Refueling Options for LS-VHTRs Based On High-Temperature Reactor Experience

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LS-VHTR Meeting
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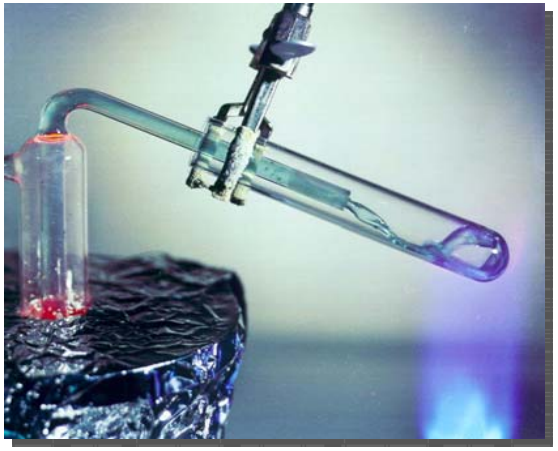
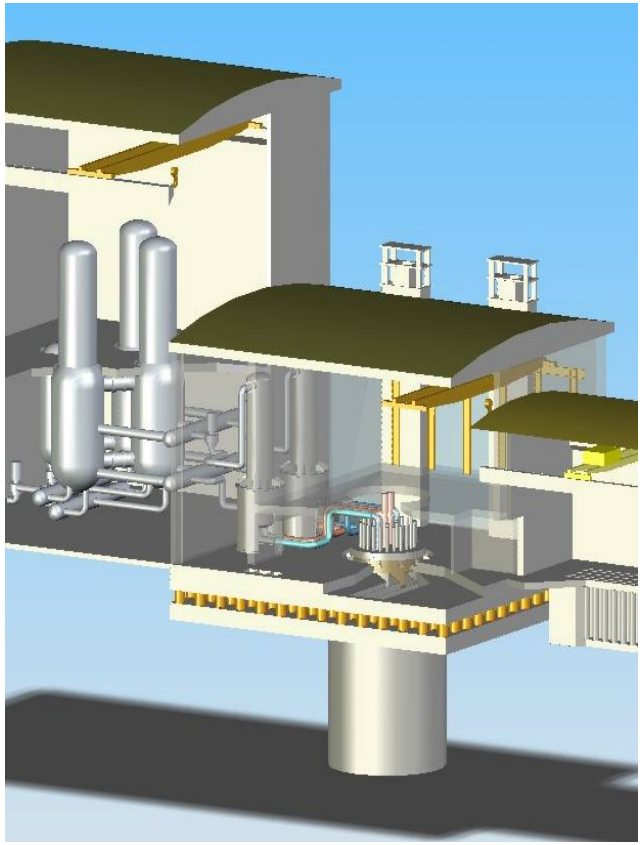
Germantown, Maryland





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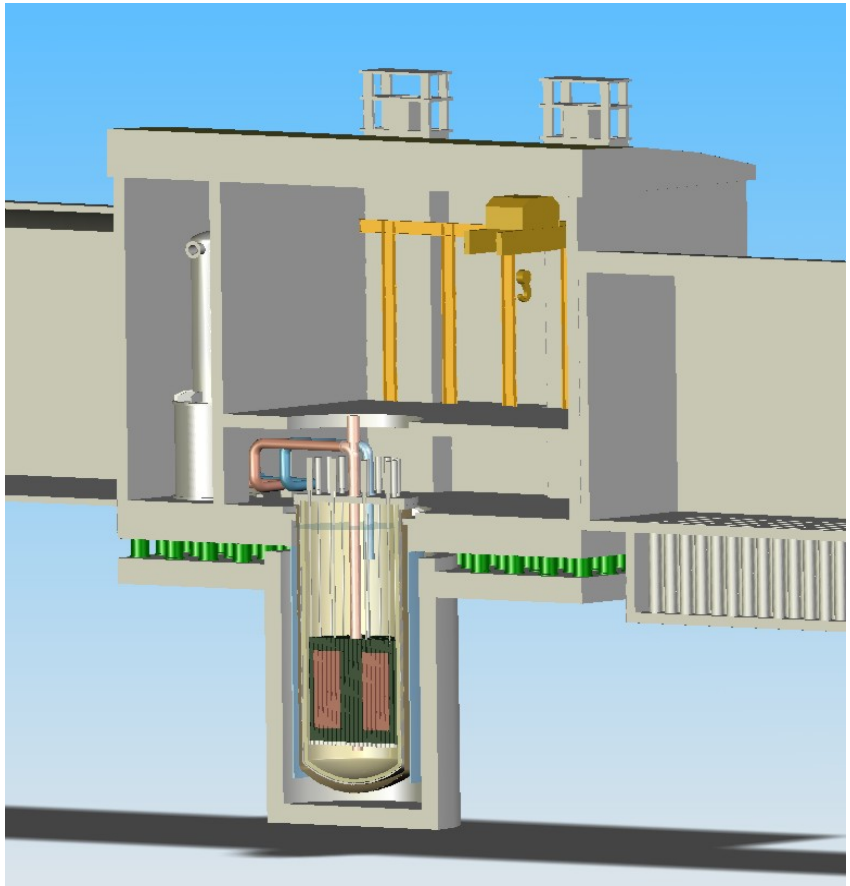
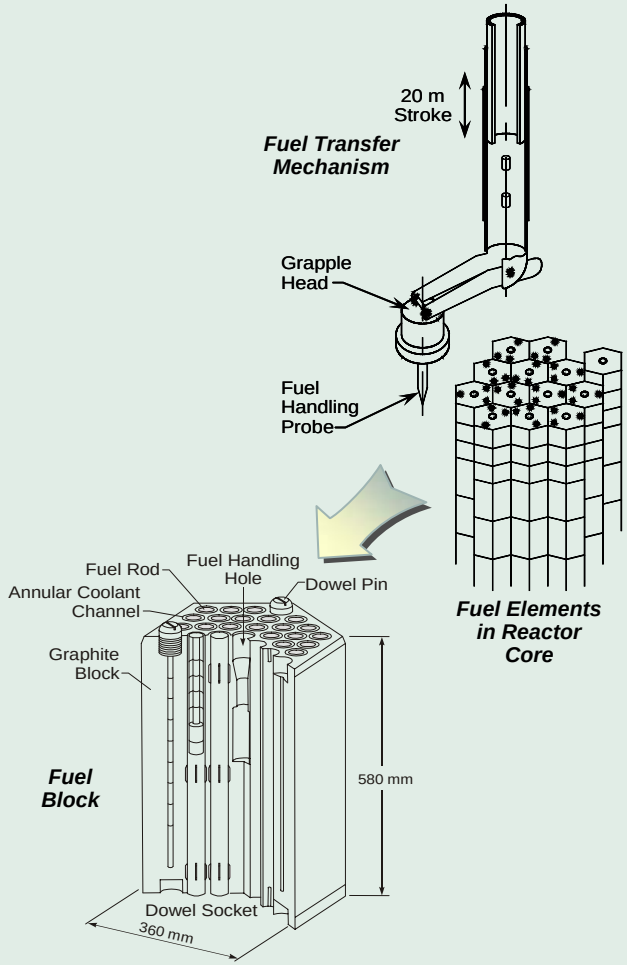
LS-VHTRs and High-Temperature Gas-Cooled Reactors Use the Same Fuels

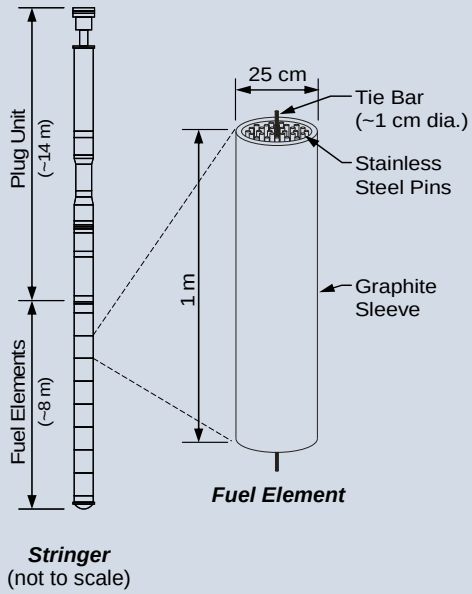


- **Three classes of gas-cooled high-temperature reactors**
  - **Prismatic fuel**
  - **Pebble-bed fuel**
  - **Pin/Assembly fuel**
- **LS-VHTR**
  - **Same three core design options**
  - **Three strategies for refueling**

