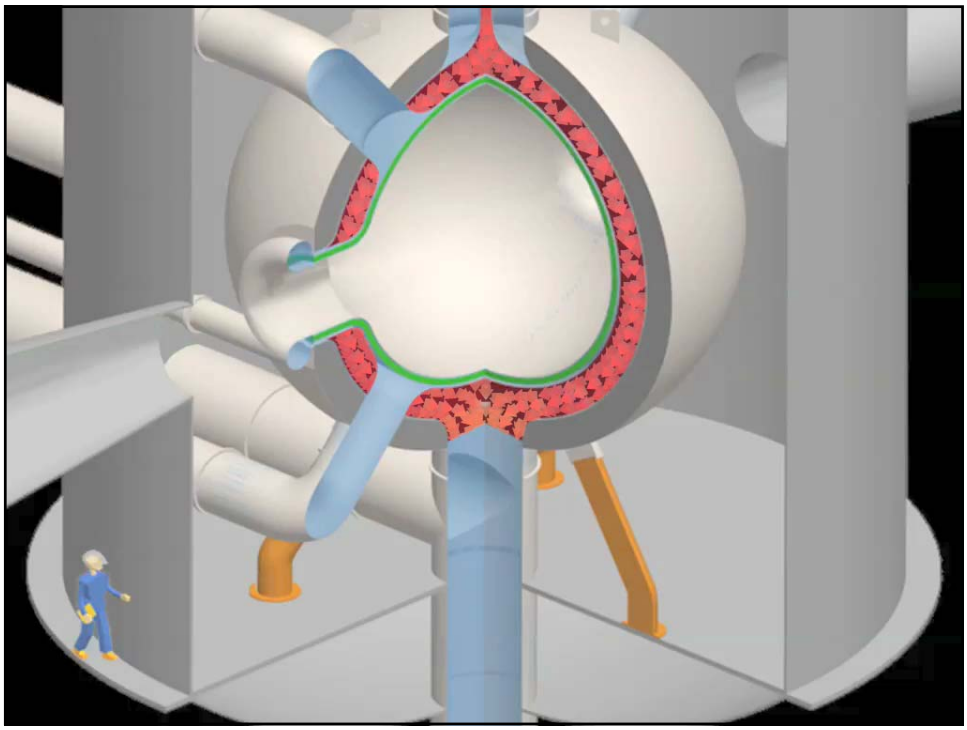
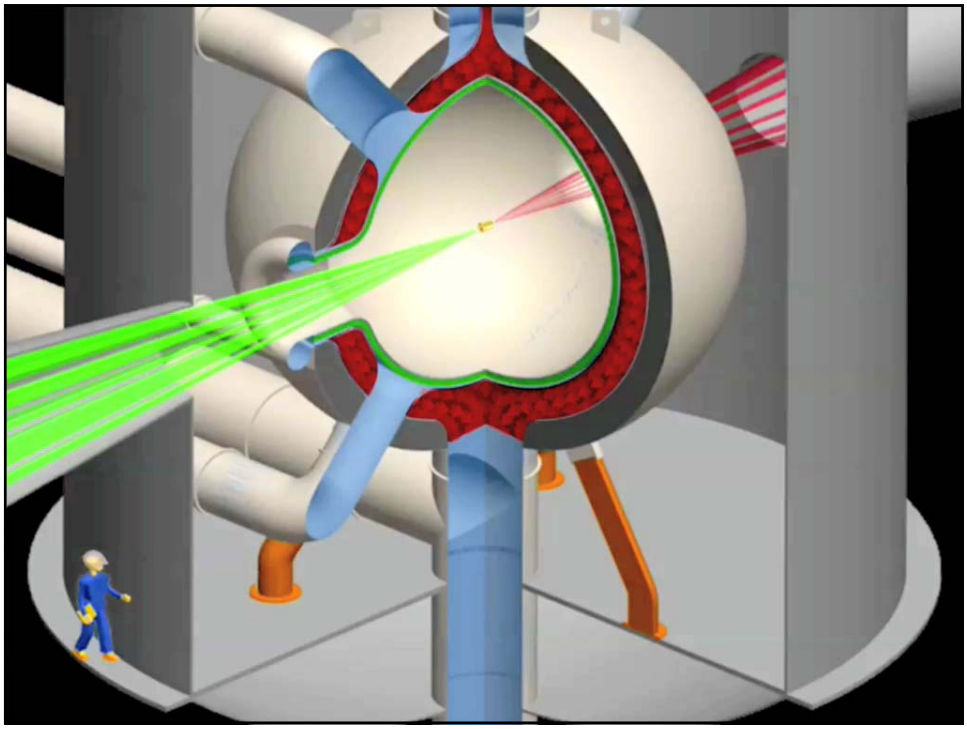
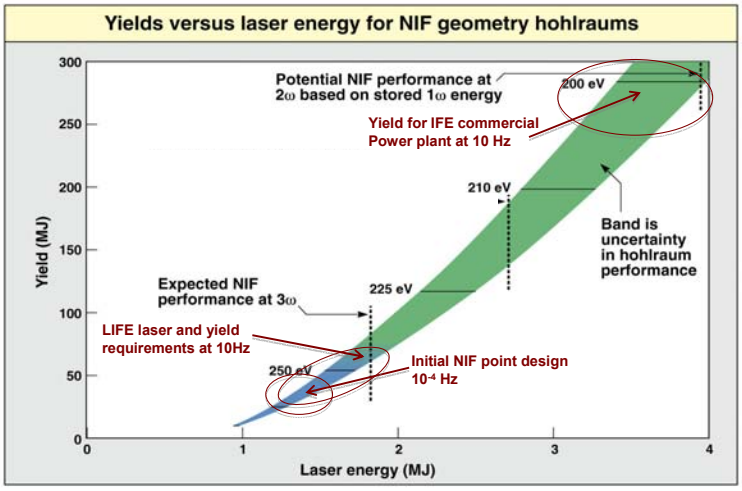




