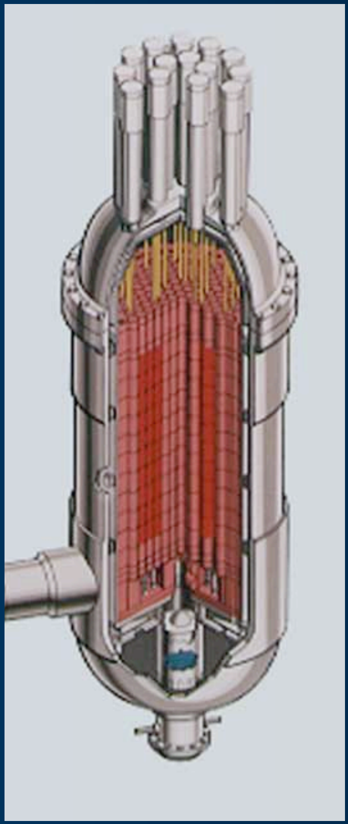
The Gen IV Modular Helium Reactor

...and its Potential for Small and Medium Grids

presented to

Society of Nuclear Engineers of Croatia

26 January 2007



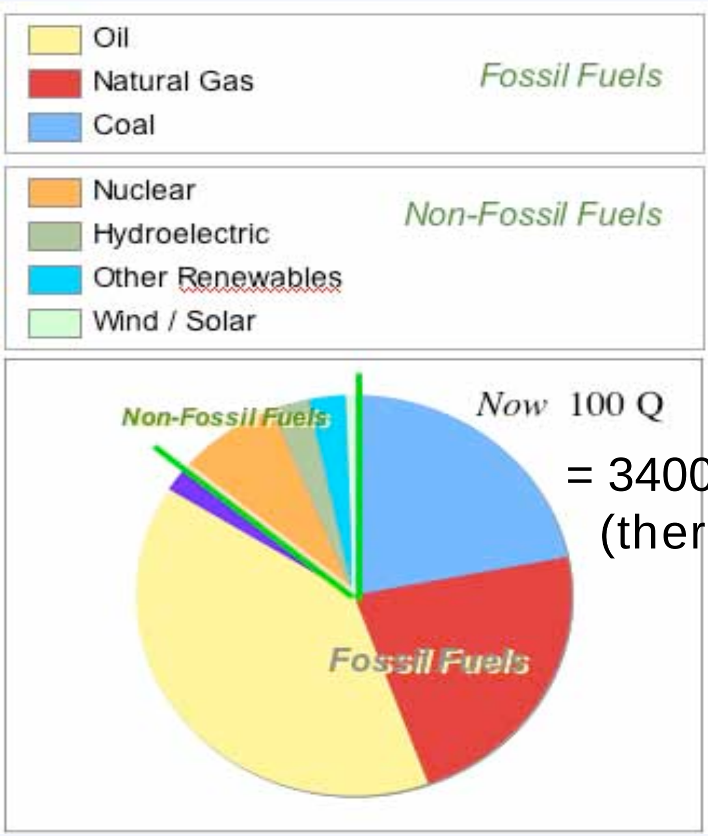
by

David E. Baldwin, Ph.D.

GENERAL ATOMICS

Sustainable Energy has Become Priority for All Nations

(Figures for the U.S. ~2000)



= 3400 GW (thermal)

Need for both

- Electricity
- Transportation fuel

Compounded by the issues of climate change

- Kyoto

e.g., replacing 50% of current fossil would require ~500 GW_e

. . . only nuclear is credible

Together with Its Promise, Nuclear Power Has Had a Number of Issues / Problems of Concern

- Safety / Security assurance
- Proliferation potential
- Long-term uranium supply
- Spent-fuel disposition
- High cooling-water demand

However, during the last 30 years, there have been significant advances addressing <u>all</u> these issues

Any re-examination of nuclear power arising from global warming or other concerns should be made in the light of these advances.

New, Advanced Reactors Will Be Evaluated Using Multiple Criteria

Gen IV goals

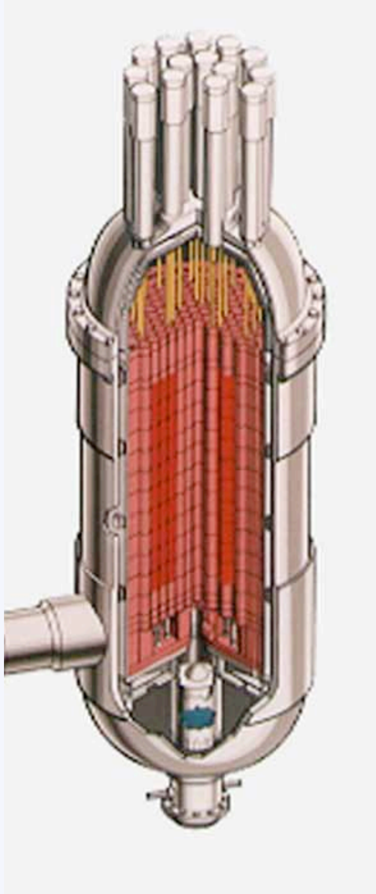
- Inherent safety / security
- Proliferation resistance
- Fuel-cycle sustainability
- Competitive Cost of Electricity (COE)

Additional requirements

- Unit-size flexibility / modularity
- Low water consumption
- Hydrogen production or other apps.
- Co-generation
- Low Ops. & Main. staff requirements
- Minimum spent nuclear fuel (SNF)
- Manageable ultimate waste form
- ...

Given the historic ~40-year penetration time for a new energy technology, we <u>must</u> get started

The High-Temperature Modular Helium Reactor (MHR) Meets the Gen IV Requirements and More

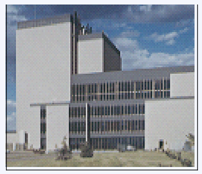
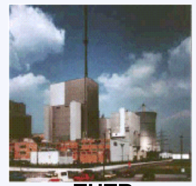


Designed first for safety, then made economic

- Low power density, low power rating and negative temperature coefficient (passive, conduction decay-heat removal)
- Refractory fuel (high temp capability)
- Graphite core (high temp stability)
- Helium gas coolant (inert)
- Secure core with scheduled fuel replacement and high graphite/fuel ratio (proliferation resistance)
- Low water demand, dry-cooling/desalination
- Modular construction (size flexibility)
- Demonstrated reactor technologies (first-generation readiness)
- Low O&M staff requirement, and
- Competitive COE

