TerraPower, LLC
Nuclear Initiative

Berkeley, California

April 20, 2009

INTELLECTUAL VENTURES

- Founding idea: to create technological advances of high economic and social value through the invention process
- One corporate goal: new concepts for practical energy systems
  - Economically attractive
  - Sustainable
  - Environmentally responsible
- Led us to investigate and conclude that :
  - Nuclear power is essential to meet growing energy needs with acceptable carbon emissions
  - Improvements are needed for nuclear endeavors to realize full deployment potential

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Intellectual Ventures' Initiative

- Exploring significant improvements to nuclear power using:
  - 21st century technologies
  - State-of-the-art computational capabilities
  - Expanded data, openly shared
- Evaluating the impact of new concepts on the entire system
  - Fuel mining, enrichment, production, reprocessing
  - Reactor design construction, operation, decommissioning
  - Spent fuel and waste management
- Pursuing an independent, privately funded path
  - Self-directed effort focused on long-term, global perspective
  - Multidisciplinary approach
- Building our team of technical staff and collaborators as an *integrated* Intellectual Ventures and TerraPower effort

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The Modeling Team

- Charles Whitmer
- Pavel Hejzlar
- John Nuckolls*
- Robert Petroski
- Tom Weaver*
- Lowell Wood*
- George Zimmerman*
- Ehud Greenspan! ☺

** E. O. Lawrence Award winners (DOE)*

Development is Supported by Leading Technical and Business Contributors

former affiliation shown in ( )

- Charles Ahlfeld, (Savannah River)
- Tom Burke, (FFTF)
- Ken Czerwinski, UNLV
- Tyler Ellis, (MIT)
- Bill Gates
- John Gilleland, (Archimedes, Bechtel , ITER, GA))
- Pavel Hejzlar , (MIT)
- David McAlees, (Siemens Nuclear)
- Jon McWhirter, (U Idaho)
- Nathan Myhrvold, CEO Intellectual Ventures
- Ash Odedra, (ITER, Archimedes)
- Josh Walter, (Purdue)
- Kevan Weaver, (Idaho National Laboratory)
- Plus 22 Contributors from Argonne National Lab, FFTF staff, MIT, UNLV

What is an "improved" nuclear system?

- Ideally, it is a global nuclear infrastructure that:
  - Meets global energy needs indefinitely
  - Avoids global warming
  - Creates virtually no risk of weapons proliferation
  - Makes nuclear waste disposal easier
  - Meets the highest accident safety standards
  - Minimizes the environmental footprint of the overall nuclear infrastructure
  - Competes favorably with clean coal power generation systems
    - Ideally, without a carbon tax
    - Alternatively, with a carbon tax to level the environmental playing field
- How close we can come?

The “Traveling-Wave Reactor “ Concept has the Potential to Approach the Ideal System

- Waves of breeding and burning will propagate through fertile material indefinitely
- Once “ignited,” a steady-state deflagration wave propagates through a U-238 core
  - The wave breeds fissile Pu-239
  - The wave fissions the bred Pu-239 as well as some of the U-238 directly
- *Huge stores of depleted uranium waste a viable fuel sufficient for tens of thousands of years for 10 billion people!*
- enriched U needed only for reactor start U-233, U-235, or Pu-239
  - Then Transplated Wave
  - Perhaps someday with only an accelerated particle beam ☺

A Single Cylinder of Depleted Uranium "Waste" has Great Energy Value as Fuel for the MTWR

- Each cylinder contains up to 14 MT of Uranium Hexafluoride
- With the high burn-up efficiency and high thermal efficiency of the MTWR, one cylinder is approximately 60 million Megawatt hours of electricity at the generator output

Depleted UF_6 Cylinder Storage Yard at Portsmouth, OH

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38,000 Cylinders of Depleted UF_6 Waste at Paducah is Fuel !

The Site Represents a Man-Made Mine of Extraordinary Value as TWR Fuel

- Supports 260,000 GW years of electrical energy assuming MTWR efficiencies
- “Waste” is already in the hexafluoride form used for fuel fabrication
- Represents an almost three millennia reserve at present U.S. nuclear generation rate
- Supports ~$100 trillion of electricity at present rates in 2007 dollars

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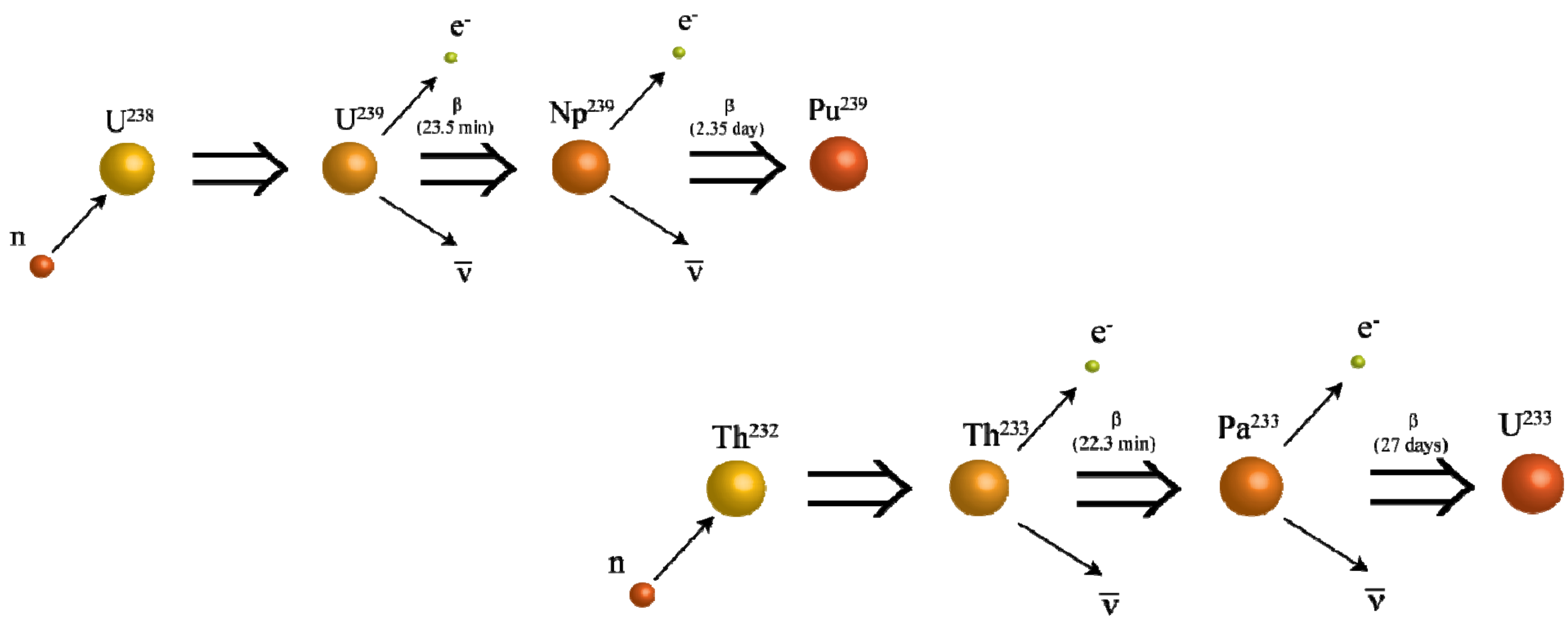
Physics