Alternative Reactor Core Configurations



Prismatic Fuel Block



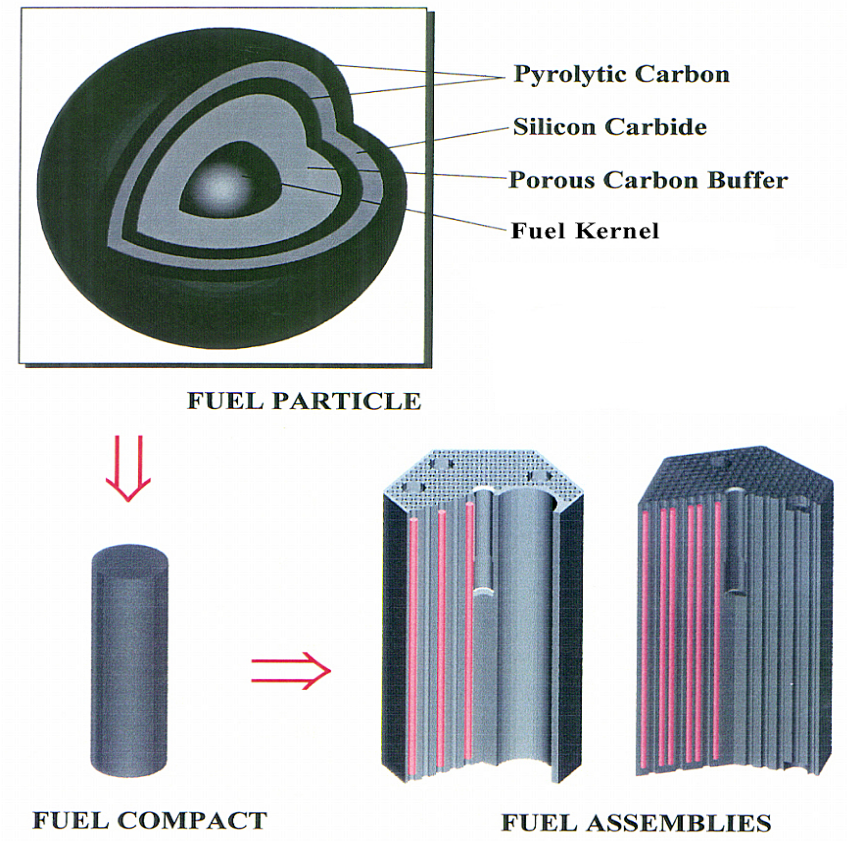
Stringer

Pebble Bed

Prismatic-Fuel High-Temperature Reactor Refueling

Gas Cooled

Liquid Salt Cooled



Prismatic-Fuel High-Temperature Gas-Cooled Reactors

- **Fort St. Vrain (1973−1989)**
  - **330 MW(e)**
  - **T_{in} = 400ºC; T_{out} = 770ºC**
  - **Pressure = 50 bar**
  - **Power density = 6.3 MW/m^3**
- **Commercial**
  - **Eight sold**
  - **Later cancelled**
- **HTTR (Japan)**
  - **30 MW(t)**
  - **950ºC**

Fort St. Vrain

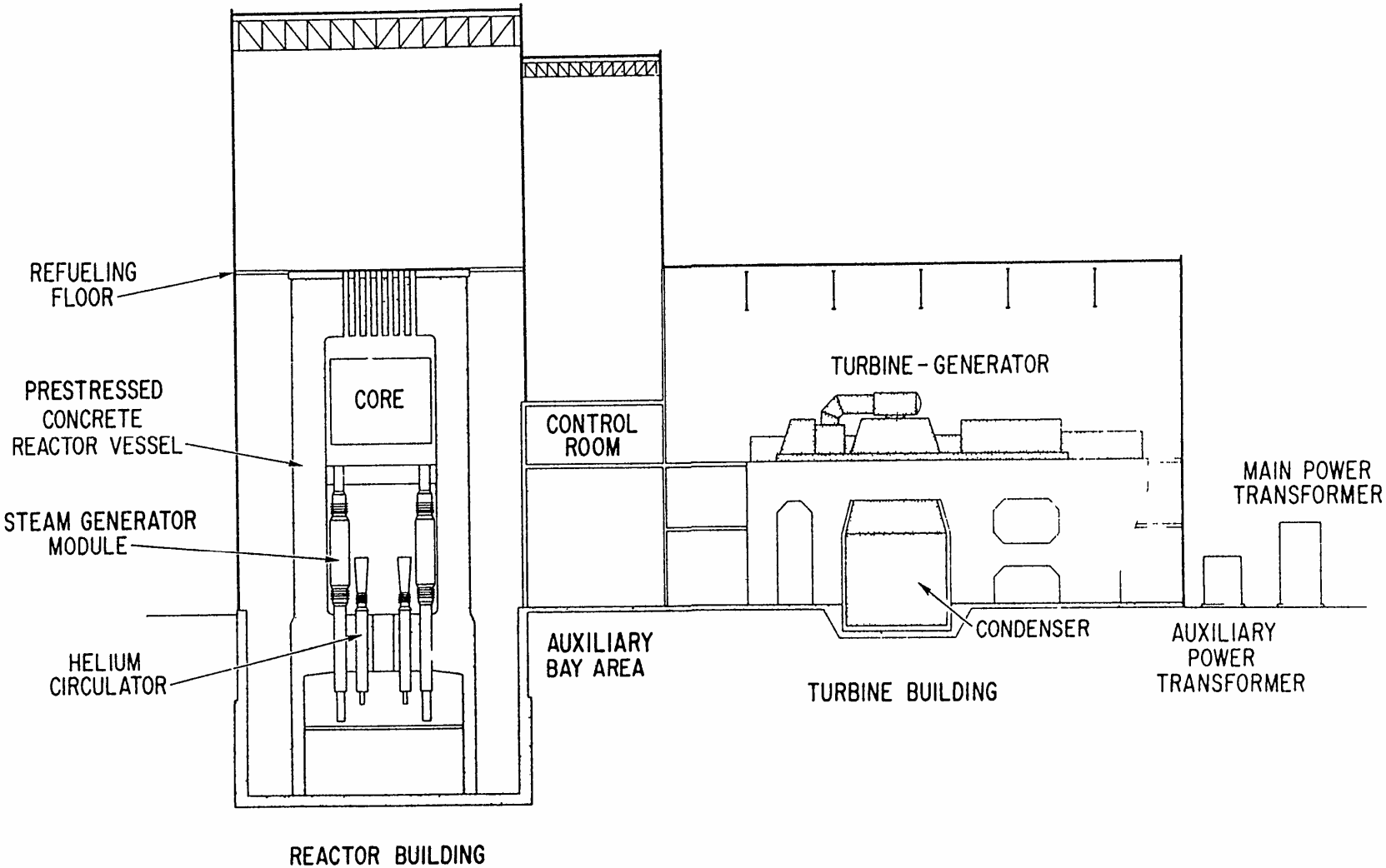
Prismatic-Fuel Gas-Cooled Reactor Refueling

- **Refueling conditions (Fort St. Vrain)**
  - **Pressure: <1 psig**
  - **He inlet temperature: <74ºC**
- **Pressure-vessel-imposed limitations**
  - **Limited number of access holes**
  - **Large distances from refueling machine to core**
  - **Each vessel penetration used to refuel multiple fuel columns**