Laser and fusion gain requirements for LIFE are within a generation of NIF's design



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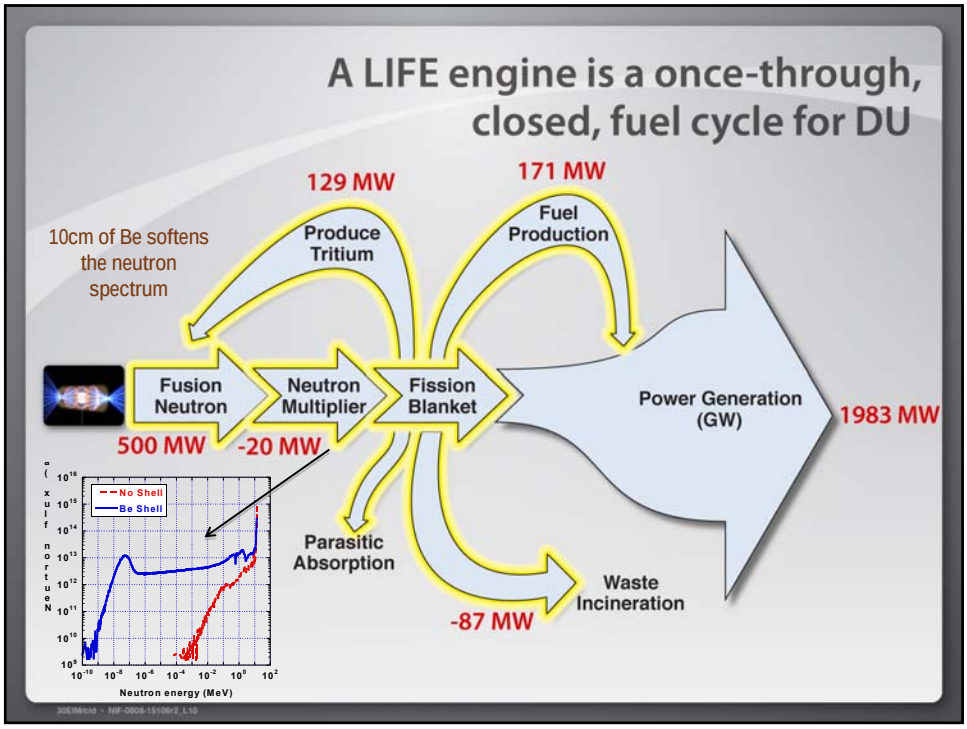
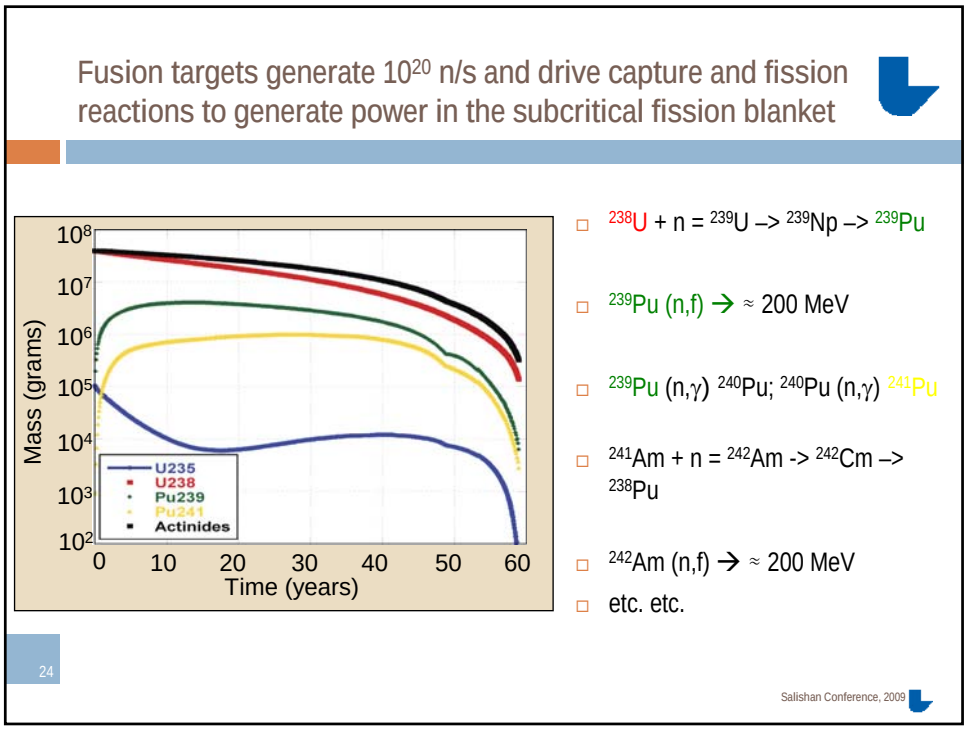

A LIFE engine is a once-through, closed, fuel cycle for DU
129 MW
171 MW
10cm of Be softens the neutron spectrum
Produce Tritium
Fuel Production
Fusion Neutron
Neutron Multiplier
Fission Blanket
Power Generation (GW)
1983 MW
500 MW
-20 MW
No Shell
Be Shell
Neutron energy (MeV)
Parasitic Absorption
Waste Incineration
-87 MW