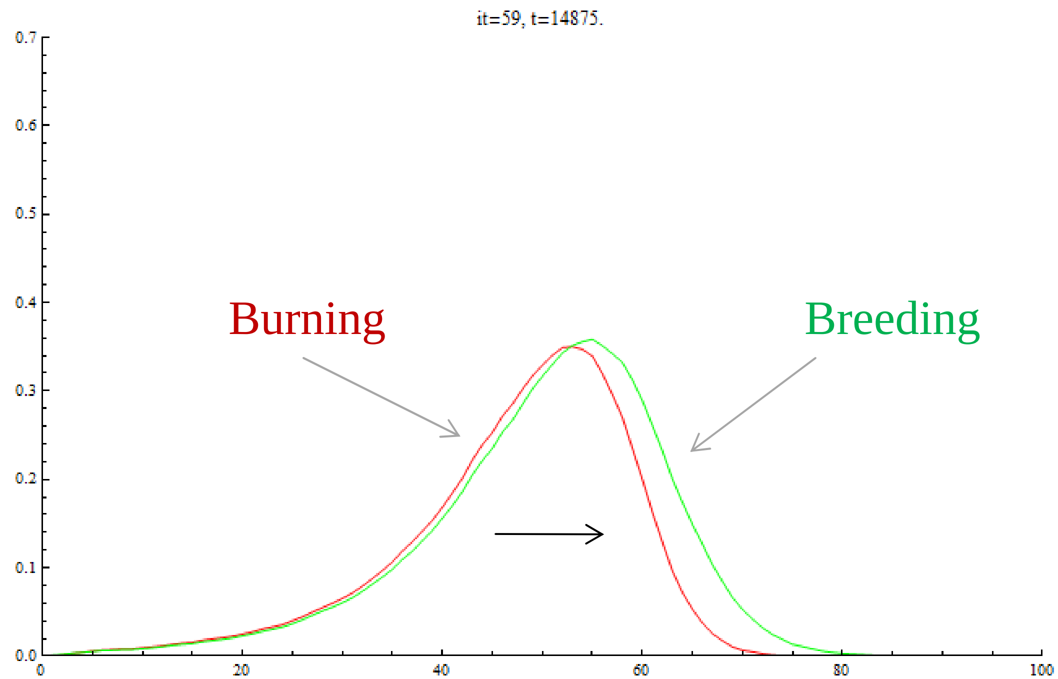
- The “usual” breeder reactions:



- … but applied differently!

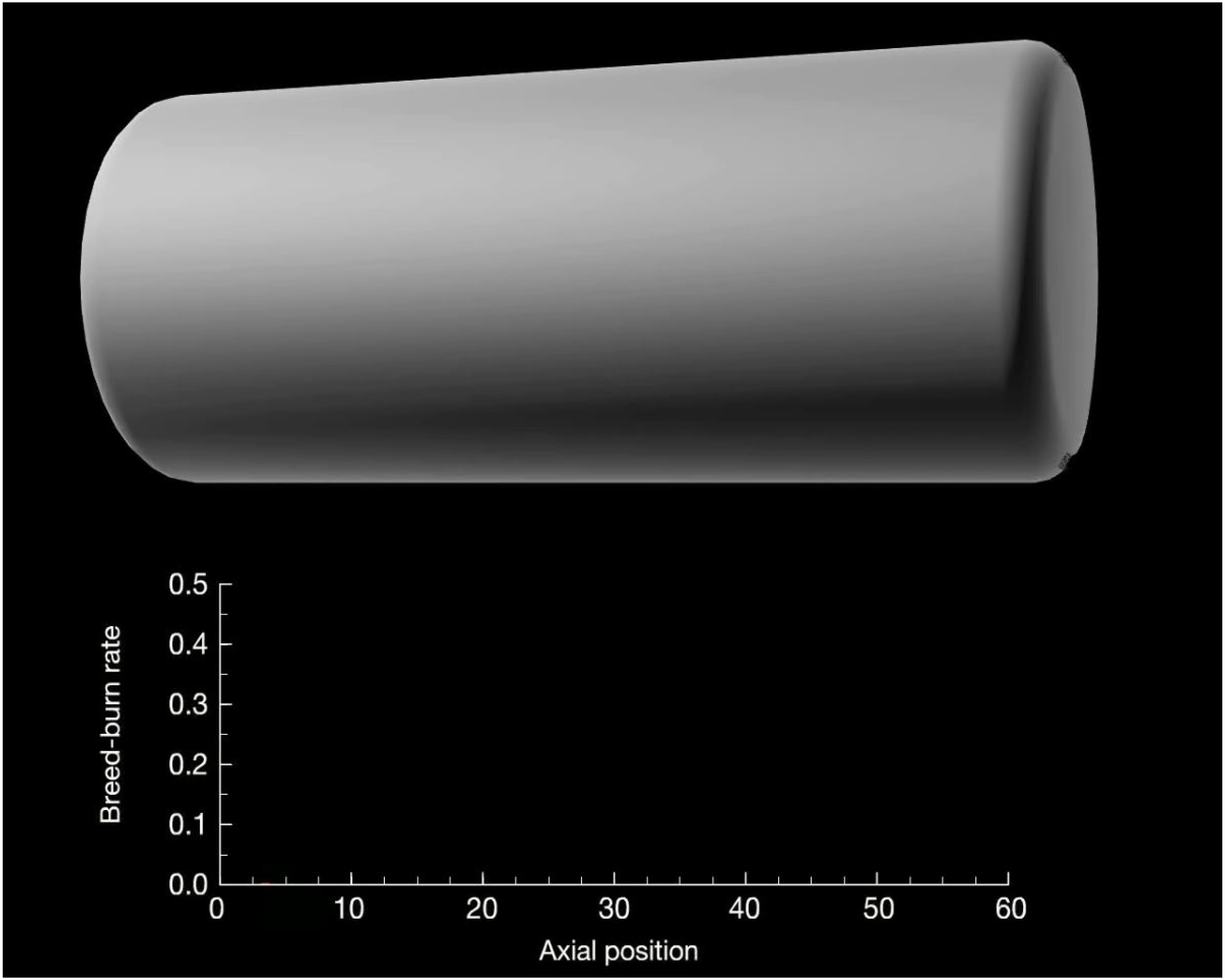
The Wave

- A self-sustaining deflagration of breeding and burning.