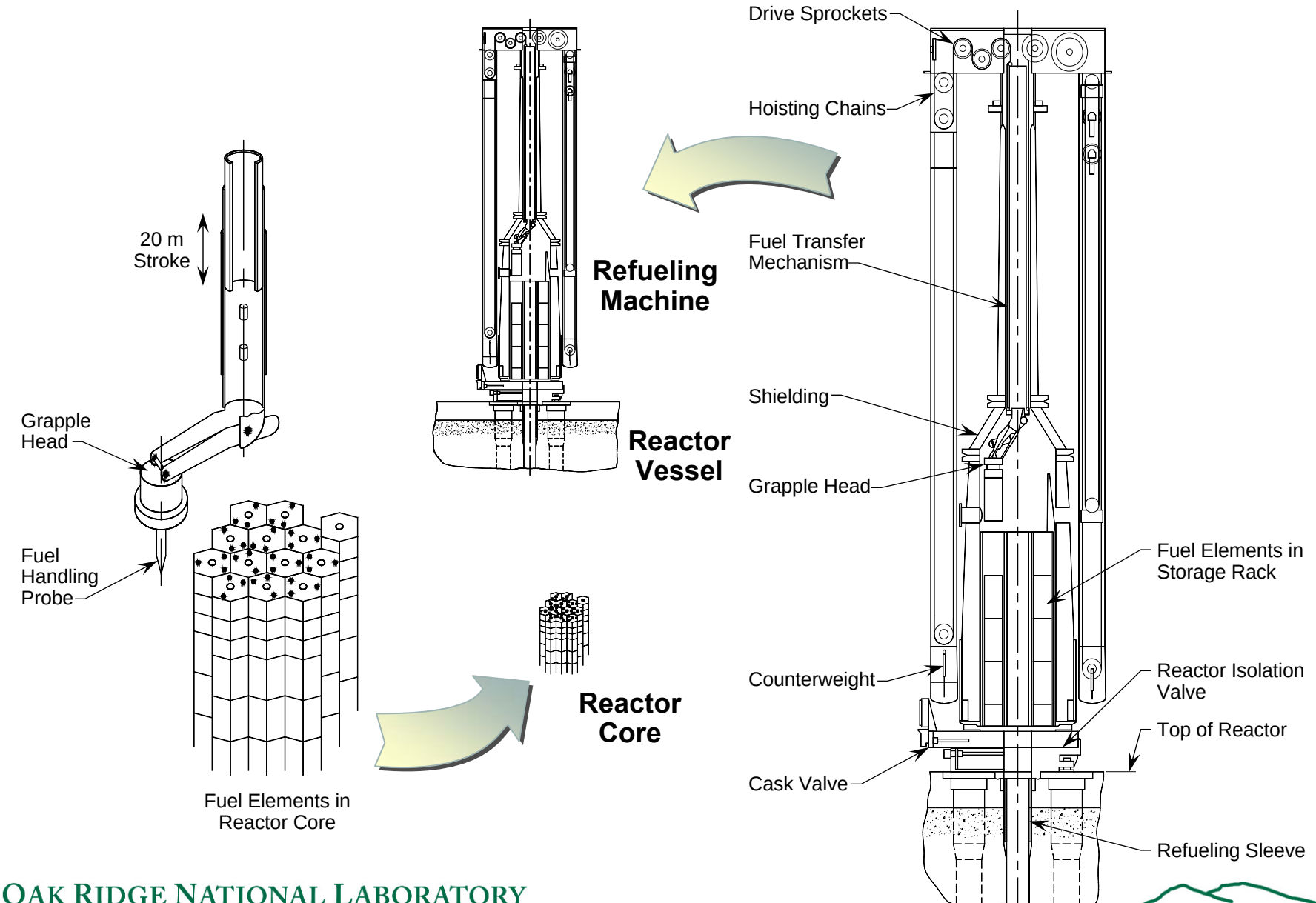
Fort. St. Vrain Refueling Machine

Fort St. Vrain: Limited Core Access

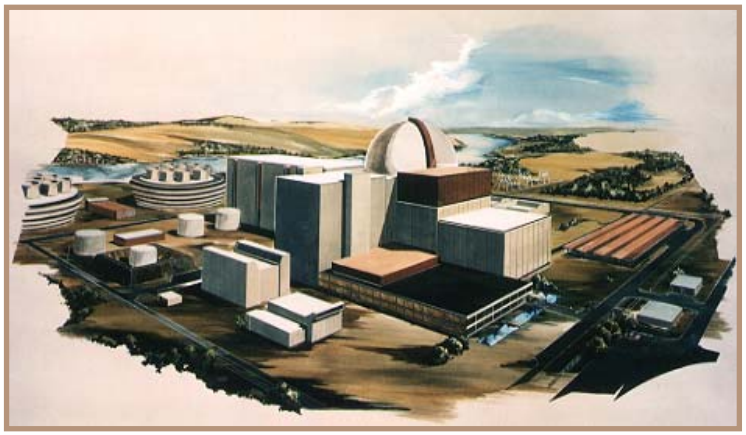
(Characteristic of High-Pressure Gas-Cooled Reactors)



Fort St. Vrain Fuel-Handling Machine



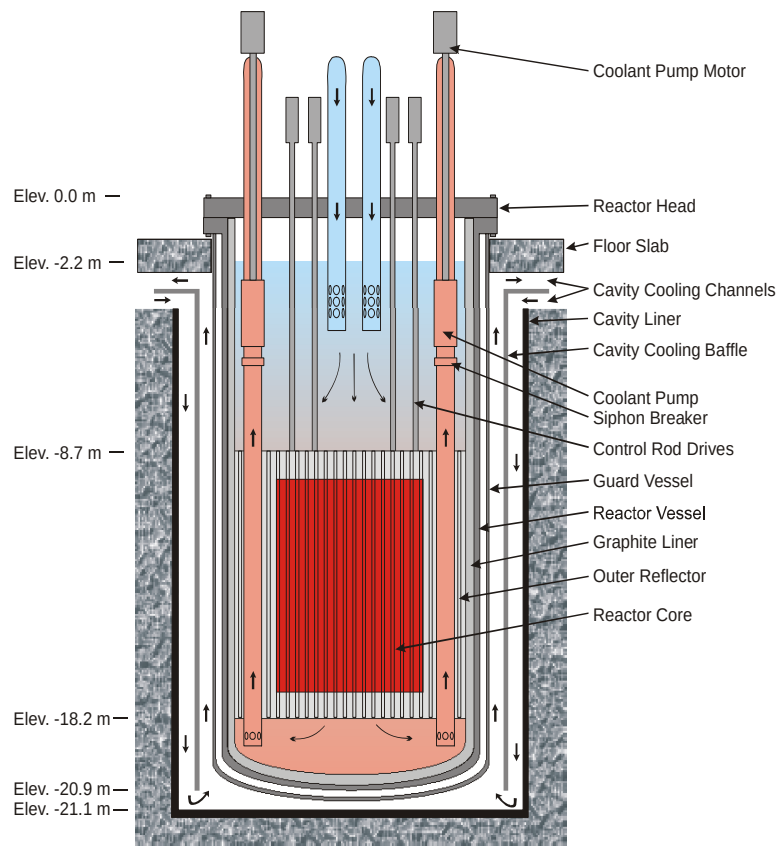
Options for Refueling of Large Prismatic-Fuel HTGRs



- **Preliminary work initiated on high-temperature online refueling of large prismatic-fuel HTGRs**
- **Work ended with HTGR program cancellation**

Prismatic Fuel: Liquid-Salt-Reactor Refueling

- **Similarities with gas-cooled reactors**
  - **Similar fuel**
  - **Low-pressure system**
  - **Inert gas atmosphere (Ar)**
- **Differences compared to gas-cooled reactors**
  - **Temperature: 450 to 550ºC**
  - **Improved core access**
    - **Rotating top shield**
    - **Short distances from lid (refueling machine motors) to reactor core (grapple)**
  - **Fewer refueling operations**



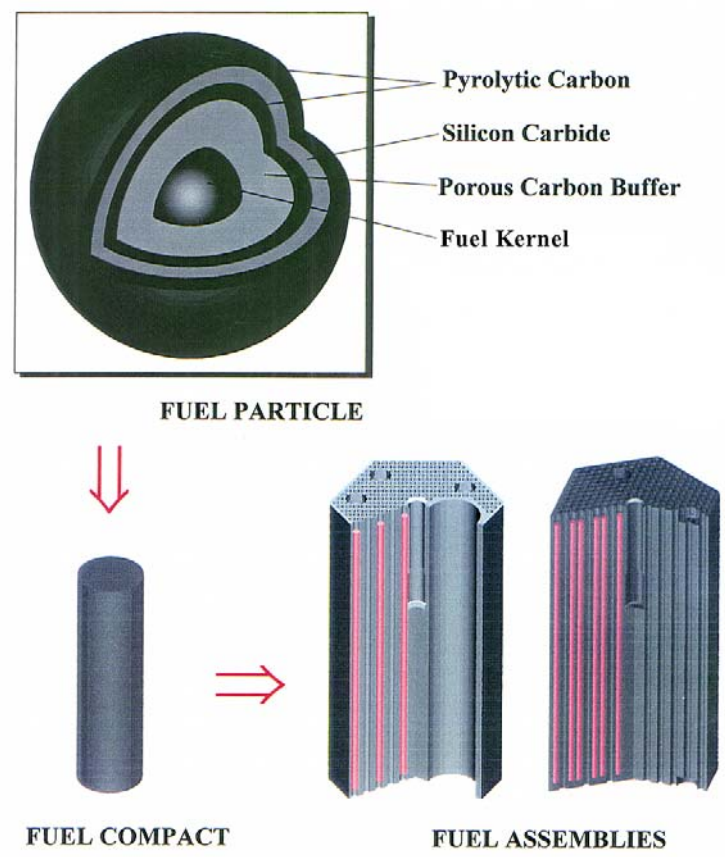
Refueling Task Comparisons for Prismatic-Fuel Reactors

(LS-VHTR has a Higher Power Density and Higher Efficiency)

Property	Ft. St. Vrain	Large HTGR	LS-VHTR
Gross power [MW(t)]	842	3000	2400
Net power [MW(e)]	342	1160	1300
Number of fuel columns	259	493	265
Number of fuel blocks per column	6	8	10
Total fuel blocks	1554	3944	2650
Blocks per MW(e)	4.5	3.4	2.0

The Size of the Prismatic Fuel Block is a Design Variable

- **Block size based on 1970s graphite technology**
- **Current technology can double to triple block height**
- **Refueling times can be reduced by increasing block size**
- **Multiple tradeoffs**