Several Uranium / Thorium Fueled MHRs Have Operated Worldwide

Power Reactors | Research Reactors



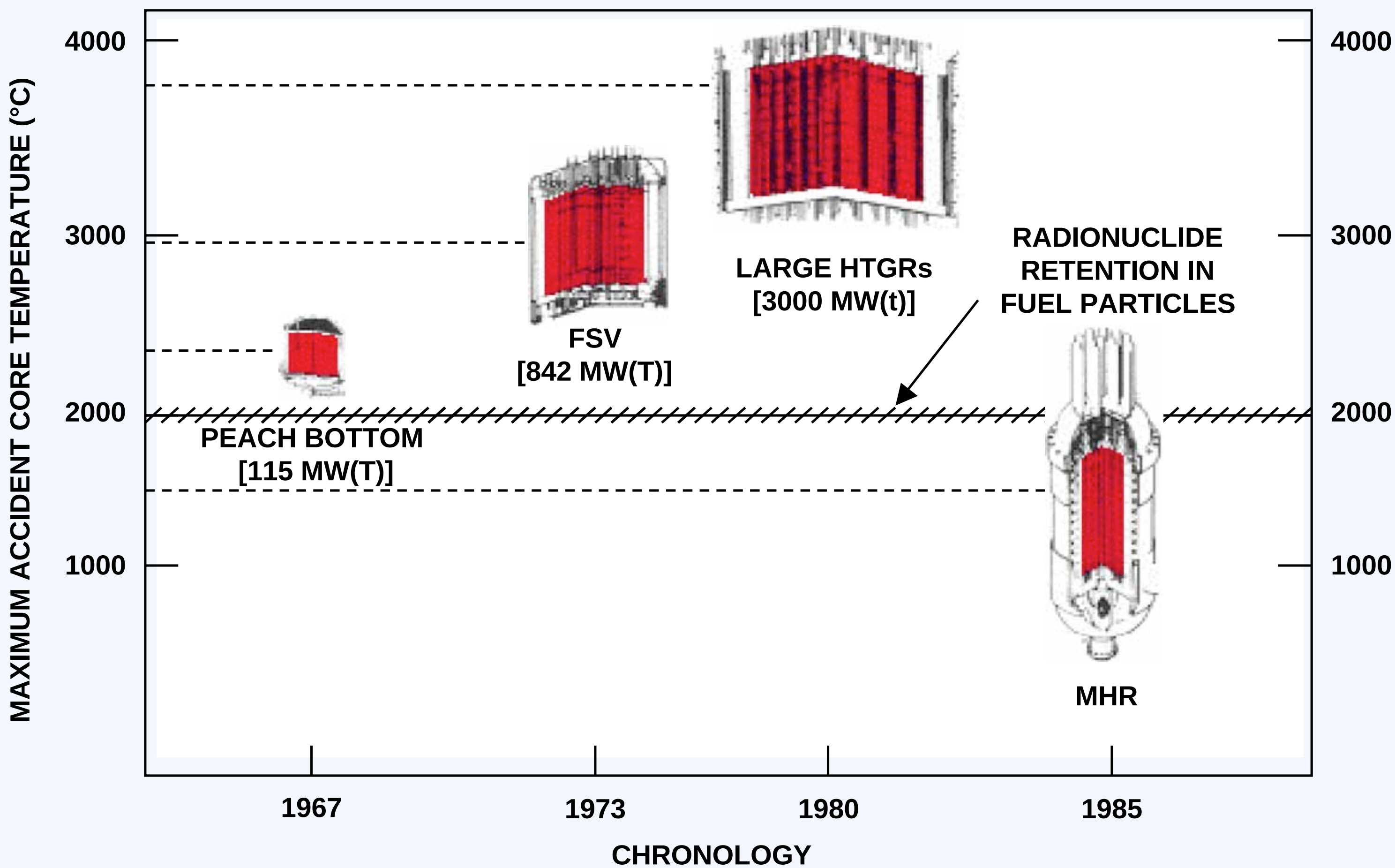
	Peach Bottom 1 1966-1974	Fort St Vrain 1976-1989	THTR 1986-1989	Dragon 1966-1975	AVR 1967-1988	HTTR 2000-	HTR-10 2003-
Power Level:							
MW(t)	115	842	750	20	46	30	10
MW(e)	40	330	300	-	15		–
Coolant:							
Pressure, Mpa	2.5	4.8	4	2	1.1	4	3
Inlet Temp, °C	344°C	406 °C	250 °C	350 °C	270° C	395°C	250 °C/300 °C
Outlet Temp, °C	750°C	785 °C	750 °C	750 °C	950° C	850 °C/950 °C	700 °C/900 °C
Fuel type	(U-Th)C_2 PyC coated particles	(U-Th)C_2 TRISO	(U-Th)O_2 TRISO	(U-Th)C_2 PyC particles	(U-Th)O_2 TRISO	(U-Th)C_2 PyC particles	(U-Th)O_2 PyC particles
Peak fuel temp, °C	~1000 °C	1260 °C	1350 °C	~1000 °C	1350 °C	~1250 °C	
Fuel form	Graphite compacts in hollow rods	Graphite Compacts in Hex blocks	Graphite Pebbles	Graphite Hex blocks	Graphite Pebbles	Graphite compacts in Hex blocks	Graphite Pebbles

*** More than 30 CO2-cooled, graphite-moderated reactors have been built and 10 are nowoperating in the United Kingdom for power production.*

TRISO particles are fuel kernels coated with SiC and PyC

Renewed world-wide interest in He-cooled reactors because of their safety and high temperature applications

MHRs Represent A Fundamental Change In Reactor-Safety Design Philosophy



... a proven core, but sized to tolerate even a severe accident

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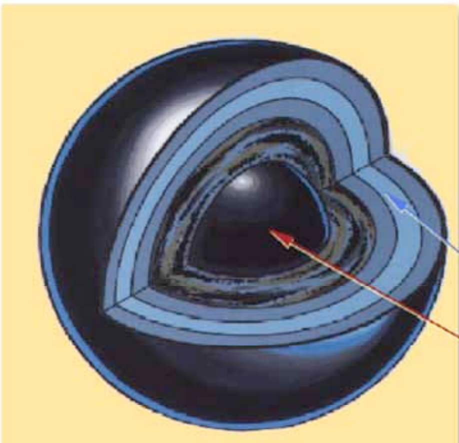
TRISO Fuel Form Is Key to High Temperature, Fuel Utilization, Containment & Proliferation Resistance

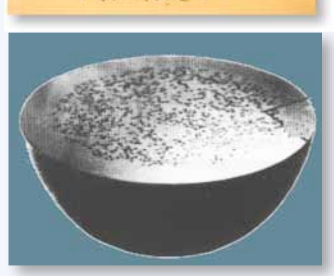


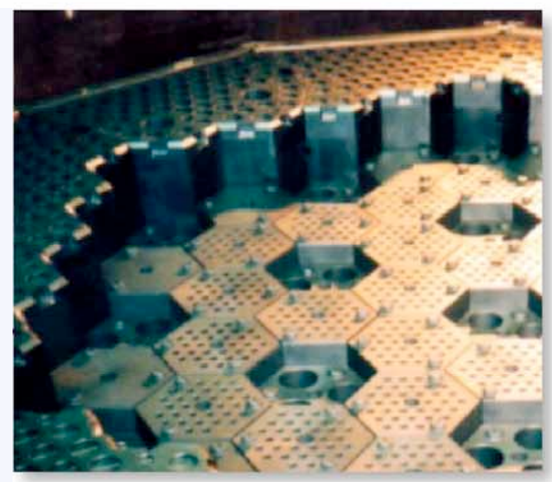
TRISO Coated Fuel Particles:

- ***Lots of cladding - extremely strong***
- ***Little fuel - fully encapsulated***

Each fuel particle forms a separate pressure containment vessel for the kernel (to 1000 atm)

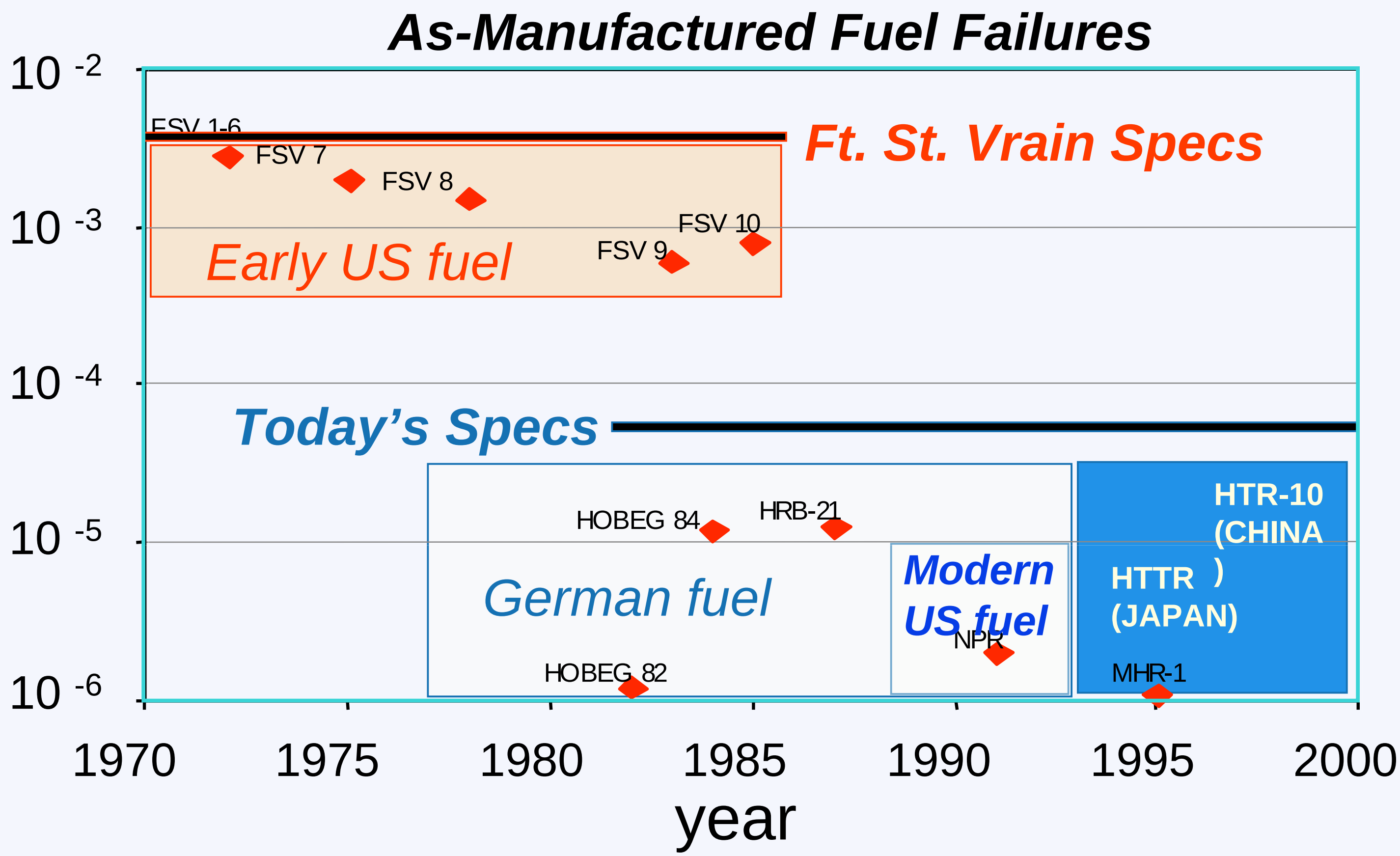
U, Th, Pu have been fabricated and tested in reactors (limited TRU)





Prismatic Block or Pebble Bed variants

Excellent Quality UO_2 TRISO Fuel Has Been Fabricated Throughout the World



However, real commercial scale must be re-established

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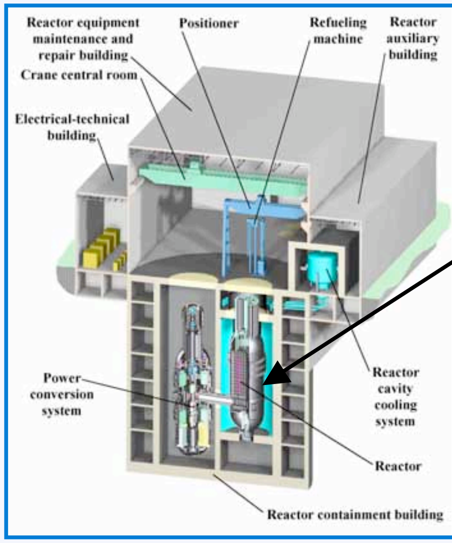
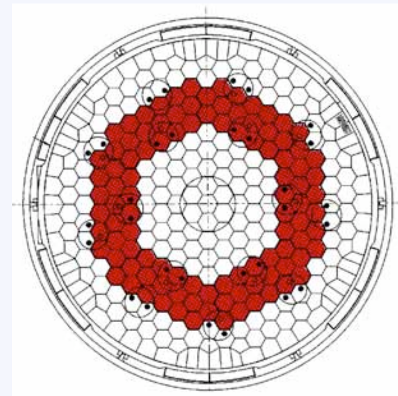
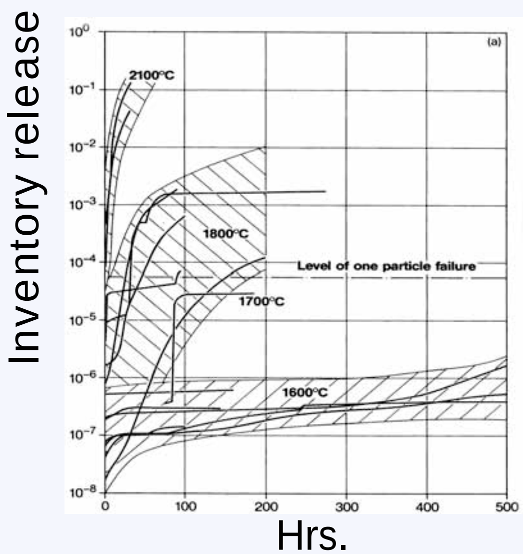
MHR Approach to Safety and Security Has Below-Grade Construction, No Active Safety Systems