Fusion targets generate 10^20 n/s and drive capture and fission reactions to generate power in the subcritical fission blanket
Mass (grams)
Time (years)
U235
U238
Pu239
Pu241
Actinides
238U + n = 239U –> 239Np –> 239Pu
239Pu (n,f) → ≈ 200 MeV
239Pu (n,γ) 240Pu; 240Pu (n,γ) 241Pu
241Am + n = 242Am -> 242Cm –> 238Pu
242Am (n,f) → ≈ 200 MeV
etc. etc.
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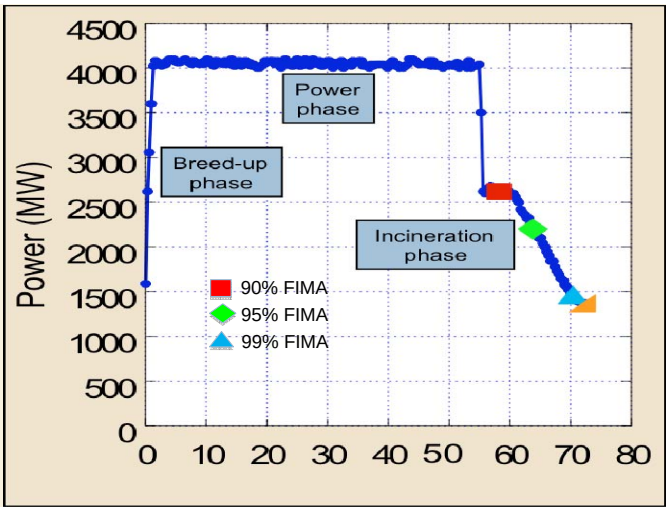
Starting from 40 MT of unenriched, depleted U, a LIFE engine can generate 4000 MW for 50 years without refueling



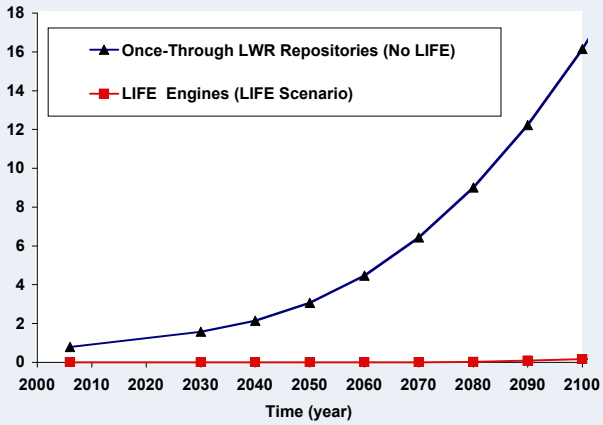
LIFE extracts virtually 100% of the energy content of the uranium fuel with minimal actinide high-level waste

	Burn-up			
Mass	90% FIMA	95% FIMA	99% FIMA	99.9% FIMA
^{235}U	8.9 kg	4.7 kg	66 g	92 µg
^{237}Np	8.6 kg	4.6 kg	610 g	46 mg
^{239}Pu	470 kg	150 kg	7.7 kg	4.7 g
^{241}Am	25 kg	5.5 kg	24 g	< 1 µg
^{246}Cm	130 kg	140 kg	9.9 kg	6.6 kg
Total Actinides	4.0 tons	1.9 tons	340 kg	10 kg

LIFE can achieve >90% fuel burn up and spent fuel pebbles meet Attractiveness Level E of DOE Graded Safeguards (USDOE 474.1-1B)