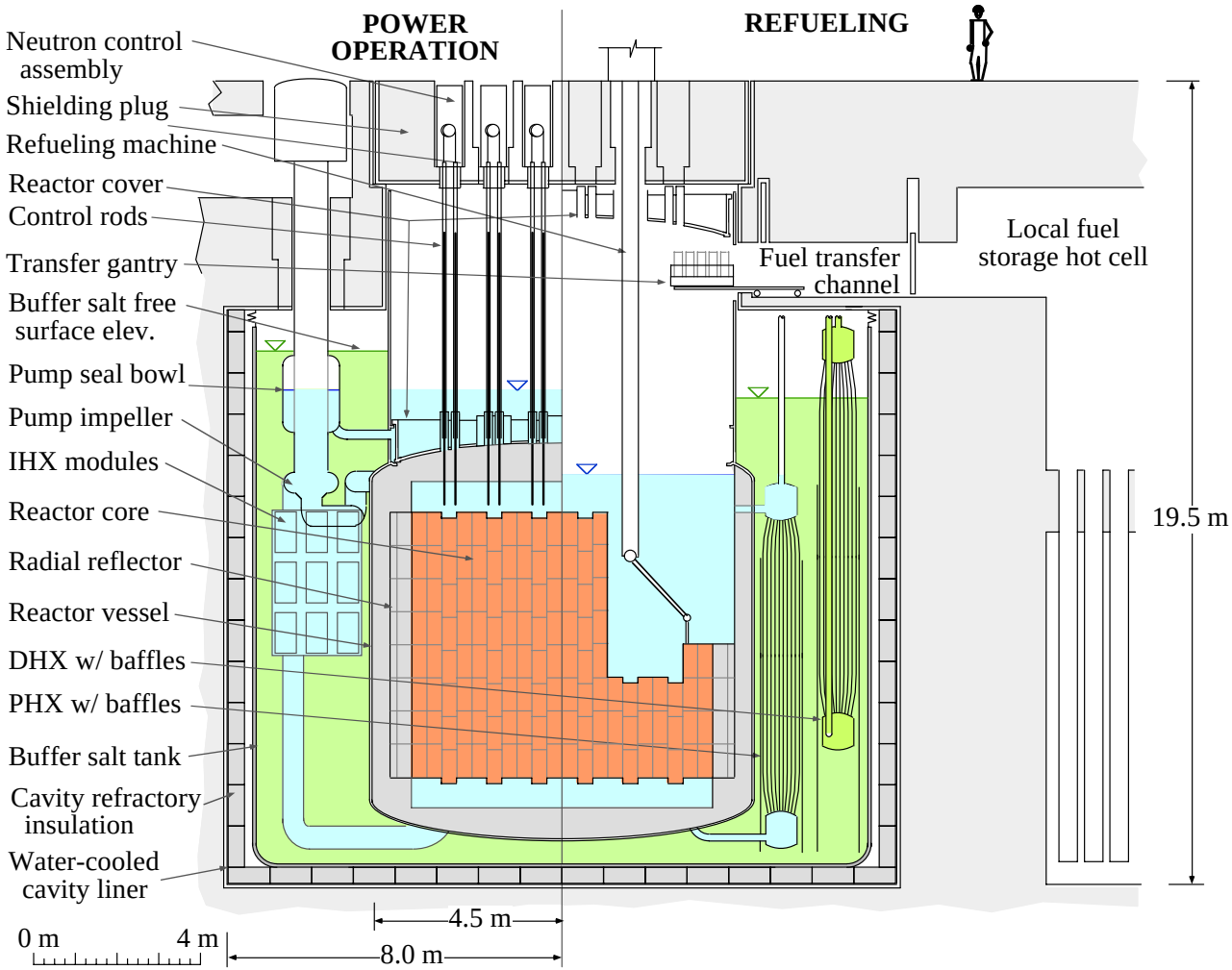


Prismatic Fuel in an LS-VHTR Relative to Other Fuel Options

- **Advantages of prismatic fuel**
  - **Smaller refueling machines (shorter)**
  - **Simplified fuel transfer (to be described)**
- **Disadvantages of prismatic fuel**
  - **Fuel may require a ballast to sink in some salts or the use of hold-down mechanisms**
  - **Many fuel elements to move**

One Option for Refueling: AHTR-MI

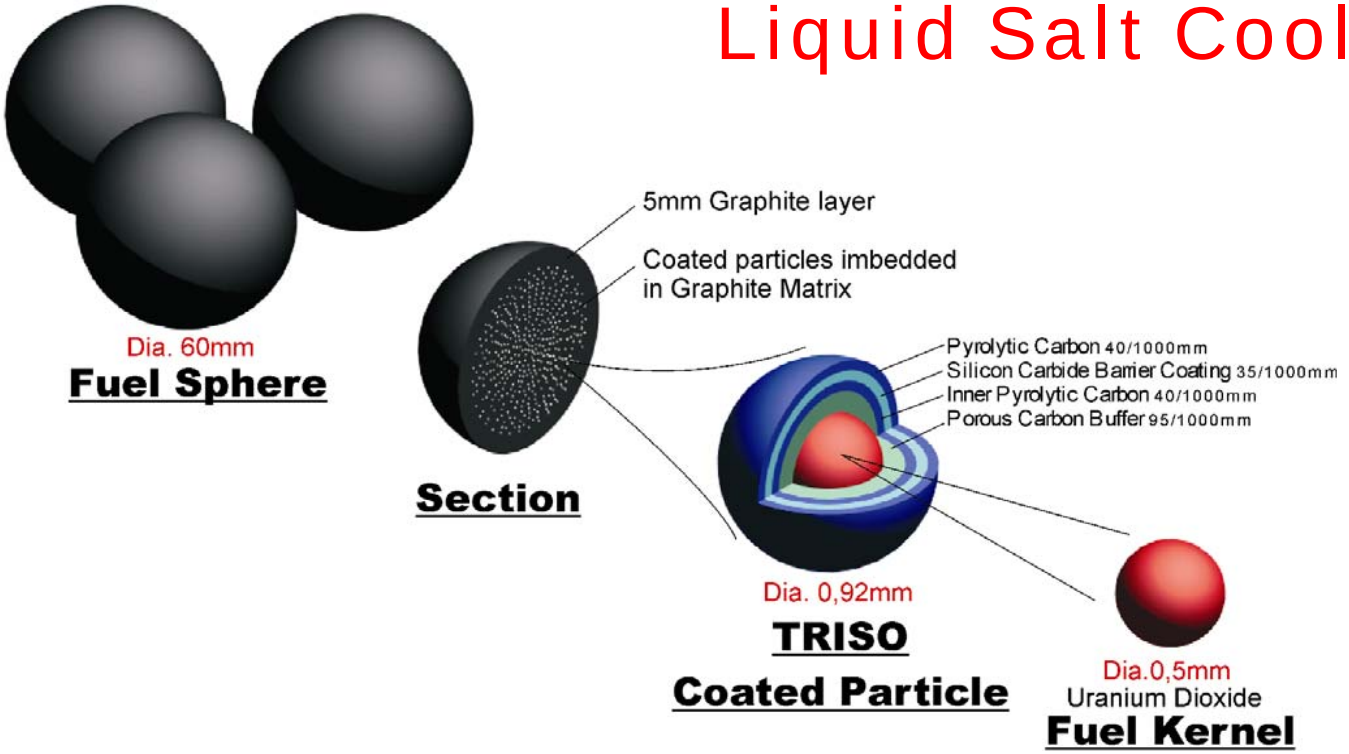
(UCB Point Design Including Refueling and Neutron Control)



Pebble-Bed-Fuel High-Temperature Reactor Refueling

Gas Cooled

Liquid Salt Cooled

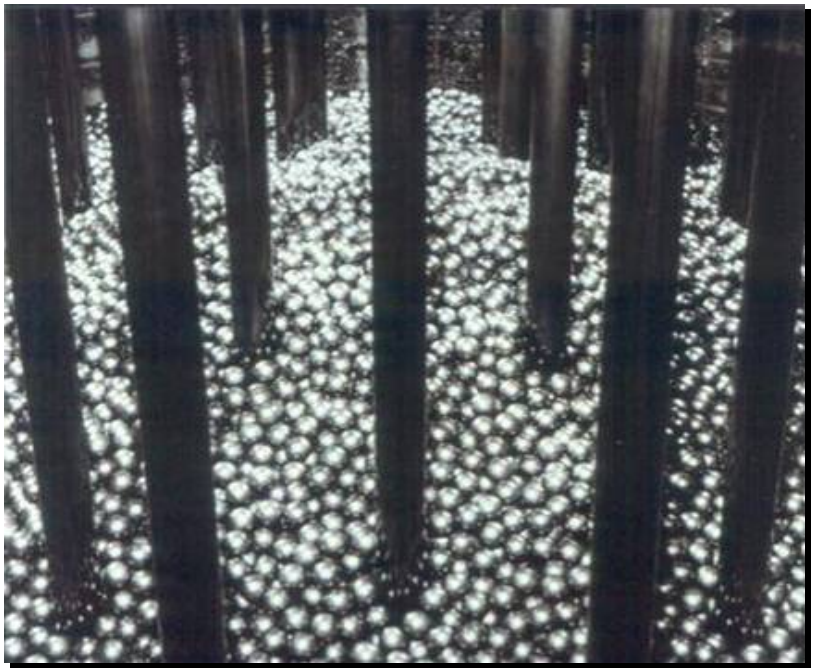


Pebble-Bed Gas-Cooled Reactors

- **Multiple reactors**
  - **AVR (1967–1988)**
    - **Germany; Decommissioned**
    - **15 MW(e); P = 11 bar**
    - **T_{out} = 950ºC; T_{in} = 270ºC**
  - **THTR (1984–1990)**
    - **Germany; Decommissioned**
    - **300 MW(e); P = 40 bar**
    - **T_{out} = 750ºC; T_{in} = 250ºC**
  - **HTR (China: operating)**
  - **South Africa (under construction)**
- **Online refueling**
- **Significant experience**