- All nuclear components below grade

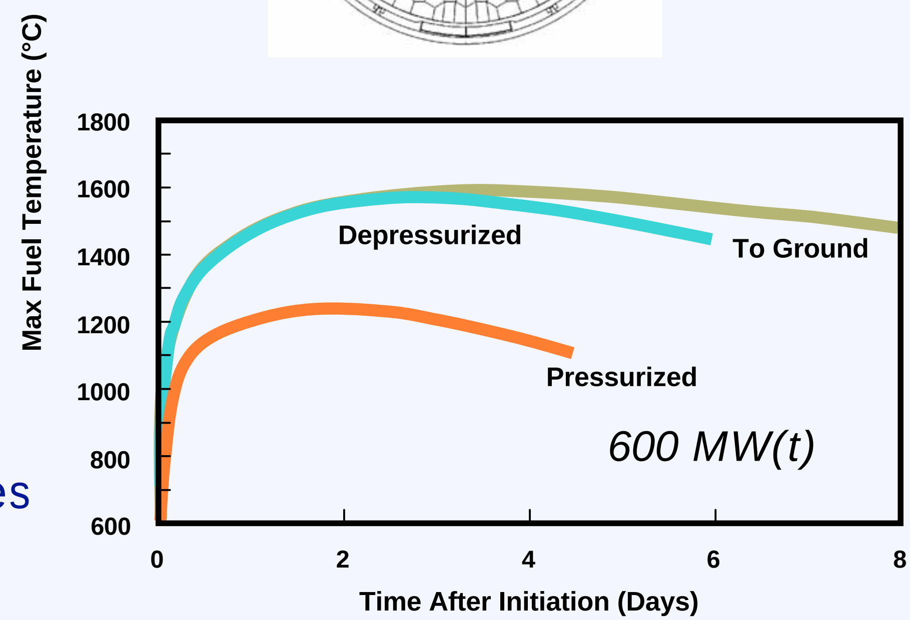


- Heat removed passively during loss-of-coolant events





- Coated particles stable to beyond maximum accident temperatures



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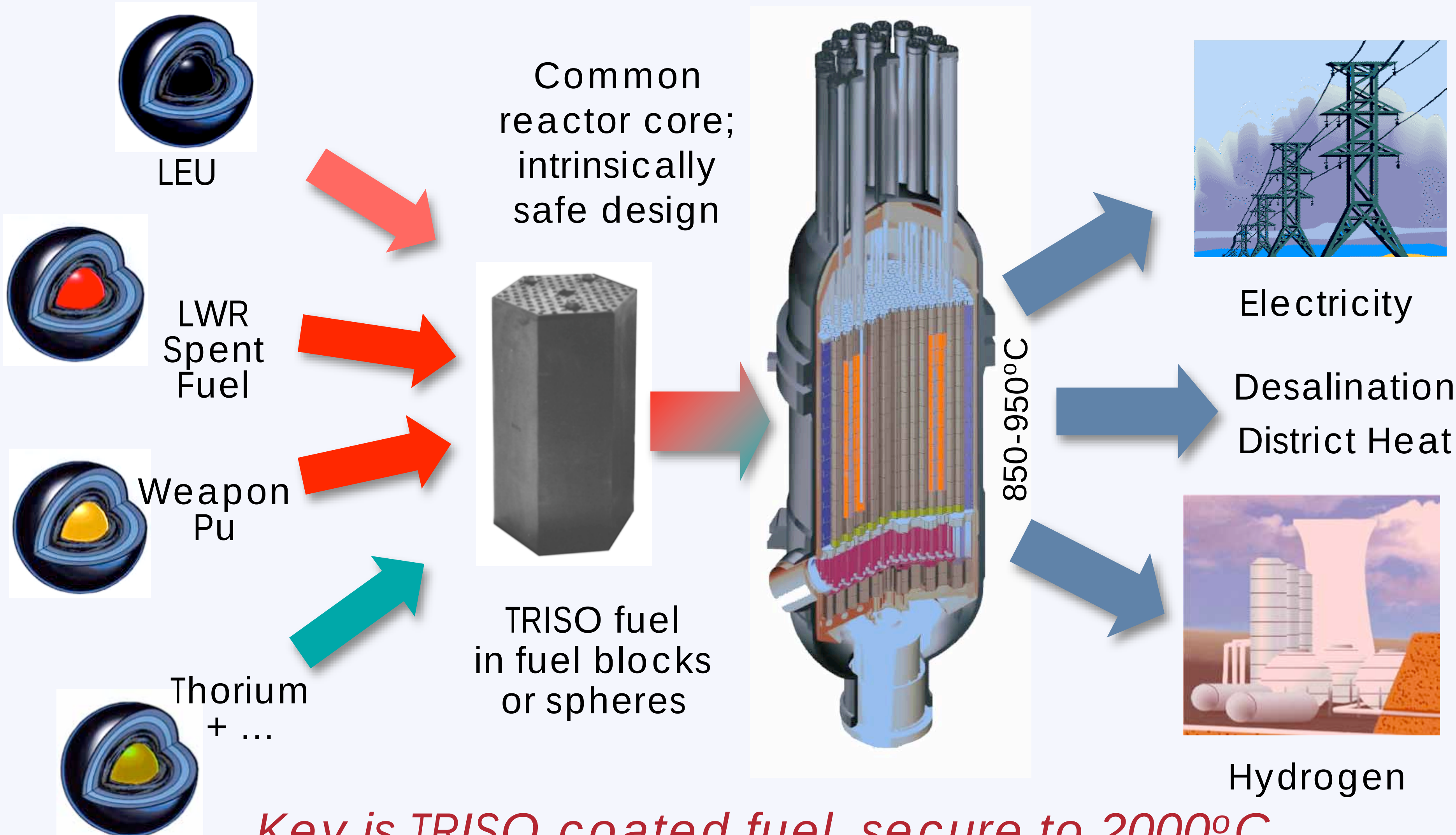
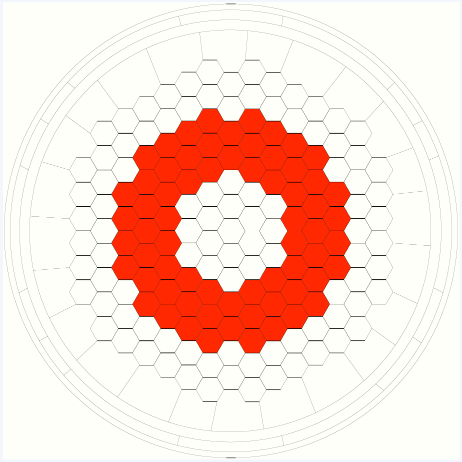
TRISO Particles, Graphite Moderator & Helium Coolant Enable Flexibility in Fuels and in Applications



