TerraPower, LLC

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September, 2010

TerraPower LLC

OUTLINE OF LECTURE

I. Introduction
II. Physics of Breeding and Conversion
III. TerraPower Initiative
IV. Traveling Wave Reactor
V. TerraPower Strategy
VI. Conclusion & Questions

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- Nathan Myhrvold started a company to invest in innovation, Intellectual Ventures.
- At an IV brainstorming session with Lowell Wood and others in 2006, the concept of the Traveling Wave Reactor was brought up as a solution to energy issues
- As interest from Bill Gates and others built, a team was assembled to determine the capabilities of the TWR
- TerraPower LLC was formed as the effort increased

Rolling Stone

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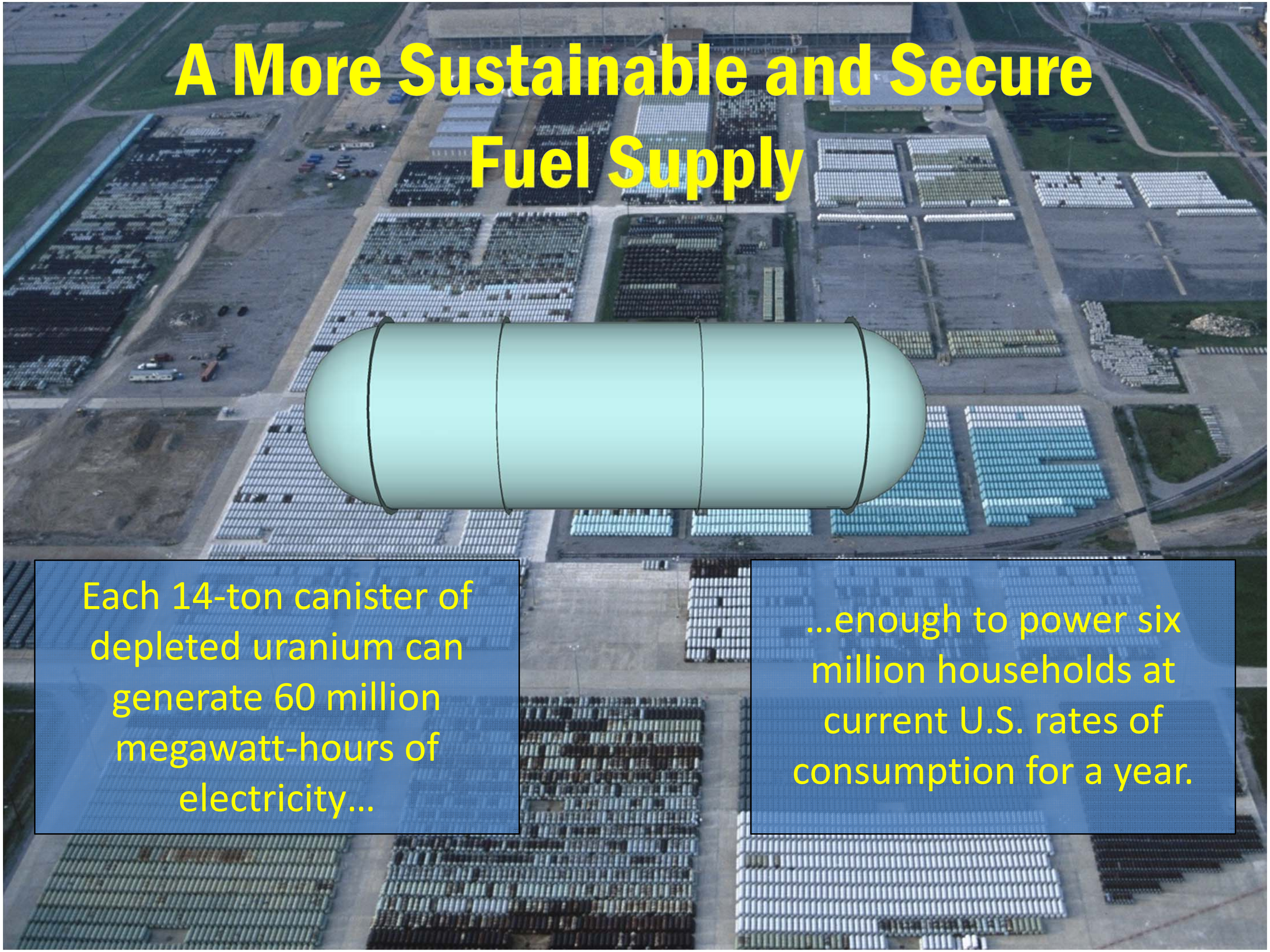
A More Sustainable and Secure
Fuel Supply
Each 14-ton canister of depleted uranium can generate 60 million megawatt-hours of electricity…
…enough to power six million households at current U.S. rates of consumption for a year.

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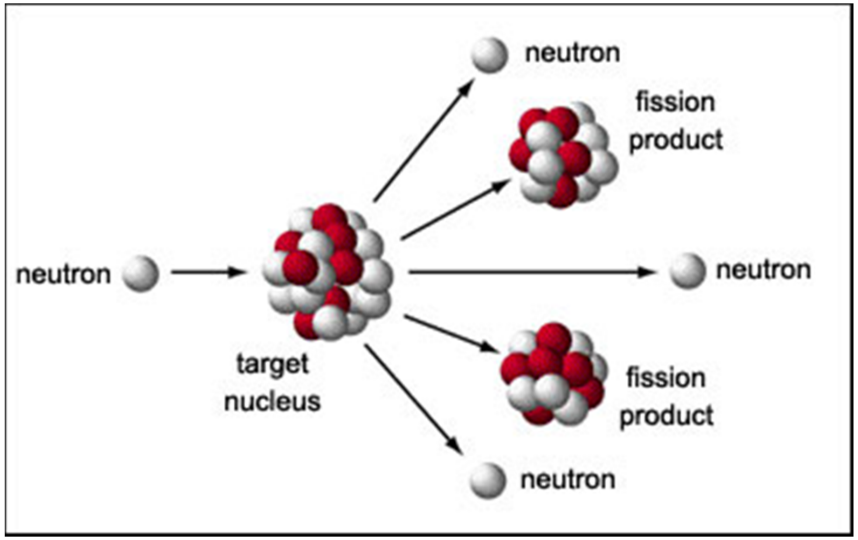
FISSION



2 or 3 neutrons produced

Average useful energy release ~200 MeV

Neutron energies ~ 1 MeV or ~14000 km/s (fast!)

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NUCLEAR MATERIALS

FISSILE: Can fission by absorption of a neutron with negligible kinetic energy

FERTILE:

1) Can fission by absorption of a neutron with substantial kinetic energy

   -OR-

2) Can absorb a neutron, become unstable, and

TRANSMUTE, or be converted, into FISSILE material

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NUCLEAR MATERIALS

FISSILE MATERIALS INCLUDE U233, U235, Pu239.

FERTILE MATERIALS INCLUDE Th232 and U238.

U235 is the ONLY Fissile Material in nature in ‘useful’ quantities

STILL only 0.7 % of natural U is U235.
Almost all the rest is FERTILE U238.

Th232 is more abundant than U.

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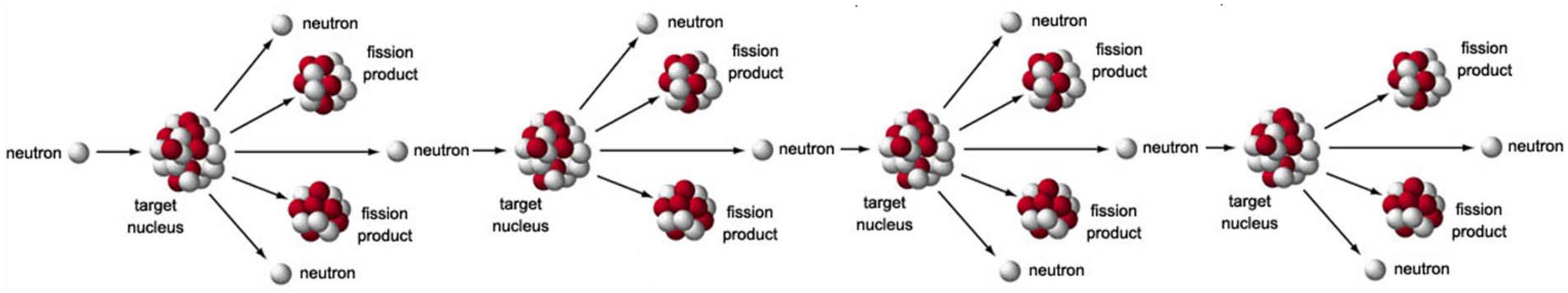
FISSION CHAIN REATION



Neutrons either leave reactor (leak) or stay in reactor (absorbed)

If neutron stays in reactor, it is absorbed in fuel or absorbed in other materials

Need ONE neutron to get absorbed in fuel AND cause another fission to sustain the chain reaction

OTHER neutrons are either a PEST…..OR……

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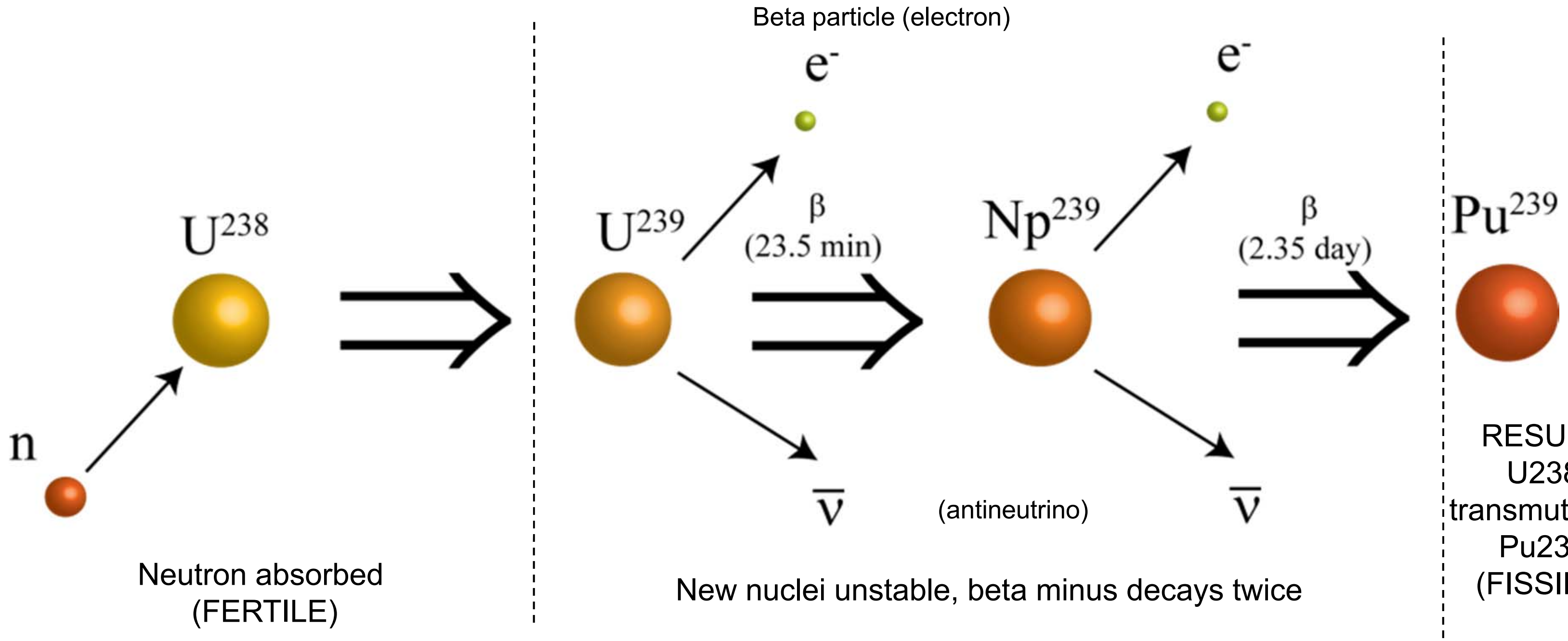
MAKE NEW FUEL!!!!