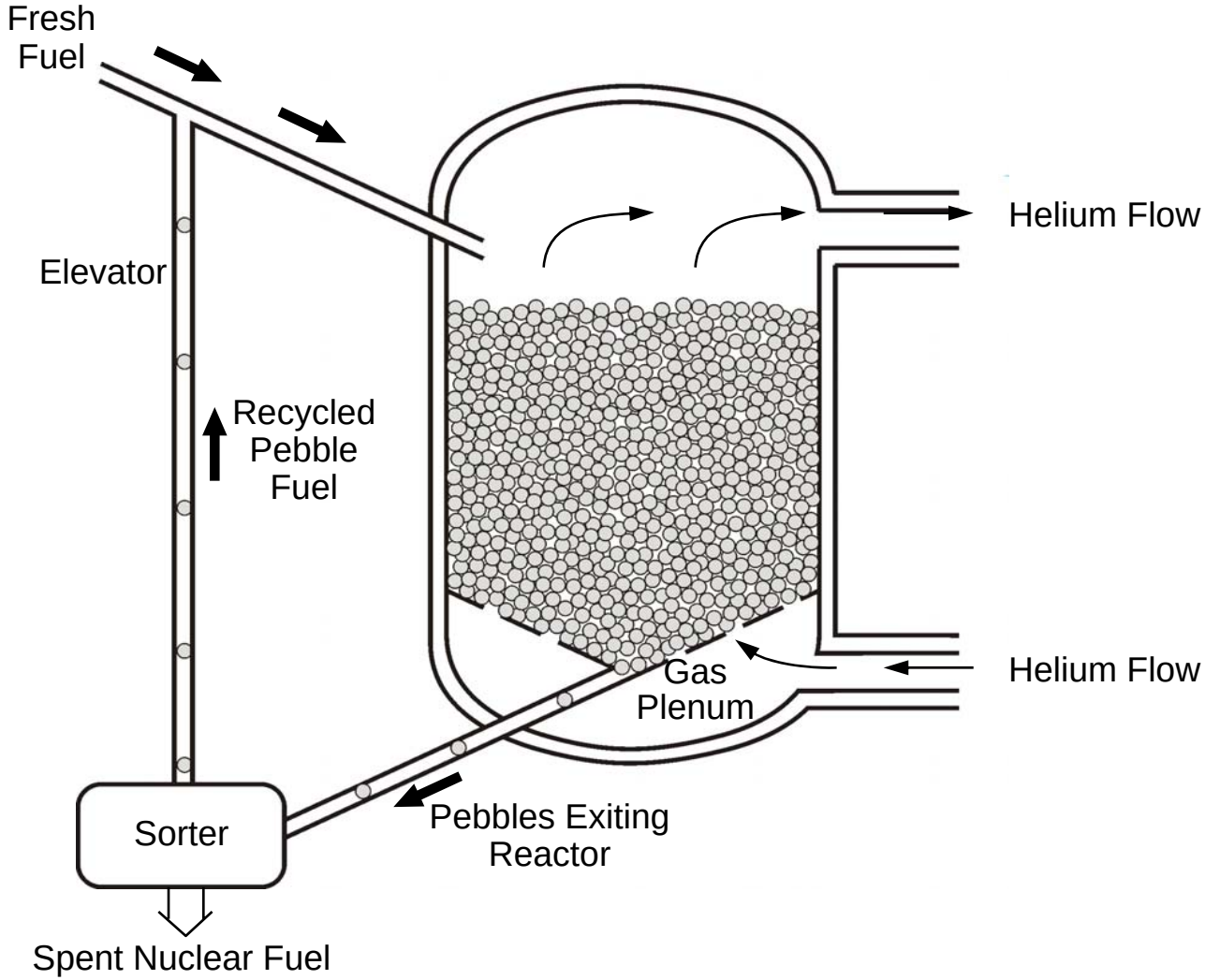
Pebble-Bed Fuel

- **Fuel**
  - **Sphere: ~6 cm**
  - **Coated-particle fuel in graphite matrix**
  - **Outer surface: clean carbon**
- **Multipass**
  - **Fuel added to top of core**
  - **Fuel flows to the bottom**
  - **Sphere sorting**
    - **High-burnup spheres discarded**
    - **Low-burnup spheres recycled**