Key is TRISO coated fuel, secure to 2000°C

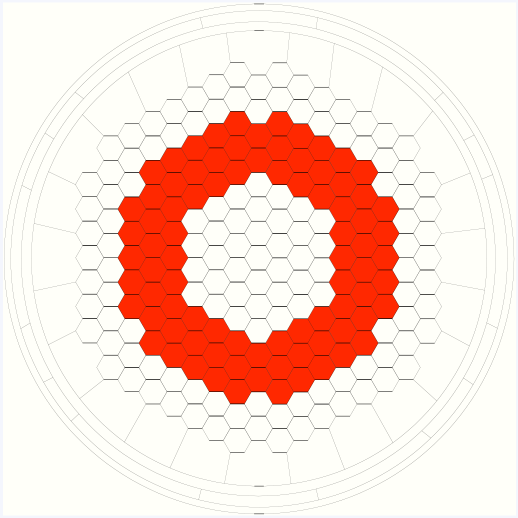
Flexible Core Design Can Meet Different Power Needs -- Module Size and Number

350 MW(t)



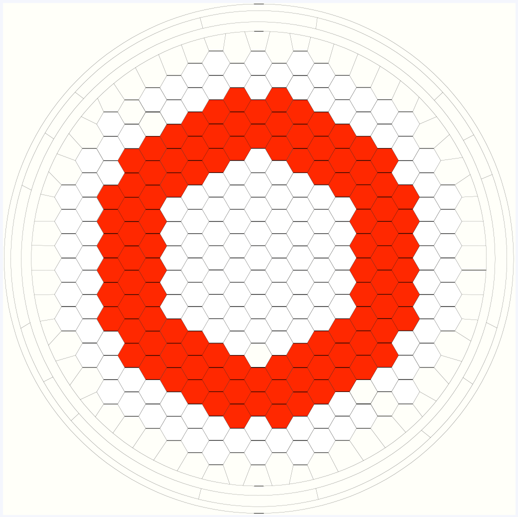
66 Columns
660 Elements

450 MW(t)



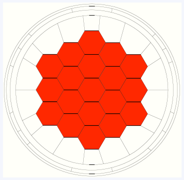
84 Columns
840 Elements

600 MW(t)



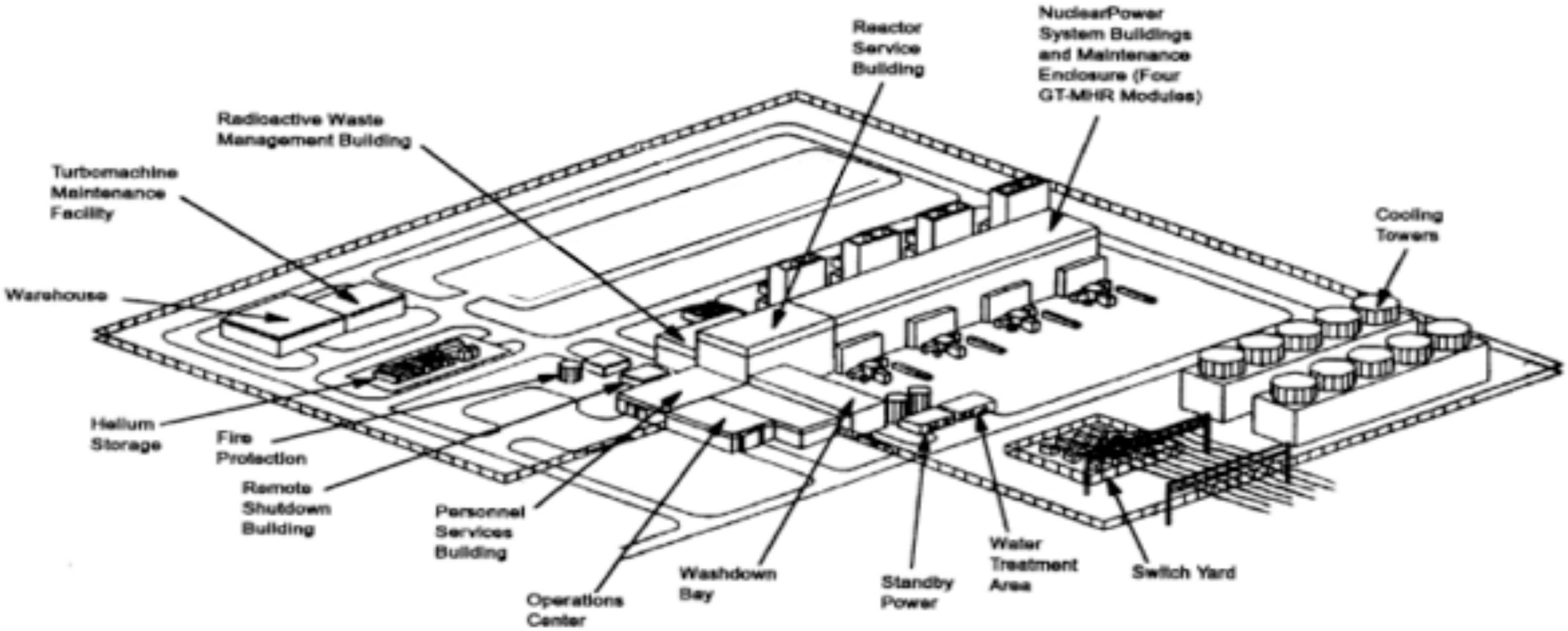
102 Columns
1020 Elements

25 MW(t)



19 Columns
76 Elements

Higher-Power Plants Are Comprised of a Number of Modules



Costing is typically for 4-module a configuration, but there is only modest cost penalty for fewer modules

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Designed for Passive Safety, Acceptable COE for the MHR is a Non-Negligible Challenge