LIFE engines minimize the requirements for geologic waste repositories

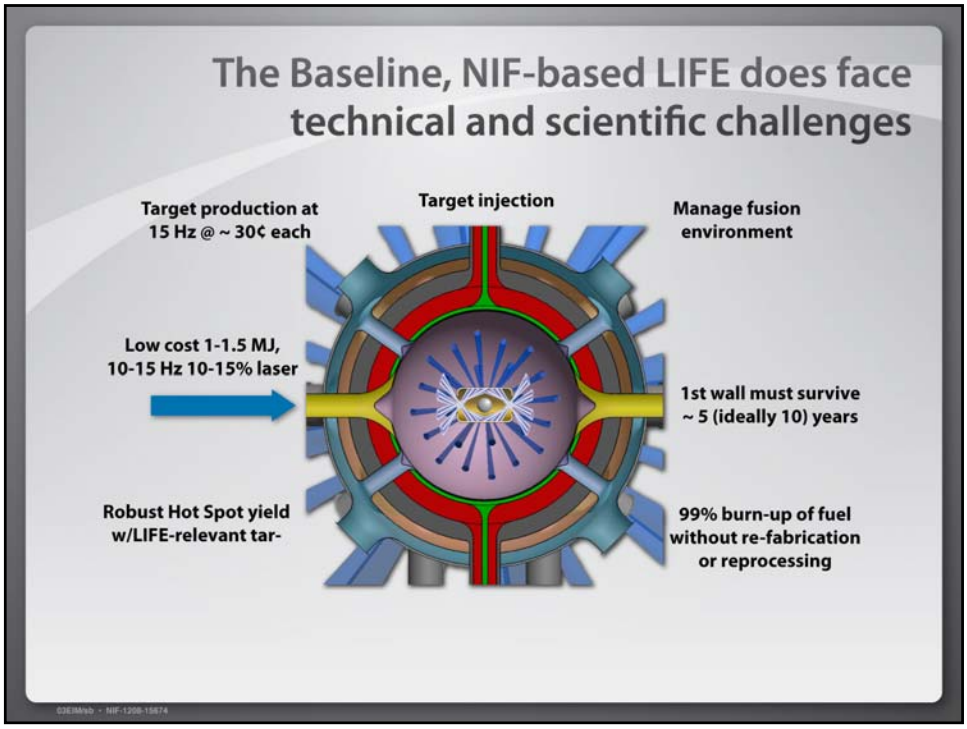
Yucca Mountain Equivalent Repositories through 2100 based on YMP statutory limit (70,000 MT) and 50% U.S. electricity scenario



Waste streams (DU, SNF) from existing fuel cycle could provide fuel for more than a thousand years

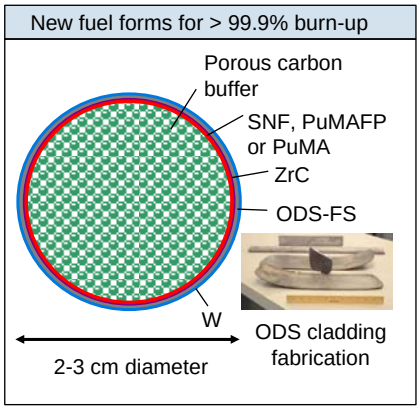
- Existing SNF from LWRs could supply 75 TWe-yrs, which is the entire U.S. electricity demand from now through 2100
- The accumulated SNF through the end of the century could provide U.S. electricity needs beyond 2100 (2 to 2.5 TWe) for another hundred years
- The DU could supply over 2TWe for an additional thousand years

This amount of fuel is the equivalent of $1000T worth of electricity at today's rates



ODS-clad Solid Hollow Core pebbles offer an attractive first step for solid fuel LIFE options

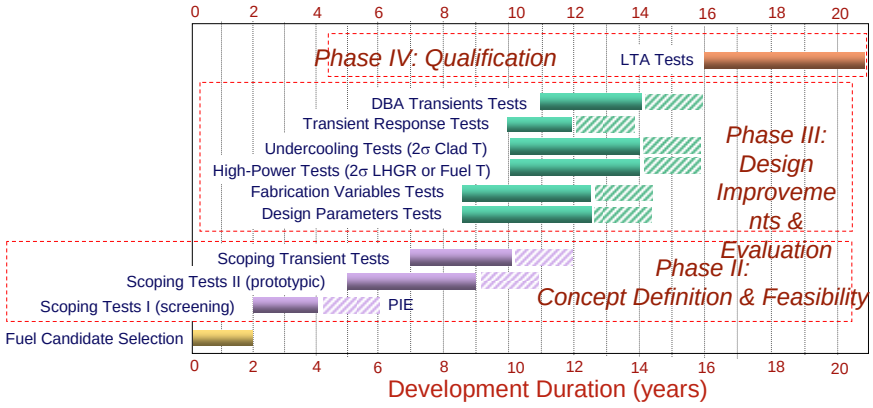
- DU to 99.9% FIMA with ~150 dpa to ODS cladding
  - — No enrichment
  - — Blanket gain of 4
  - — 33× better resource use (GWe/MT) than LWR
- LIFE waste contains few actinides
  - — Total actinide mass is ~21 kg
  - — Pu is only 190 grams
- Segmented blankets will defer / eliminate the incineration tail