THTR Reactor Core

Online Refueling of the High-Pressure Helium-Cooled Pebble-Bed Reactor

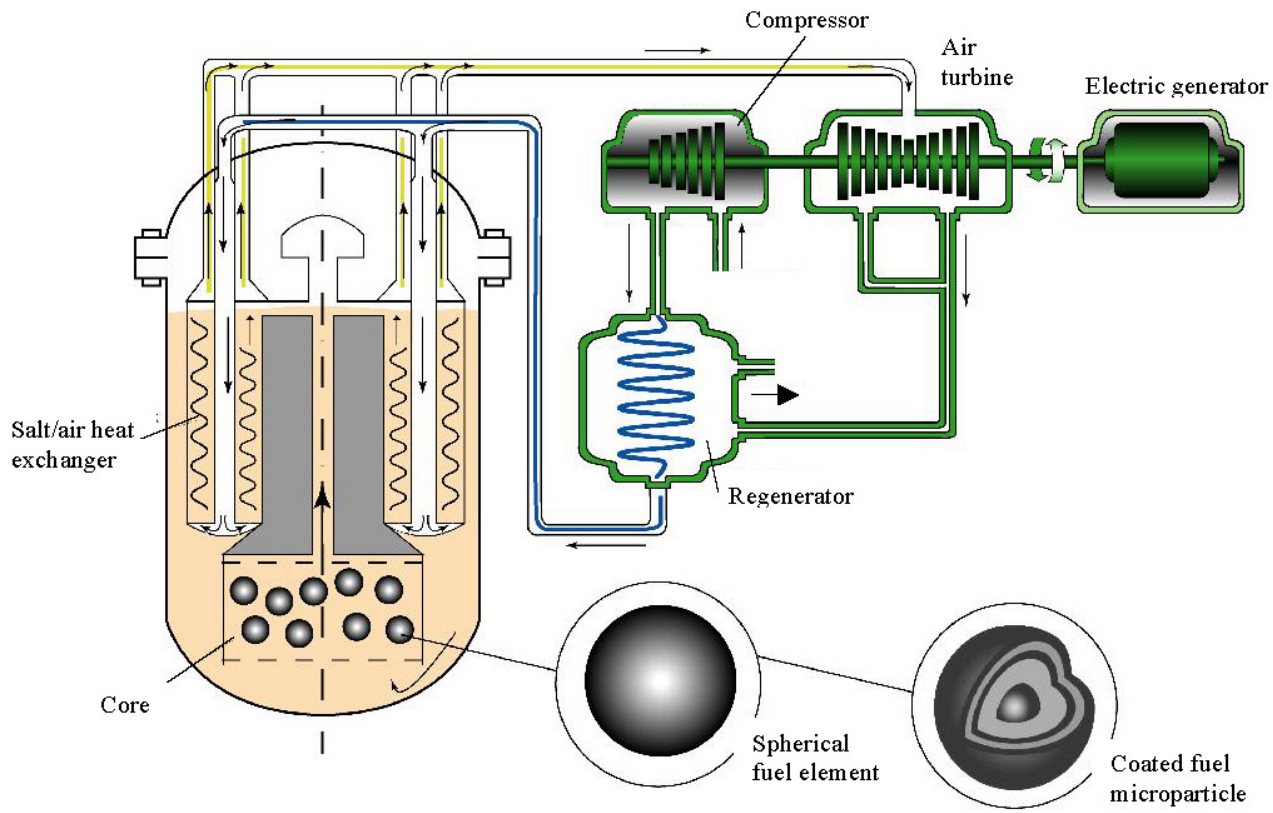


Liquid-Salt Pebble-Bed Reactors

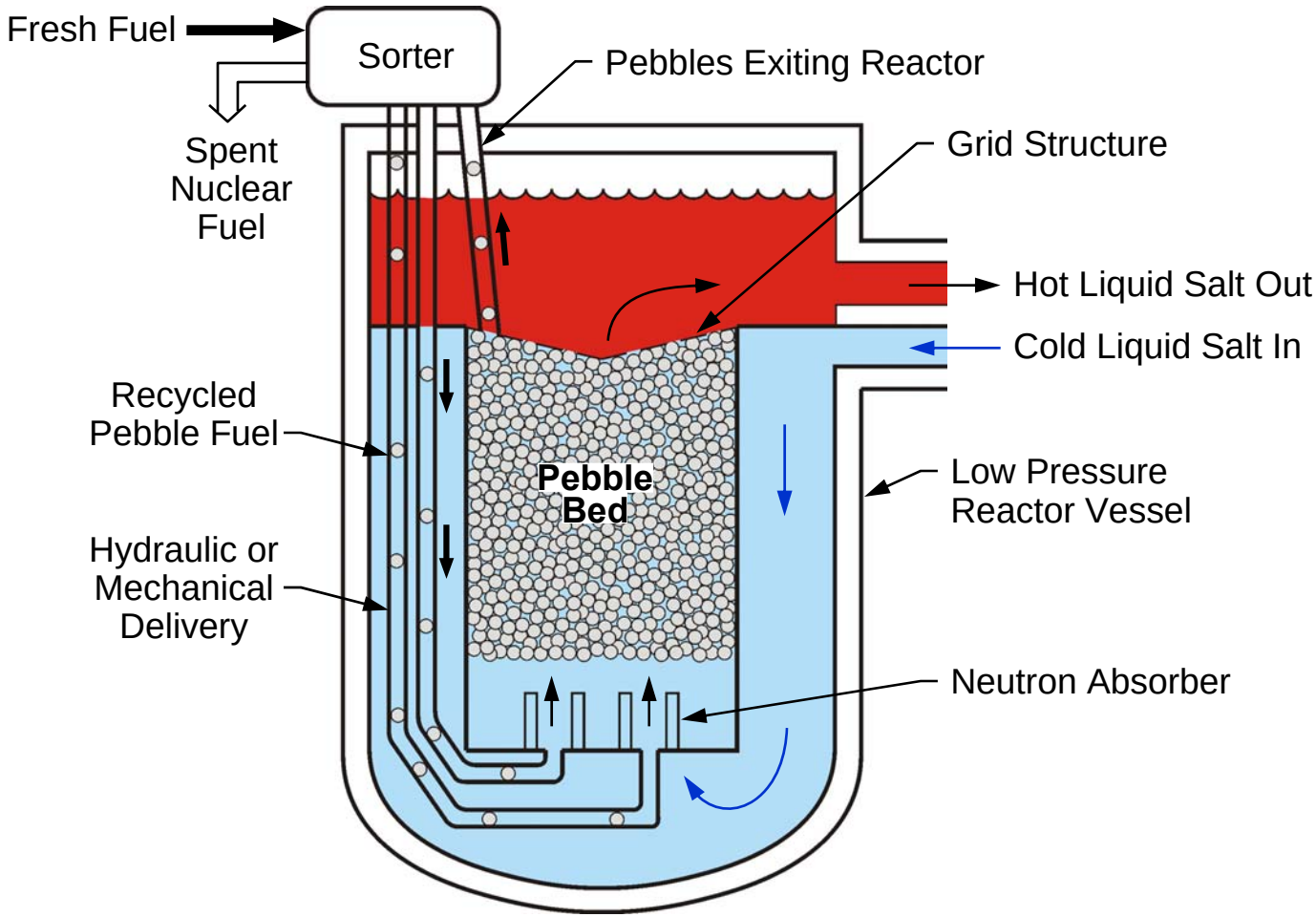
- **Multiple studies conducted**
  - **Small reactors**
    - **Microparticle-fuel autonomous molten-salt reactor (MARS)**
    - **Kurchatov (Moscow)**
    - **Power: 16 MW(t), 6 MW(e)**
  - **Large reactors [to 4000 MW(t)]**
    - **Delft University of Technology (Netherlands)**
    - **S. J. deZwaan (2005)**
- **Viable options**
  - **Fixed ratio of coolant to fuel**
  - **More-limited salt selection**

MARS

(Small, Remote Location, Open-Cycle Air Turbine, Pebble-Bed, Natural-Circulation Salt Coolant)



Online Refueling of the Low-Pressure Salt-Cooled Pebble-Bed Reactor



Pin-and-Assembly High-Temperature Reactor Refueling

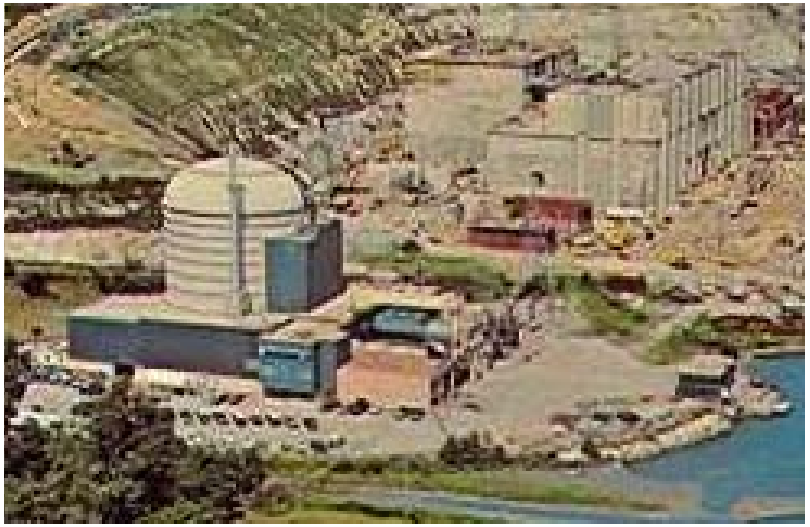
Gas Cooled

Peach Bottom I
Advanced Gas-Cooled Reactor

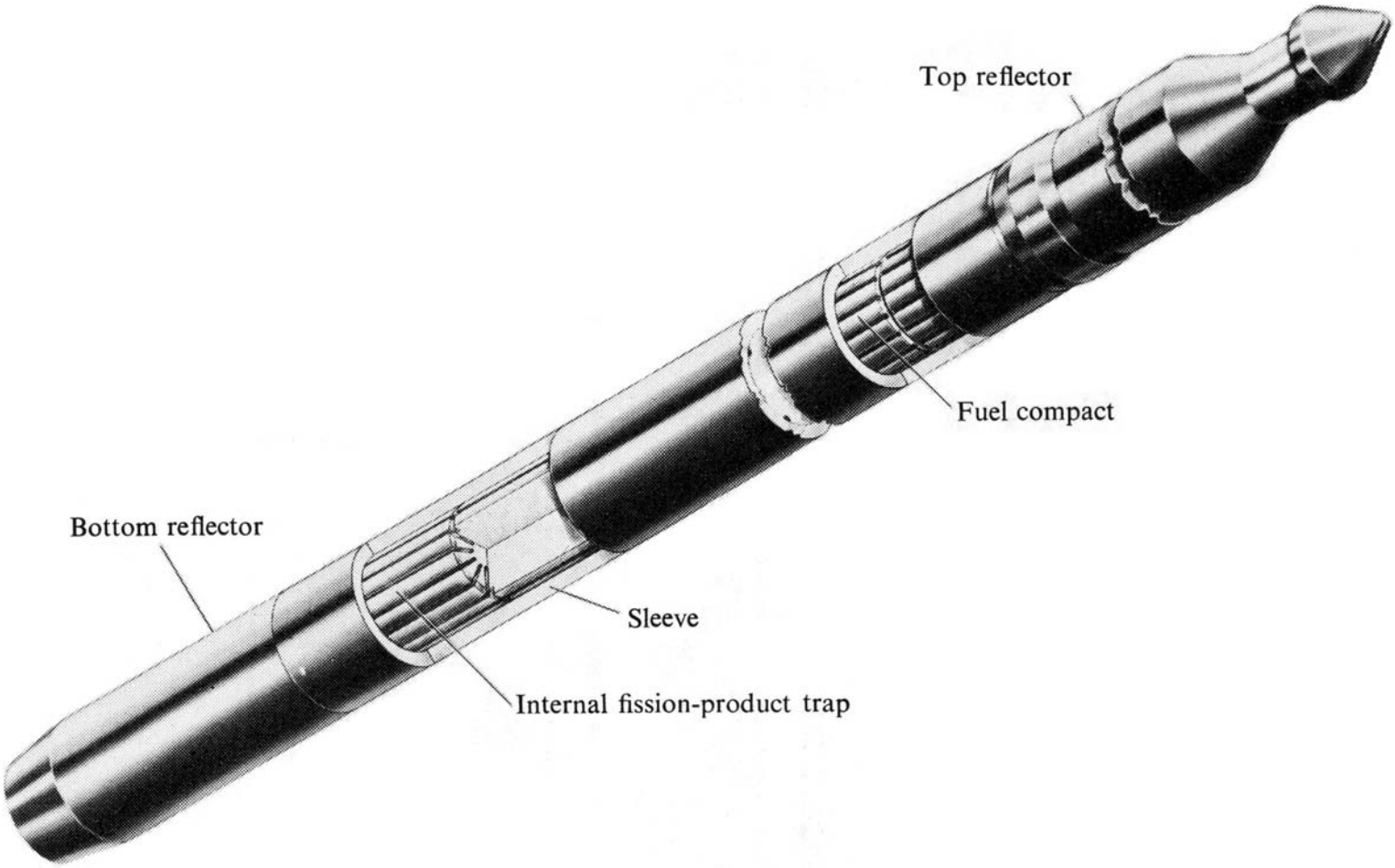
Liquid Salt Cooled

Peach Bottom HTGR

- **First high-temperature reactor in the U.S.**
- **In operation: 1967−1974**
- **Power: 40 MW(e)**
- **T_{out} = 770ºC**
- **T_{in} = 344ºC**
- **Pressure: 24 bar**
- **Fuel: compacts within assembly**
- **Power density: 8.3 MW/m^3**



