



# Transportation, Storage and Disposal of Spent Fuel from Advanced Reactors

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## Mission Driven Innovation

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.



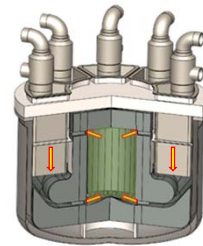
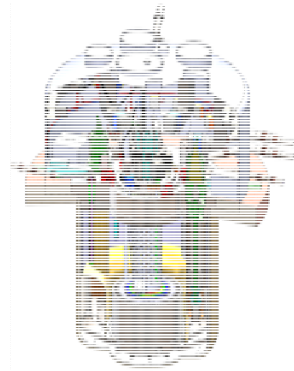
**John Gilleland** is a co-founder of TerraPower where he is currently the Chief Technical Officer. From 2008 to 2015, Dr. Gilleland served as TerraPower's Chief Executive Officer (CEO). Under his leadership, TerraPower transitioned from an idea to a globally recognized center for innovation and development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

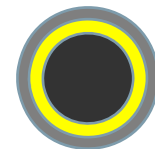
## TerraPower's History & Mission

- In 2007 TerraPower was established by visionary investors and led by Bill Gates
  - All forms of energy were initially considered
  - **Carbon-free, Scalability** and **energy density** consideration led TerraPower to innovate in nuclear energy
- Today's nuclear industry faces challenges
  - **Social, economic and technological challenges** have limited nuclear
  - Next generation nuclear technology offers the potential to solve many of these limitations
- Focus on next generation nuclear that excel in economics, safety, resource utilization, waste, and proliferation resistance
  - Resulted first in the Traveling Wave Reactor (TWR) development starting in 2008
  - And then the Molten Chloride Fast Reactor (MCFR) development beginning in 2013

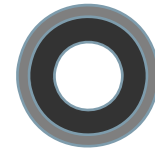


## TWR Fuel Transportation, Storage, and Disposal Considerations

- TerraPower recognized early that fuel development was required to achieve the objectives of the TWR.
- Primary focus was on increasing the performance of the fuel at high temperature and high flux over a long duration
- Also focused on getting the sodium bond out of the fuel rod – our commercial reactor is based on mechanical bonded annular fuel.
  - Simplifies waste disposal
  - Metal fuel swells with burnup to fill in gaps



Sodium Bonded Fuel



Mechanically Bonded Fuel



## Advancing TWR Fuels and Materials Technology

### US SFR Legacy Data Collection

Compile and analyze archived DOE test data

### Commercial Fab. Process Development

Commercial scale fuel and HT9 material production

### FCCI Barrier Development

Fabrication and testing

### Fuel Irradiation Tests

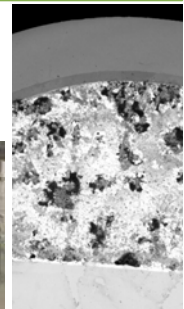
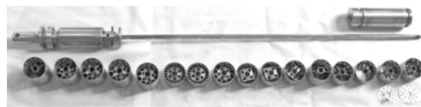
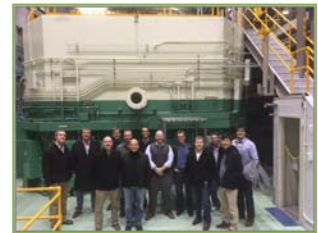
Testing of advanced metal fuel in the ATR w/ post-irradiation exam

### Transient Behavior

Transient performance of HT-9 clad fuel pins

### HT9 Optimization and Testing

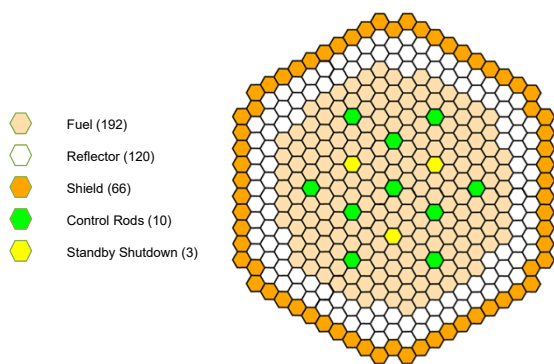
BOR-60 Materials Irradiation Testing, Ion Irradiation Program