Simplified Wave Reactor Concept

Single Pass In-Situ Fuel Production and Burn


0.5
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Breed-burn rate
0
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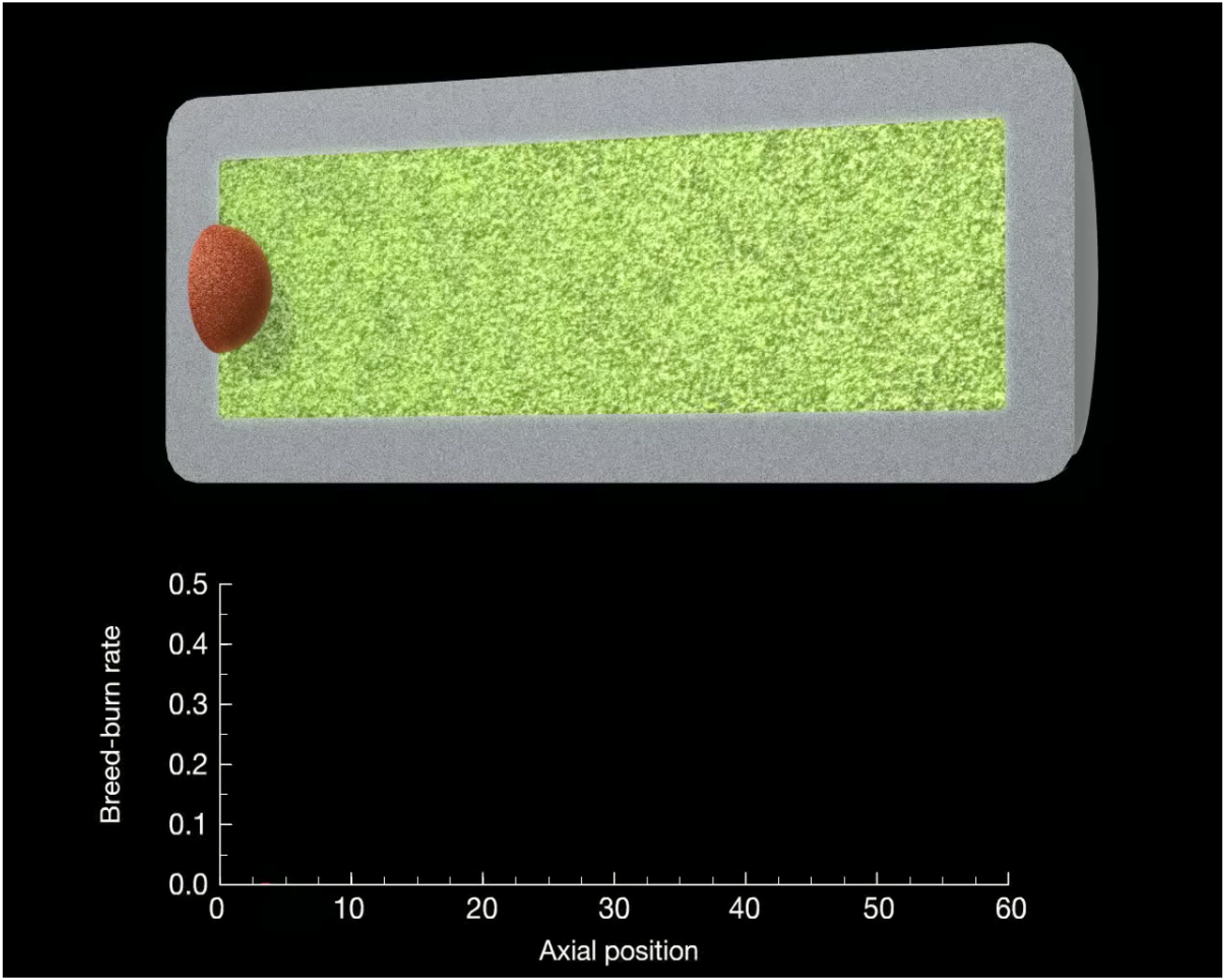
Axial position



Breed-burn rate
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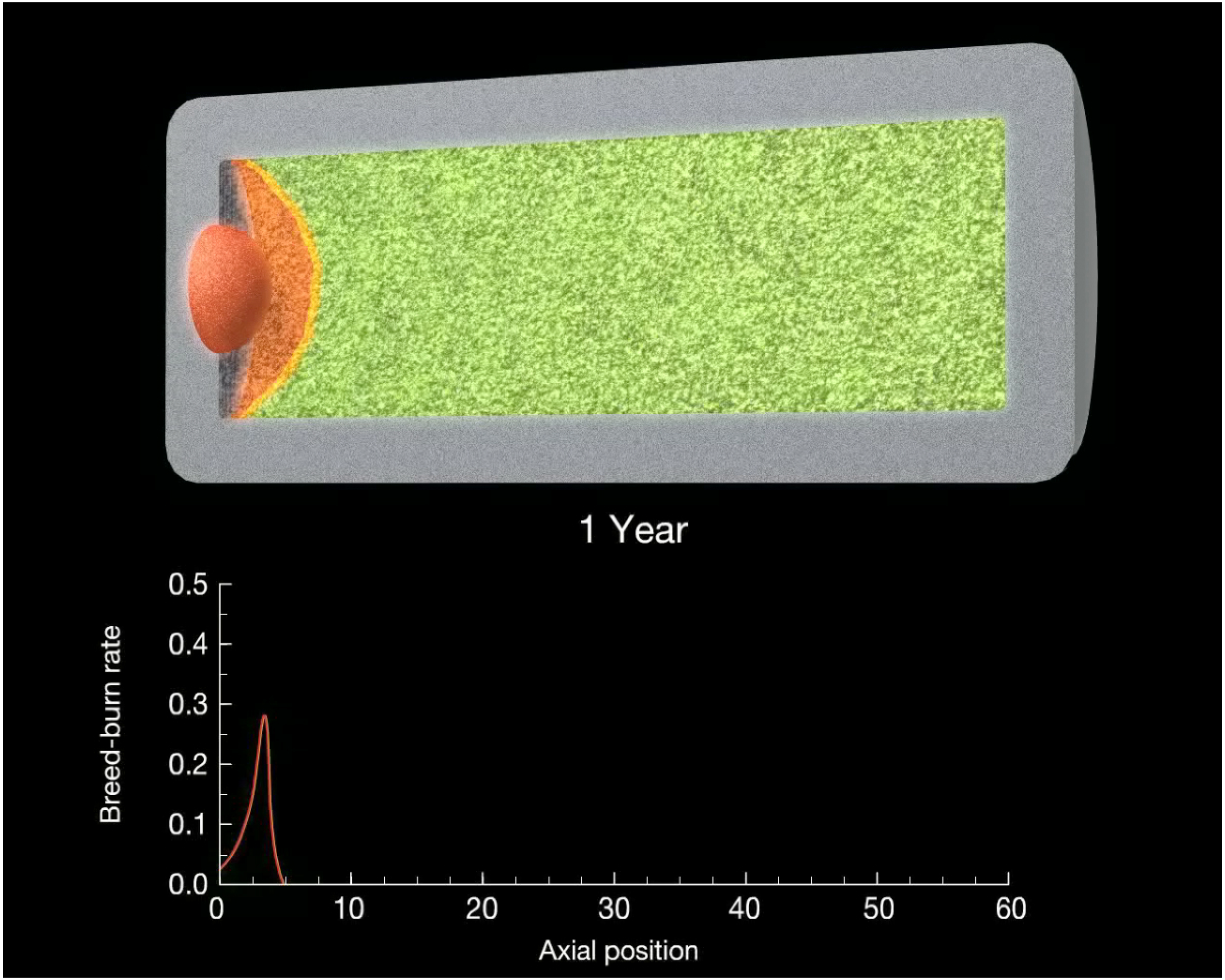
Axial position


