Traveling Wave Reactor Program Overview

Jon McWhirter

What you'll hear today

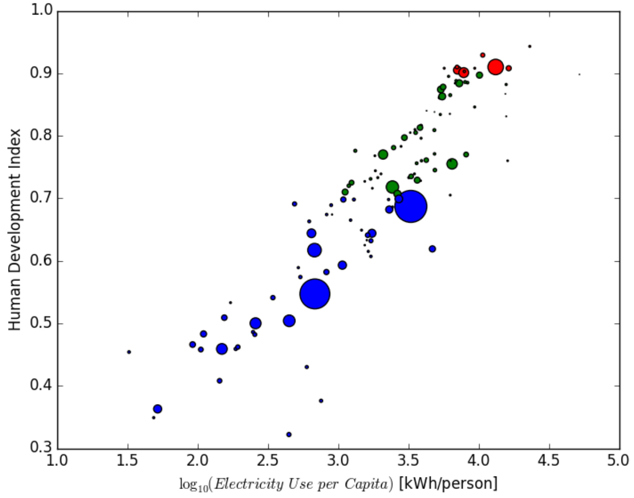
- TWR history and promises
- Intro to breed-and-burn
- Challenges of TWR development
- Ongoing testing programs

Energy is related to quality of life

"Energy is part of a historic process, a substitute for the labor of human beings. As human aspirations develop, so does the demand for and use of energy grow and develop." -- David Lilienthal (former chairman of AEC)

- Current world population is 7.7 billion; going up to ≥**10 billion**
- Current global primary energy use is ~**2 kW per person**
- Average in the U.S. is about **10 kW per person (too much!)**
- Need **100 TW (6x) increase over present**
  - Concentrated in China and India, as those massive populations develop
  - But don't forget the billion-and growing-in Africa

How can we supply 3-6 times more energy without running out of resources and/or seriously damaging the environment?



Correlation between electricity use per capita and Human Development Index

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By 2040...
THE WORLD'S POPULATION WILL INCREASE TO 9 BILLION PEOPLE
ELECTRICITY DEMAND WILL GROW 93%
USAID
USAID
SAID
Photo Credit: UN Photo/UNICEF/ Marco Domino

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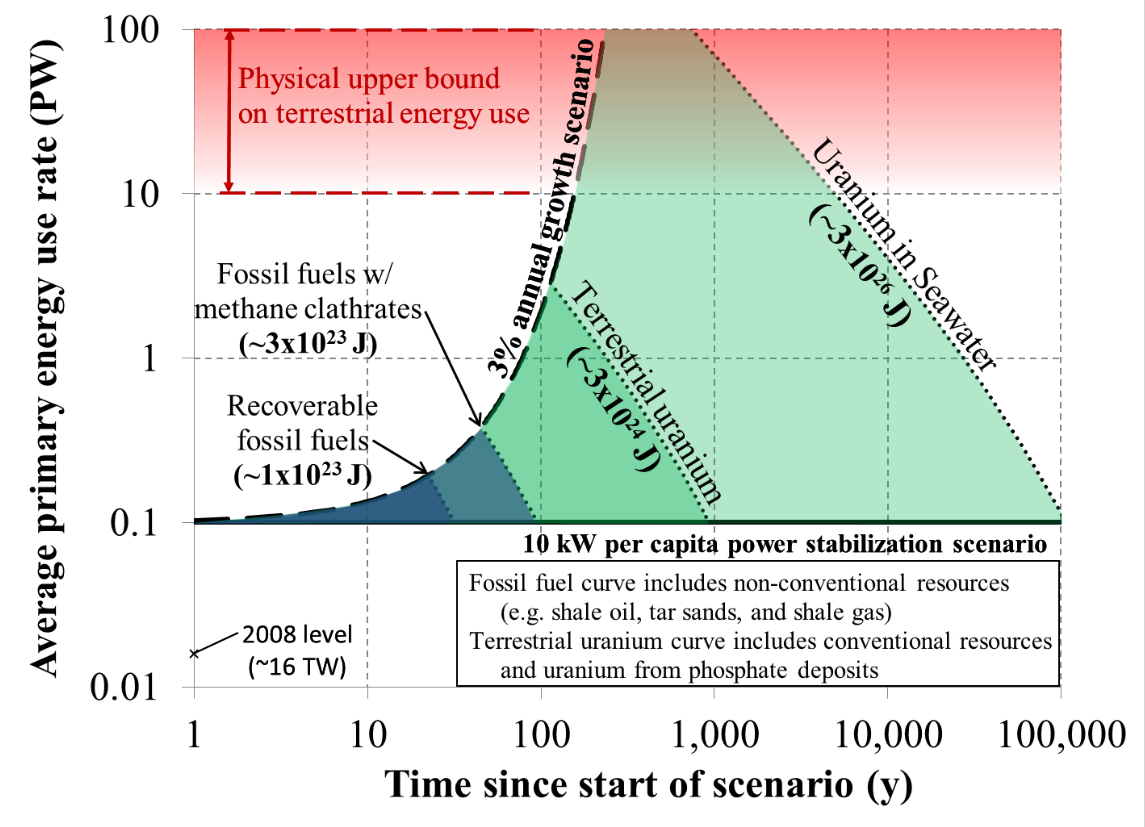
Energy scenario maps for various resources

- There are lots of fossil fuels
  - Mostly coal, non-conventional oil + gas, and under-ocean methane clathrates
  - Burning all the non-clathrate resources would raise atmospheric CO_2 levels by a ***factor of ~5*** *(i.e., Cretaceous period levels)*
- There is a huge amount of terrestrial uranium available **(~30,000,000 MT)**
  - With a total energy content 1.5 orders of magnitude higher than fossil fuels
- Amount of uranium present in seawater is simply astonishing (**~4,000,000,000 MT**)
- These massive energy resources allow nuclear fission systems to be considered *"planetary-scale sustainable"*

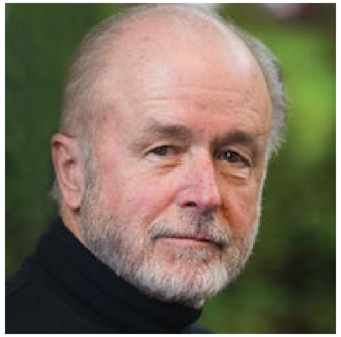


Energy scenario maps for fossil and uranium resources

TerraPower's Formation

TerraPower is a nuclear innovation company based in Bellevue, Washington. The company originated with Bill Gates and a group of like-minded visionaries who evaluated the fundamental challenges to raising living standards around the world. They recognized energy access was crucial to the health and economic well-being of communities, and decided that the private sector needed to take action and create energy sources that would advance global energy deployment.

Nathan Myhrvold the former Chief Strategist and Chief Technology Officer of Microsoft, the founder and CEO of Intellectual Ventures and co-founder and Vice Chairman of the Board of TerraPower. Dr. Myhrvold believes that nuclear energy is the *only proven generation source that can provide the large-scale, base load electricity needed to meet the world's growing energy demands while combating global warming.*



John Gilleland is a co-founder of TerraPower where he is currently the Chief Technical Officer. From 2008 to 2015, Dr. Gilleland served as TerraPower's Chief Executive Officer (CEO). Under his leadership, TerraPower transitioned from an idea to a globally recognized center for innovation and development of new nuclear reactors and other advanced nuclear systems.

Bill Gates is co-founder of Microsoft, co-chair of the Bill & Melinda Gates Foundation, and co-founder and Chairman of Board of TerraPower. Since TerraPower's founding in 2006, Bill has challenged the company to use technology to *design the next generation of innovative nuclear reactors that will provide the world with a more affordable, secure and carbon free energy*.