MHR cost disadvantages

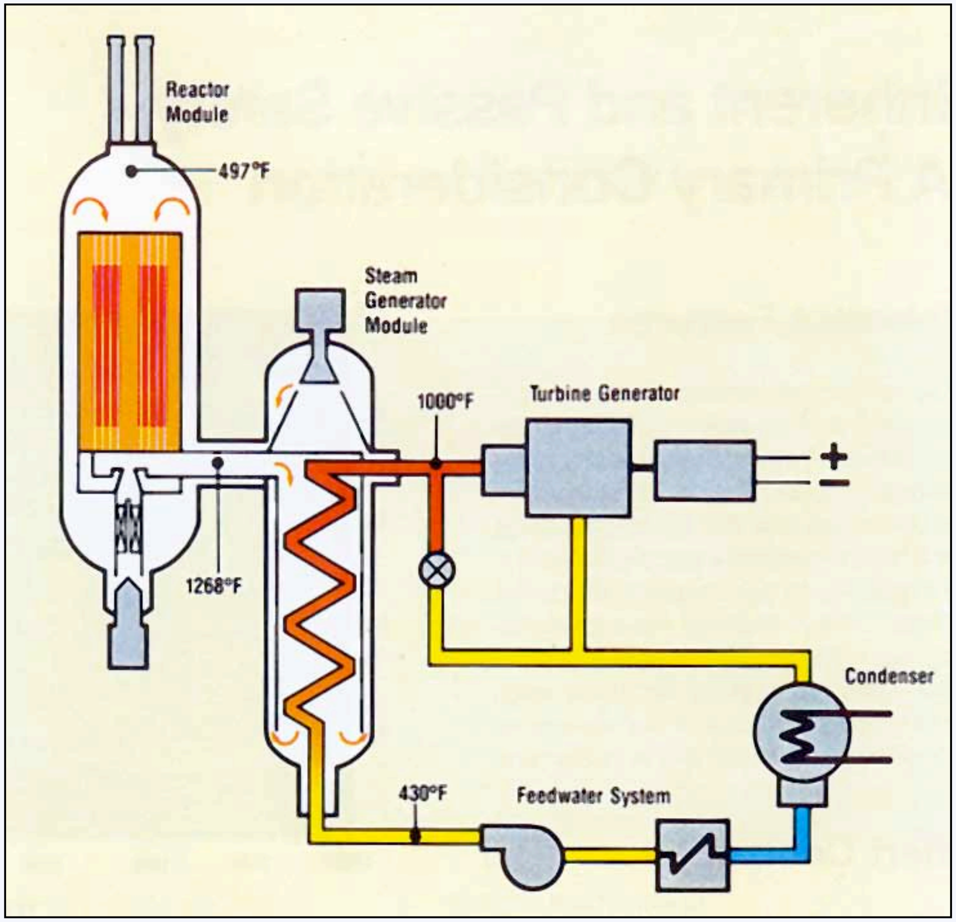
- Low power density
- High-cost TRISO fuel form

MHR cost advantages

- Absence of active safety systems
- High conversion efficiency
- High fuel utilization
- Absence of steam-processing equipment
- Low Ops. & Main. (O&M) costs

The net result is distinct cost advantage for advanced MHRs

As a Near Term, MHTGR Could Generate Steam at 1000°F (540°C) and 2500 PSI (17 MPa)

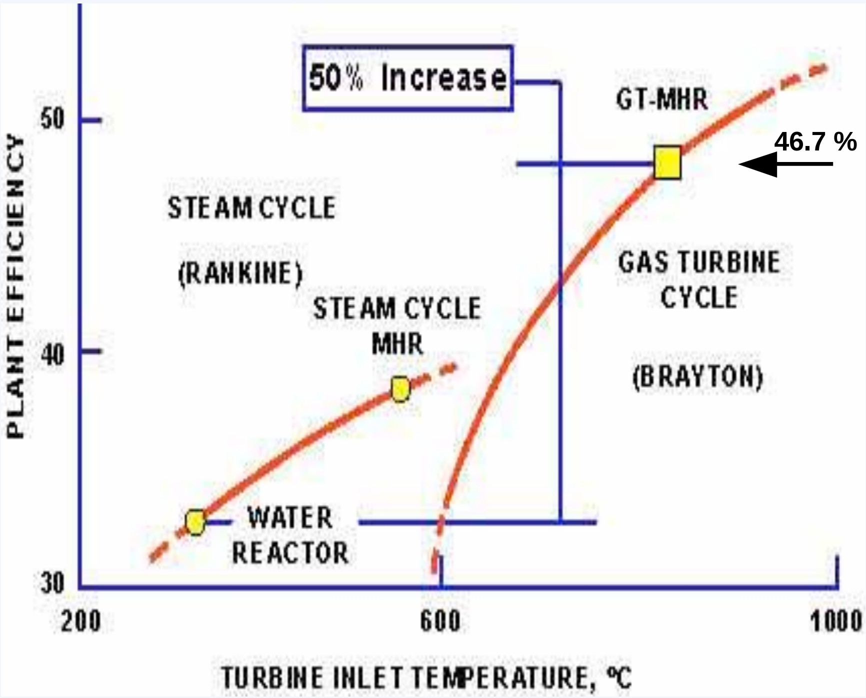


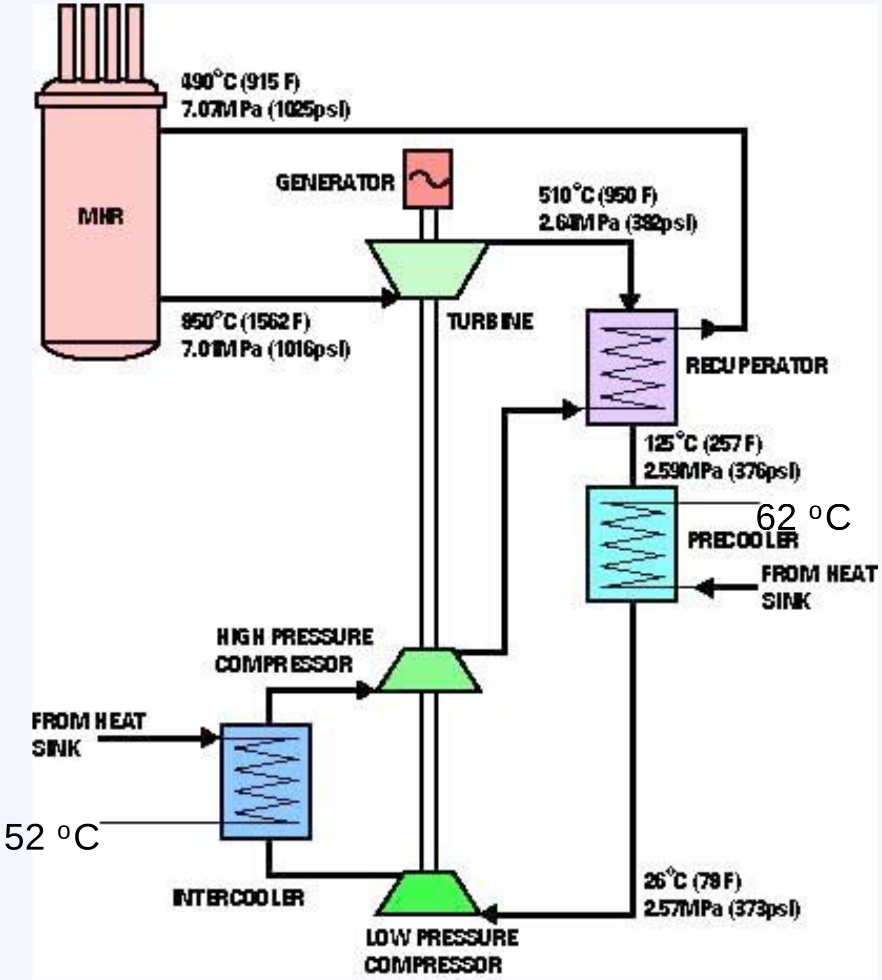
- Uses components available today
- Completed
  - ✓ Preliminary Design
  - ✓ NRC Safety Evaluation
- Matches naturally to district heating

