TerraPower
2006 to 2016
&
New Nuclear Benefits and Costs
University of Michigan
TerraPower’s Start

• Poverty propagates without energy; the impacts are pervasive. Commercially viable technologies will help accelerate economic development.

• The world needs safe, clean, affordable energy quickly.

• Today, a fifth of the world’s population doesn’t have access to reliable electricity. By 2040, the world’s population will increase and energy demand will grow.

• TerraPower was created to maximize the potential that fission energy has to offer.
TerraPower Today

- Innovation Center
- Privately Funded by Visionaries
- Mission Driven
- Construct and Demonstrate
- International: Best Performer & Biggest Impact
contemplative awe
profound feelings
Beauty, Guilt, Action
Electric Energy is Essential to Quality of Life

About 3,000 kWhrs/yr is necessary to have what we consider a good life.

Source: http://hdr.undp.org/en/content/human-development-index-hdi
While Facing the Consequences of CO₂

“No challenge poses a greater threat to future generations than climate change.” – President Barak Obama

“Climate change does not respect borders; it does not respect who you are – rich and poor, small and big. Therefore, this what we call global challenges, which require global solidarity” – Ban Ki-moon

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Source: U.S. National Oceanic and Atmospheric Administration (NOAA)
In 2016 – the World Acknowledges the Challenge

Photo credit: Gobierno de Chile, "Ceremonia de lanzamiento de la Iniciativa "Mission Innovation", November 30, 2015, Creative Commons Attribution 2.0 Generic License from http://mission-innovation.net/
Early 2007 – Findings

• Nuclear is an essential element of any global carbon reduction solution.

• The entire nuclear enterprise should be and can be improved with 21st century engineering, data and technologies.

• A Company should be founded to meet the challenge.
Ecomodernist Solution

• Initial question: In a world that requires an 80% reduction in CO₂, how do we ensure access to energy while minimizing the impact to our environment?

• “Ecomodernism” proposes that urbanization and technology are the solution, not the problem, for those suffering from energy poverty

• Traditional environmentalists have advocated a turn away from technology and a return to a lifestyle from an earlier age – this approach ignores both the size of the problem we face and the realities of the developing world

• Ecomodernism advocates the decoupling of human well-being from environmental impacts
  • Decoupling energy production from the environmental impacts requires finding CO₂ free energy sources that are scalable to meet the size of the world’s energy needs – today only nuclear power meets these criteria
2006: Gates

- Nuclear is an essential element of any zero carbon answer to climate change.
- The entire nuclear enterprise should be and can be improved with 21st Century post-digital-age modeling, data and technologies.

2015: Ecomodernist Manifesto:

- “Only high energy density technologies can provide means to meet low carbon energy goals without unacceptable impacts on nature.”
- “Nuclear fission today represented the only present-day zero carbon technology with the demonstrated ability to meet most, if not all, of the energy demands…”
- “A new generation of nuclear technologies that are safer and cheaper will likely be necessary for nuclear energy to meets its full potential…”
“In a carbon-conscious world, nuclear power’s great advantages are not only the traditional ones of fuel diversification and self-sufficiency. It is also the only large-scale, well-established, broadly deployable source of electricity generation currently available that is carbon free.”
—Daniel Yergin, IHS Cambridge Energy Research
So What about Costs of New Nuclear?!?

• Based on our own direct experience the design and development activities will be in the range of a billion dollars

• The first reactor will cost a few billion dollars.
A Generation IV reactor must offer great new benefits on a total system-wide basis.

Without competitive costs new reactors are just theory, but ..... 

Government support is required to support technical development and to institute pricing of externalities.

Without rationale level-playing-field price subsidy policies, rationale energy selection is not possible.
Cost Comparison of Electrical Energy Sources

• Over two billion people in the poorest countries on earth face a dilemma
  • They need cheap, reliable and rapidly deployable base load power – which pushes these countries to build coal power plants
  • Coal plants increase health problems and mortality rates for the local communities (particulate, NOx, SOx, Mg)
  • Additionally, these emissions contribute to global climate change (CO2) – the impact of which disproportionately falls upon the poorest countries

• Only nuclear remain competitive with fossil fuels across the world
  • Onshore wind is very competitive in area with good wind resources – remains an intermittent source of electricity
  • Standardization of nuclear design, improved modularization of construction a growing supplier base are helping to reduce the uncertainty of nuclear construction cost

• On demand renewable power remains too expensive for widespread adoption
  • Renewable by themselves can provide low cost electricity in the right environments
  • To get reliable on demand power renewable must be coupled with storage technologies and these technologies remain very expensive

Source: International Energy Agency (IEA)

IEA 2015 Worldwide LCOE Comparison

Median
Range
The new reactor must favorably impact all aspects of the nuclear endeavor:

- Safety
- Weapons risk
- Terrorist risk
- Waste disposal
- Cost
- Fuel availability

The new reactor must rely on inventive use of existing technology.