Peach Bottom HTGR Fuel Element

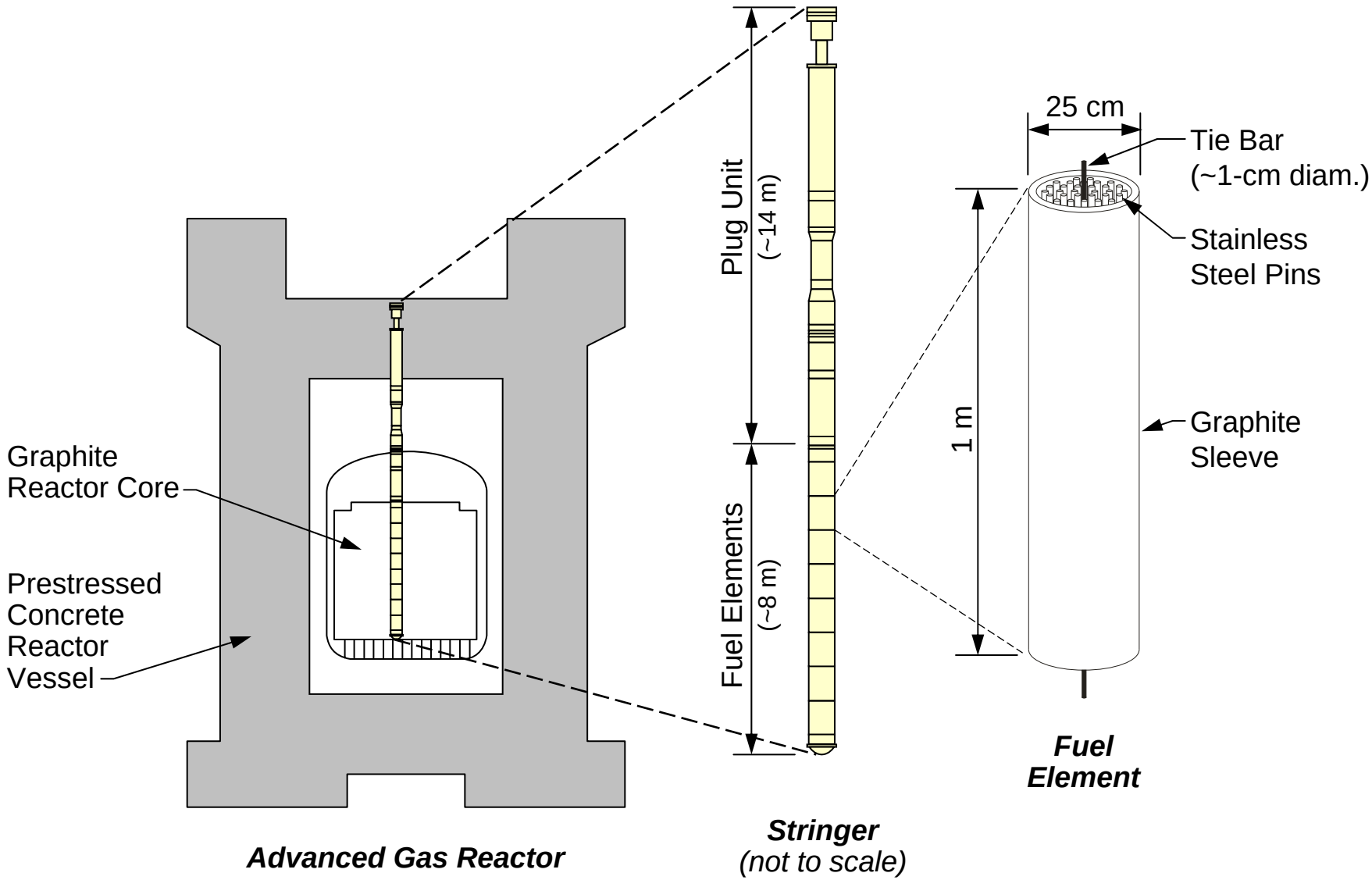


Peach Bottom Fuel Characteristics

- **Multiple generations of fuel**
  - **Initial fuel: vented fission products**
  - **Later fuel: coated particle**
- **LS-VHTR option**
  - **Potential for modified liquid-salt variant**
  - **Full-length core elements**
  - **Has not been investigated**
    - **Neutronic questions**
    - **Mechanical and materials questions in a large reactor**

Advanced Gas-Cooled Reactor United Kingdom Dungeness B

British Advanced Gas-Cooled Reactor



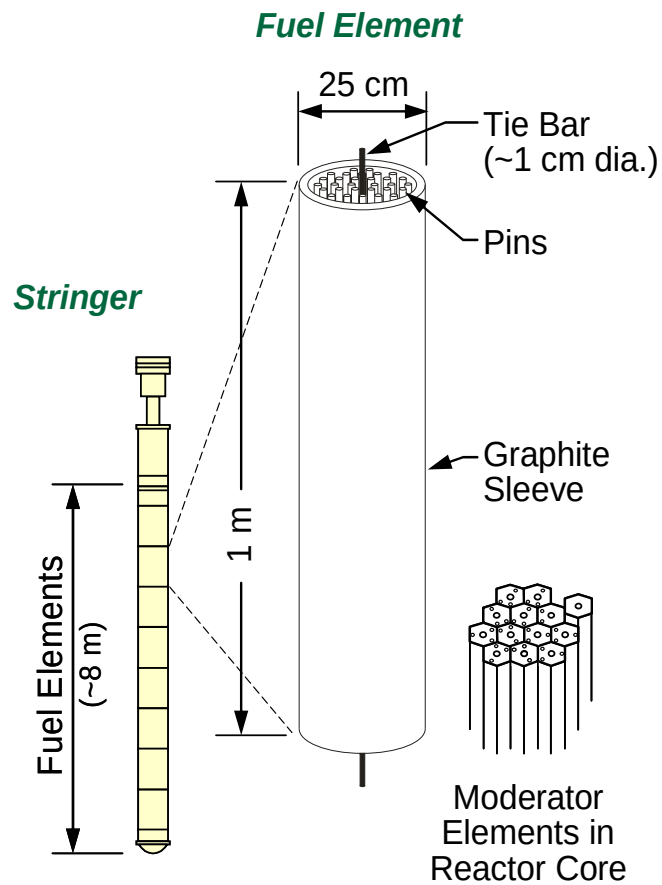
AGR Refueling

- **14 AGRs**
  - Similar but not identical
- **Dungeness B**
  - 1110 MW(e) for station
  - Two reactors: 555 MW(e) each
  - Reactor parameters
    - Metal-clad fuel
    - Carbon dioxide coolant
    - Graphite moderated
  - Startup: 1983, 1985
- **AGR refueling online**
  - Station dependent (online at some, off-line at others)
  - 43.3 atmospheres
  - 640ºC nominal
  - 750ºC peak channel

Dungeness B Refueling Machine

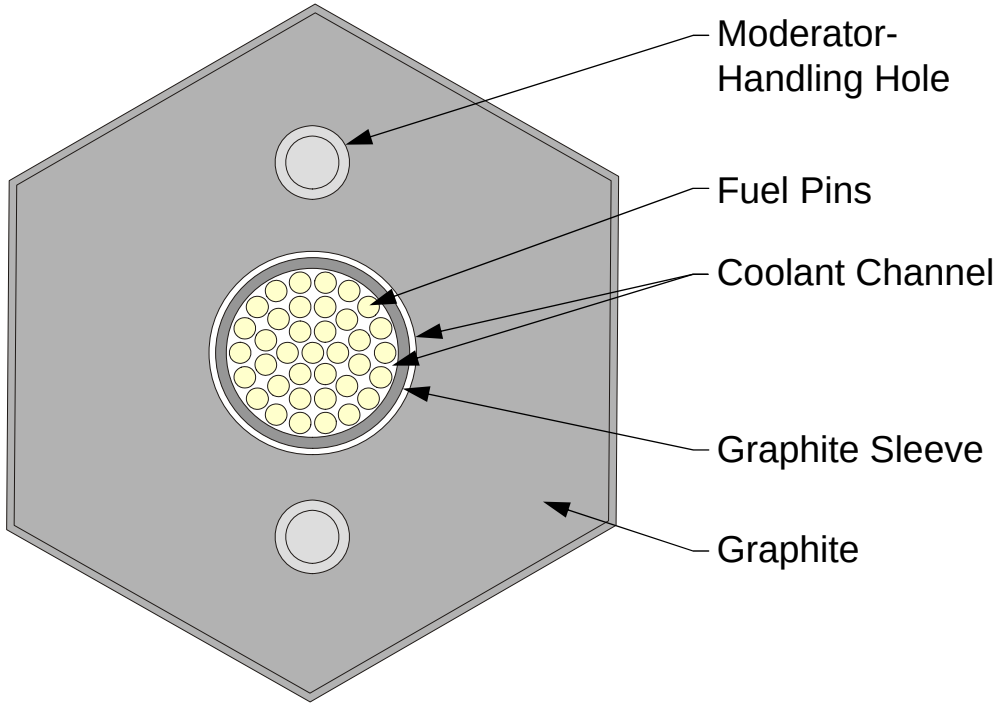
An LS-VHTR Equivalent of the AGR Is Potentially Viable

- **Same refueling strategy with shorter distances from lid to core**
- **Replace steel components in the stringer with high-temperature carbon composites**
  - **Advances in carbon-carbon composites**
  - **Preliminary assessment did not find any "showstoppers"**
- **Moderator composed of columns of graphite blocks with center holes**
- **Use modified Japanese HTTR pin design**
- **Core-length assembly**
- **AGR team is examining SiC clad (carbon dioxide environment) variant for the AGR**