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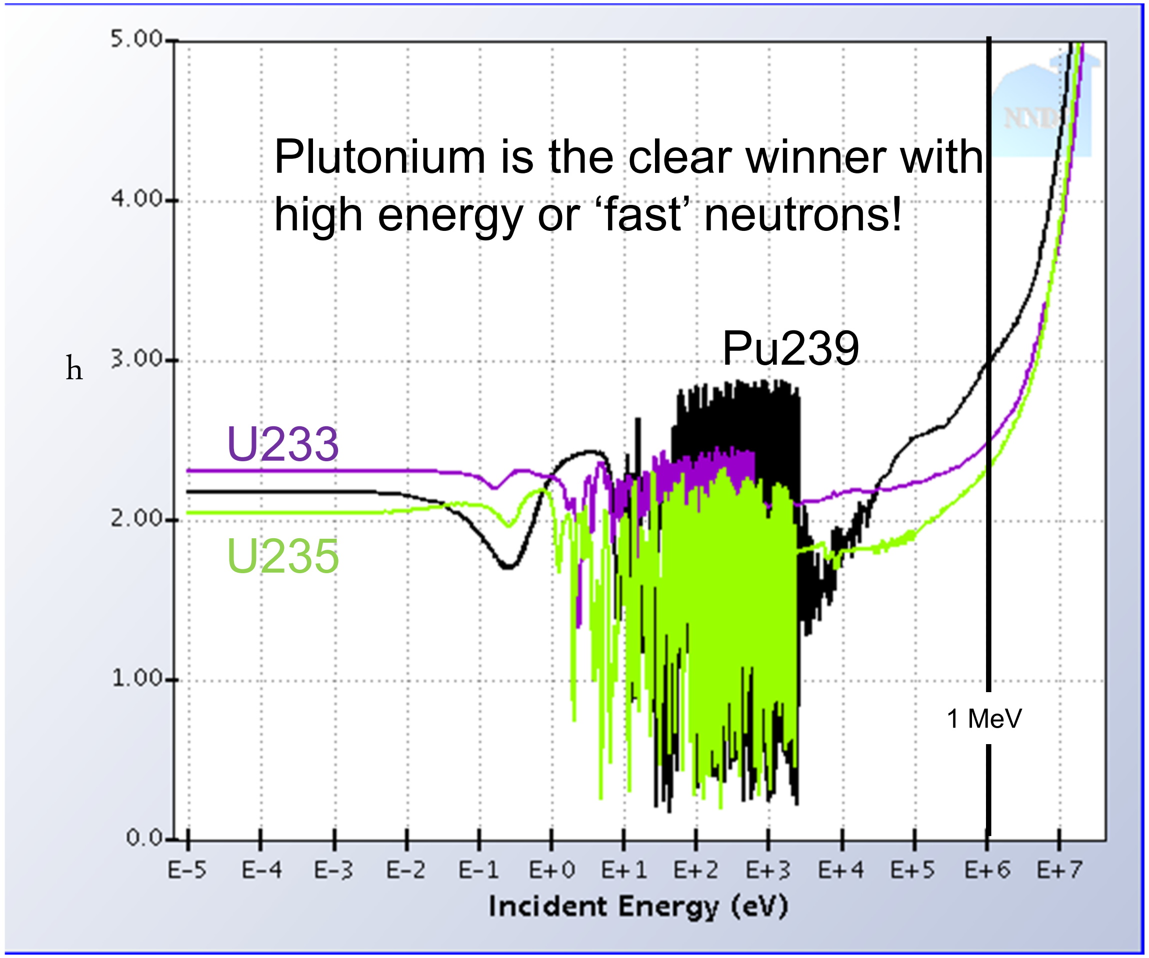
For Transmuting U238

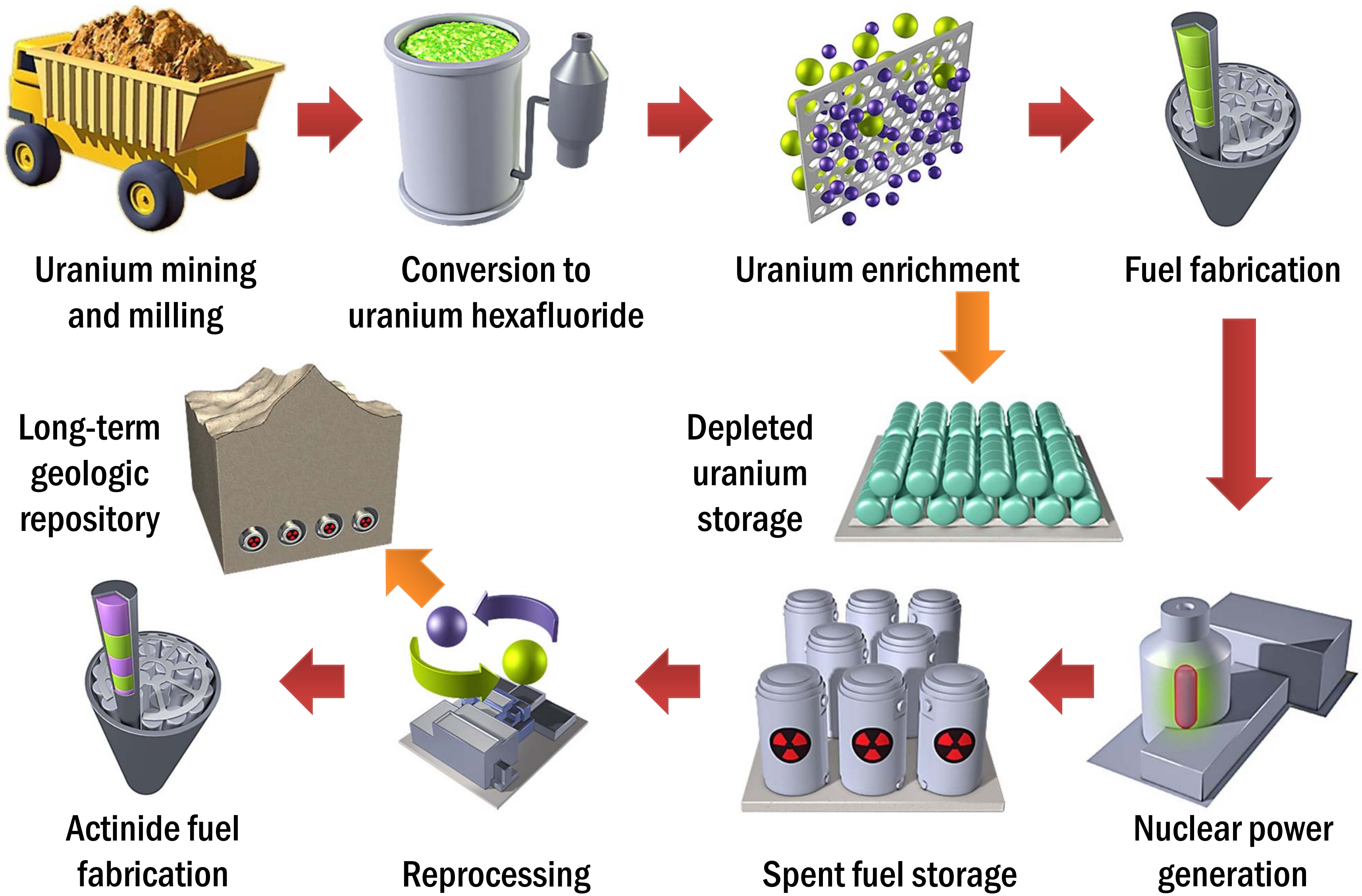
Would like as many fission neutrons released per neutron absorbed as possible

$$\eta = \frac{\text{average \# of } \textit{neutrons} \text{ produced}}{\text{each } \textit{neutron} \text{ absorbed}}$$

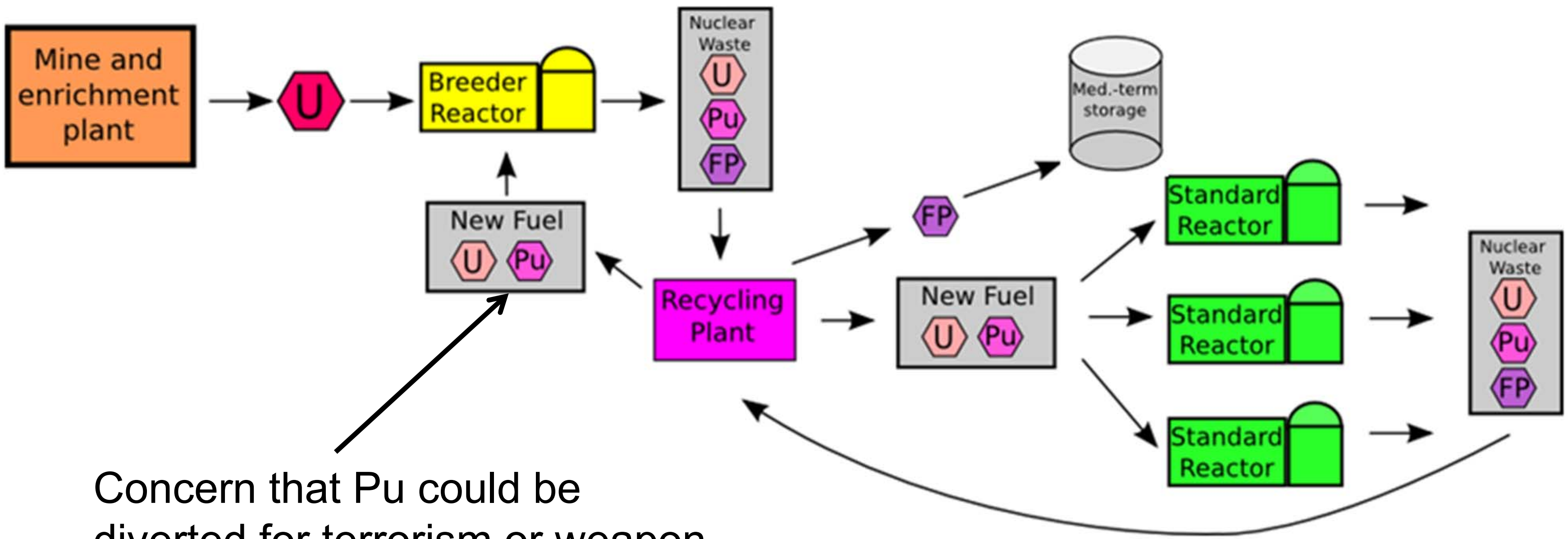
Neutrons produced per Neutron Absorbed (η)



The Current Nuclear Energy System is Complex and Expensive



Breeder Cycle



Concern that Pu could be diverted for terrorism or weapon

Adapted from http://www.whatisnuclear.com/articles/recycling.html

Other terminology

- Burnup – how much heavy metal (fertile and fissile) is consumed
- Major Actinide – Uranium and Plutonium
- Minor Actinide - nuclide resulting from fissionless absorptions such as Neptunium, Americium, Curium and Californium

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TerraPower, LLC

- **Origins:**
  - Studies began in 2006
  - TerraPower is the first spin-off of Intellectual Ventures
- **The Mission:**
  - Develop a sustainable and economic nuclear system that greatly reduces current proliferation risks and creates new planning options for nuclear waste.
- **The Approach:**
  - Explore new concepts without prejudice
  - Embrace 21st century physics and technology
  - Develop better modeling and evaluation tools
  - Recruit a mix of world-class senior scientists, superstar students, and diverse industry experts

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Driving Forces Behind TerraPower "Security and Sustainability"

BILL GATES

NATHAN MYHRVOLD
Owner and Founder,
Intellectual Ventures

JOHN GILLELAND
CEO, TerraPower

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A More Sustainable and Secure Fuel Supply

For the World

Fuel Source	Supplying 80% of world electricity demand at 2008 U.S. per capita rates of consumption (years)
Stockpiles of depleted uranium, as of 2009	80
Projected stockpile of depleted uranium in 2100	1,060
Stockpiles of LWR spent fuel, as of 2009	20
Projected stockpiles of LWR spent fuel in 2100	140
Known reserves of uranium	320
Estimated uranium phosphorite deposits	1,720
Estimated uranium seawater deposits	233,330