Several basic concepts with hundreds of fuel and coolant combinations were evaluated.

Remarkably, the Traveling Wave Reactor met all the selection criteria.
So What is a Traveling Wave Reactor?

A traveling wave reactor is a once-through fast reactor that runs on subcritical reload fuel that is bred up to a useful state and burned in situ.

This mode of operation is sometimes visualized as a reactor in which breed-burn waves and the fuel move relative to each other.
TWRs can operate with reload fuels including depleted uranium, natural uranium, and low-enriched fuel which ordinarily would not be critical in a fast spectrum.
One Approach to Lower Cost: Simplify Nuclear Infrastructure

- Uranium mining and milling
- Conversion to uranium hexafluoride
- Uranium enrichment
- Fuel fabrication
- Long-term geologic repository
- Depleted uranium storage
- Spent fuel storage
- Nuclear power generation
- Actinide fuel fabrication
- Reprocessing
Depleted Uranium: Very High Energy Content When Used in TWRs

In a TWR, 1 cylinder of DU can yield years of electricity for the ~850,000 people in San Francisco.

Twelve Ton Type 48Y UF₆ Cylinder = More than 2 Years of Electricity for San Francisco
TerraPower’s Traveling Wave Reactor

- Provides **energy security** for all nations for centuries by using waste uranium
- Improves **safety** through passive systems
- Reduces **costs** through fuel cycle simplification and large fuel reductions
- Reduces nuclear **waste**
- Enhances **environmental benefits**
- Reduces **proliferation** risk
- Enables a global nuclear **export market**
- Improves **public acceptance** of nuclear power
The Traveling Wave Reactor

A Change to Cylindrical Geometry Has Advantages

• Fresh fuel is moved into the wave
• The burning region remains stationary
• Exhausted fuel is moved to outer rings
Family of TWRs

Linear Geometry (e.g., Candle, Prismatic...)

Toroidal Geometry

Cylindrical Geometry (e.g., Standing Wave)
TWR-C Fuel Cycle

73 MT enriched uranium
228 MT depleted uranium
(Initial Core)

Year
0 10 20 30 40 50 60

46 MT Depleted
46 MT Depleted
46 MT Depleted
46 MT Depleted
46 MT Depleted

46 MT spent fuel removed
46 MT spent fuel removed
46 MT spent fuel removed
46 MT spent fuel removed
46 MT spent fuel removed

254 MT of usable fuel from first TWR transplanted to next TWR + 46 MT depleted

46 MT Depleted
46 MT Depleted
46 MT Depleted
46 MT Depleted

46 MT spent fuel removed
46 MT spent fuel removed
46 MT spent fuel removed
46 MT spent fuel removed

276 MT spent fuel

MT = Metric Ton of Uranium or Heavy Metal

TWR-C runs only on depleted uranium after initial core. **Reuse of fuel** in a “Successor” TWR significantly **reduces radioactive waste.**

254 MT of usable fuel from prior TWR transplanted to next TWR

276 MT spent fuel

Spent fuel to Borehole

254 MT of usable fuel from first TWR transplanted to next TWR
Overall Safety Attributes

In any accident scenario the TWR will shut down and stay cooled with no need for external power, no operator action:

• Multiple features that assure shutdown:
  1. Redundant and diverse control and shutdown systems
  2. Inherent (passive) reactivity feedbacks that stabilize the reactor at low power even if redundant active shutdown systems fail
  3. Shutdown that occurs with no operator action or external power

Reason: Metal Fuel
Overall Safety Attributes

• Multiple features that assure **cooling**: 
  1. Low coolant pressure and “double hull” style vessel = no leaks 
  2. High boiling point & large volume of sodium coolant = no boiling 
  3. Coolant stays cool and *does not boil* due to redundant and diverse decay heat removal systems

Reason: Liquid sodium coolant
Instead of
Realities that Raise Nuclear Development Costs
TWR Fuel and Material Qualification

**Fuel Performance Modeling**
- Fabrication Development
- Fuel Qualification Integration

**NEUTRON IRRADIATION TEST PROGRAMS**
- ATR
  - Advanced Fuel Scoping
  - Fuel Behavior
  - Adv. Component Performance
- BOR-60
  - Fast Spectrum
  - HT9 and Other Core Materials
  - Fuel System Qualification
- TWR-P
  - Fast Spectrum
  - Prototypic, full size
  - Fuel System Qualification