1 Year
Breed-burn rate
0.5
0.4
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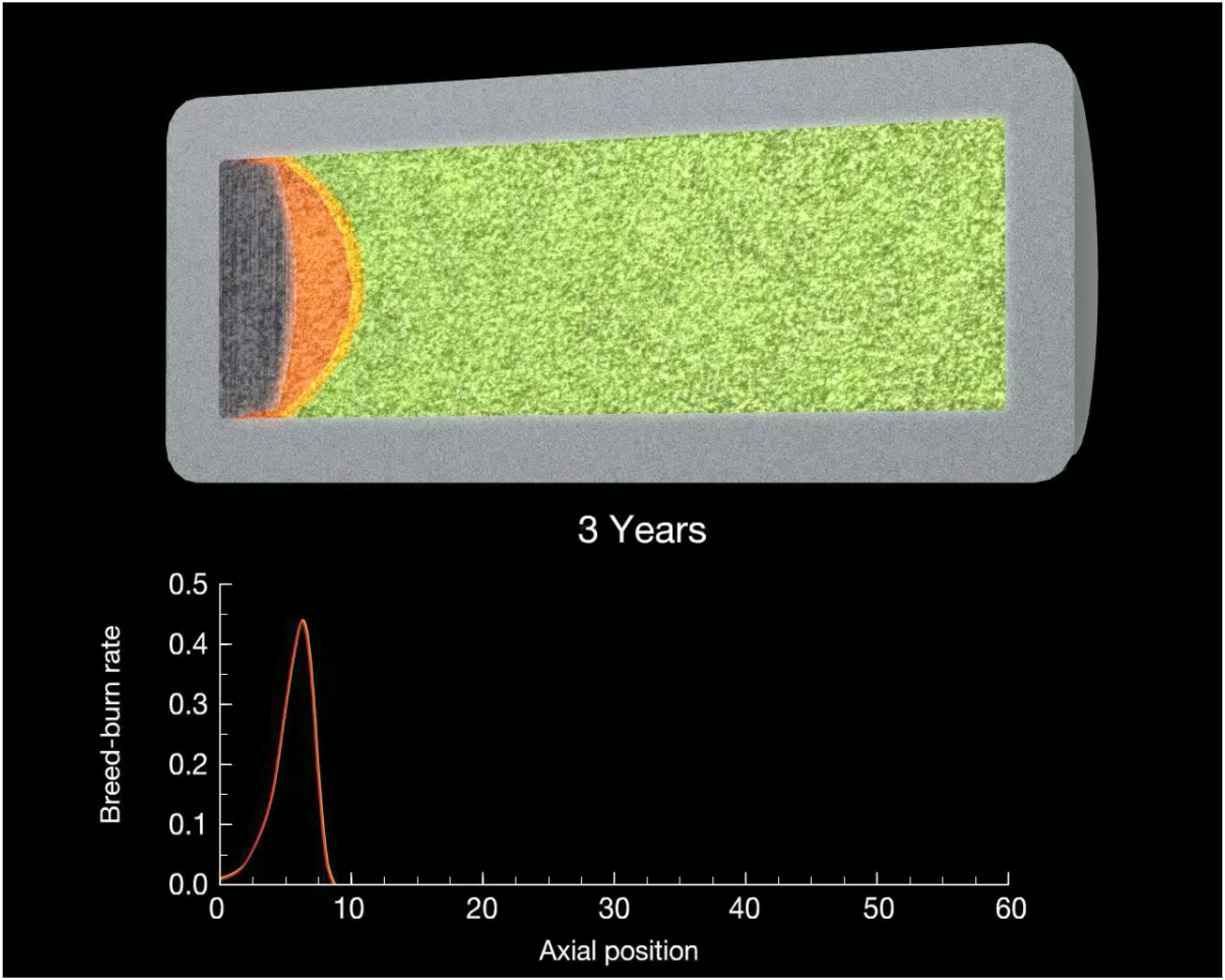
Axial position


3 Years
Breed-burn rate
0.5
0.4
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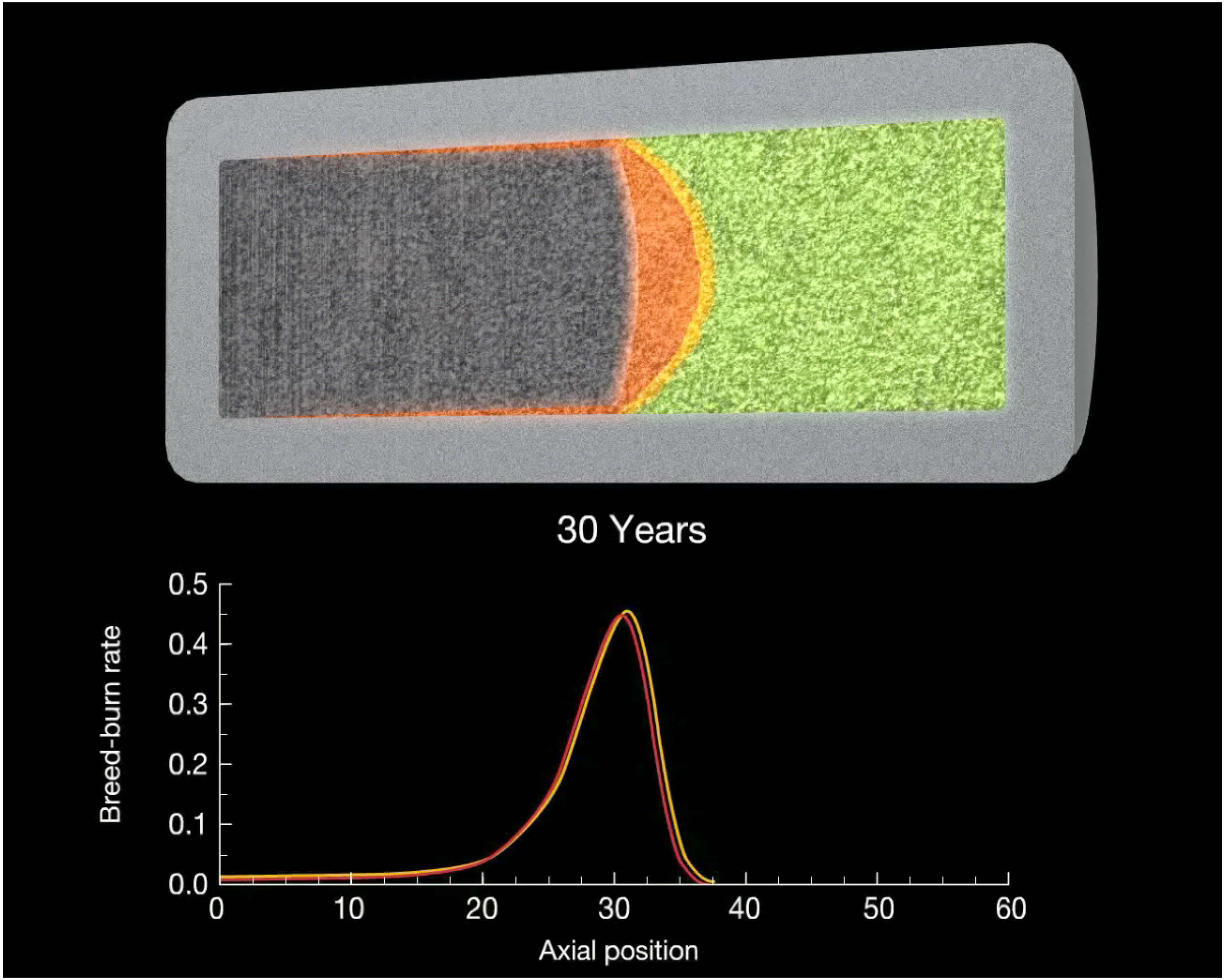
Axial position