## TWR Fuel Management Strategy

- Wet storage for a minimum of 10 years with water chemistry management
  - decouples core unloading and cask loading
- Traditional pool loading for the storage/transport casks
  - Inlet nozzles may be removed to reduce assembly height
- Transport and storage in an inert environment
- Potential disposal in deep bore holes or smaller bore holes at a near-surface repository

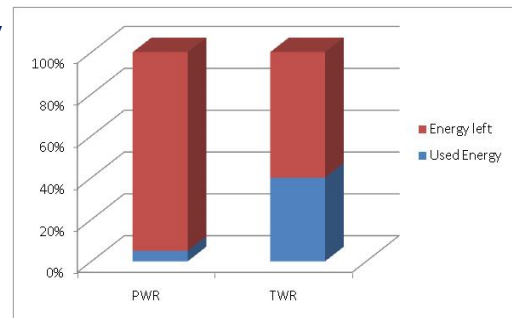
# TWR Fuel Parameters



Parameter	Value (at 20C)
# of core assemblies	192
Assy duct outer flat to flat (mm)	160
# of pins per assembly	217
nom. pin od. (mm)	8.3
fuel assembly height (mm)	4800
wire dia (mm)	1
fueled height (cm)	124
initial enrichment %	13-18
Peak burnup targets (FIMA)	20%
cladding material	HT9
years in wet storage (min)	10
Max Decay Heat (10 Years)	515 W
Fuel geometry	helium bonded
BOL heavy metal mass (kg)	120

## Benefits of Deep Boreholes

- Reducing chemistry guarantees low solubility
- Extremely low rock permeability and water content/mobility
- No near field temperature limits
- Inherent modularity: drill as needed, pay as you go
- Widespread applicability
- Simpler to analyze and easier to understand
- Synergism with engineered geothermal systems.





## Addressing Disposal Issues

- Metal fuel is more chemically reactive than the oxide form – keep the water out
  - Uranium metal to Uranium Oxide(s) increases fuel volume within cladding
- Sodium may be inside the fuel pin and/or as “unreacted sodium” inside the fuel sub-assembly
  - Steam cleaning of assemblies
  - Removal of sodium from the fuel design
- The actinide concentration in SFR discharge fuel will be much higher than in LWR discharged fuel.
  - Casting high heat conducting material into void space in the package as a void filler (e.g. commercially available Zn-4wt%Al alloy)
  - Copper canister walls
  - Cementation with inclusion of SiC gravel of gap between canister and borehole walls (also assures irretrievability)

## MCFR Fuel Polishing and Resultant Waste Streams

- The spent fuel could be used as startup fuel for subsequent reactors with no reprocessing requiring separation of actinides
- MCFR technology includes Fuel Polishing designed to filter and cleanup the fuel salt of volatile and noble metal fission products
  - Removal of insoluble fission products
  - Removal of fission products which could significantly increase corrosion such as oxygen and sulfur
  - Removal of dissolved noble gases such as  $^{135}\text{Xe}$  from the molten salt
  - Removal of gases that might accumulate in the void space above the reactor core
  - Addition and removal of fuel salt from the system
  - Manage the fuel salt chemistry
  - Drain and flush the reactor with a non-radioactive “flush” salt so that maintenance can be performed.
- More analysis and testing will be needed to determine the composition of the various waste streams

## MCFR Fuel Salt Removal Process

- Periodically small batches of fuel salt will be removed from the fuel salt systems, at the separation vessel.
- An empty defueling container would be placed in an electrically heated support mechanism.
- Container heated to temperature of the salt
- Helium is added or vented from the container until the pressure matches that of the separation vessel.
- Slow controlled cool down process
- Resultant fuel is a crystalline salt

## Conclusions

- MCFR spent fuel waste requires additional development to ensure that it can be properly stored, transported and disposed of.
- Intact TWR fuel can be safely transported and stored. It is recommended that it be disposed of in deep boreholes, but all avenues are open.
- Special handling of leaking fuel rods from TWR reactors will be required, and is being addressed in our ongoing development plan.