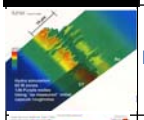
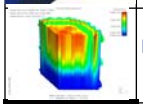
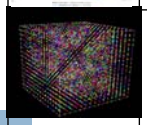
ODS-FS cladding solution is applicable to all versions of LIFE engine

Qualification of a new nuclear fuels and materials currently takes a minimum of 20 years

Source: K. Pasamehmetoglu, D. Crawford. GNEP Fuel Development Road Map



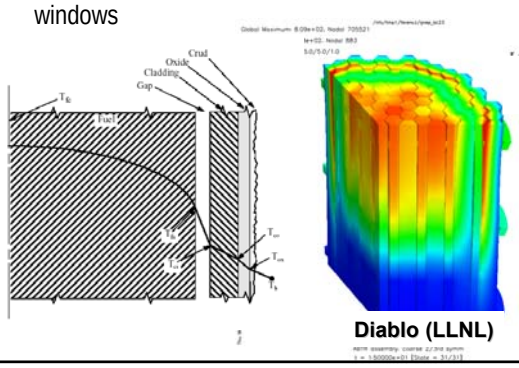
Petascale systems will enable LIFE and other energy technologies

Area		Petascale Applications	TeraFLOPS	PetaFLOPS	ExaFLOPS
	Environment and Climate	Ocean, atmosphere, and land coupled climate models	Greenhouse gas effects 100–1,000 multicentury coupled climate simulations 50-km resolution	Energy technology consequences 100–1,000 century-long earth system model simulations 50-km resolution	High-resolution earth system Century-long simulations 1-km resolution
	Fusion Targets	3D Hydrodynamics and Fusion Ignition	ICF Capsule wedge with mid-mode perturbations	Full 3D hydro simulations with manufactured geometries and surface roughness	Fully 3D atomistic hydrodynamics simulations of capsule implosions
	Nuclear Rector Physics	Neutronics, CFD, Thermo-hydraulics	Reactor core sections Turbulent flow	3D fuel simulations with materials constitutive models Two-phase flow	Full Monte Carlo neutronics Full Reactor CFD
	Fuel and Structural Materials	Design, development and testing of new materials	Band gaps in alloys, molecular behavior in simple fluids 10s of atoms with fully quantum mechanical, ab initio calculations	Molecular motion in confined geometries, kinetics of phase change 10s of thousands of atoms with ab initio codes	10s of millions of atoms ab initio codes (would require algorithm development)

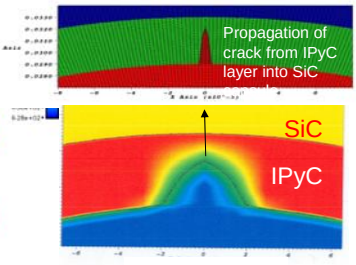
Multi-physics codes on high-performance computers have the potential to increase the design efficiency of LIFE

- Current fuel performance codes rely on 1.5D simulations using empirical model database obtained from LWR and SFR irradiations
- Lack of geometric and constitutive model complexity yields narrow operational windows

- ASC codes have been modified to analyze these systems in full 3D with geometric perturbations and materials variability
- High-throughput for fuel design requires dedicated access to Petascale HPC



Diablo (LLNL)