30 Years
Breed-burn rate
0.5
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0.2
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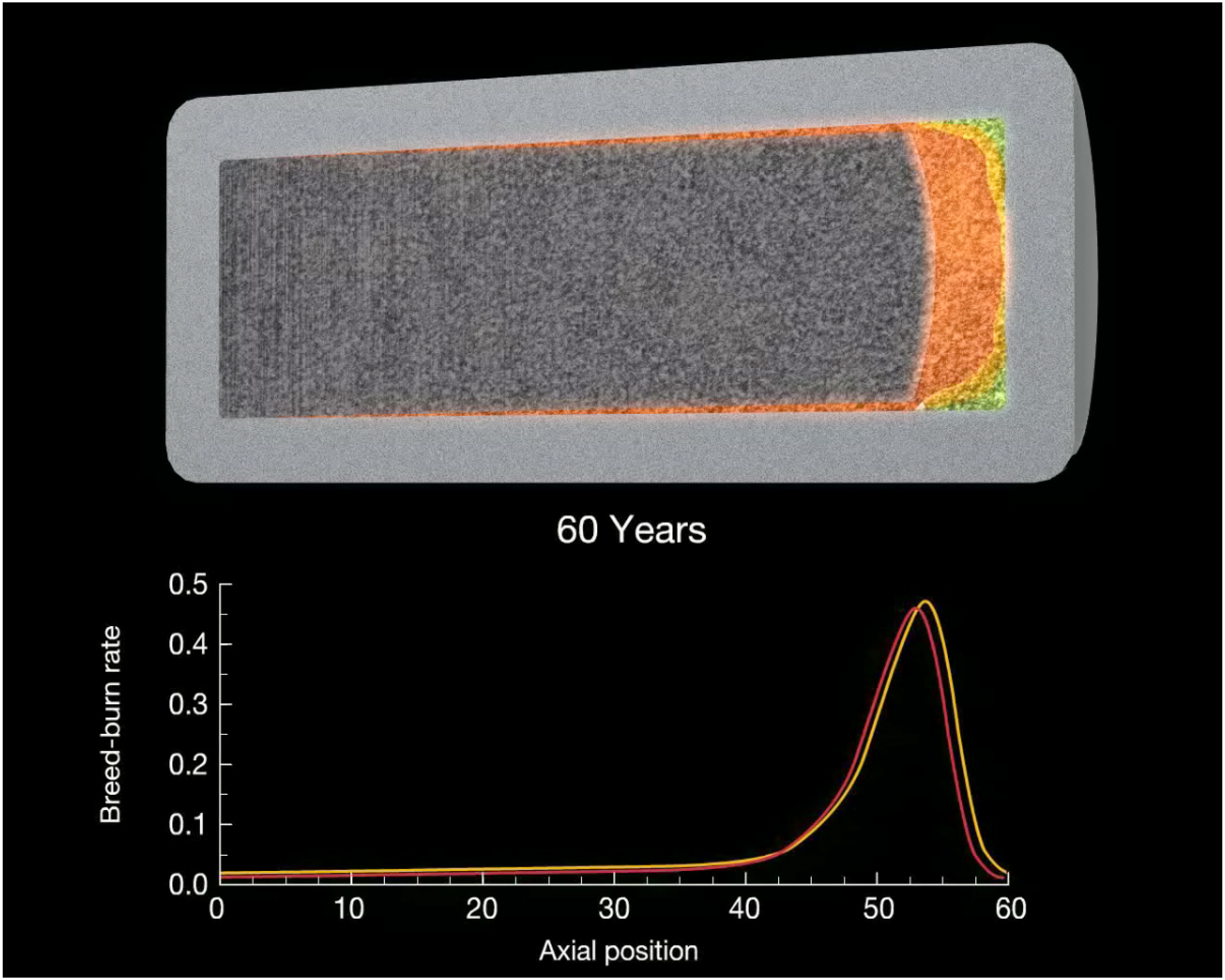
Axial position


60 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
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50
60
Axial position

The Early Results Encouraged us to Keep Going

Uranium

- A range of core arrangements using U-238 as fuel support a steady-state wave
- The wave may be “transplanted” to the next plant, thus eliminating need for an enrichment plant to make the igniter for the next plant
- Materials damage limits, tough problem but probably doable

Thorium

- An Ideal He-cooled thorium-fueled system sustains a wave!
- Paucity of neutrons presents practical engineering challenges
- Uranium 238- Thorium-232 Hybrid?

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Previous Work

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

Early Thoughts about TWR Concepts

- Engineering sketches of several embodiments,
  for different markets with different requirements
  - Plant power ratings
  - Physical deployment approaches
  - Fueling approaches
  - Site characteristics
  - Levels of investment