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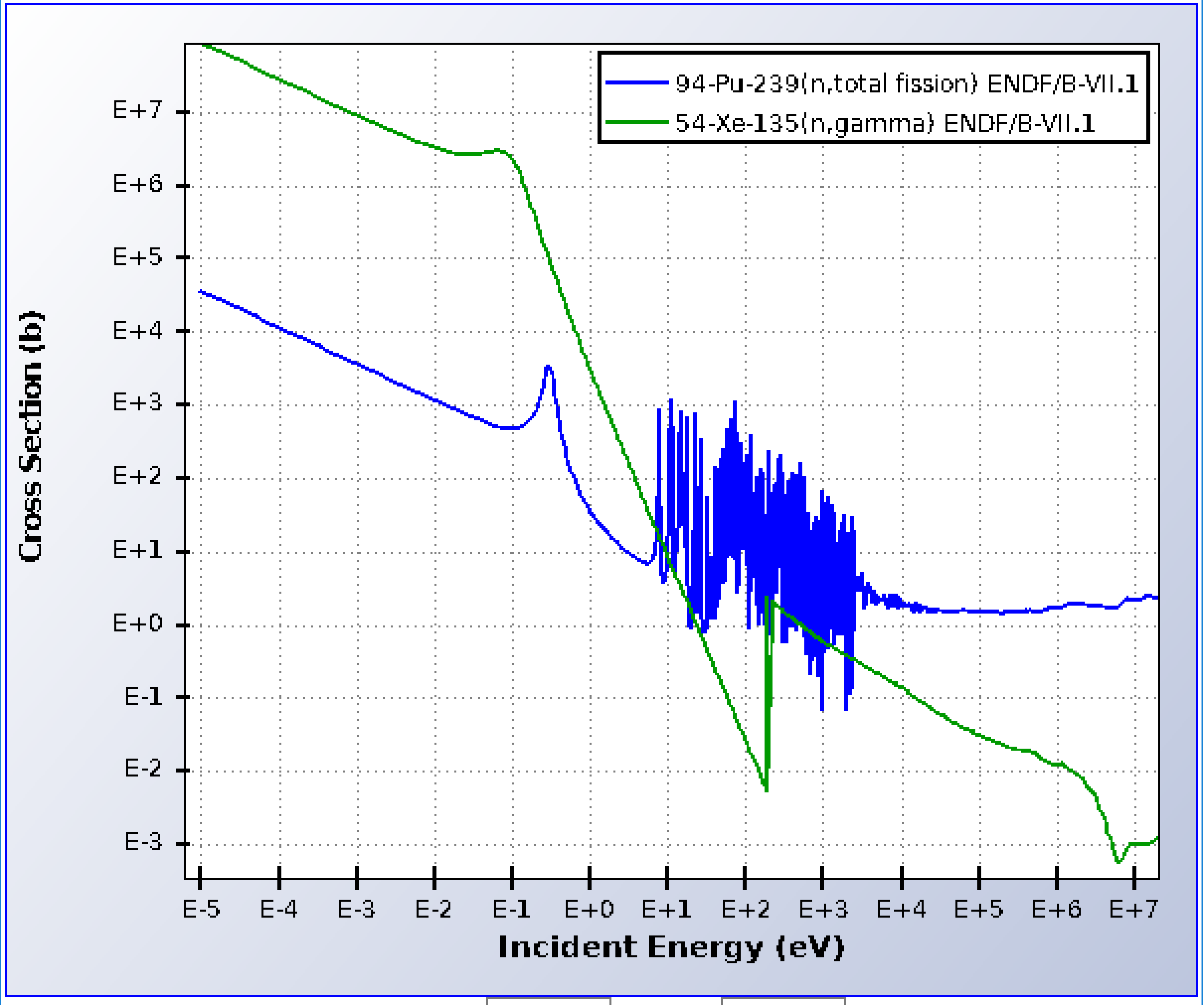
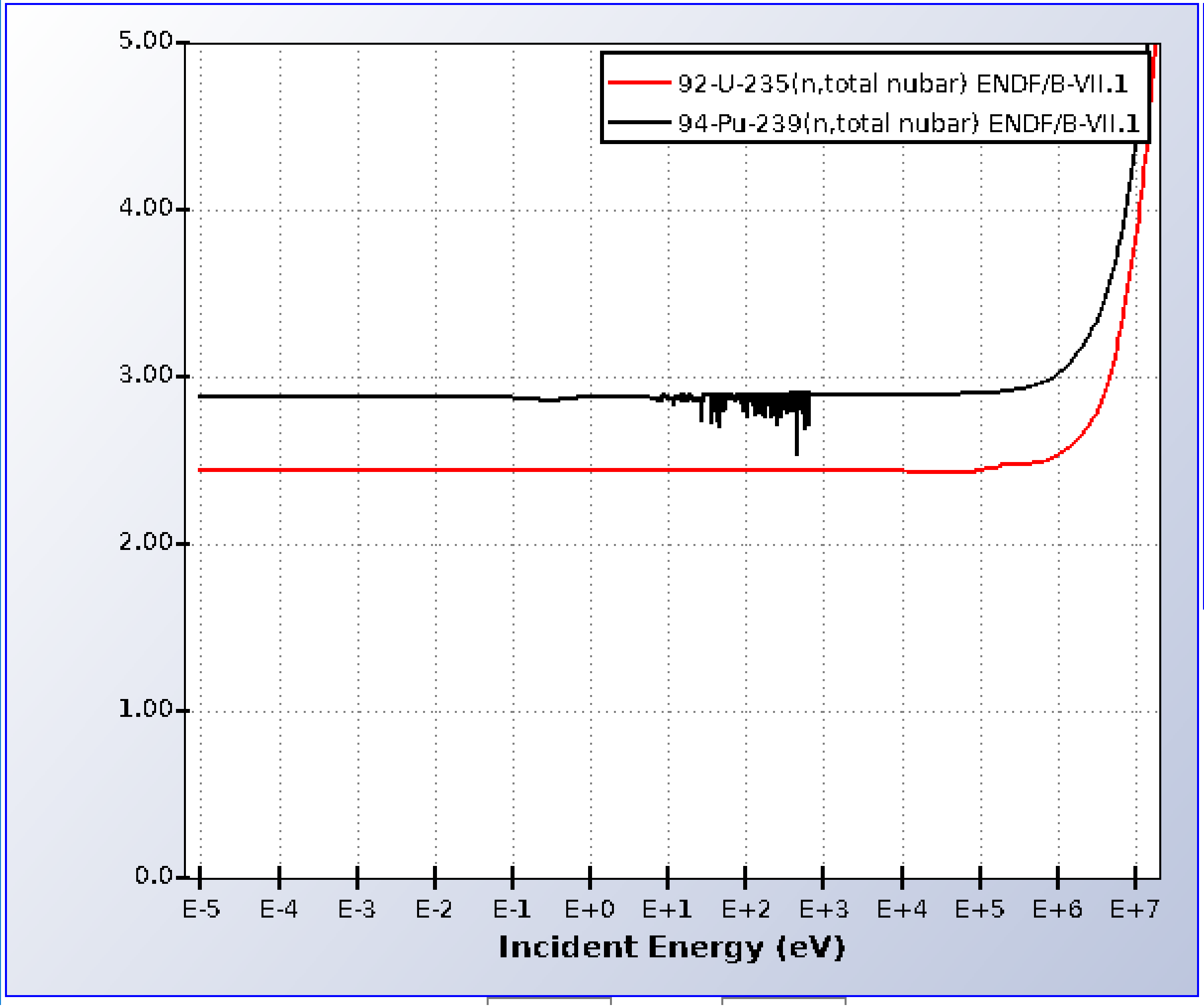
Why Fast Neutrons and Why Plutonium?





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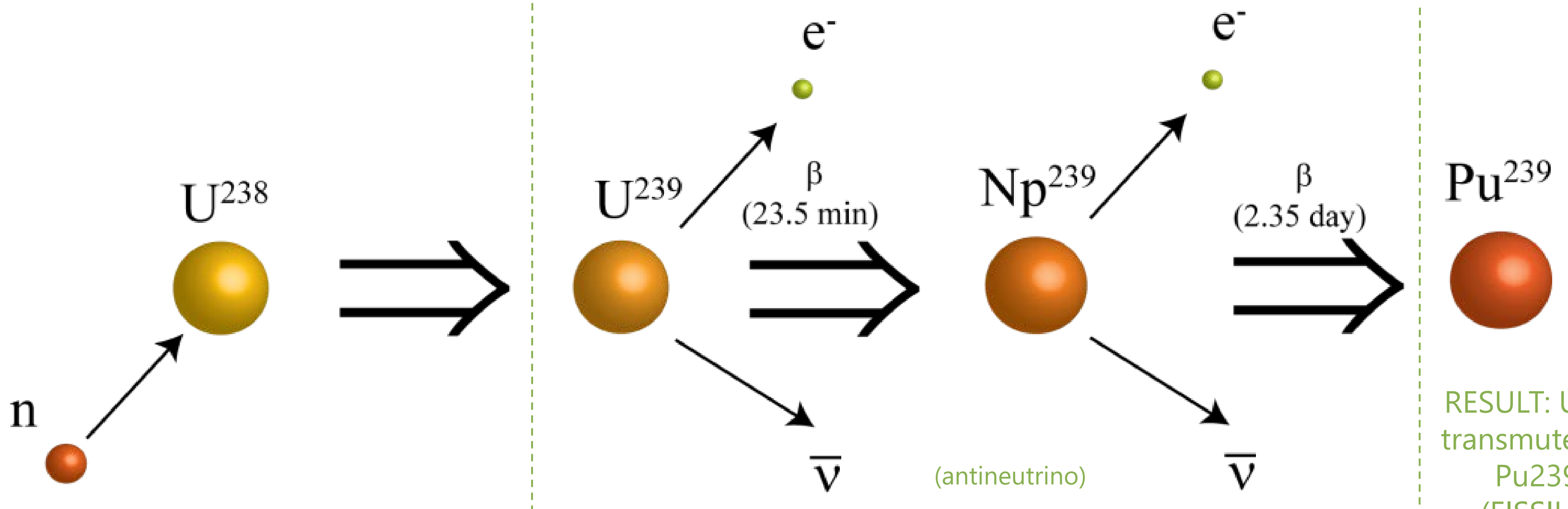
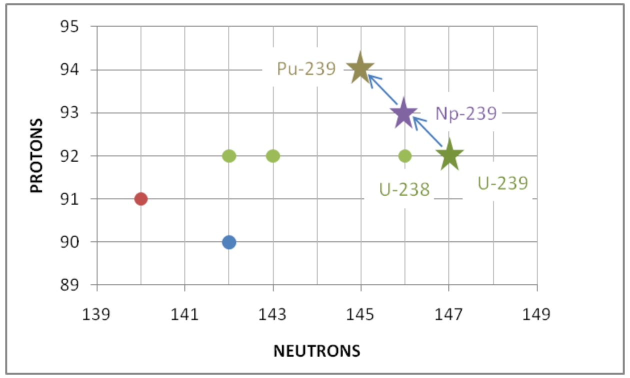
TRANSMUTATION OF U238 TO Pu239



Neutron absorbed (FERTILE)

New nuclei unstable, beta minus decays twice

RESULT: U238 transmuted to Pu239 (FISSILE)



Key TWR Capabilities

DU storage facility in Paducah, KY

- Utilize otherwise unusable depleted uranium as fuel
  - Stockpile can power USA for 200 years
- Reduce nuclear waste
- Achieve *passive safety*
  - Can cool itself in Fukushima-like events without active systems
- Reduce costs and proliferation risk associated with fuel cycle facilities
  - Enable fleet operation without enrichment facilities ← **Key point**
  - Obtain benefits of breeder reactors ***without requiring reprocessing facilities***

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A Long Intellectual History

1958	1979	1996	2000	Early 2000s	2006–2009
Saveli M. Feinberg: *Unenriched fuel concept*	*Michael J. Driscoll:* *Breed-burn concepts*	Edward Teller, Lowell Wood: Breed-burn waves	Hugo van Dam: Formal analysis of fission waves	Hiroshi Sekimoto: Analysis of CANDLE	Intellectual Ventures: **INVENTION!** Extensive physics and engineering work on TWR

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Breed-and-burn avoids reprocessing

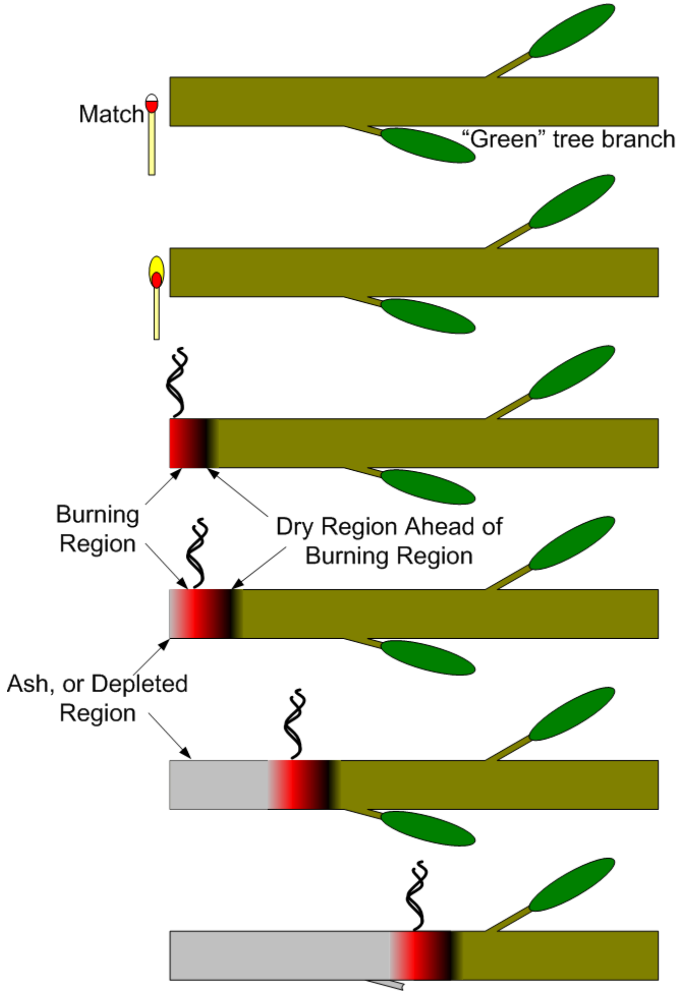
Key nuclear physics:

- U235 (0.7%) fissions readily
- U238 (99.3%) captures neutrons, becomes Pu239 (which fissions readily)

Thereby *breeding fuel*

<u>BREED:</u> If you can keep your U238 in a fast neutron cloud for long enough, a lot of Pu239 will be created