The Computer Cluster

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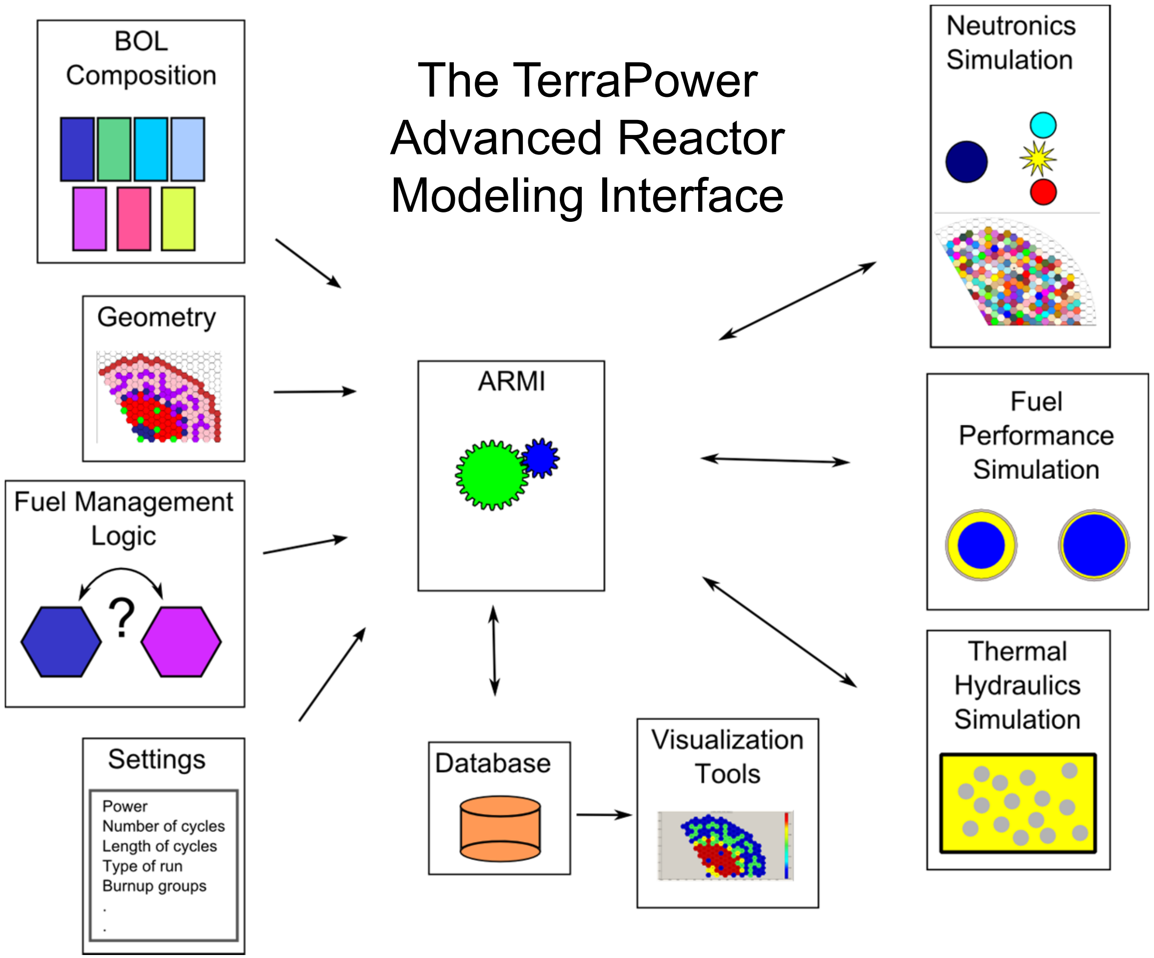
Neutronics Modeling Toolbox

MCNPXT -- Heavily modified MCNPX (high-fidelity)	MC**2-REBUS-DIF3D (high-speed)
• General fuel motion • Burn chain improvements • Parallel performance • Memory management • Automatic control search • Fuel performance coupling • Advanced FP mapping • Full-core models with ~8 cm burn mesh (over 100k burn zones!) • Pin-level and homogenized triangle detail	• Deterministic fast reactor suite from Argonne National Lab • Allows many configurations to be tested at once on the cluster • Generates detailed safety coefficients

Driver System



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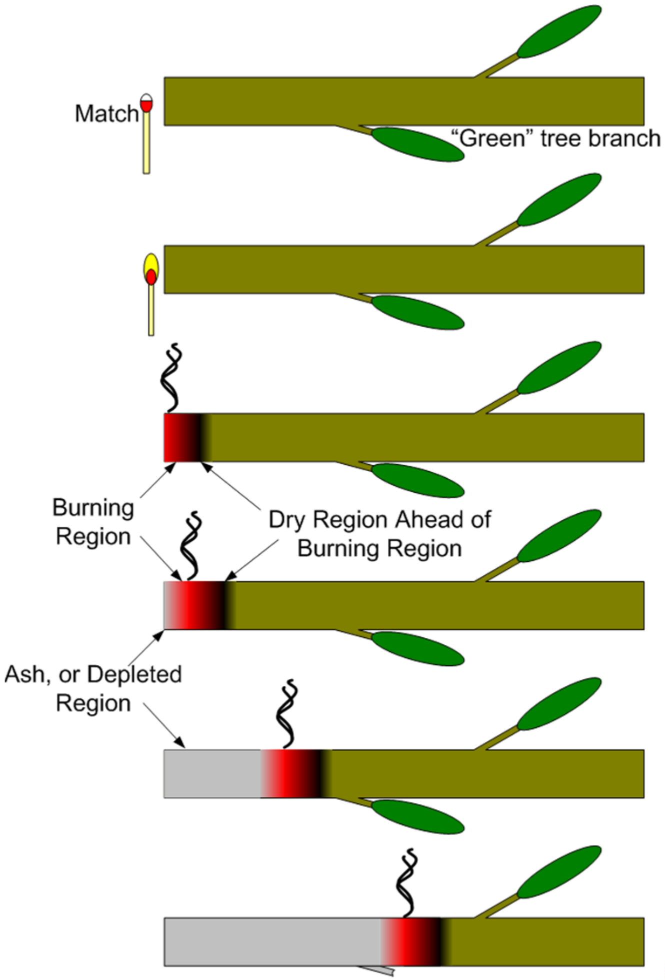
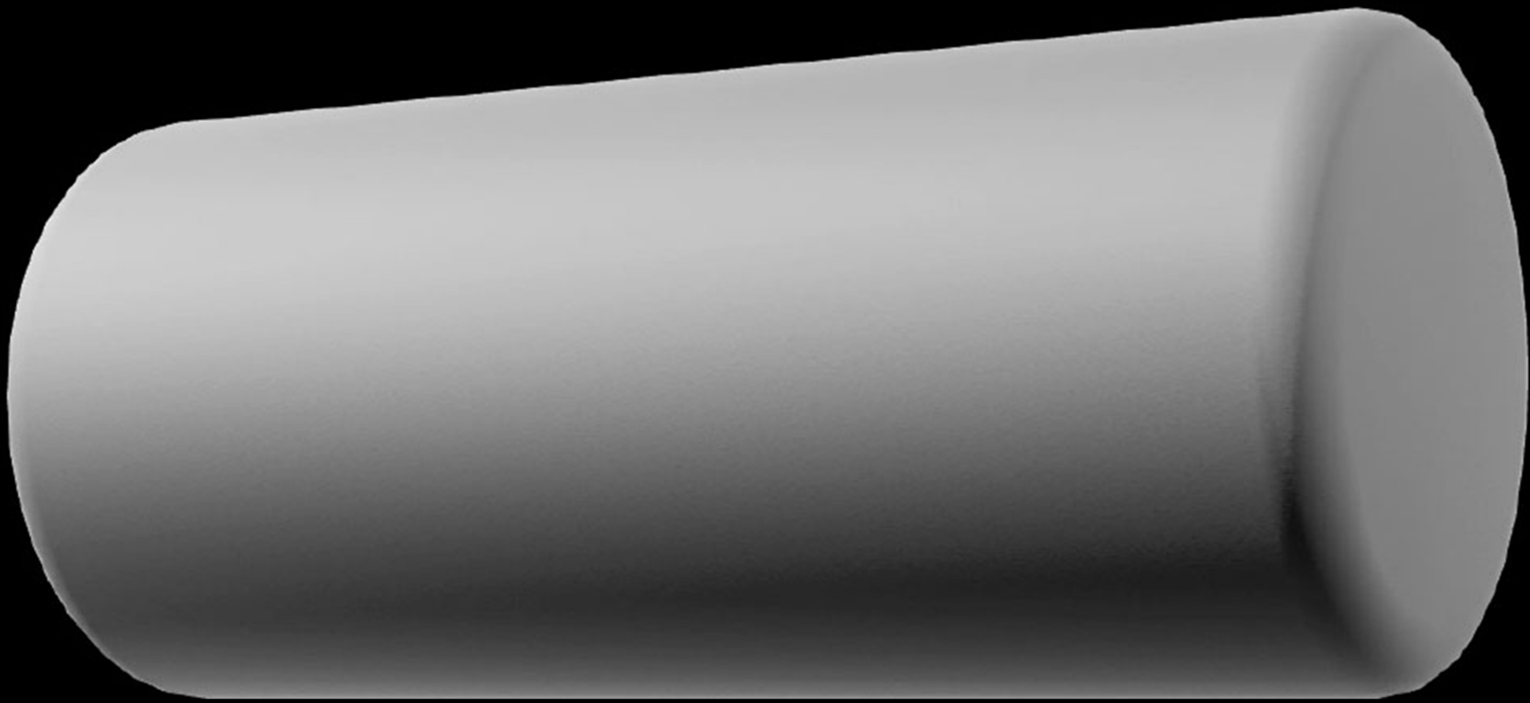
Traveling Wave Idea

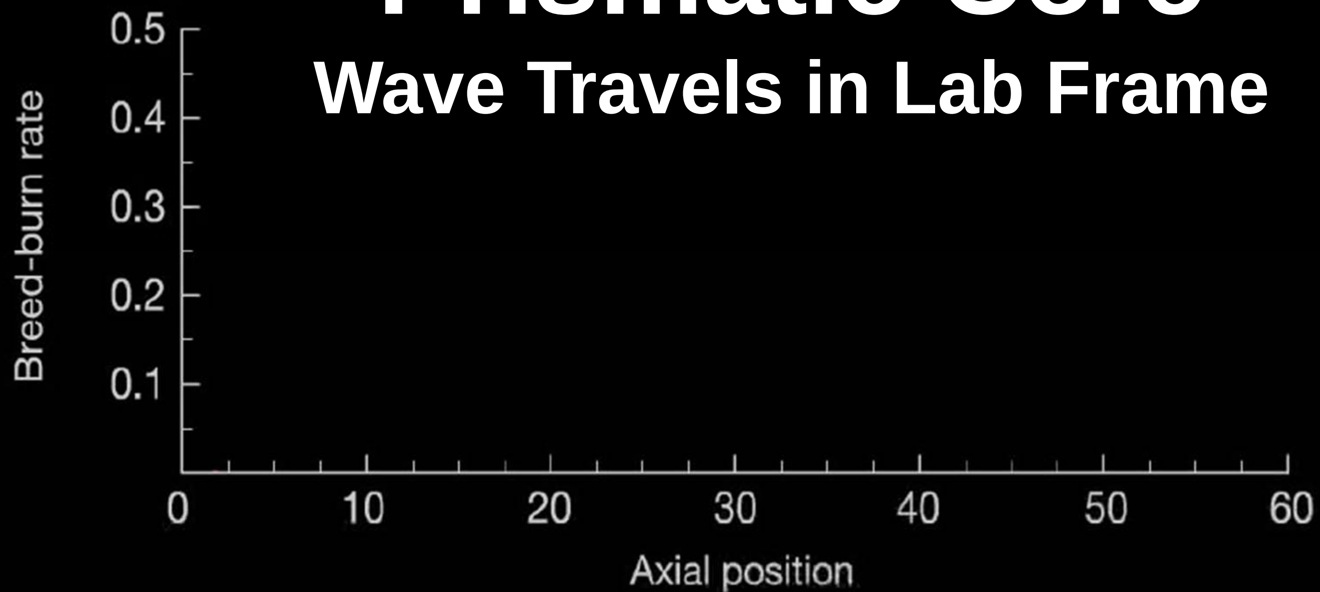


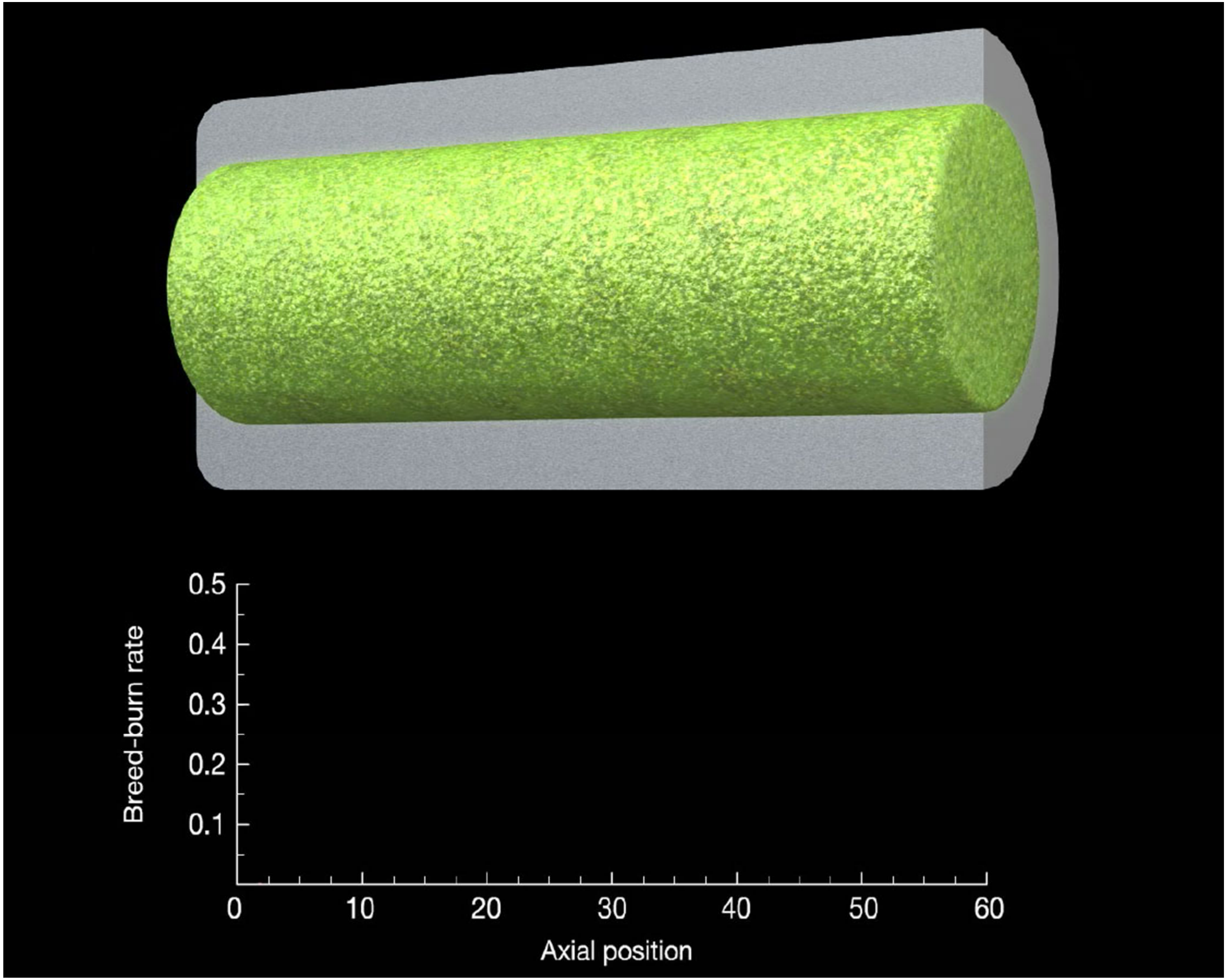
Ignite at one end of a fertile "stick," wave develops and propagates down the length of the "stick"