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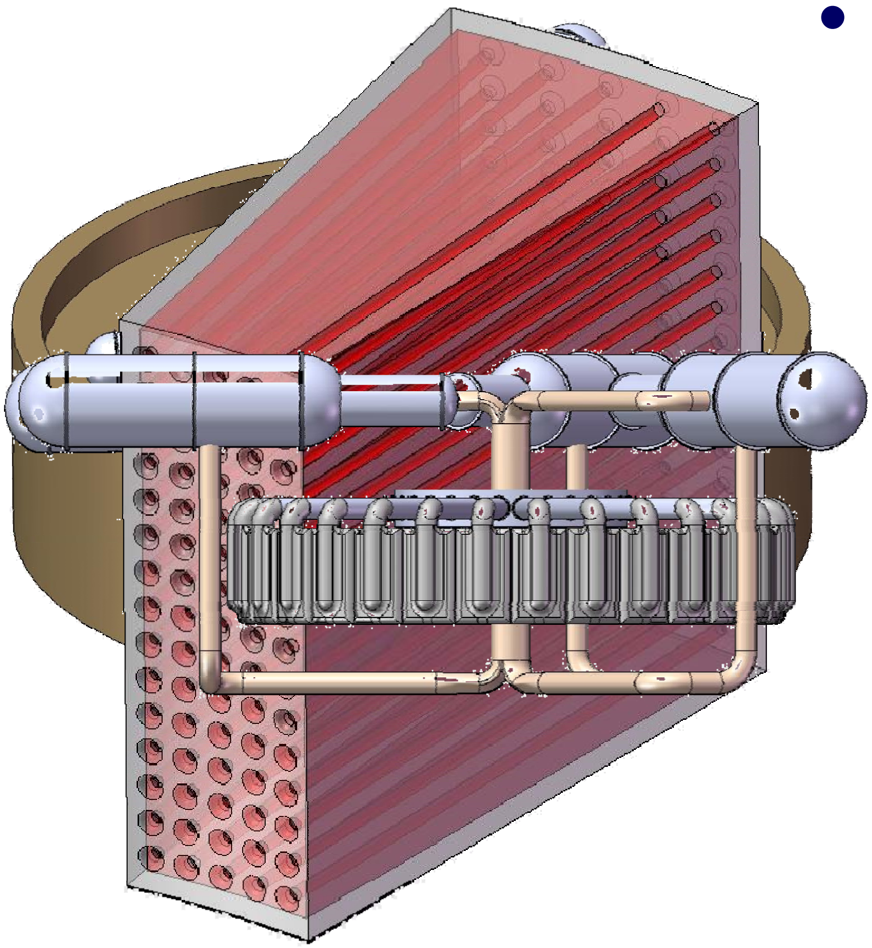
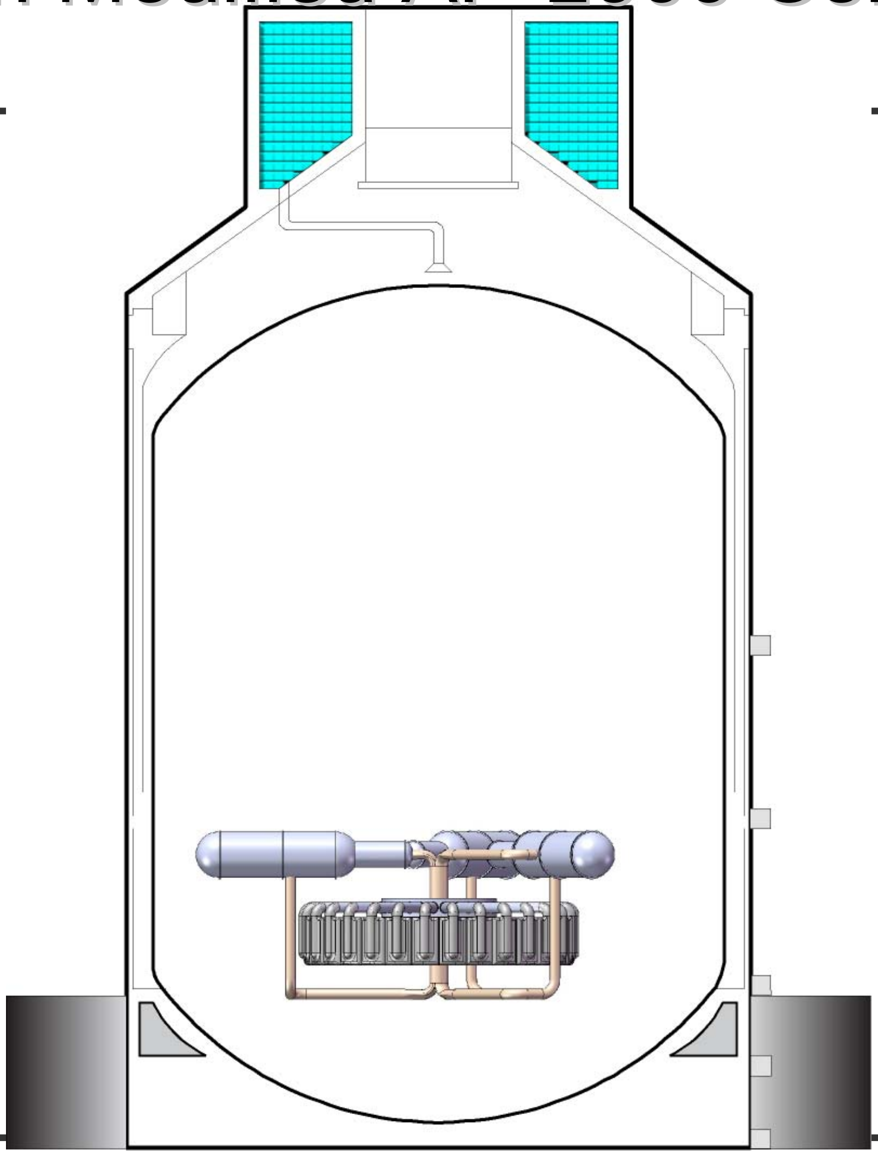
Large-Core Traveling-Wave Reactor