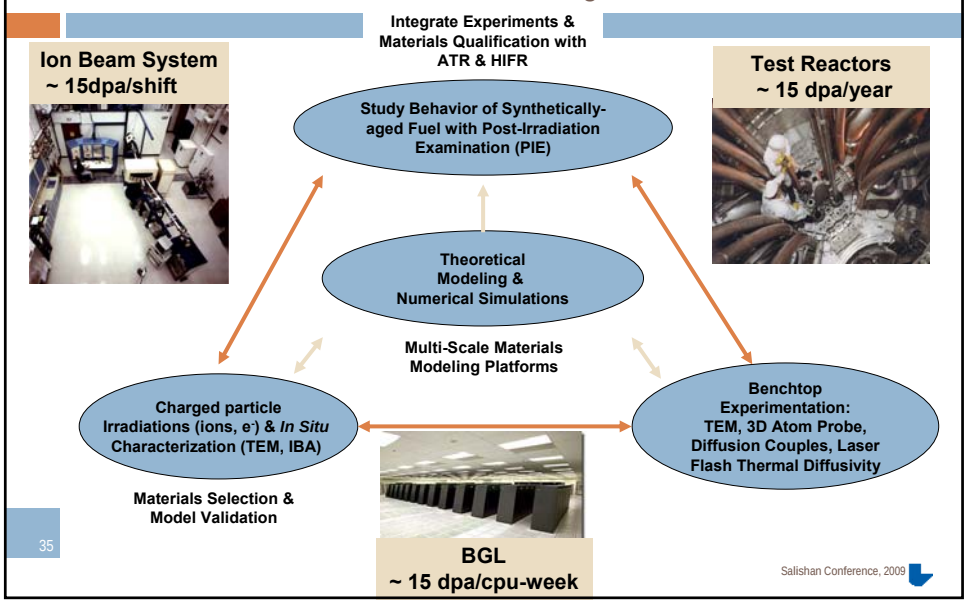
ALE3D (LLNL)

We are applying the stockpile stewardship method of weapons certification to nuclear fuel qualification

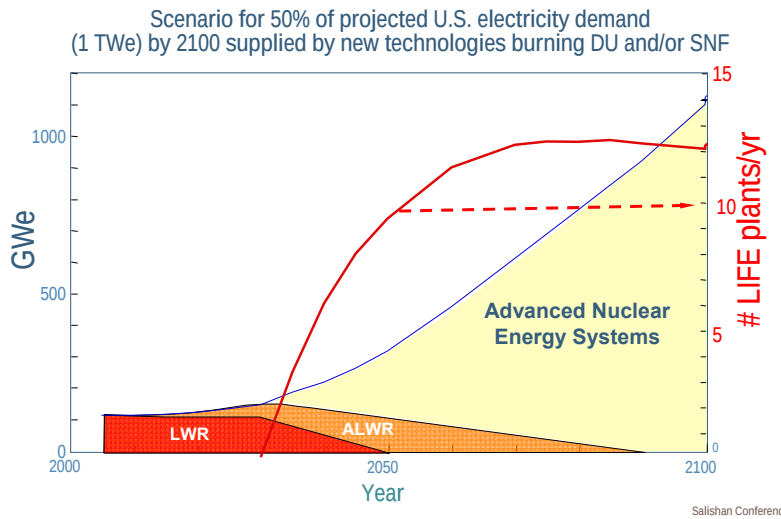
New irradiation test facilities that are able to reproduce the irradiation conditions anticipated in the LIFE environment will be need for V&V

- Elements of Strategy
  - Apply QMU methodology to large scale multi-physics simulations to guide requirements for improvements constitutive model fidelity and accuracy
  - Employ a multi-scale modeling paradigm to build physics-based constitutive models accurate in a wide operational window
  - Develop an out-of-pile experimental capability to benchmark and validate mechanistic constitutive models
  - Employ synthesis chemistry capabilities to accelerate aging studies of relevant fuel chemistries with short reactor exposures.