**Supplies product**
**Supplies results**

**US Photonics, Veridiam**
- Adv. Component Fab

**U of Michigan**
- Ion Irradiations

**Kobelco, Veridiam**
- Cladding, Duct Fabrication
- Other Core Components

**LANL, PNNL, BWTS**
- Historic / pre-irradiated material

**MCE**
- Un-irradiated material

**IV Laboratories**
- Adv. Component testing

**UNLV, TAMU**
- FCCI studies, High BU Fuel Studies

**INL**
- Irradiation Testing Collaborator
- Fuel Fabrication Development
- EBR-II/FTF Historic Fuel Data
- Test Pin Fabrication
- Fuel Pin Shipping
- Post Irradiation Examination

**B&W/NFS**
- Commercial fuel fab

**QUALIFIED TWR FUEL**

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Fuel Designs & Manufacturing Supply Chain Development = $
TWR-P Core Layout

Includes:
- Driver & Feed Fuel Rods
- Control Rods
- Standby Rods
- Reflectors
- Radial Shields
Focus on design for manufacturability and assembly
Leveraged knowledge of fuel fabrication experts from FFTF and AREVA
Water flow testing performed to confirm design correlation and bundle $\Delta P$

Proven capability to manufacture TWR fuel assembly; testing results confirm pressure drop
Slay Risk Dragons Early

Fuel Development at Industrial Scale
Advice to Next Generation Innovators

• Set impossible sounding goals and ....
• Don’t be shy about your own ideas – particularly original ones.

• Think big – look at total global impact of your idea – not just reactor

• Give preference to invention over technology development

• Develop full suite of benchmarked design and evaluation tools and ...
• Conduct merciless sanity checks

• Slay the big risk dragons first .... or slip past them remembering that ..
• The perfect is the enemy of the good.
Study Well
Be Creative
Save Our World!
Thank you.
Background Information
The World’s Current Energy Breakdown

• Fossil fuels dominate the world’s energy usage
  • Fossils fuels have provided the world with convenient and inexpensive energy
  • Fossil fuels are an essential element to today’s economy

• More recently though fossil fuels role in our planet’s future has been questioned
  • Fossil fuels, and their resulting CO₂ emissions, are now recognized as a primary contributor to climate change
  • Fossil fuel commodity prices have become increasingly volatile making long-term resource planning nearly impossible

• “A cheap, clean source of energy would change everything” – Bill Gates
  • The world faces an epic challenge to create cheap, safe and CO₂ free energy that will enable the world to avoid the worst cases scenarios of climate change will also lifting much of the world out of poverty

• Nuclear is gaining momentum because of its lack of CO₂ emissions and low cost
  • China set a target of building 30 nuclear power plants in counties along the Belt and Road Initiative
  • 70 countries in total are planning or developing their own nuclear projects and it is estimated 130 more nuclear power plants will have been built by 2020

![Energy Breakdown Chart](chart.png)
Transportation fuel of the future – already here

• One gallon of gasoline produces 8,887 g/CO₂ when burned – equivalent of 10 kWh of electricity

• 10 kWh of electricity, including total life-cycle CO₂ production, produces:
  • 9,750 g of CO₂ from Coal
  • 6,000 g of CO₂ from NG
  • 900 g of CO₂ from Hydro
  • 550 g of CO₂ from Solar
  • 150 g of CO₂ from Nuclear
  • 150 g of CO₂ from Wind

• Increasing vehicle fuel efficiency can improve CO₂ emissions from cars but **large leaps are required** to dramatically reduce CO₂ emissions
  • The wind, solar, and nuclear electricity of today **can make an immediate impact on climate change** by shifting our transportation infrastructure from oil to electricity

Source: James Conca, U.S. EPA, UK Office of Science and Technology

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Count on volatility not low prices

- History shows that OPEC squabbles, wars in the middle east and global recessions all can drive oil prices up and down
  - Commodities in general, and oil specifically, are volatile commodities – makes long-term planning difficult or impossible
  - No reason to believe this volatility will subside or that we have reached a new long-term equilibrium price for oil
- Current world oversupply of oil will likely keep short to medium term prices low but it is the long-term prices that must drive policy
- Across the world people are driving more cars and are concentrating in large urban areas, this is creating two pollution problems:
  - Localized smog and particulate pollution driving up health care cost
  - Global CO₂ pollution problems warming the earth and creating erratic and deadly weather patterns

Source: Energy Information Administration