<u>BURN:</u> This Pu239 can eventually “take over” as the primary fuel



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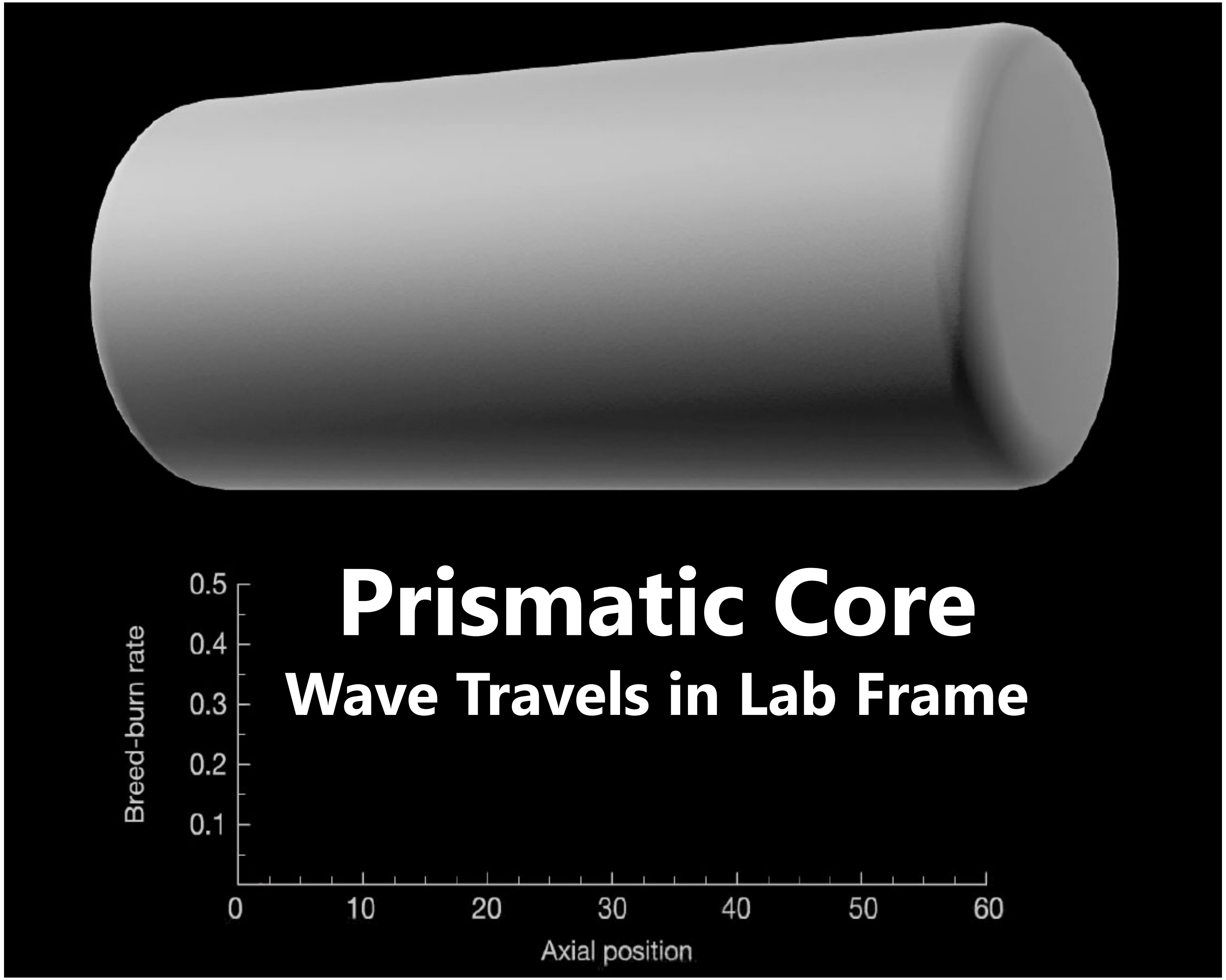