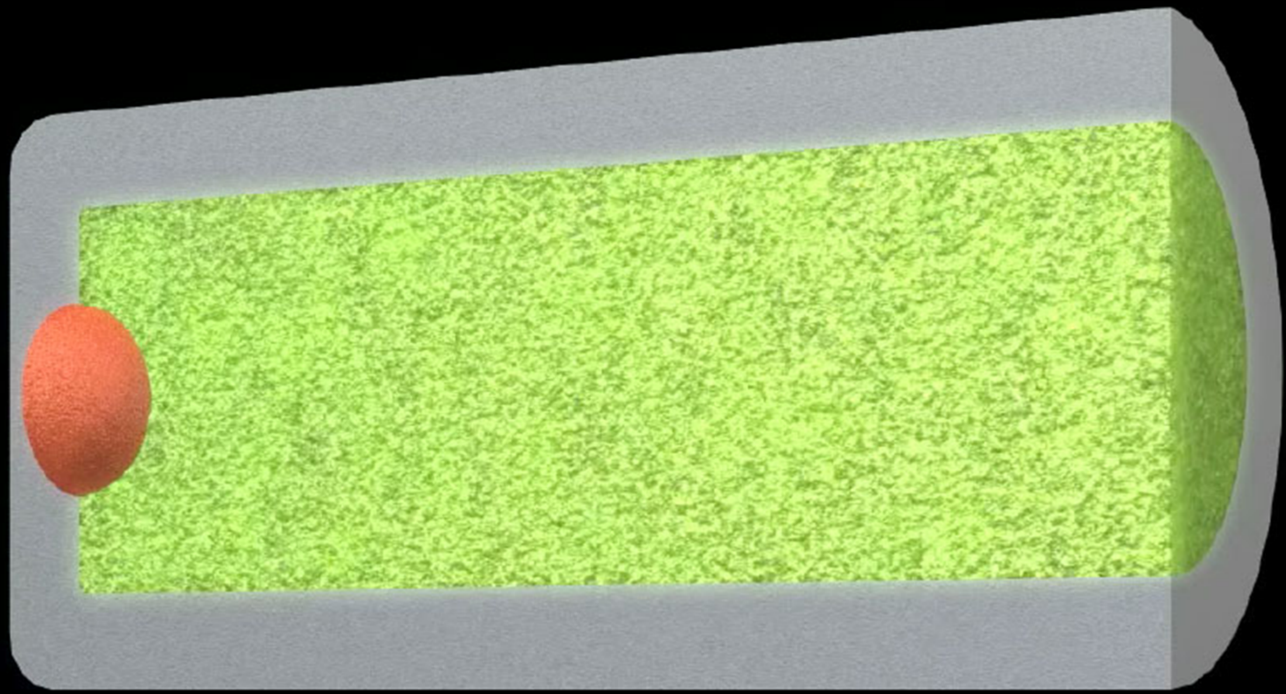
Prismatic Core

Wave Travels in Lab Frame

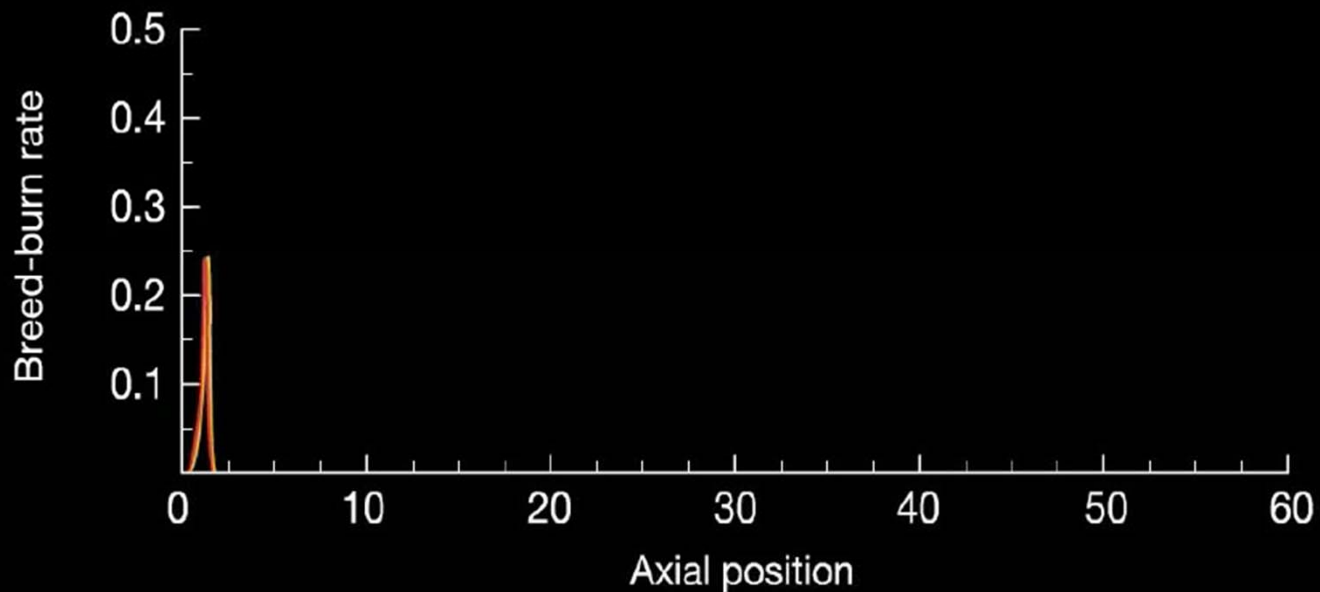


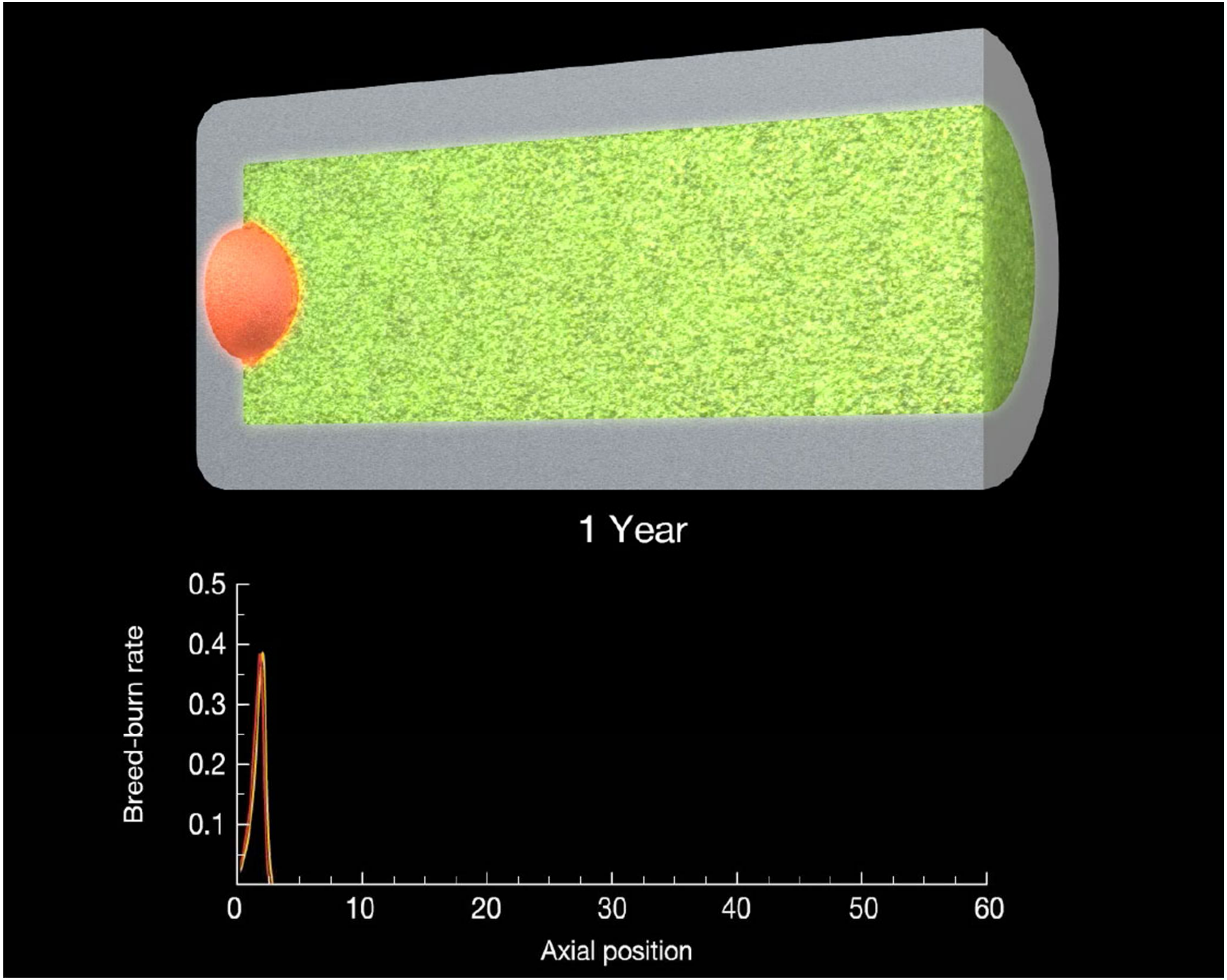


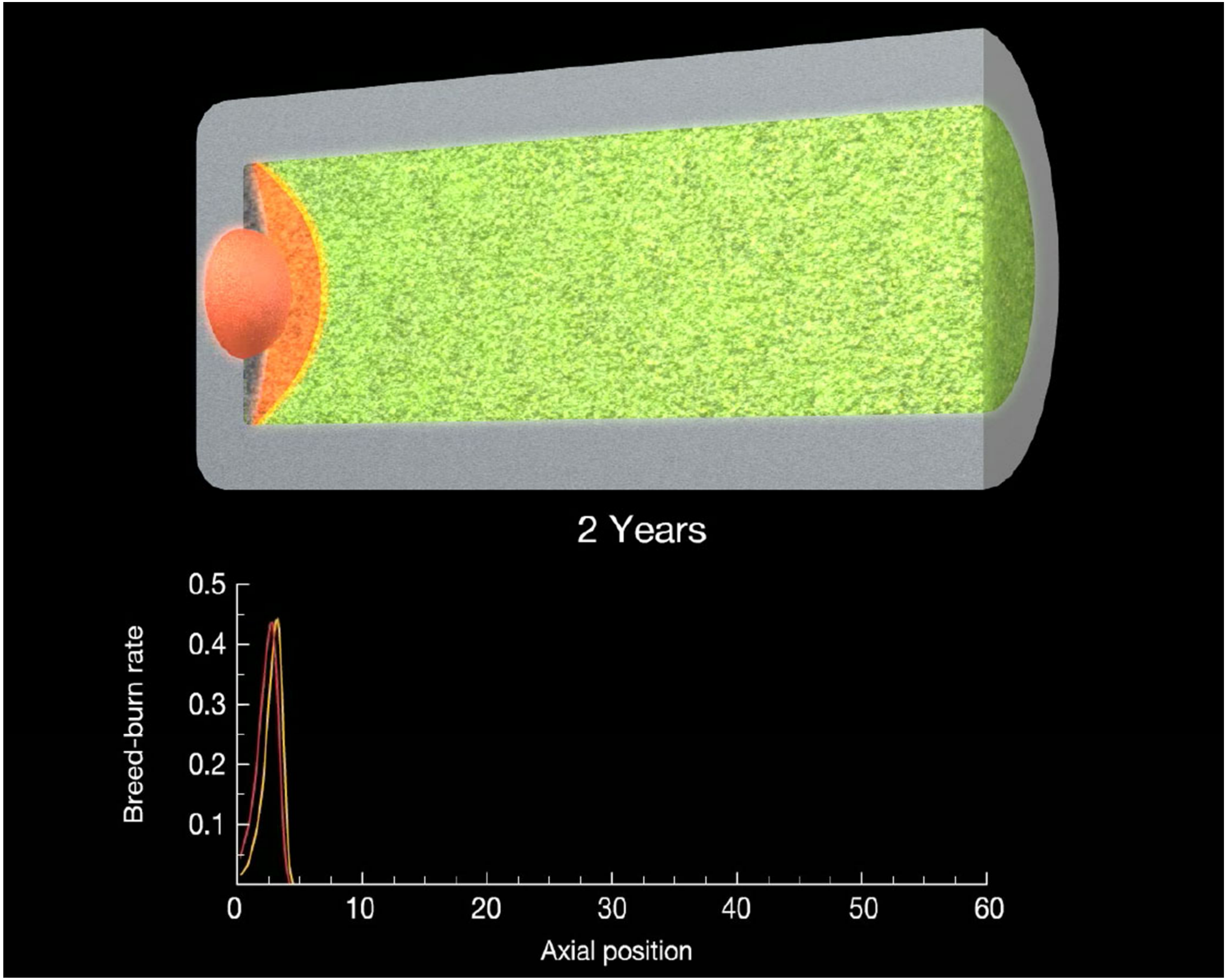
0.5
0.4
0.3
0.2
0.1
Breed-burn rate
0
10
20
30
40
50
60
Axial position