....steam quality equivalent to modern fossil-fired steam power plants

High Temperature Gas Reactors Are Well Suited to a More Efficient Brayton Cycle … Advanced MHR

Power Conversion





Exhaust heat from the pre- and inter-coolers could be applied to district heating, but needs re-optimization

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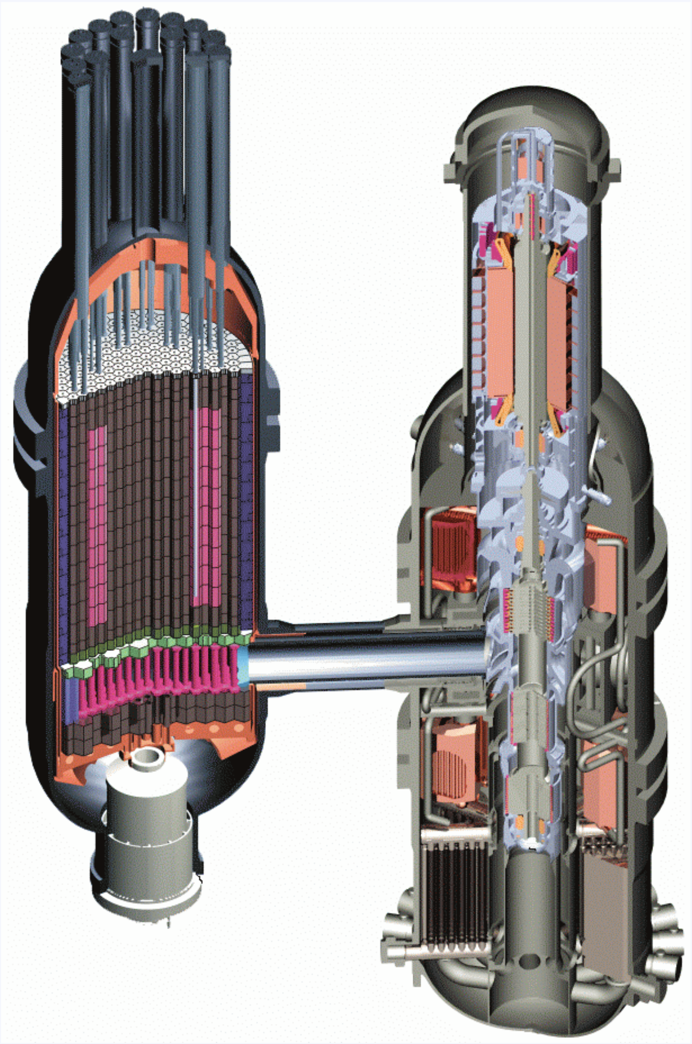
The Direct Brayton-Cycle PCU Offers Many Advantages



Power Conversion Unit (PCU)

- ~50% efficiency
- Vertical orientation
- Short interconnect
- Single Shaft, w/ flexible coupling
- Integrated generator
- Electromagnetic bearings
- Recuperator & Intercooler
- Asynchronous with frequency conversion

- Completed Preliminary Design in Russia in 2003 @ 285 MW(e)
- Component testing in progress
- Early generation might, e.g., use two half-sized PCUs

MHR Plants Size and Power Conversion Options Range From Immediate Term To Longer Term

RELATIVE GENERATION COST

140 MWe MHTGR

- 350 MWt
- Steam cycle
- 39% Efficiency
- 700°C Core outlet
- Proven tech
- Near term (~6 yr)

220 MWe CC-MHR

- 450 MWt
- Combined cycle
- 48% Efficiency
- 850°C Core outlet
- Heat exch. req'd
- Modest R&D req'd
- Medium term (~10 yr)

290 MWe GT-MHR

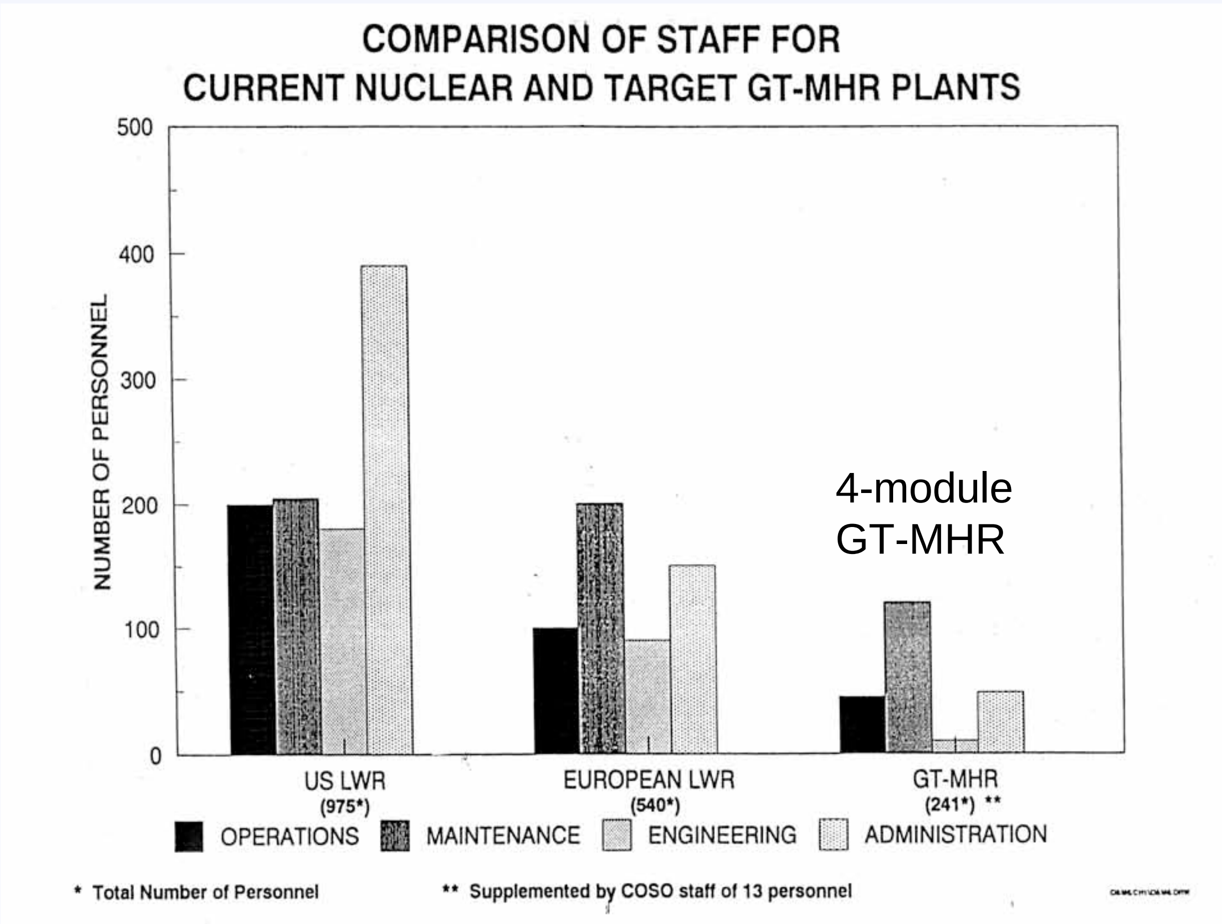
- 600 MWt
- Brayton cycle
- 48% Efficiency
- 850°C Core outlet
- More R&D req'd
- Longer term (~15 yr)