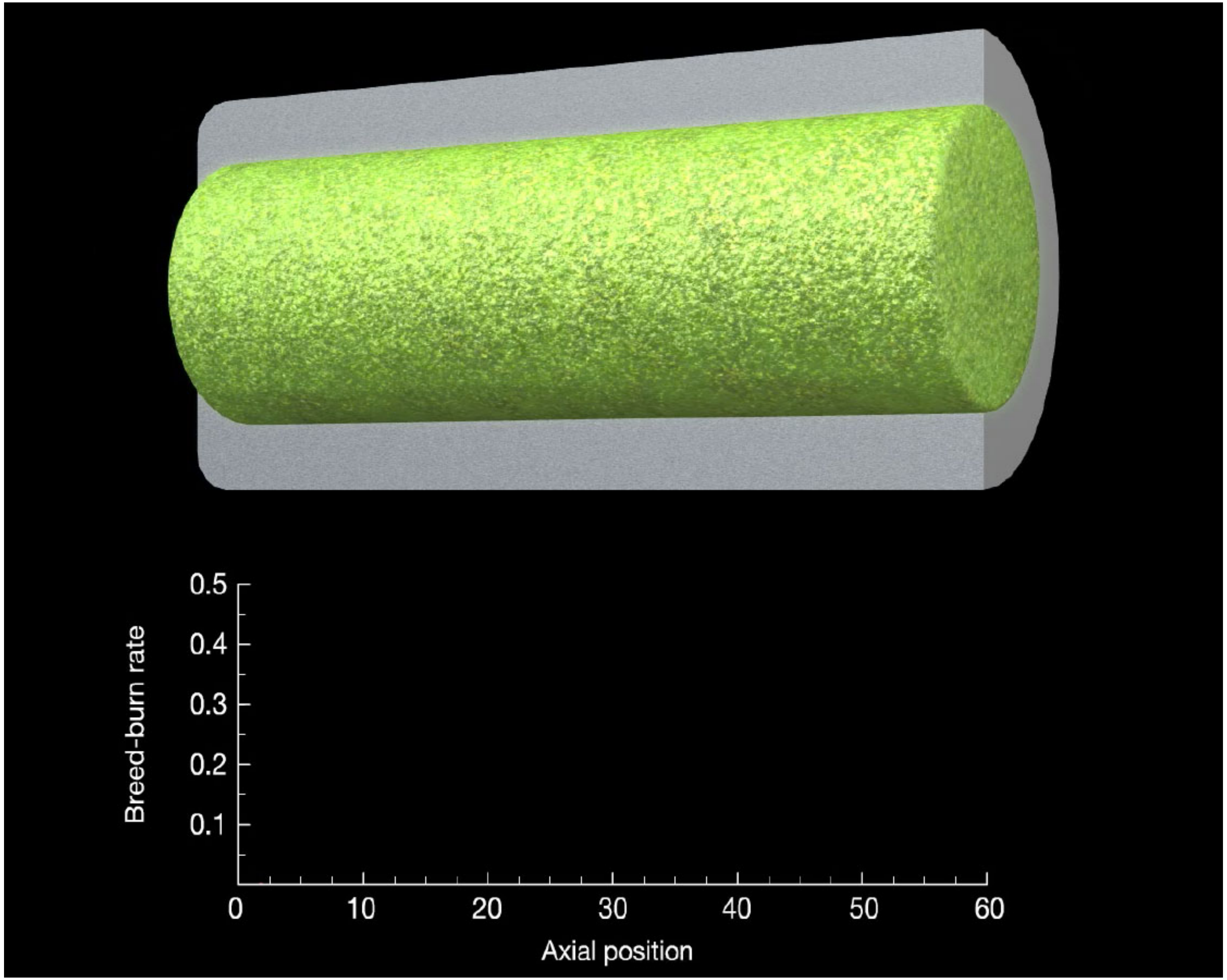
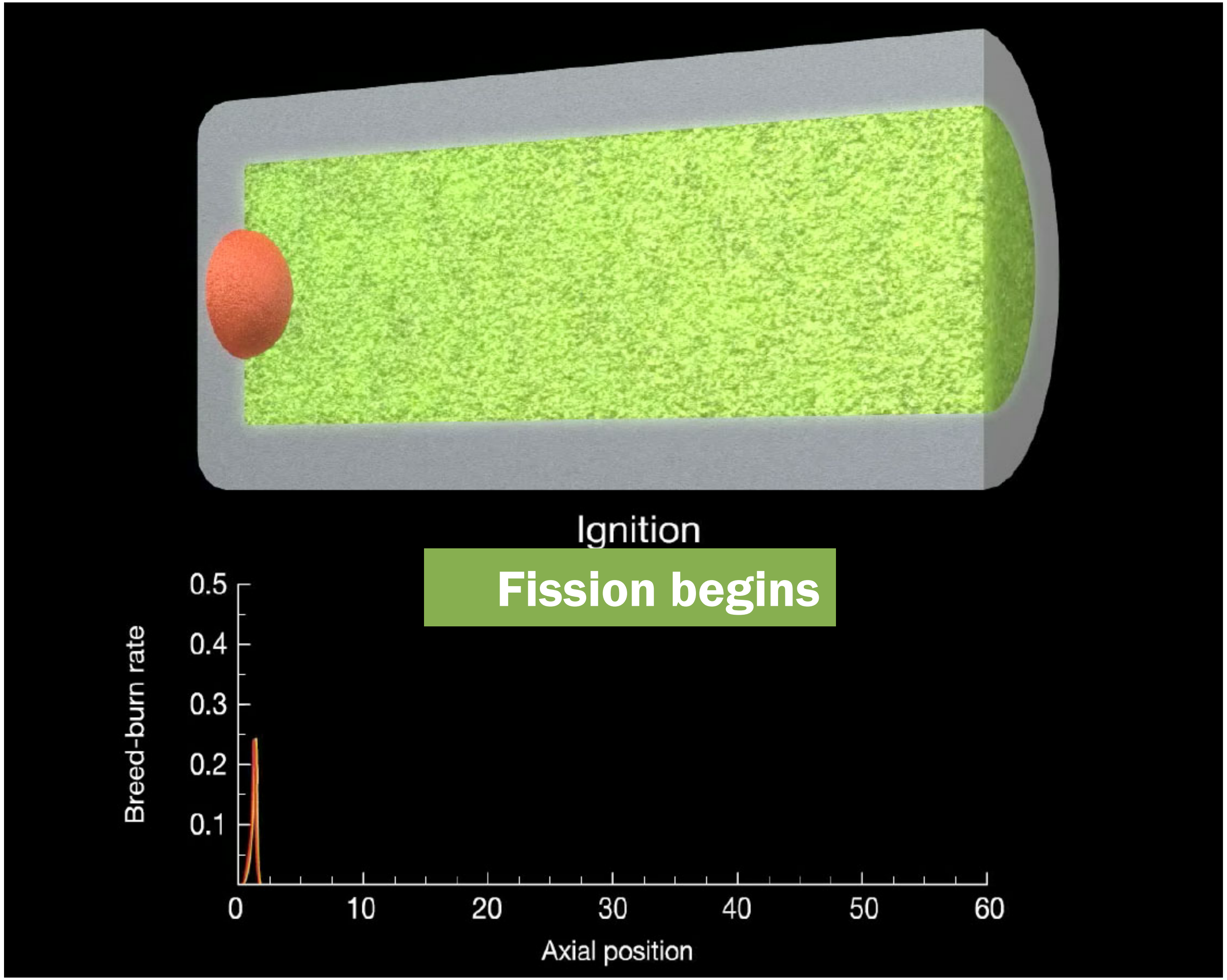
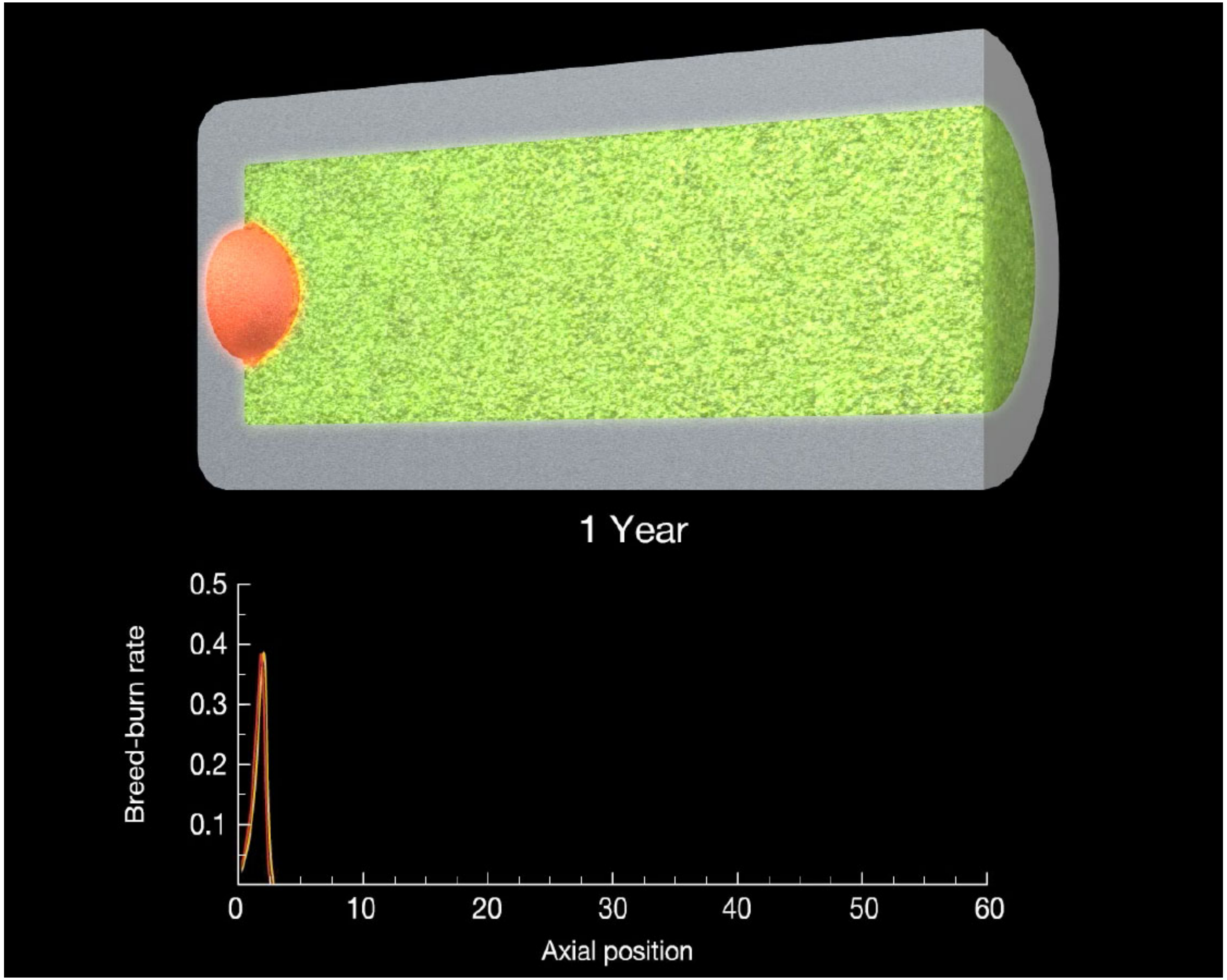
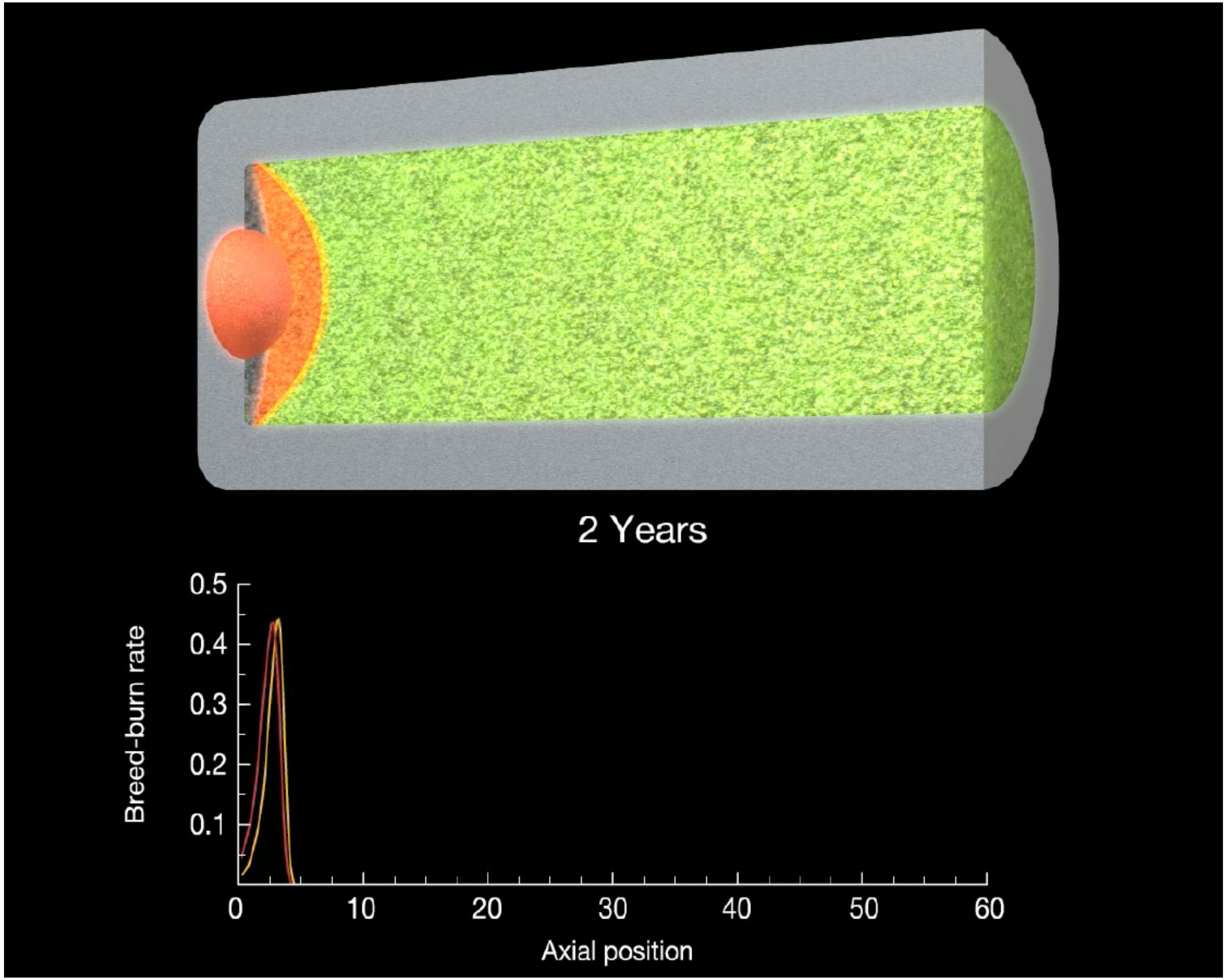