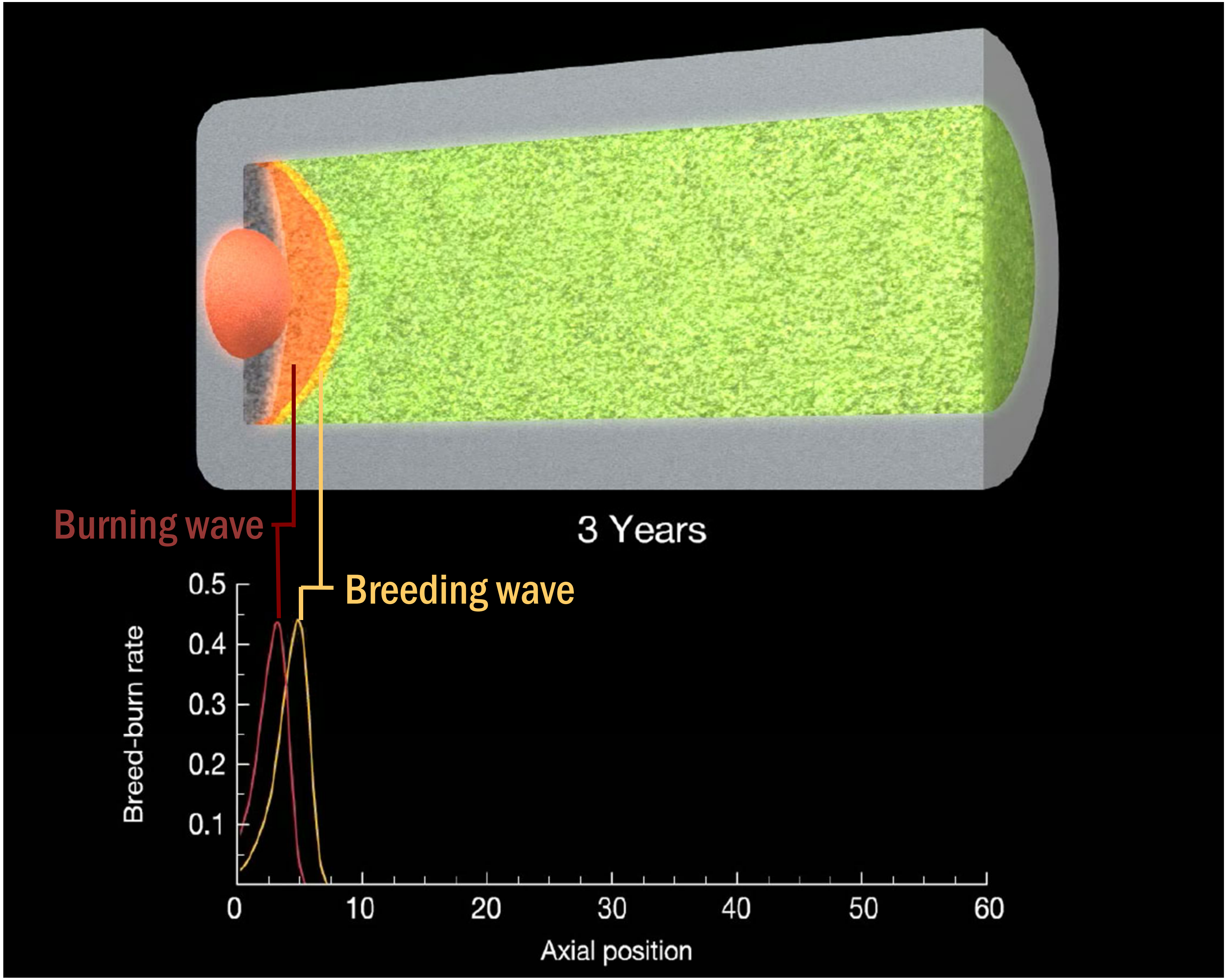


Fission begins

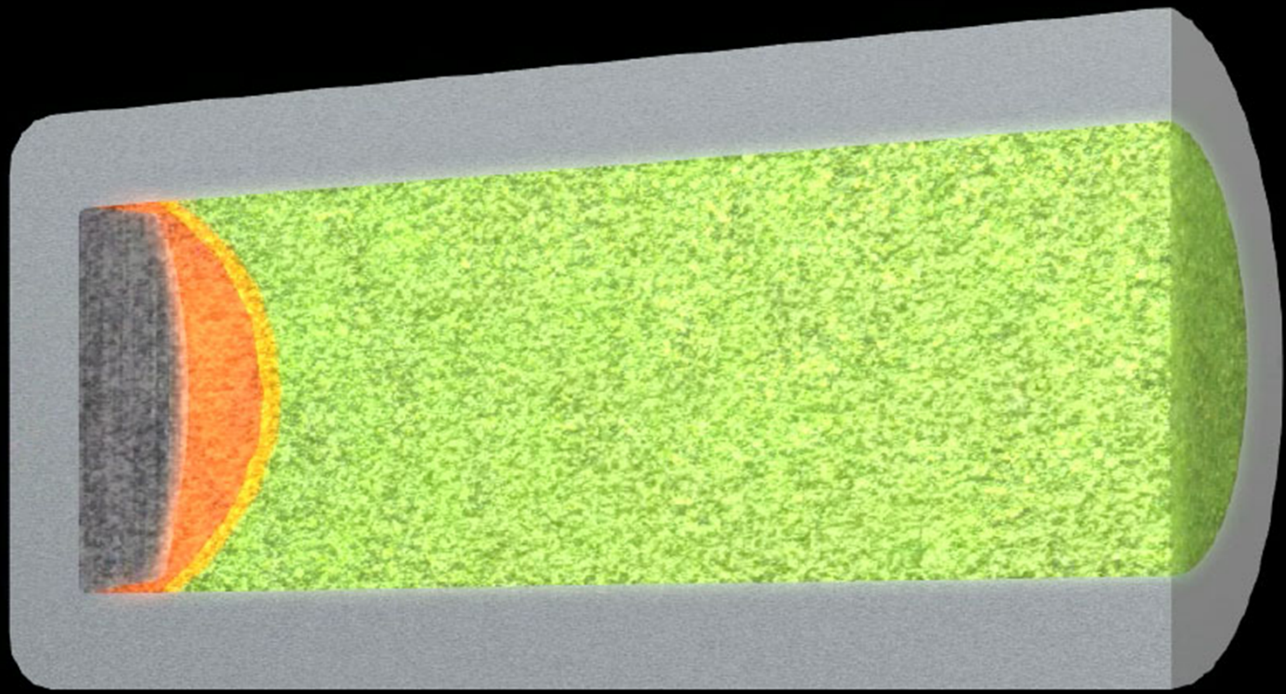



1 Year
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position

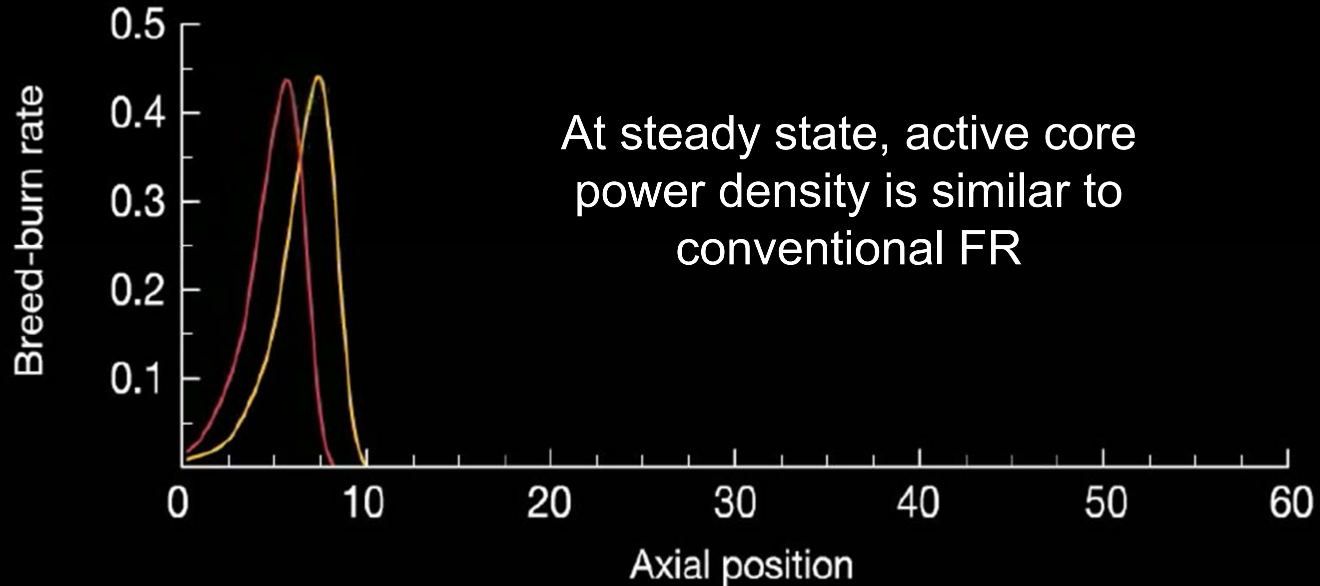

2 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position



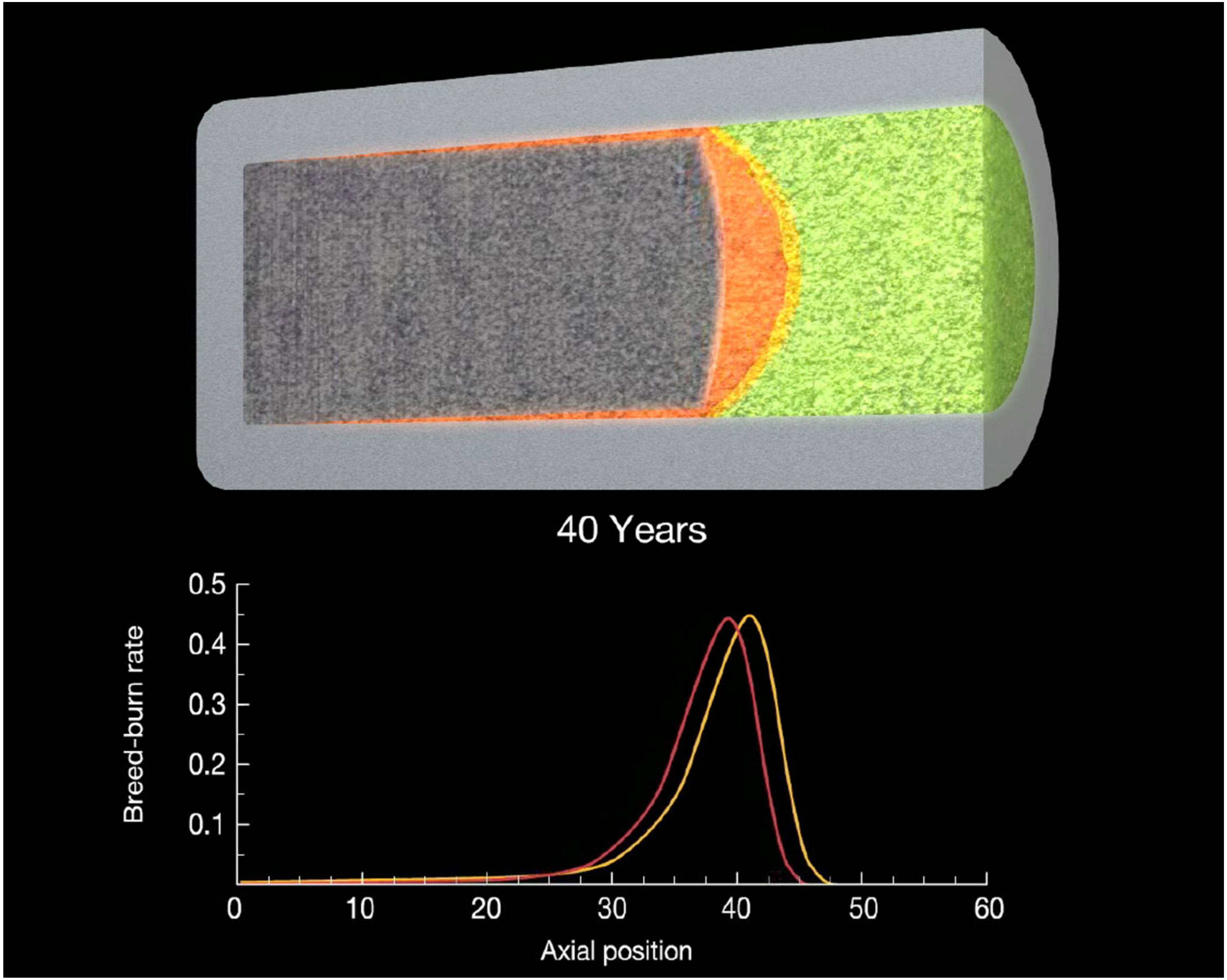
Burning wave
3 Years
Breeding wave
0.5
0.4
0.3
0.2
0.1
Breed-burn rate
0
10
20
30
40
50
60
Axial position

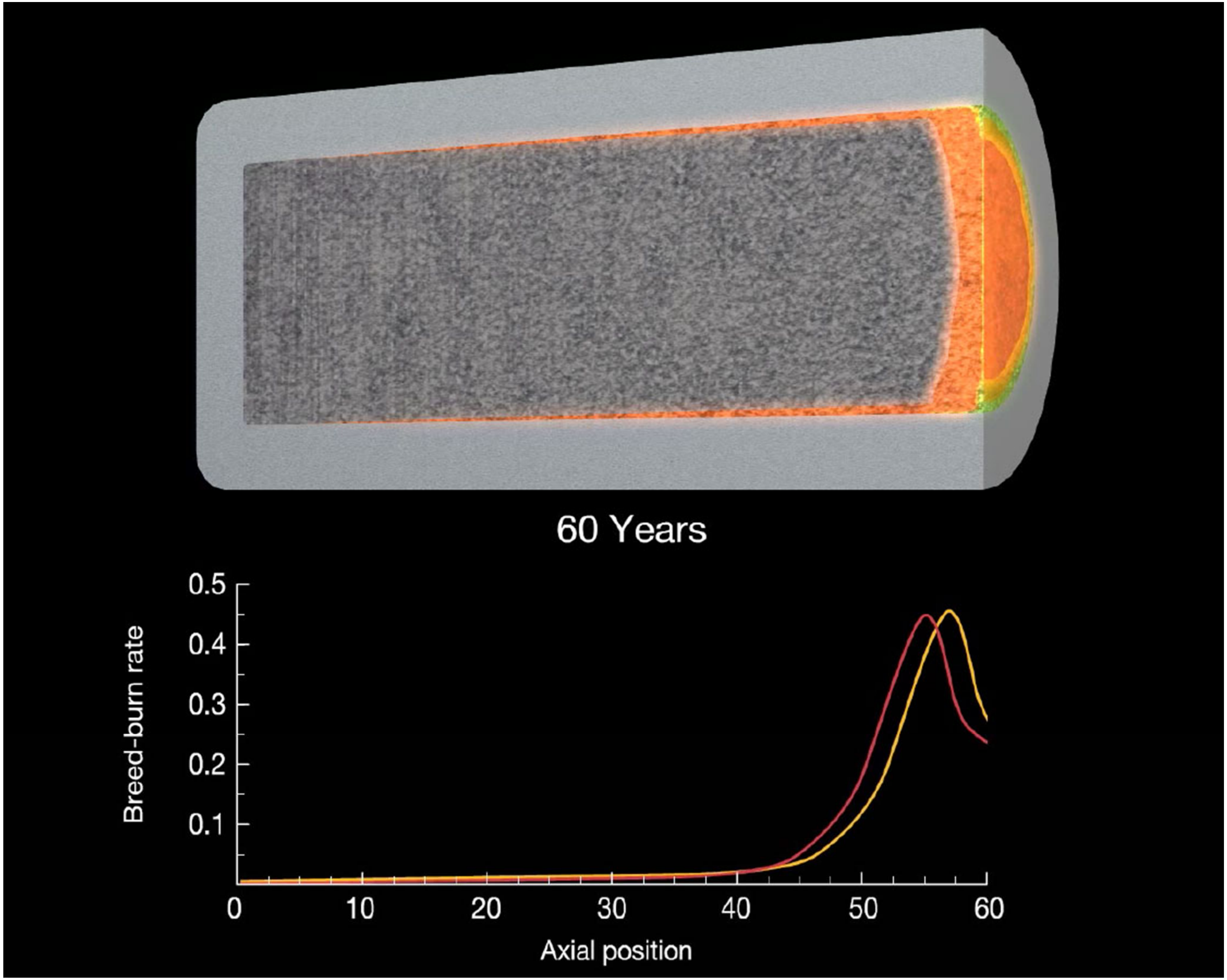


5 Years



At steady state, active core power density is similar to conventional FR


40 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position


60 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position

Capabilities of the Traveling-Wave Reactor (TWR)

- Breeds fuel just before it burns it
- Can run for generations on depleted uranium alone, once a fission wave is launched
- Produces electricity for several decades while sealed, without reloading