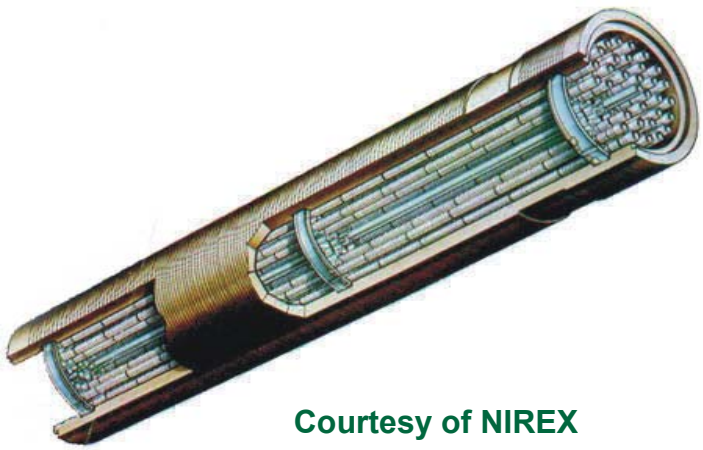
Graphite Columns Would Replace Fuel Blocks

(Moderator Replaced Once or Twice in the Reactor Lifetime with Salt Removed)

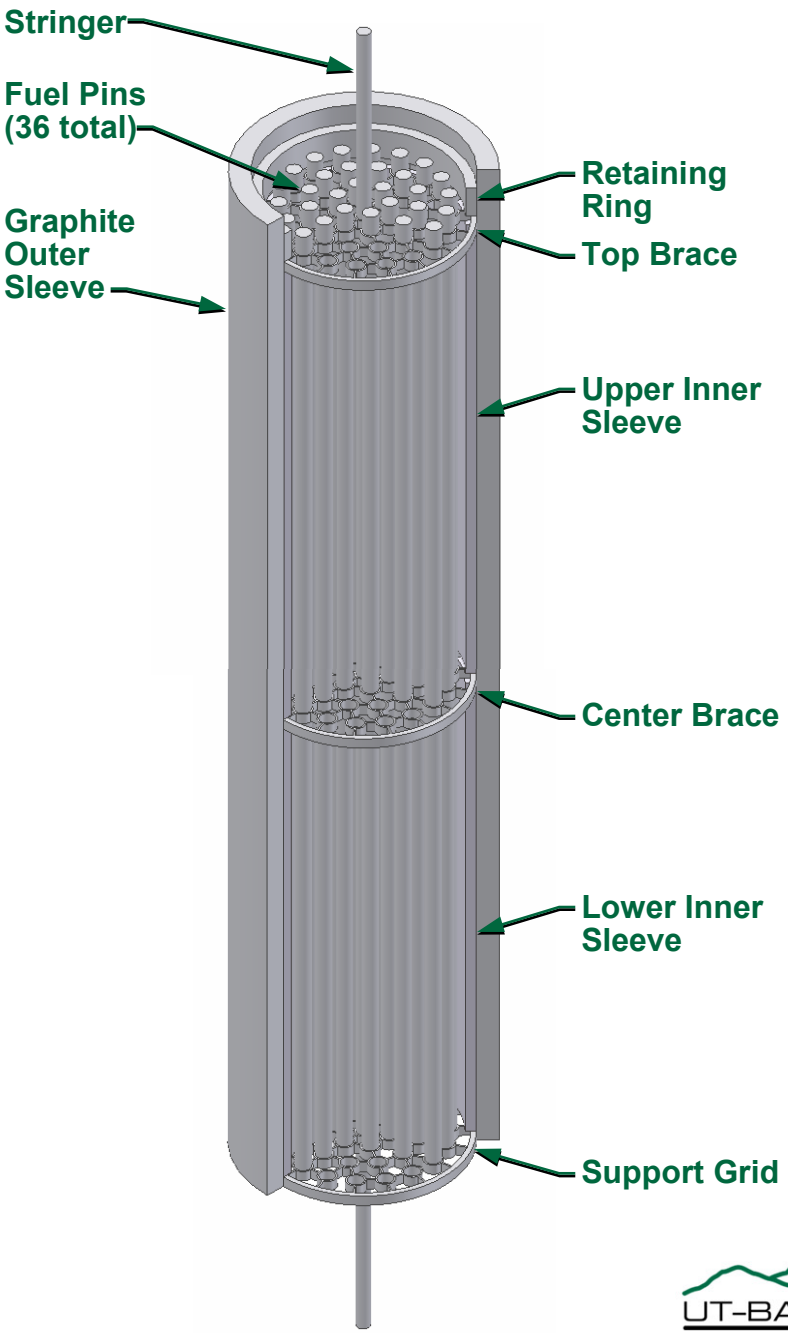


LS-VHTR / AGR Fuel Assembly

(Small Fuel Assemblies on a Stringer To Avoid Pin Length and Other Constraints)

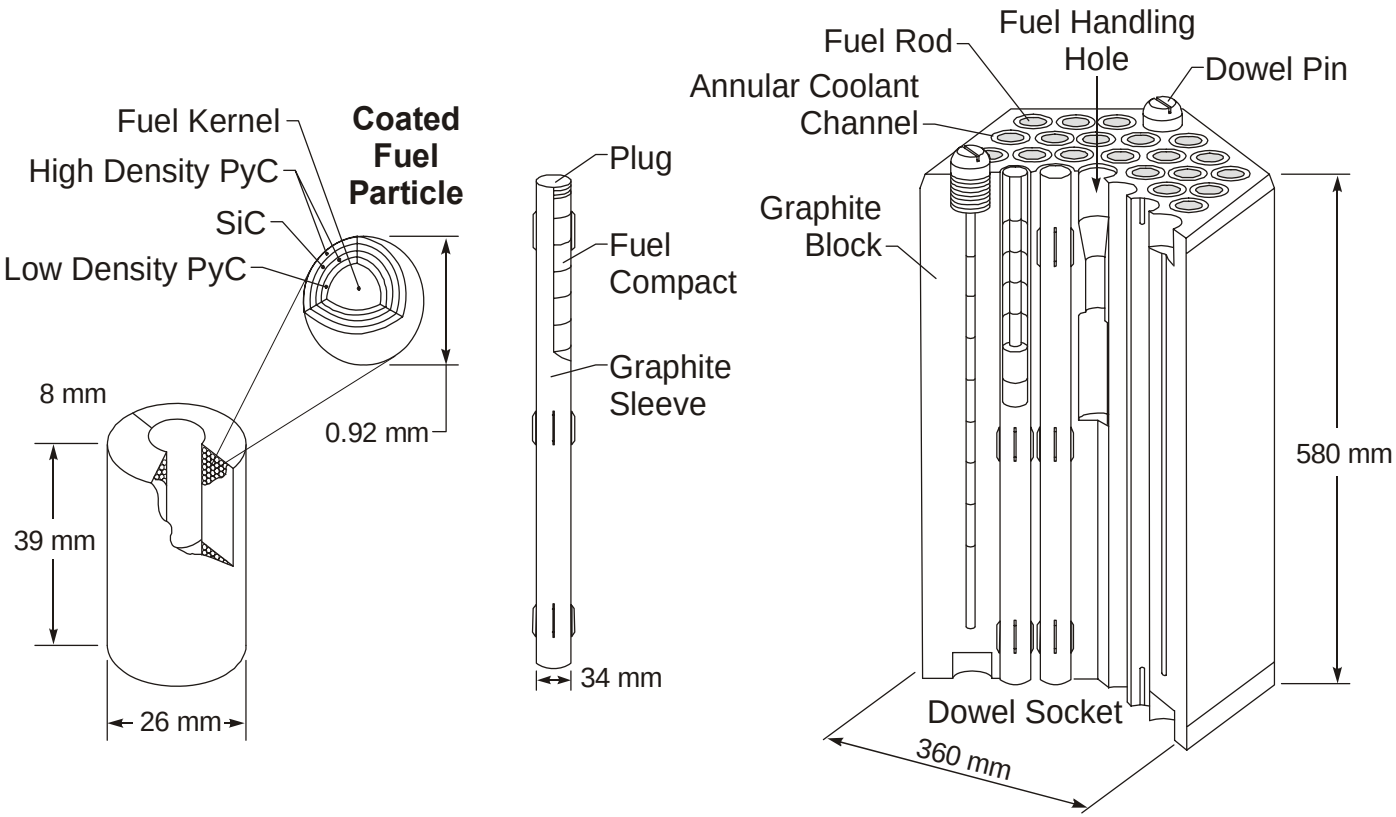


Courtesy of NIREX



HTTR Fuel (Japan) Has a Pin Design

(Limited-Height Pin is a Candidate for a LS-VHTR Pin Assembly)



Fuel Compact **Fuel Rod** **Fuel Block**

Conclusions

- **Three gas-cooled reactor core options**
  - **Massive refueling experience**
  - **Includes high-temperature, high-pressure refueling**
- **Three parallel salt-cooled reactor core options and fuel designs**
- **Multiple options for refueling**
- **Major R&D required for refueling but no fundamental issues identified**
- **Core design coupled to refueling strategy**