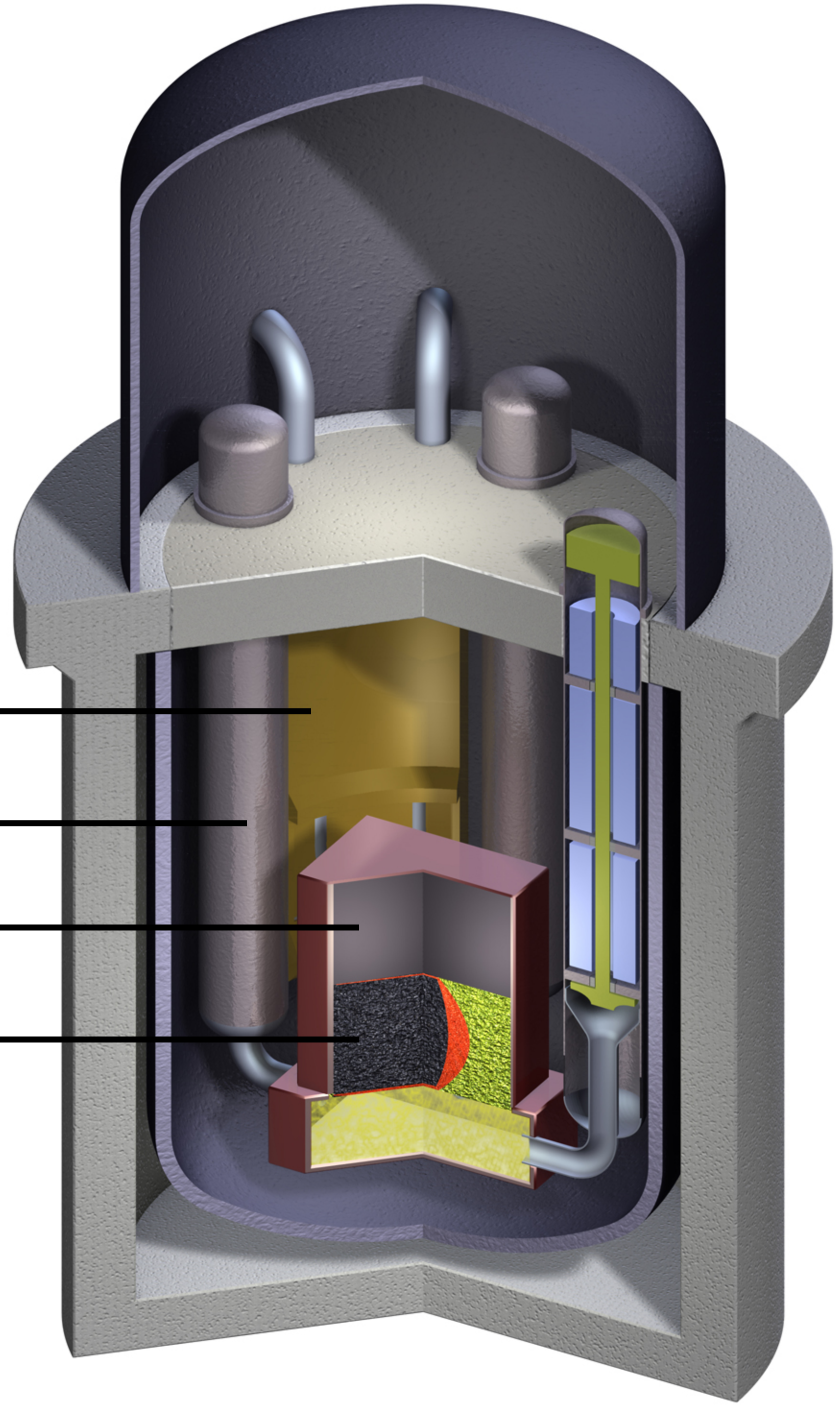


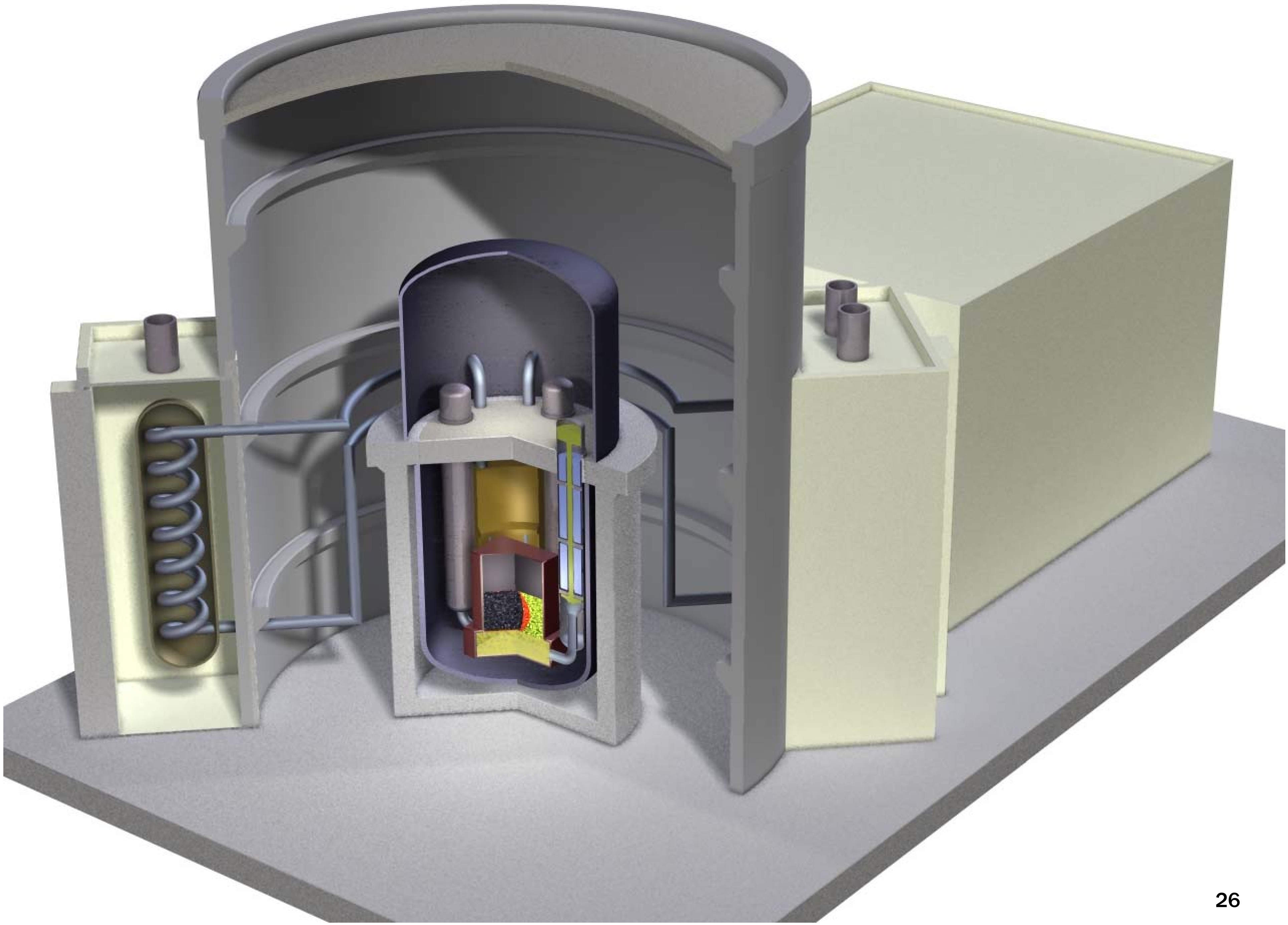
- Design features:
  - ~1,000 MW_e
  - Core life of up to 100 years without reloading or reprocessing
  - Enriched uranium at start-up only
  - Toroidal core geometry
  - Core composed of modular wedges
  - Perhaps a path to true modularity
    - More predictable schedule
    - More predictable cost
    - Deployable in regions that lack nuclear infrastructure

LCTWR in Modified AP-1000 Containment



1 GW$_e$ sodium-cooled pool-type reactor





Long-Term Potential

- **Enough fuel for millennia of TWR fleet operation**
  - Depleted uranium

Long-Term Potential

- **Enough fuel for millennia of TWR fleet operation**
  - Depleted uranium
  - Thorium
  - Spent LWR fuel

Long-Term Potential, cont'd.