- Consumes LWR spent fuel, once the waste has been reduced to metal form
- Contains the entire fuel cycle in a single can
- Operates with well-developed technologies

A Path to Simplifying the Fuel Cycle

- TWRs have a unique ability to perform *just-in-time* breeding of fertile fuel into fissile fuel
- Used fuel from TWRs need only be recast and reclad to enable reuse (without requiring chemical separation of major actinides)

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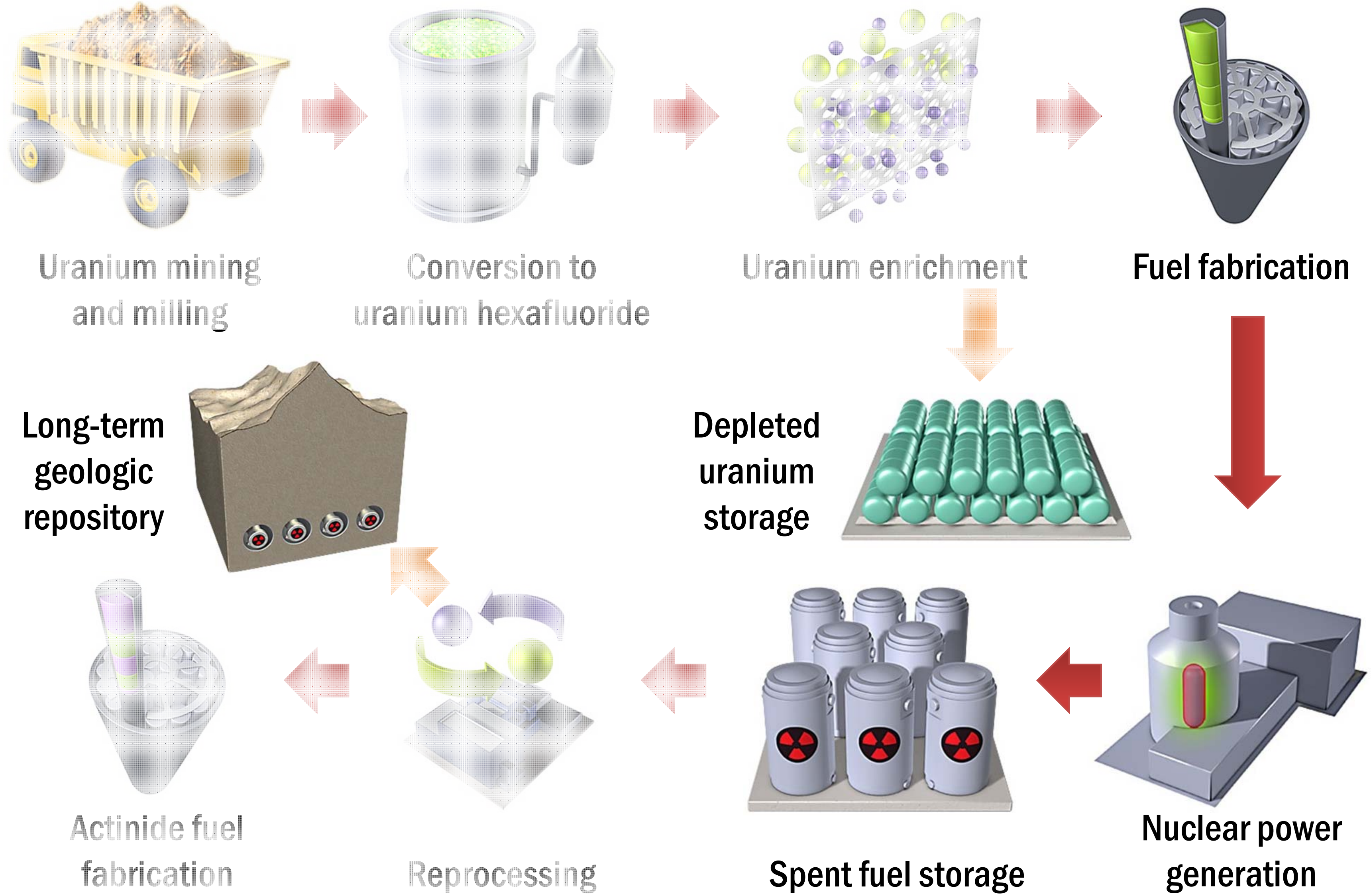
TWRs Make Many Steps Unnecessary

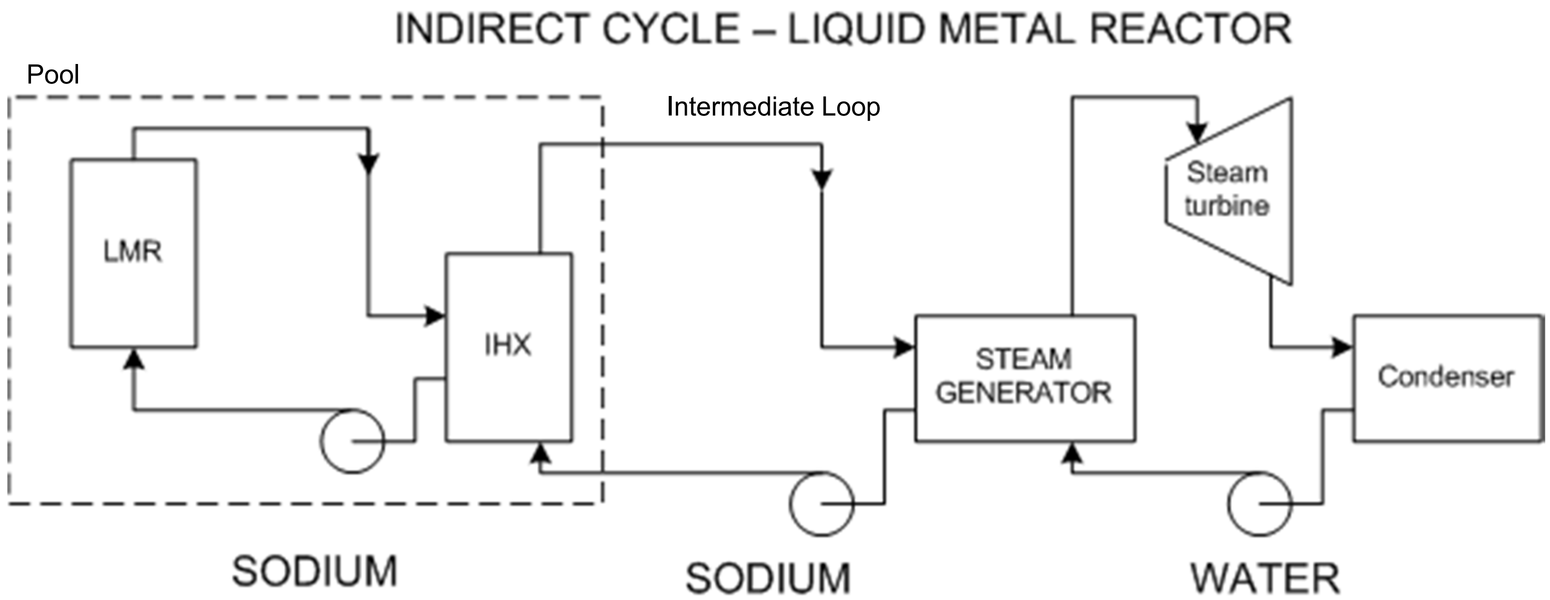


Engineering a Candidate Gen-I TWR

- Considered all practical system options
- Selected proven technologies to reduce First Plant uncertainties
- Accommodated challenging features (e.g. high power density, high burnup, power peaking, etc.)
- Developed reactor after considering various design alternatives