Prismatic Core
Wave Travels in Lab Frame
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position

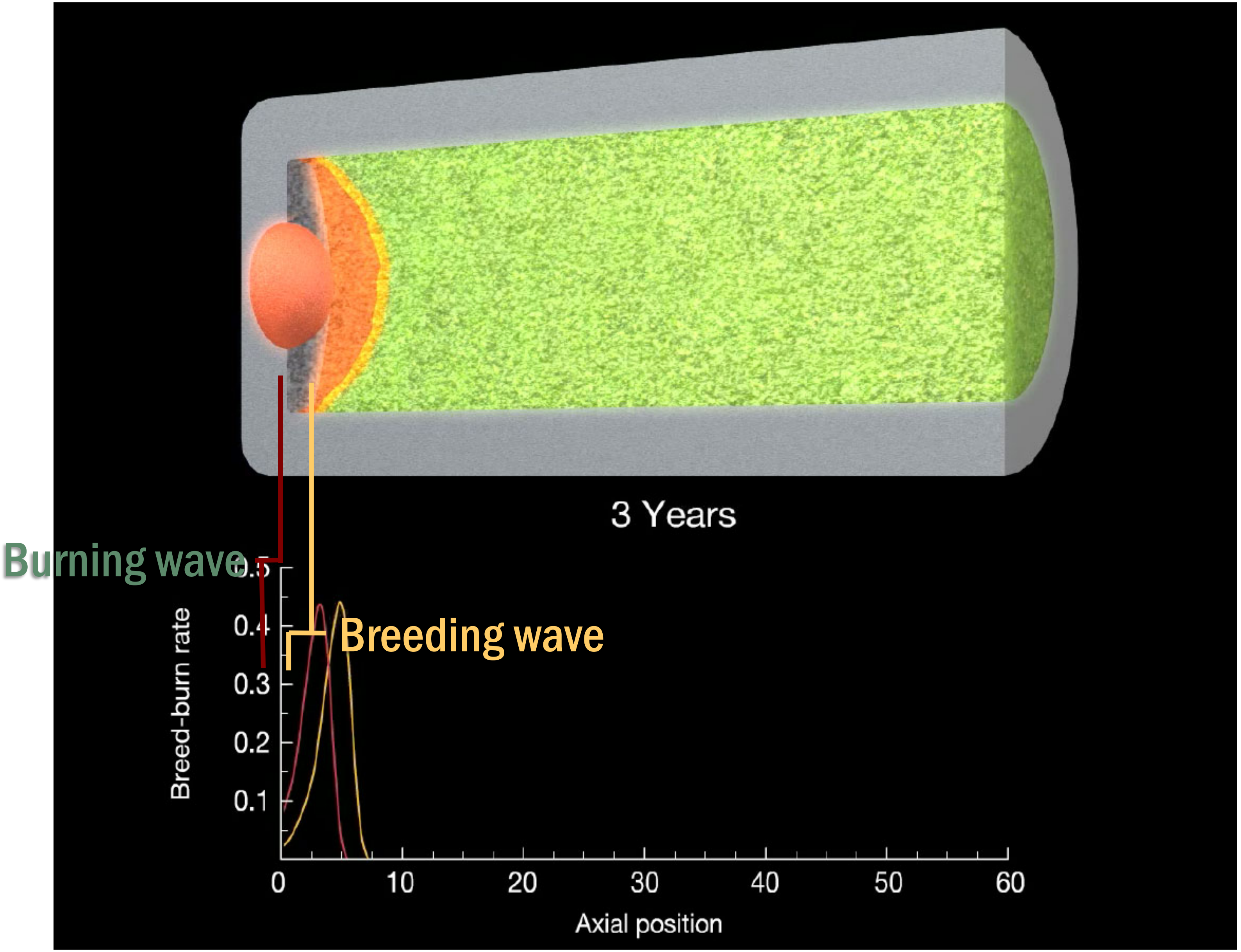

Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position



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


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


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

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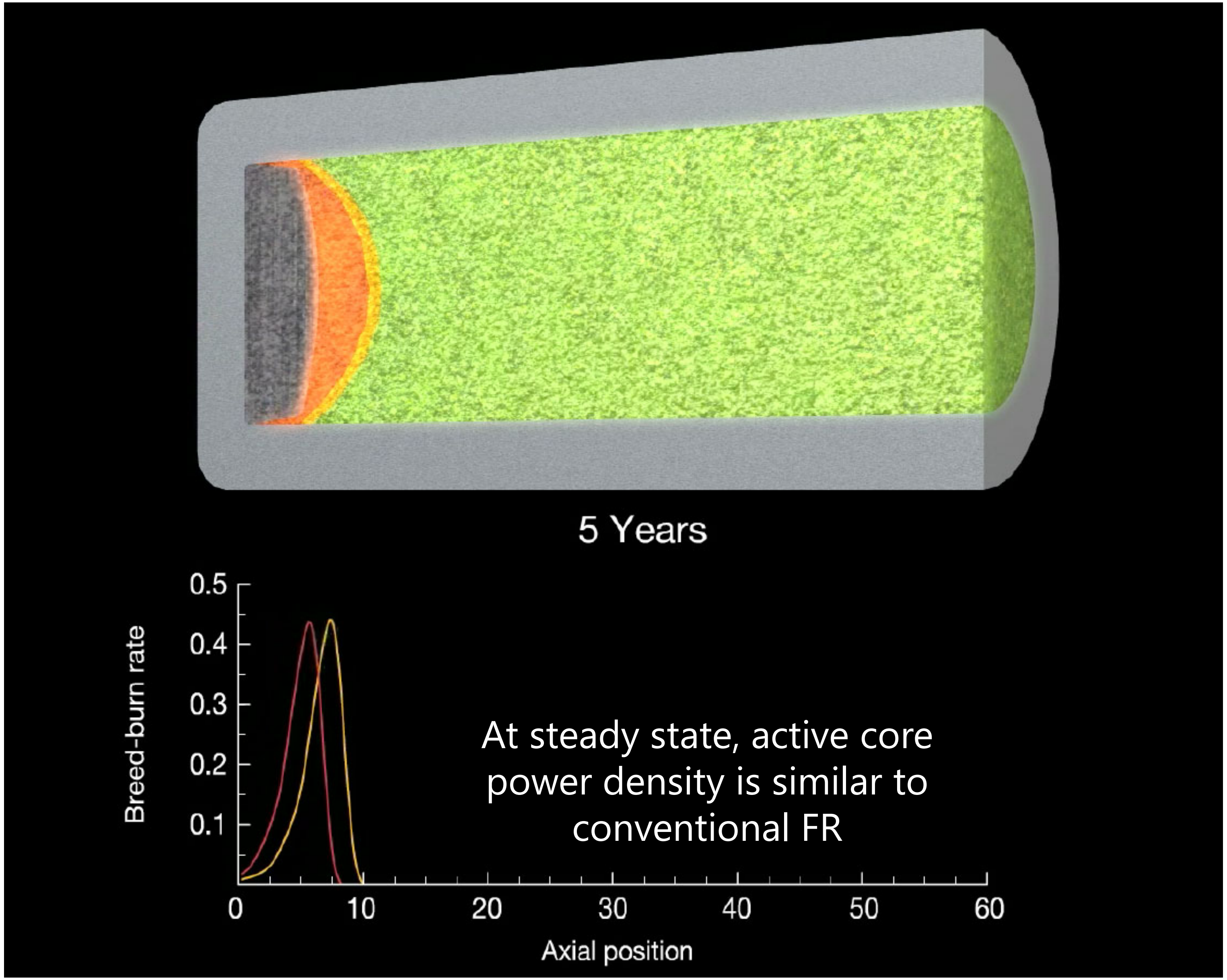
5 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position
At steady state, active core power density is similar to conventional FR

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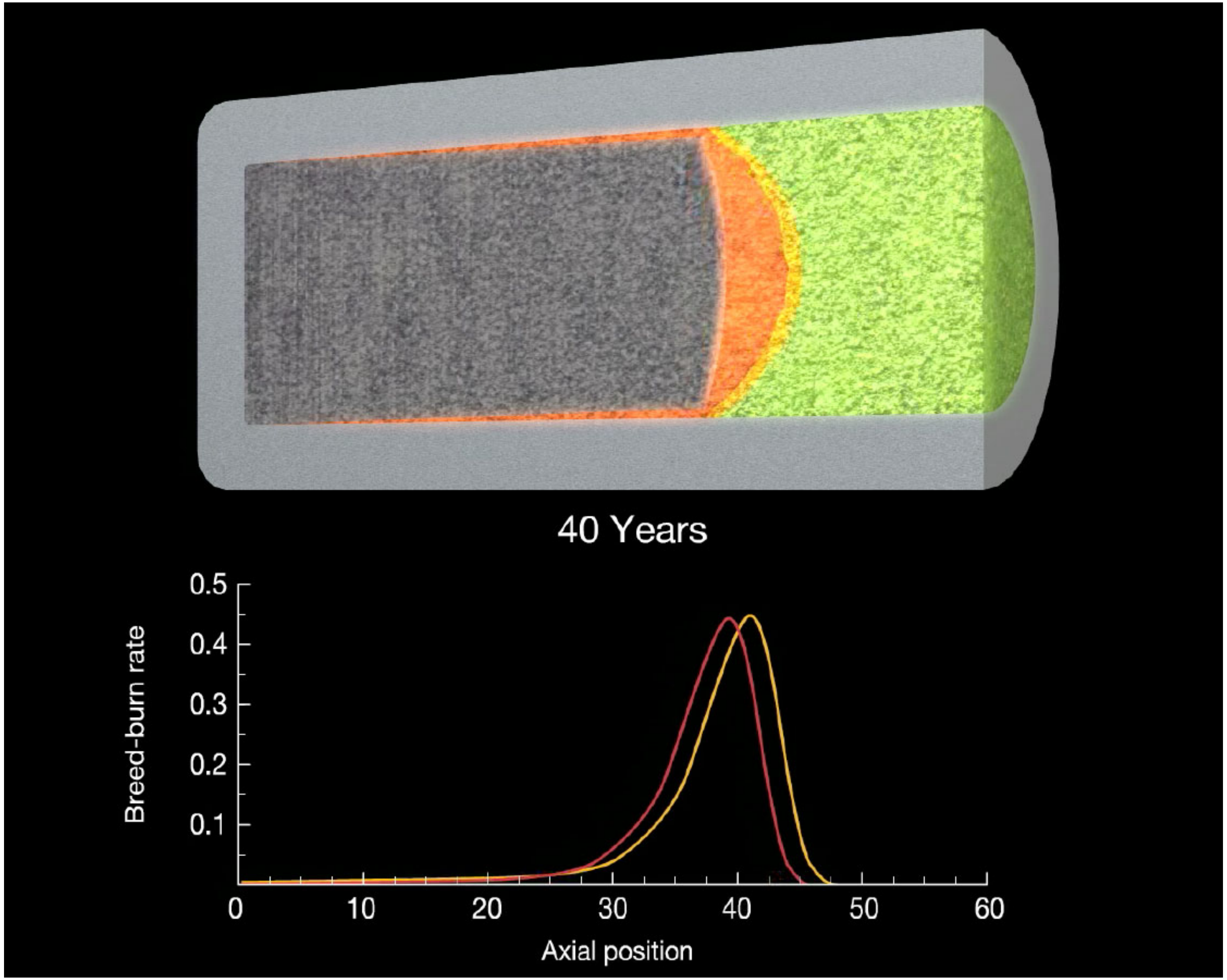
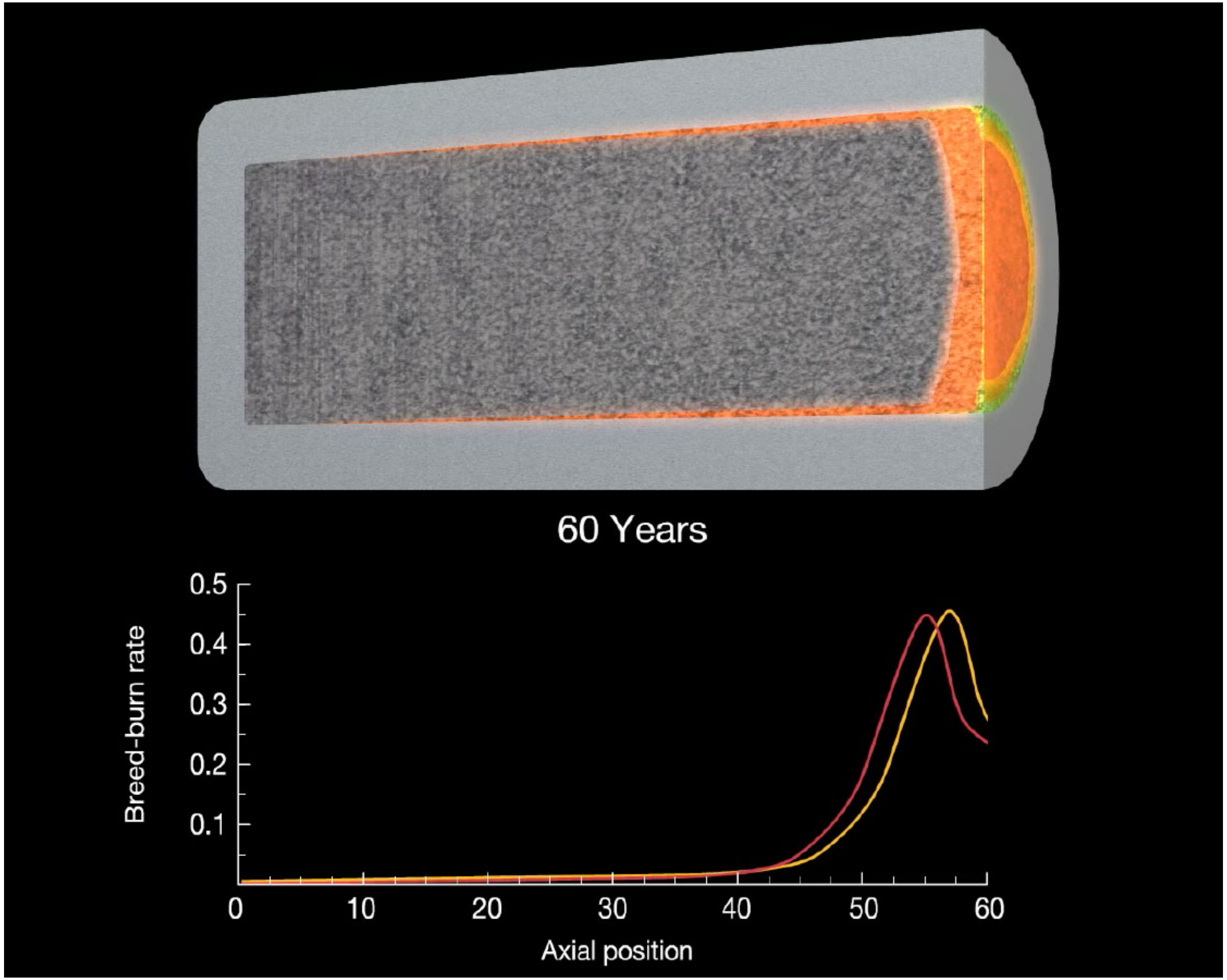