- **Simple, once-through fuel cycle**
  - Economically more attractive
    - Little, then no enrichment
    - No reprocessing
  - Better proliferation resistance
    - Little, then no enrichment
    - No reprocessing
  - Even fewer greenhouse-gas-emitting steps than in the (already low-carbon) fuel cycle for conventional nuclear power
  - Lower risk of accidents during fuel transport and processing

Characteristics of a Traveling Wave Reactor (TWR)

- Reactor core behaves as an *in-situ* breeder
  - Small, fissile region “ignites” breeding & burning in fertile core
  - No reprocessing/recycling of fuel is required
- Critical region propagates a slow-moving wave
  - Wave speed less than 1 cm/month
  - Wave manipulated to achieve not more than 20% - 30% burn-up in first pass.
- Once “ignited”, no fissile material required
  - Thorium or depleted uranium is predominate core material
  - Igniter requires enriched U or Pu
  - Core life of 60 years or more is practical
  - Spent fuel waste comparable to LWR per unit energy produced

Simulations for a First Generation TWR

- Rebuilt MCNPX-CINDER90 for TWR simulations as well as completely new tools
- Modeling tools benchmarked by TerraPower and Argonne against existing fast and thermal references
- 1-D models for general physics understanding
- 2-D cylindrical models for igniter & finite TWR
- 3-D homogeneous and heterogeneous modeling underway
- 2000 core blade system being implemented

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Engineering a Candidate Gen-I TWR

- Considered all practical system options
- Selected proven technologies to reduce FOAK uncertainties
- Accommodated challenging features (e.g. high power density, high burnup, power peaking, etc.)
- Developed reactor point design – considering other point designs

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 U & Th	Other Ceramics	Liquid Metal – Na, Pb, Pb-Bi	Combined Cycles

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Coolant Performance at High Power Density

Reactor	Coolant	Power Density (MW/m³)
PWR	Light Water	98
CANDU	Heavy Water	12
BWR	Light Water	56
Gen IV - GFR	Helium	100
Gen IV - LFR	Lead-Bismuth	69
Gen IV - MSR	Molten Salt	22
Gen IV - SFR	Sodium	350
Gen IV - SCWR	Super Critical H_2O	100
Gen IV - VHTR	Helium	10

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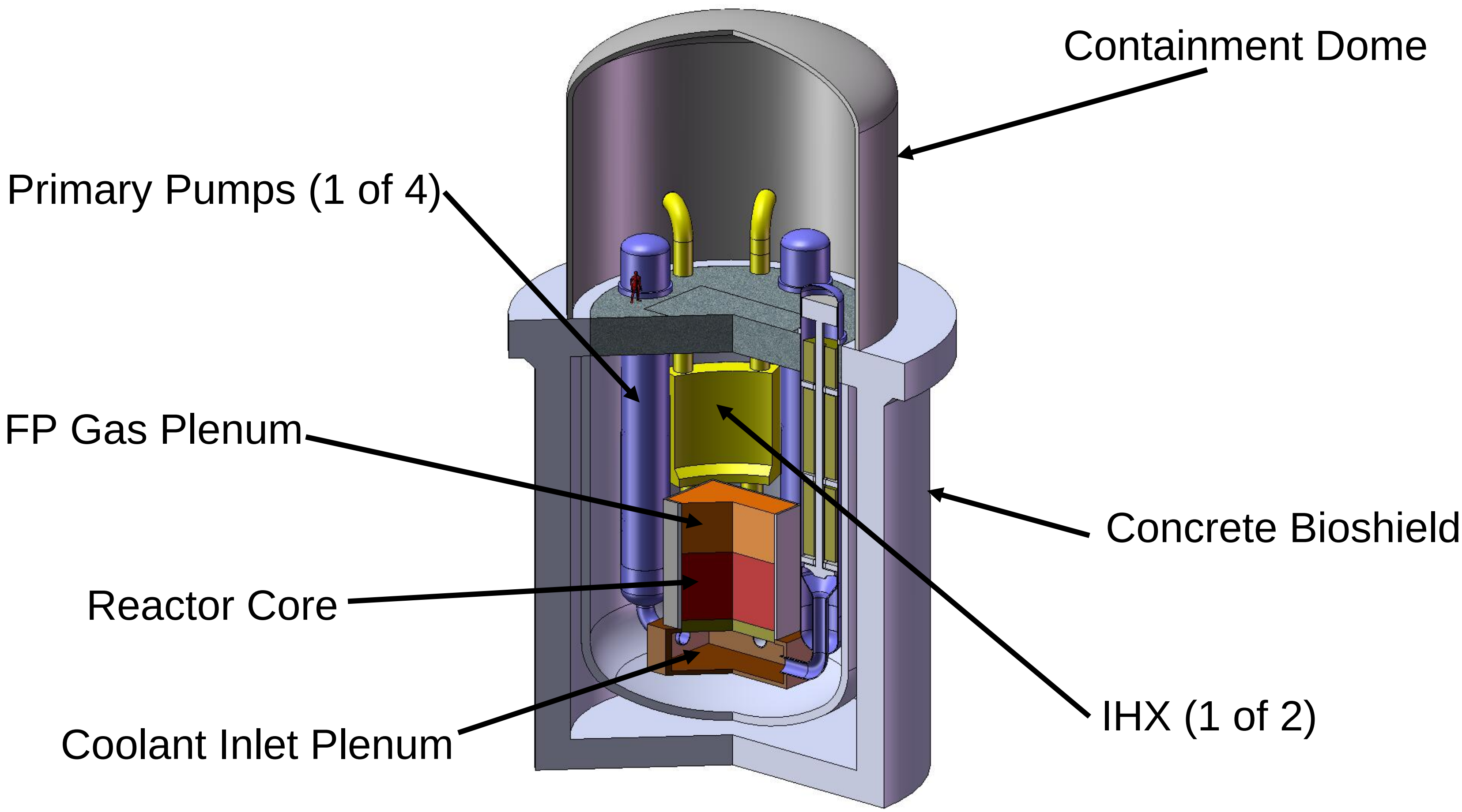
Major Design Features for Gen-I TWR

- 1000 MW_e low-leakage core design
- Uranium metal alloy fuel and igniter
- Na cooled, pool-type configuration
- Steam driven Rankine energy conversion
- HT-9 fuel clad & core internals
- B_4C control and safety rods
- Innovative IHX

A Gen-I TWR Nuclear Island Using Proven Fast Reactor Systems



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Realistic Deployment Schedule

- Any development plan must take into account the realities of thorough testing and regulatory requirements.
- Operation of a Traveling Wave Reactor can be demonstrated in less than ten years
- Commercial Deployment can begin in less than fifteen years

Advantages of TWR from an NP Perspective--

- Waste contained in reactor during 40-100 year life of plant
- Use of fissionable U-235 used only during startup
- Reduced risk of diversion of material during operation and fuel transport
- Host country does not need “nuclear infrastructure” to safely operate reactor or insure fuel supply.
- Reprocessing of fuel and separation of weaponisable material not required

Current and Future Work

- We have engaged Burns&Roe to assist in a one GW(e) plant conceptual design and cost estimate
- We will soon embark on a “right size” (100MW(e) to 300 MW(e) ?) trade study in which we will attempt to determine the impact of modularity on safety, reliability, cost and program predictability.
- The results of these studies will give required insight into the best prototype development approach.