Fuel Composition	Fuel Form	Primary Coolant	Energy Conversion
Uranium	Oxide ceramic	Gas: Helium, CO_2	Steam: Rankine cycle
Thorium	Metal alloy	Other: water, molten salt	Direct Brayton cycle
Mixed uranium and thorium	Other ceramics	Liquid metal: Na, Pb, Pb-Bi	Combined cycles

ENERGY CONVERSION



LMR – Liquid Metal Reactor
IHX – Intermediate Heat Exchanger

Problems with implementation of TWR

Cooling – must remove heat from where it is produced….this moves with the TWR

Materials limitations…

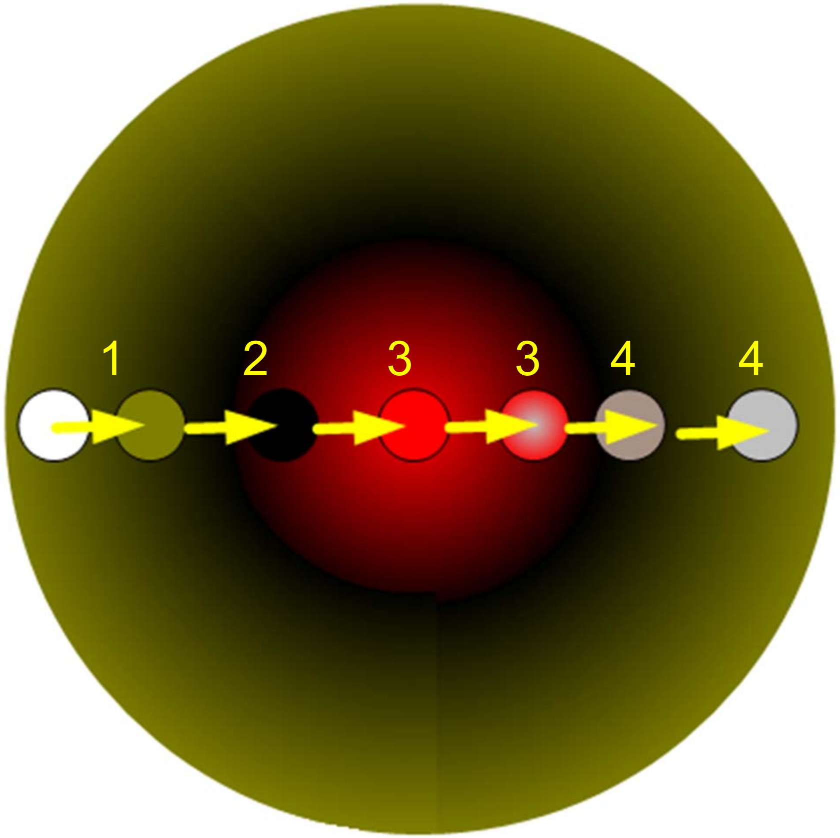
Structural materials must endure high energy (fast) neutron bombardment

-All new materials must be tested

-BUT facilities for testing are very limited

-Make Maximum use of existing knowledge and technologies

Cylindrical Standing Wave Idea-
a fire surrounded by green wood....