40 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
Axial position


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

Wave Modeling Performance in Raw Metal

URANIUM

- Density: 10 g/cc
- Wave Power: 200 GW/m2
- Wave Velocity: 3.8 cm/day
  - Limited (primarily) by half life of Np239 (2.35 days)

cf THORIUM

- Wave Power: 1.9 GW/m2
- Wave Velocity: 13 cm/yr
- - Limited (primarily) by half life of Pa233 (27.0 days)

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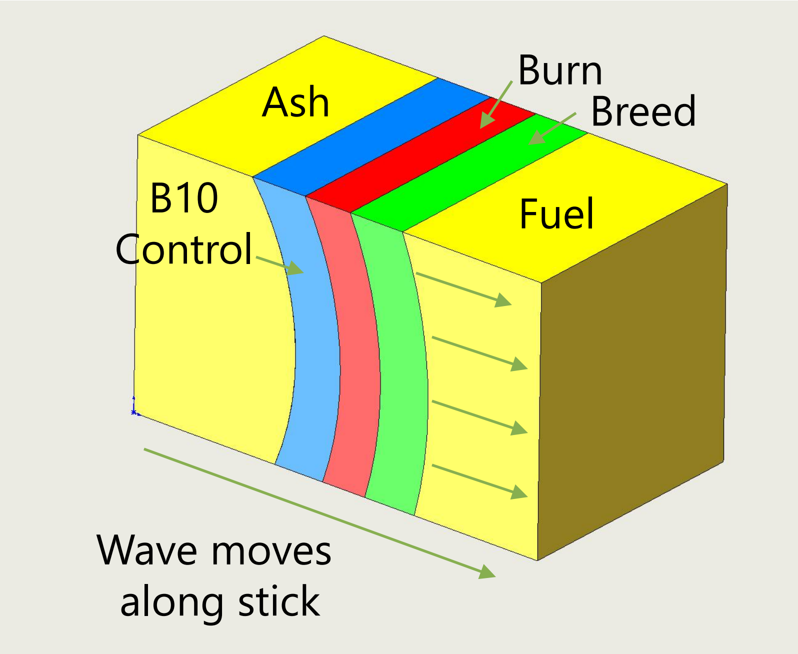
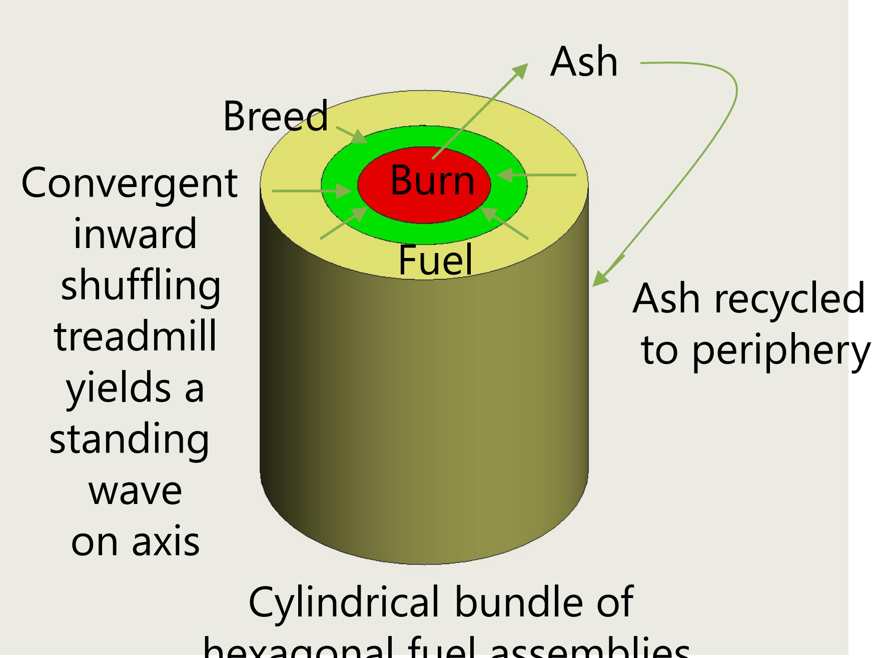
Traveling Wave Reactors Compared

Linear Traveling Wave:



Cylindrical Traveling Wave:



Cylindrical bundle of
hexagonal fuel assemblies

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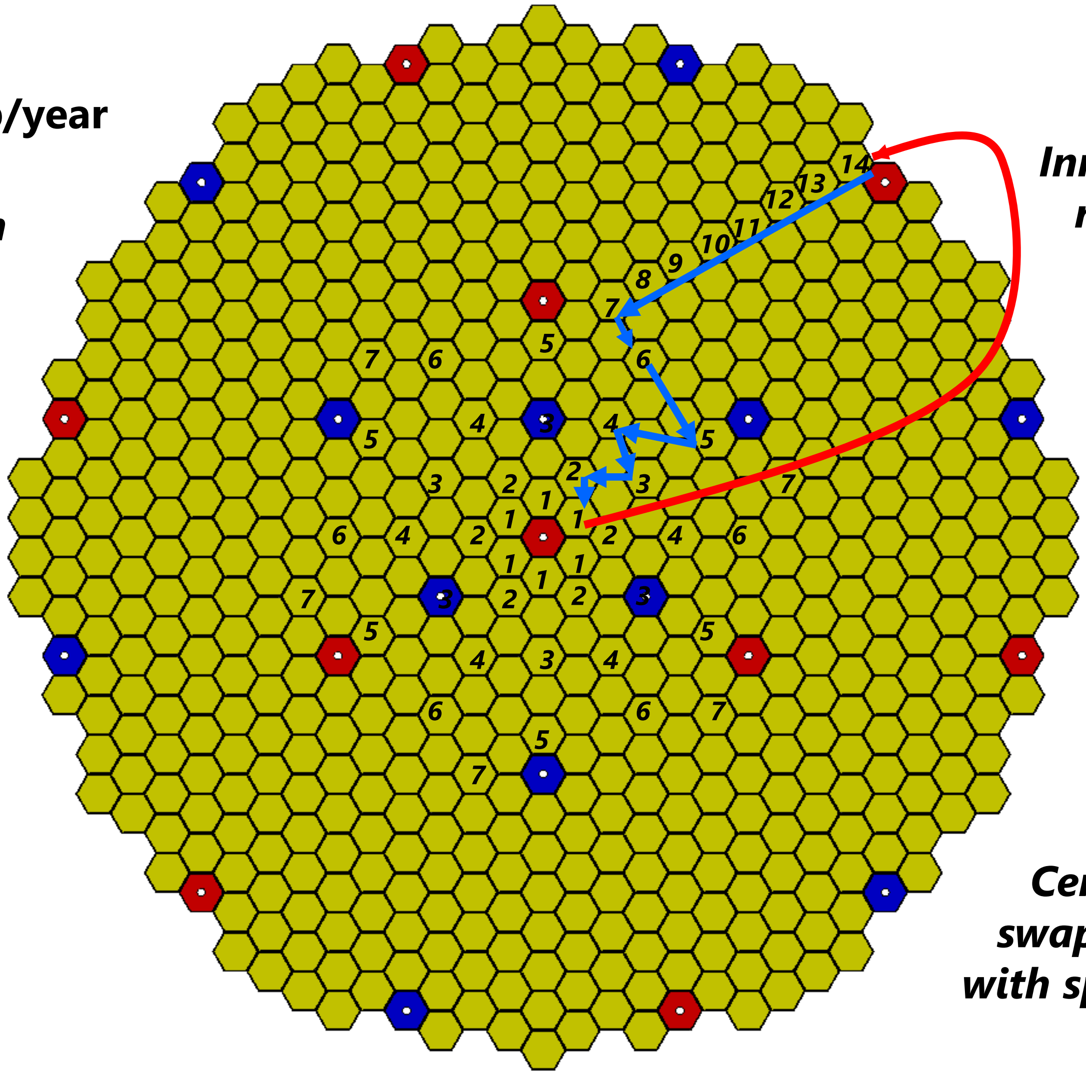
Typical Shuffle Step in a CTWR

One shuffle step/year

6 hexes in each ring move in

14 rings x 6 = 84 hexes move/year

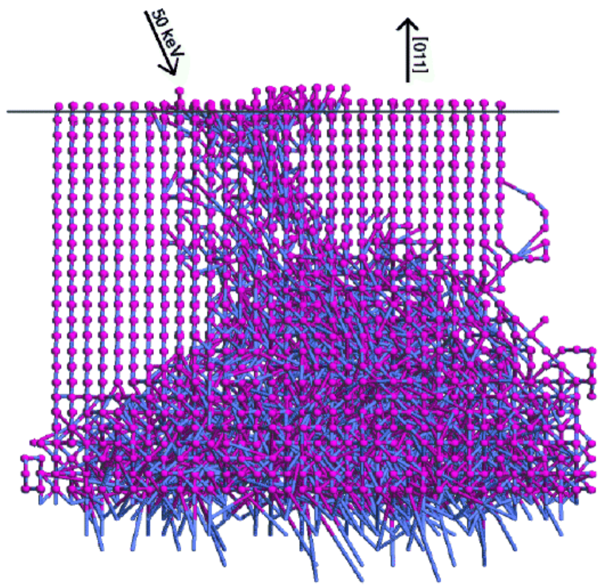


Innermost hex recycled to periphery

Central safety rod swapped periodically with spares on periphery

Challenges due to breed-and-burn

1. To breed enough fuel, the fuel pins and their supporting materials must withstand considerable neutron damage
2. We can't afford neutron leakage and must therefore have large core with engineered reactivity feedback



An atomic displacement cascade caused by an incident 50 keV neutron

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Irradiated fuels & materials degrade

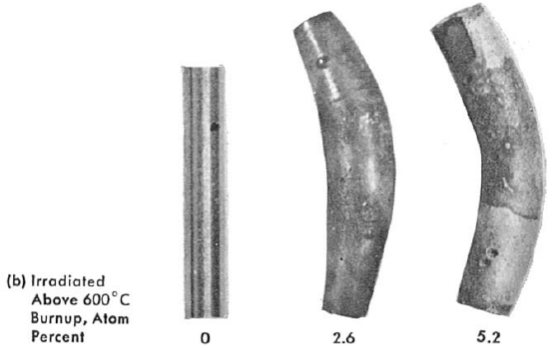


FIG. 3–55. Irradiated specimens, showing "ballooning" due to temperature effects.