Credibility of Qualification Case Relies on our Ability to Capture and Predict Fuel Behavior in a Wide Range of Conditions



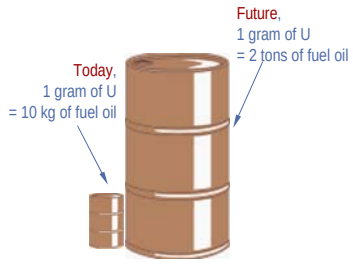
Starting in 2030, LIFE could help satisfy increasing U.S. baseload electricity demand



LIFE, a Fusion-Fission Energy system combines the best aspects of nuclear fusion and fission – neutrons and energy

- Generate 1000's MW of base load, carbon-free electricity
  - Fusion source 10x smaller than a fusion plant
  - LIFE engine fission blanket is subcritical and passively safe
  - No U enrichment required
  - Utilizes virtually 100% of the energy content of the nuclear fuel
  - No chemical separation and reprocessing
  - Waste form contains less than 1% long lived actinides
  - Extends the life of the Yucca Mountain Geologic Repository by over factor of 20
- Burn all of the existing and future LWR Spent Nuclear Fuel to generate electricity
- Burn excess weapons Pu without MOX

Extract the energy content of nuclear fuel and minimize nuclear waste and proliferation concerns



The LIFE engine enables the development of sustainable energy for the planet

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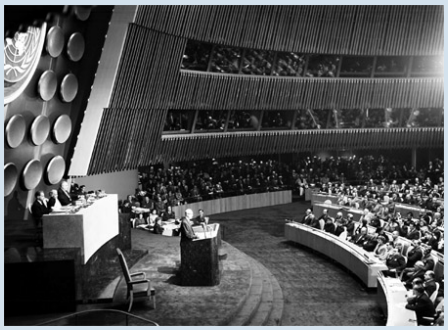
"Atoms for Peace" … and LIFE



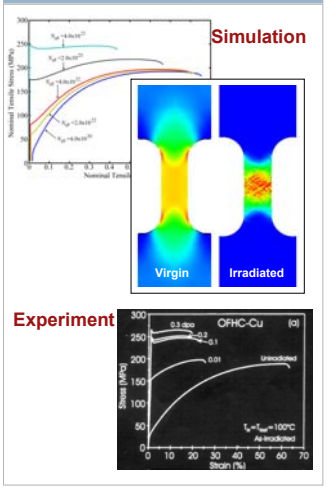
"To the making of these fateful decisions, the United States pledges before you – and therefore before the world – its determination to help solve the fearful atomic dilemma –to devote its entire heart and mind to find the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life."

President Eisenhower, December 1953

Multiscale Materials Modeling and Simulation can help accelerate the development of advanced materials

- Provide a sound scientific basis for the design and development of new nuclear fuels, cladding and structures
- Narrow the parameter space that must be experimentally investigated
  - Predict swelling, evolving fuel chemistry, mechanical integrity, etc.
  - Evaluate compatibility of cladding options with various combinations of fuel and coolant
  - High confidence extrapolations of fuel element performance to large irradiation doses - reduce uncertainty
- Performance models coupled with "neutronics" packages will create robust fuel design software
  - Identify life limiting mechanisms and test solutions

Materials performance for LIFE fuel design



Straightforward Conclusions

- The energy technology/environmental impact issue will achieve comparable status with national security as a long term driver of US policy
- Even if you don't care (or believe) in the environmental impact, the decrease in the supply of affordable oil will have to be dealt with
- The perceived sense of impending climate change/energy insecurity will be a crucial element in determining national policy
- Crises - either energy based or environmental - can be important catalysts in producing rapid policy changes
- It will take luck, skill, and aggressive leadership to cope with the challenges created by the energy use/environmental and economic impact dilemma of the current world

Materials modeling and simulation will reduce design uncertainties leading to accelerated insertion of new materials at reduced cost

- Provide a sound scientific basis for the design and development of new nuclear fuels, cladding and structures and narrow the parameter space that must be experimentally investigated.
- Predict swelling, evolving fuel chemistry, mechanical integrity, etc.
  - Evaluate compatibility of cladding options with various combinations of fuel and coolant
  - High confidence extrapolations of fuel element performance to large irradiation doses - reduce uncertainty
- Performance models coupled with "neutronics" packages will create robust fuel design software
- Thermo-mechanical performance of a fuel pin in service conditions
- Identify life limiting mechanisms and test solutions