1) Move a “green” stick towards the heat

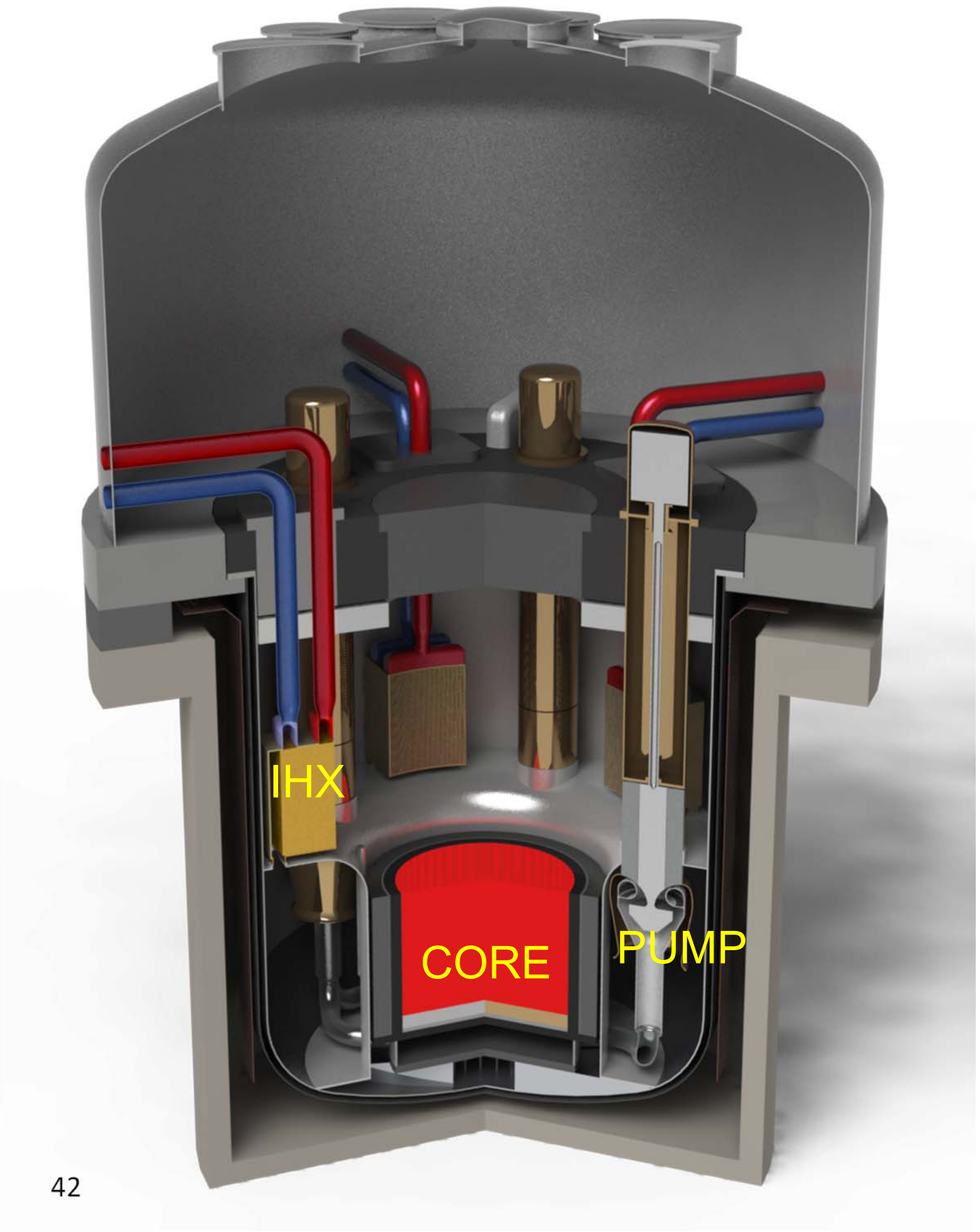
2) Prepare the stick for burning

3) Burn the prepared stick

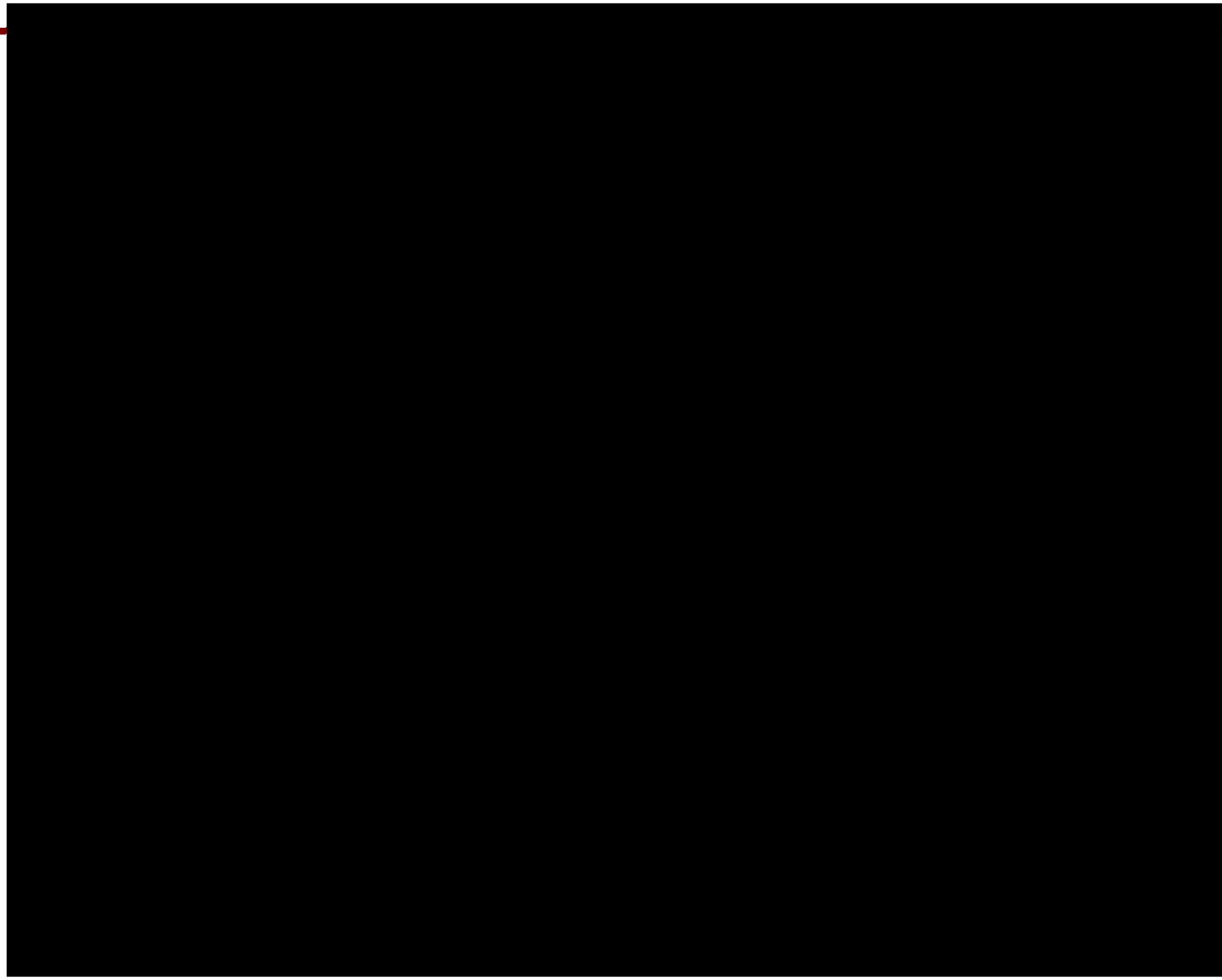
4) Stick is consumed, emerges as ash

Cylindrical Standing-Wave Reactor

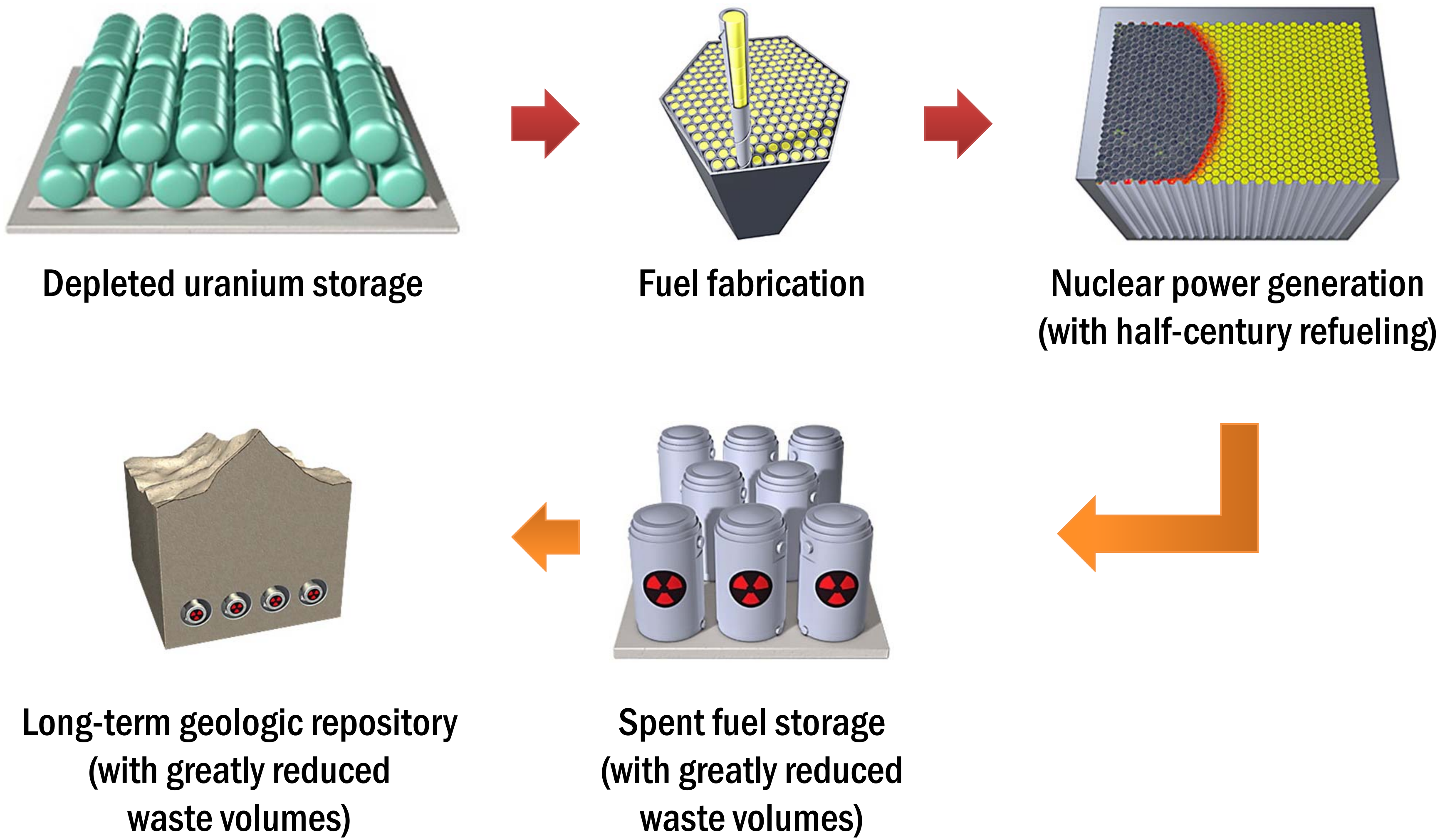
- Wave is stationary in the lab frame; fuel is moved radially
- Power density is typical of a previously built fast reactors



Shuffling Movie



A Simpler, More Secure and Economical Nuclear Energy System



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TerraPower TWR Development Status

- TPRP Conceptual Design & Cost Estimate Complete
  - Credible engineering design for a complete TWR power plant
  - Competitive with Gen III+ LWRs on both performance & cost
  - Sustainable, proliferation resistant fuel cycle
- TP-1 Conceptual Design & Cost Estimate
  - Builds on TPRP conceptual design experience
  - Complete by end of 2010
  - Focused on aggressive design-construct schedule for 2020 startup
- Future Work
  - Evaluate alternative fuel forms (e.g. spent LWR fuel)
  - Advanced reactor component & energy conversion designs

Purpose for TP-1

TP-1 is our “Initial Technical Baseline”

- Specific project-based technology development program
- More technical depth than TPRP
- More contact with equipment suppliers (pumps, IHX, Steam Generator)
- Develop administrative infrastructure for documents
- Contracted help to build licensing basis
- Next Step: Preliminary & Final Design

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Design for a 500 MW_e TWR – TP-1

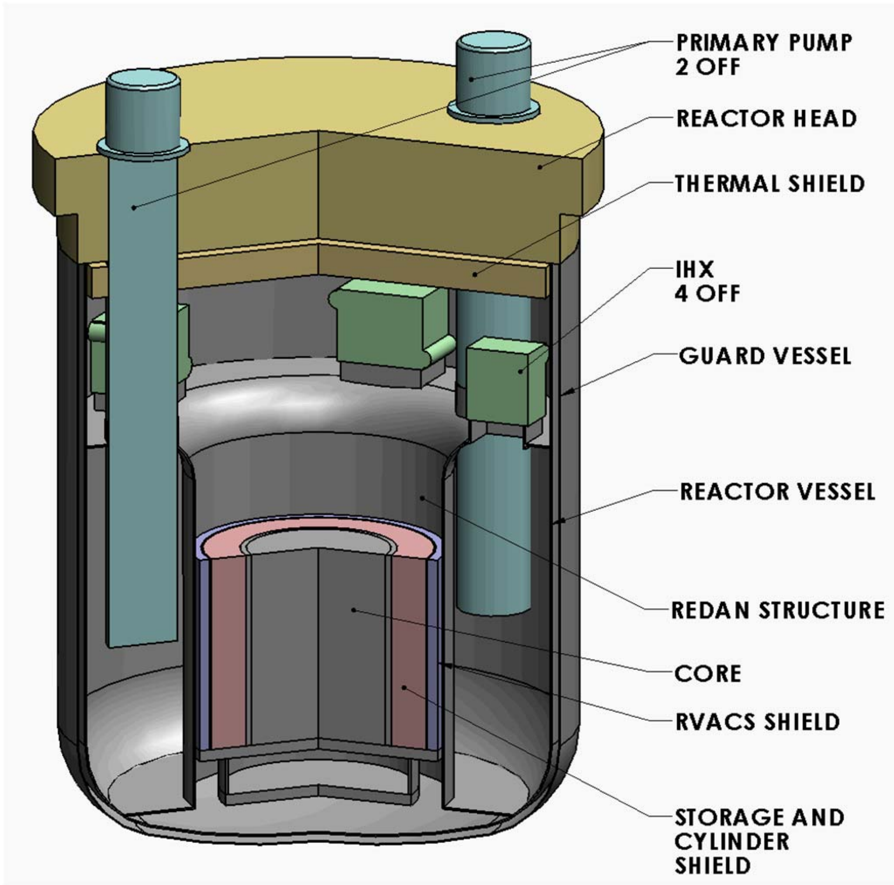
- **TP-1 Missions**
  - First electricity producing TWR – Startup about 2020
  - Confirms "standing wave" concept, verifies shuffling strategies
  - Demonstrates key plant equipment and verifies that models agree with operational performance
  - Provides bases for 500 & 1150 MW_e TWR plants
  - Last step of fuel and material qualification
- **TP-1 Design Features**
  - Accommodates lead test fuel assemblies
  - Limited refueling capability for post irradiation fuel examinations
  - First-of-a-kind instrumentation, maintenance considerations

TP-1 Design Parameters

Power Level	1200 MW_{th} / 500 MW_e
Operating Temperatures	360°C / 510°C
Core ΔP	1 MPa
Availability	90% average over 5 yr period
Minimum Lifetime	40 years
Fuel Type	U-Zr alloy in HT-9 clad
Primary Pumps	Mechanical (2)
Intermediate Heat Exchanger	Printed Circuit (4)

Unique Features of TP-1

- Reactor Vessel Auxiliary Cooling System is the only safety-grade decay heat removal system
- Accommodates lead test assemblies
- 2 fuel open test assemblies and 1 materials open test assembly
- Limited refueling capability for Post Irradiation Examination



TWRs Push the Limit of Fuels/Materials

- High fluence and burnup (~28% burnup, 500 displacements per atom {dpa})
- Current data exists for only 20% burnup and 200 dpa
- Need more irradiation program data and alternative mitigation strategies

Plans to Extend Fuels and Materials Database

- We are analyzing previously irradiated HT9 from US research reactor
- We have initiated optimum fuel alloy experiments
- We have begun discussions with fast reactor facilities in Russia to perform fuel and material irradiations
- Timetable to 2020 deployment is on track

Other Physics

Safety / Transient Analysis

- SASSYS analyzes design-basis and severe accidents
- Models full plant transients
- Tracks flow, pressure, and temperature of coolant and fuel through transients
- Millisecond timing for certain phenomena

Thermal Hydraulics

- SUPERENERGY provides detailed assembly-level temperature and flow distribution histories
- In-house codes perform power-flow matching

Our Ultimate Goal:
Design an Ideal Nuclear System

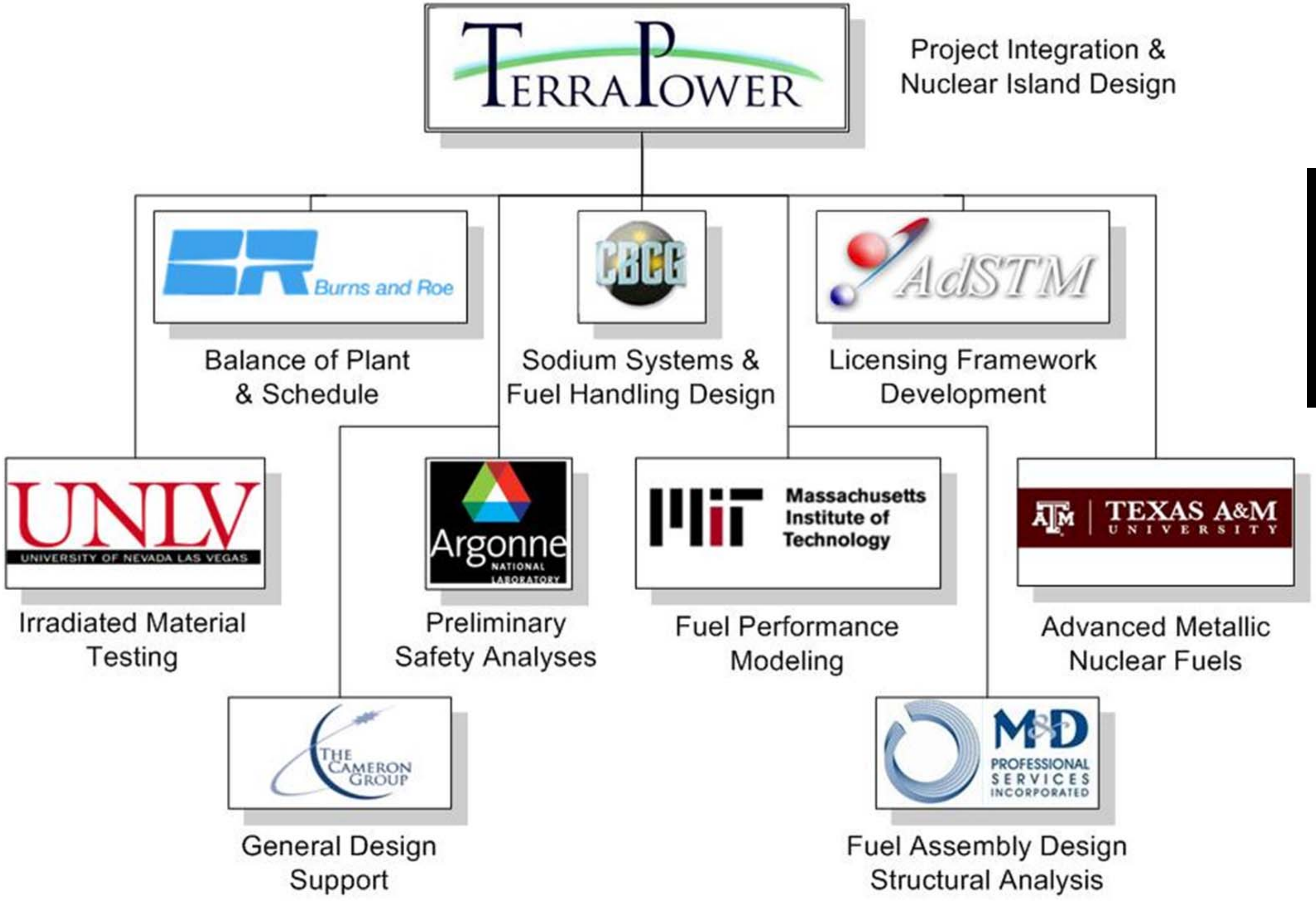
- Sustainable
  - Minimizes its environmental footprint
  - Burns waste
  - Meets global energy needs indefinitely
- Safe
  - Meets the highest safety standards
- Affordable
  - Competes with or beats existing nuclear systems

TerraPower Reactors Approach The Ideal

- Sustainable
  - Minimizes its environmental footprint
  - Burns waste
  - Meets global energy needs indefinitely
- Safe
  - Meets the highest safety standards
- Affordable
  - Competes with or beats existing nuclear systems

- Sustainable
  - ✓ Phases out mining
  - ✓ Burns depleted uranium and other waste as fuel
  - ✓ Known fuel supplies are sufficient for many centuries
- Safe
  - ✓ Uses latest safety features
- Affordable
  - ✓ Needs no reprocessing, and eventually no enrichment

Conceptual Design Team



AND International Collaboration is Anticipated

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THANK YOU FOR YOUR ATTENTION

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