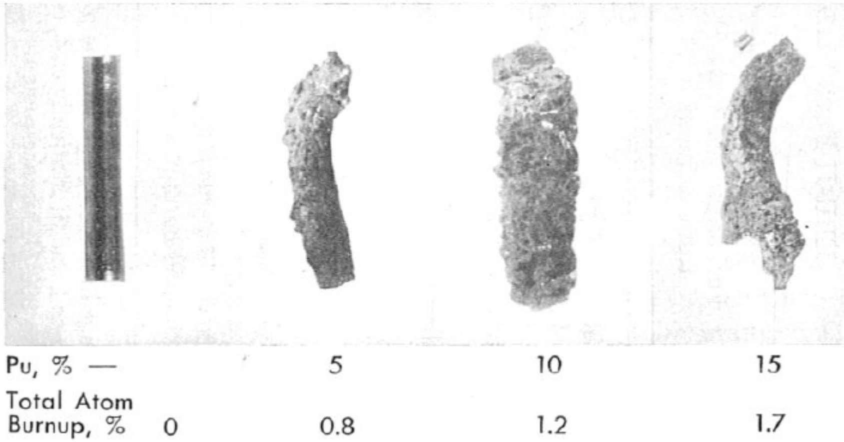
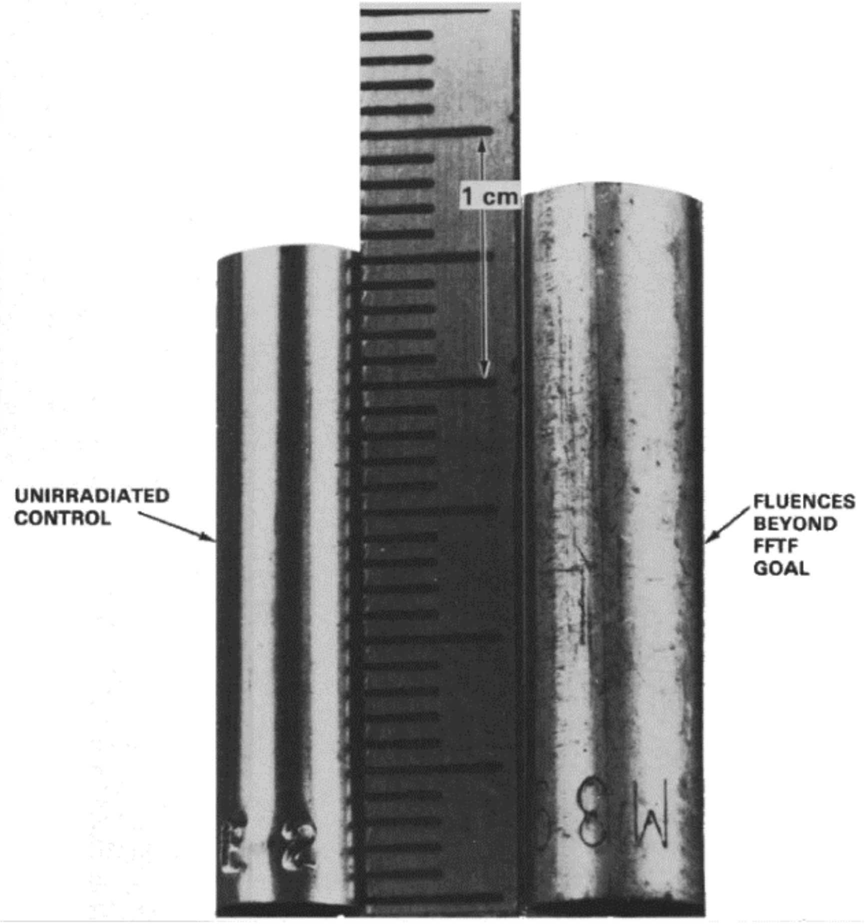
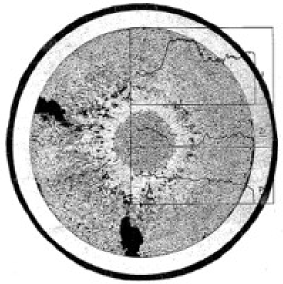


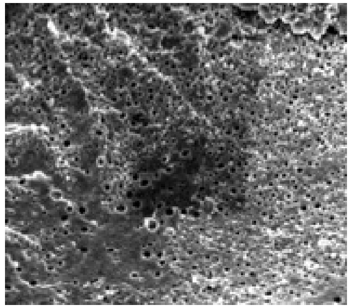
FIG. 3–56. Effect of irradiation on cast uranium-plutonium alloys.



Growth of AISI SS316 after irradiation up to 1.5x10^{23} fast fluenc
(Straalsund et al., 1982)

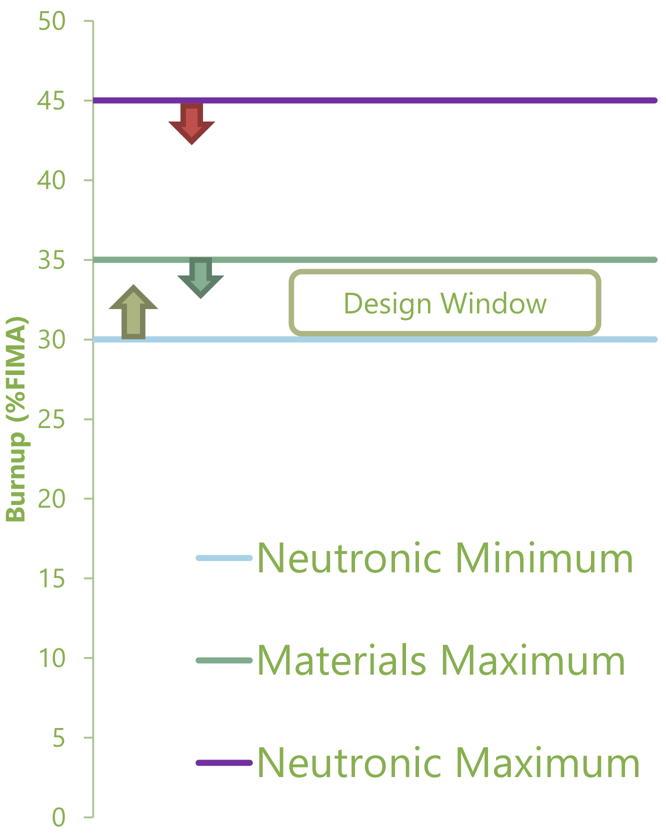


Porosity formed in U-Pu-Zr fuel due to irradiation



TWRs have *minimum* burnup

- Models and calculations show >28% burn-up (500 DPA) required to sustain a wave in uranium
  - Cores shown require ≥ 28% peak burn-ups
  - These values exceed previous experience and need confirmation of material and fuel capabilities
- Fast neutrons open neutronic window
  - Favors metallic fuel
- Advanced fuels & materials open material window
- Requires substantially higher burnup and fluence than has been demonstrated
  - Favors Ferritic-Martensitic steel
  - Substantial materials development required to realize the burnup and dose goals



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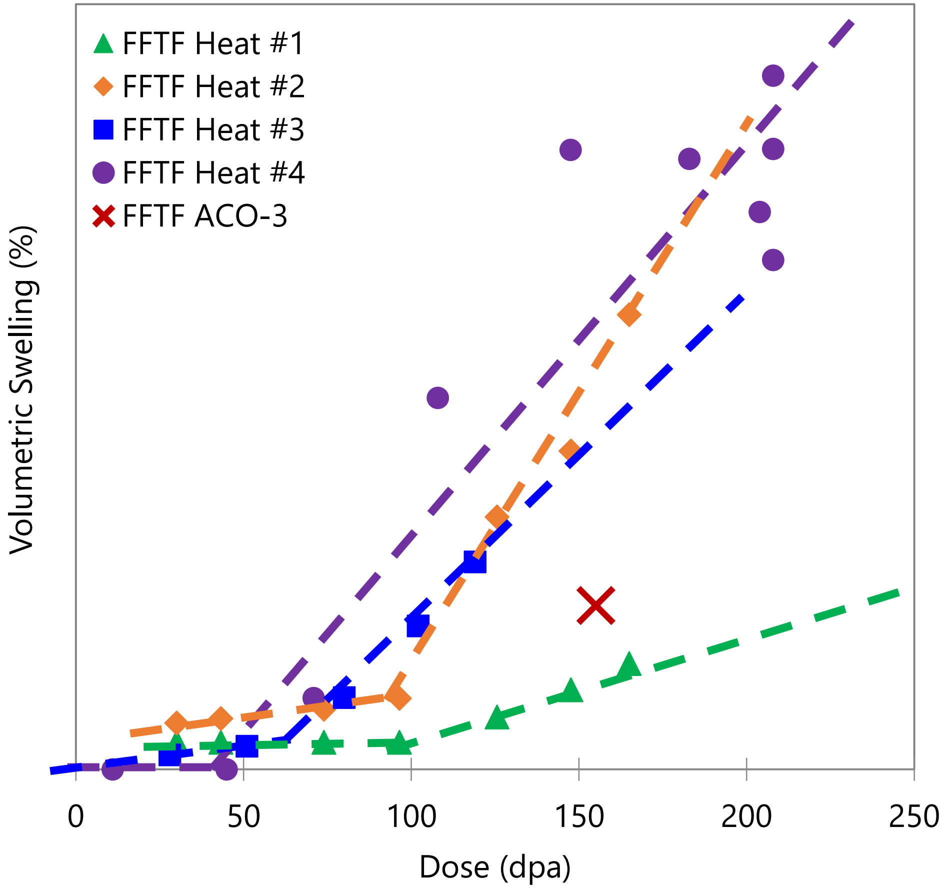
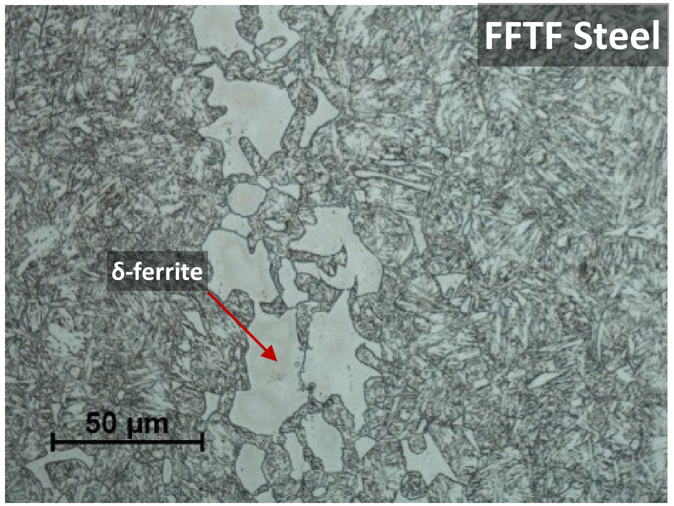
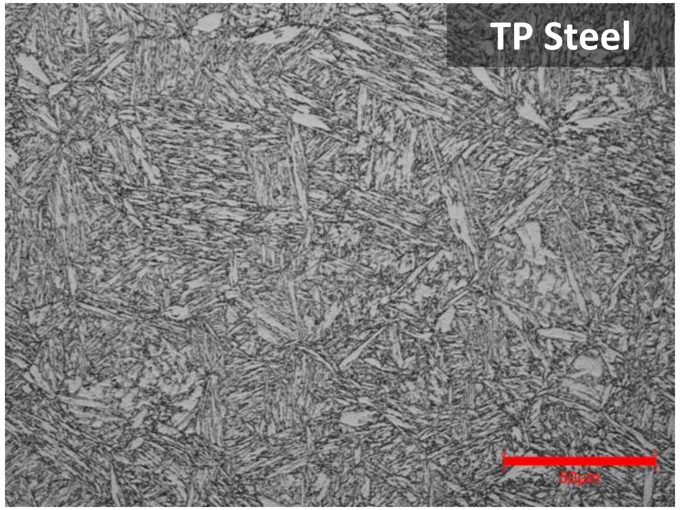
Predicting Neutron Irradiation Performance

Some heats of HT9 used in the US DOE FFTF program show significantly lower swelling rates than others. Heat #1 was promising to achieve 600 dpa for TWR.



TerraPower optimized the chemistry and processing of HT9 steel to provide a clean microstructure that we expected to outperform the heats from FFTF under irradiation.





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HT9 Swelling Performance in FFTF

The method used to verify this consists of three parallel studies:

1) Ion irradiation of TerraPower HT9 and archive, unirradiated material from the FFTF program under the same conditions, i.e. same ion species and energy, to 600 dpa. (rapid prediction of improved properties)

2) Ion irradiation and neutron irradiation of archive, unirradiated material from the FFTF program (1:1 correlation between ion and neutron irradiation in ferritic steels)

3) Neutron irradiation of TerraPower HT9 to 600 dpa in the fast spectrum, sodium cooled BOR-60 reactor (design and qualification data)

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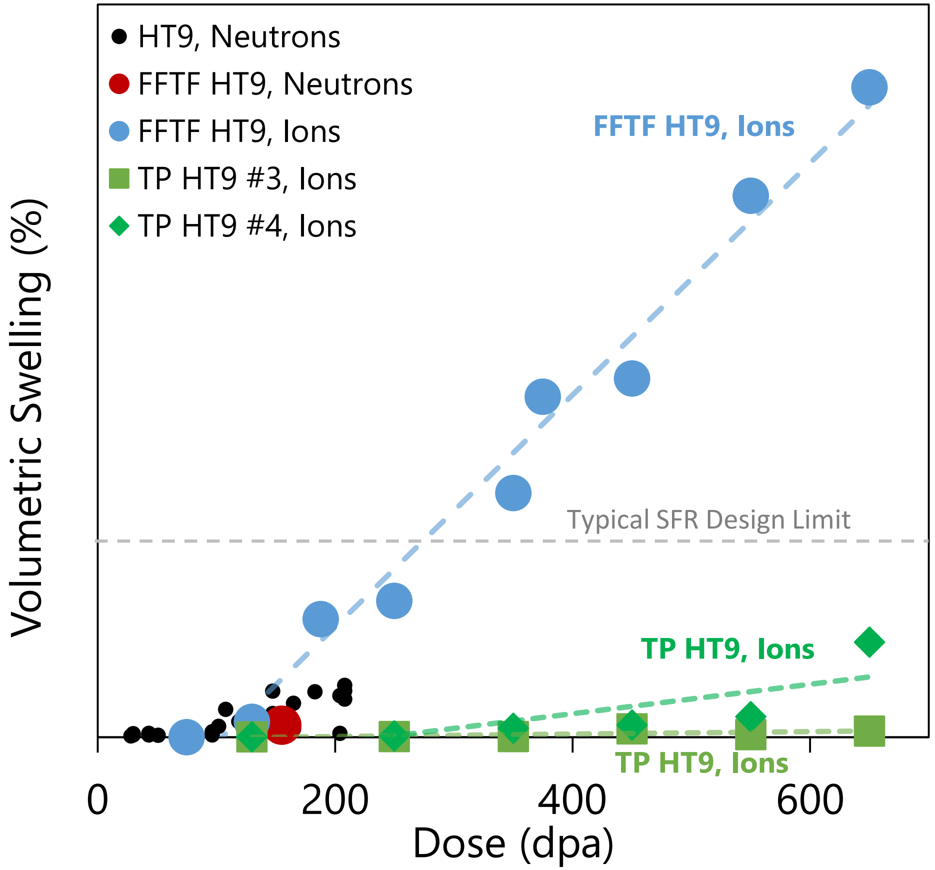
Study #1: HT9 Ion Irradiation Comparison

HT9 performance improvements have been demonstrated using ion irradiation with direct comparison to FFTF material. Current results obtained using preimplanted He followed by Fe ion irradiation. Ongoing work using dual-beam He plus Fe ion irradiation.



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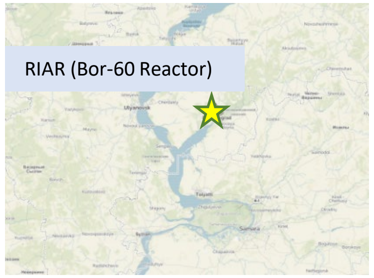
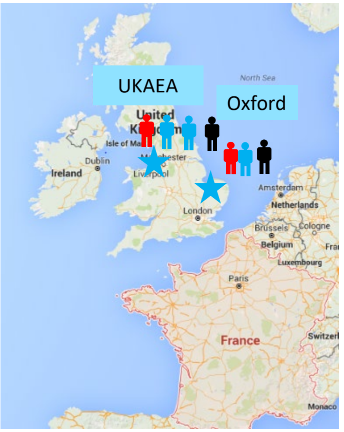
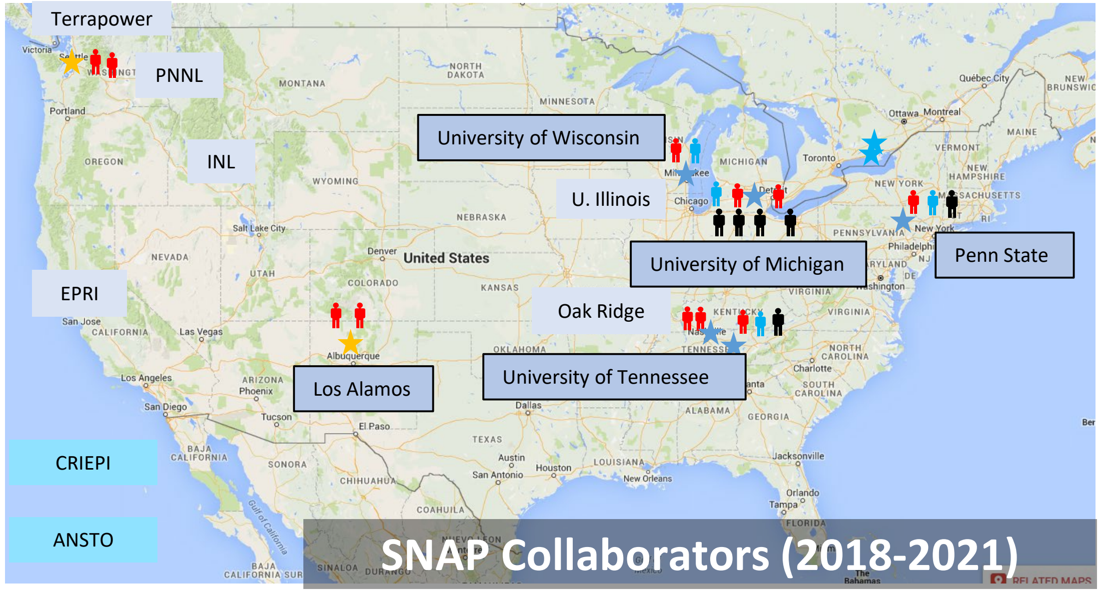
Study #2: HT9 Ion Irradiation Comparison

TerraPower is a partner in the USDOE IRP/SNAP project, which combines the resources of 6 universities and 8 government organizations for irradiation and characterization. Objective is to develop a correlation between neutron and ion irradiated materials (microstructure, swelling, and mechanical properties) to predict the performance of ferritic alloys (e.g. HT9) out to high doses



- ★ IRP Funded Participant
- ★ Independent Funding
- ★ Collaborators
- Principal Investigators/Senior Scientists
- Research Scientists/Postdocs
- Graduate Students





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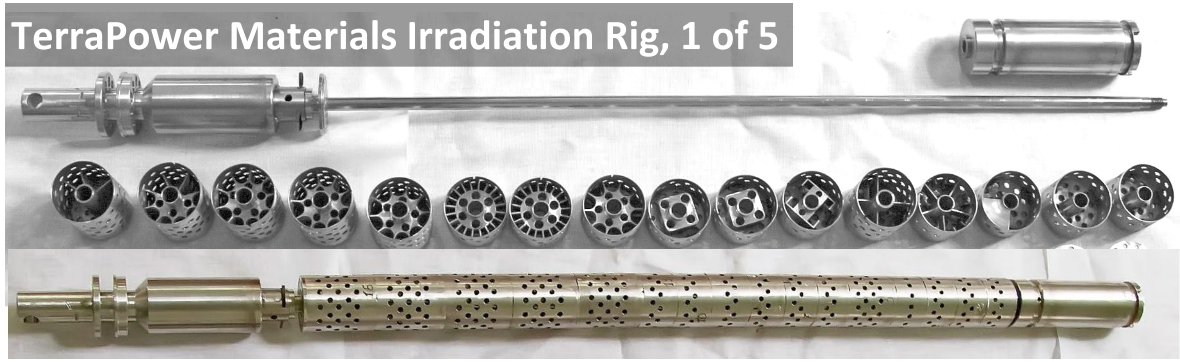
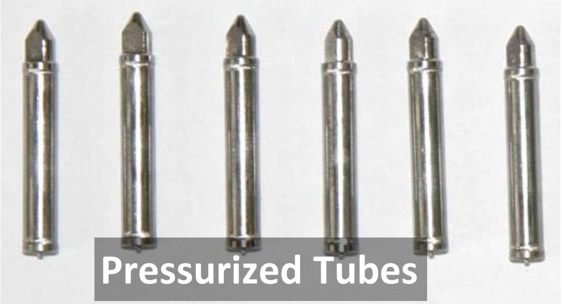
Study #3: Neutron Irradiation of TP HT9 at BOR60

Over 1000 samples, including FFTF HT9 as well as TerraPower HT9, T91, and T92 have been irradiated in the BOR60 SFR.





102 HT9 samples (2 heats)
Laser welded
360, 400, 450, 525, 600°C
10-150 MPa hoop stress
Irradiated to ~85 dpa (peak)

380 Total HT9 samples (4 heats)
360, 400, 450, 525, 600°C
100 extracted at ~17 dpa
(mech. testing underway)
280 irradiated to ~85 dpa (peak)

45 HT9 samples (2 heats)
360, 400, 450, 525, 600°C
Irradiated to ~85 dpa (peak)

190 Total HT9 samples (4 heats)
360, 400, 450, 525, 600°C
50 extracted at ~17 dpa
(mech. testing underway)
140 irradiated to ~85 dpa (peak)

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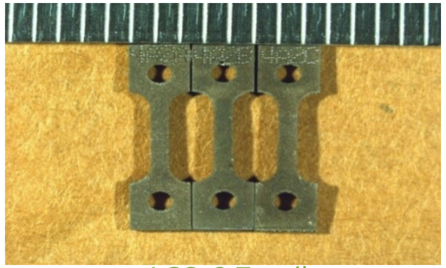
BOR-60 Materials Test, TWR-P and TWR-C

Goals Include: Irradiate HT9 to 280 dpa by 2019, provide data on optimized production process HT9

Rigs 1 and 2 inserted into BOR-60 Dec 24, 2013.

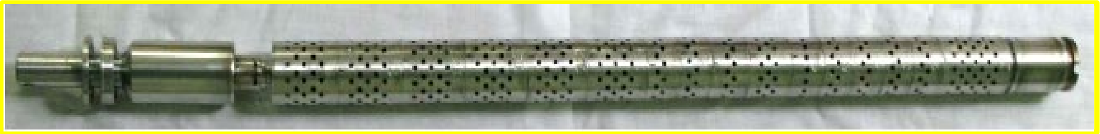
- 360 and 400˚C
- New TerraPower Optimized Material (>350 specimens).
- DOE Pre-Irradiated (~150 specimens)
- BOR-60 Irradiation has accrued > 20 dpa to date
- Temperature maintained by gamma heating


Pressurized Tube


ACO-3 Tensile


TEM Capsule

Assembled Suspension with 16 sample/monitor holders




Container with Assembled Suspension Inside

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The reconciliation between neutron fluence and ion fluence ongoing

Thanks for your attention