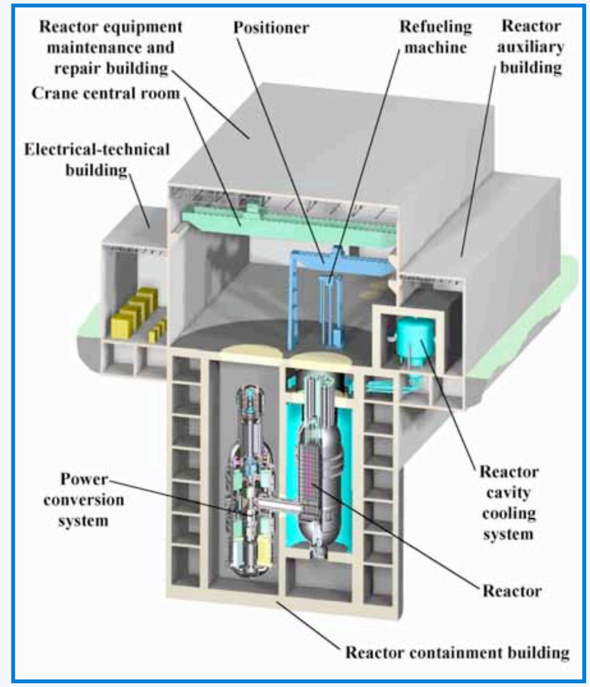
310 MWe VHTR

- 600 MWt
- Brayton cycle
- 58% Efficiency
- 1200°C Core outlet
- More R&D req'd
- Longer term (~20 yr)

MORE PROVEN — **TECHNOLOGY** — **LESS PROVEN**

GT-MHR Ops. & Main. (O&M) Staffing Less Than Light Water Reactors (LWRs)





Little Balance-of-Plant

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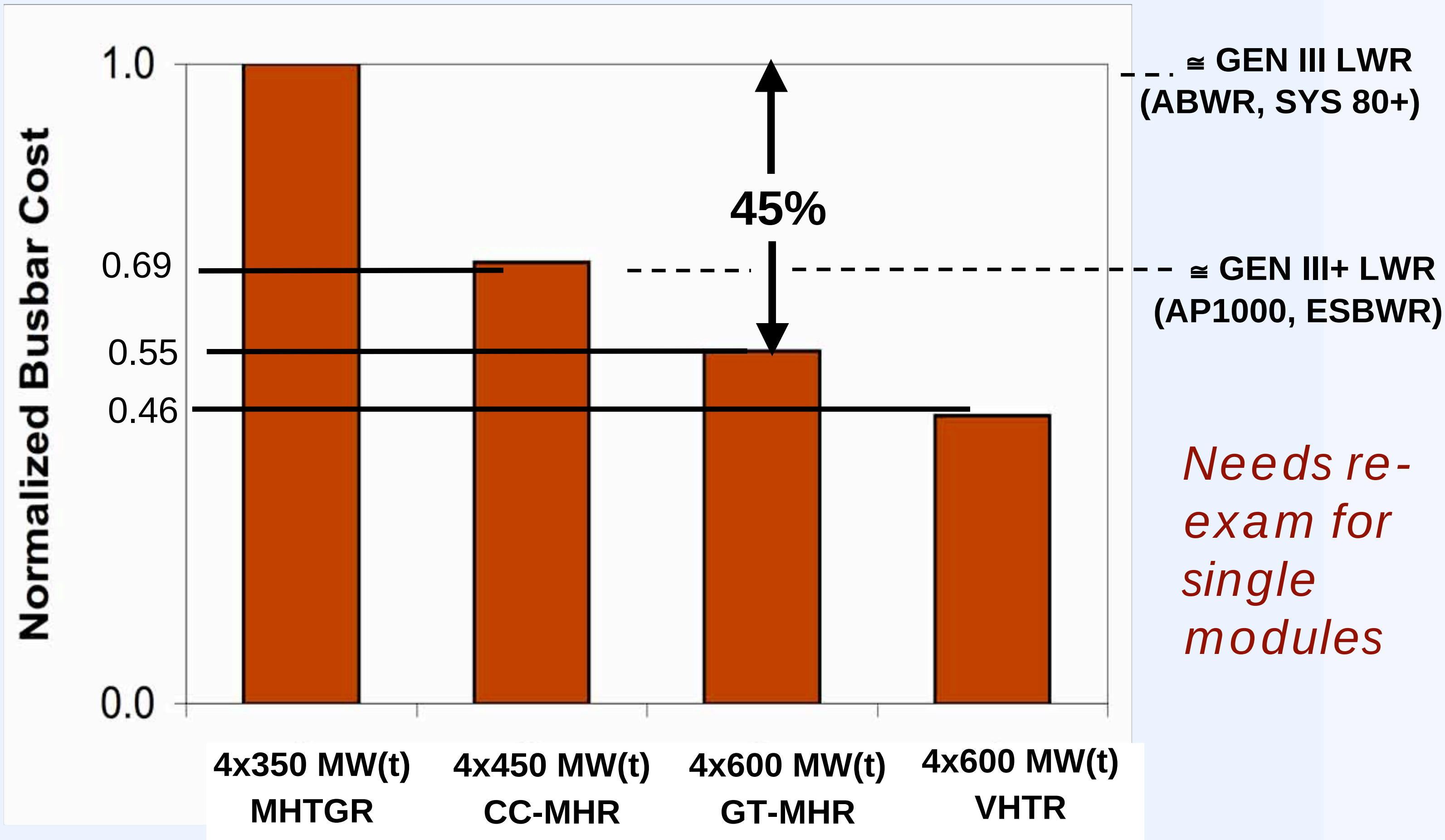
Larger Module Sizes & Advanced Conversion Technologies Reduce NOAK Electricity Costs

All ~1000 MWe installations



Efficiency	39%	48%	48%	58%

Needs re-exam for single modules

Gas Reactors Are Well-Suited for Air Cooling

Advantages

- *Less heat/MWe rejection due to higher efficiency*
- *Larger ΔT is available for heat rejection*
- *Heat is rejected over a range of temperatures*
- *Reduction in efficiency is smaller for higher heat rejection temperature*
- *Efficiency is nearly restored with small water cooling, which can be applied to desalination or district heating*

Disadvantages

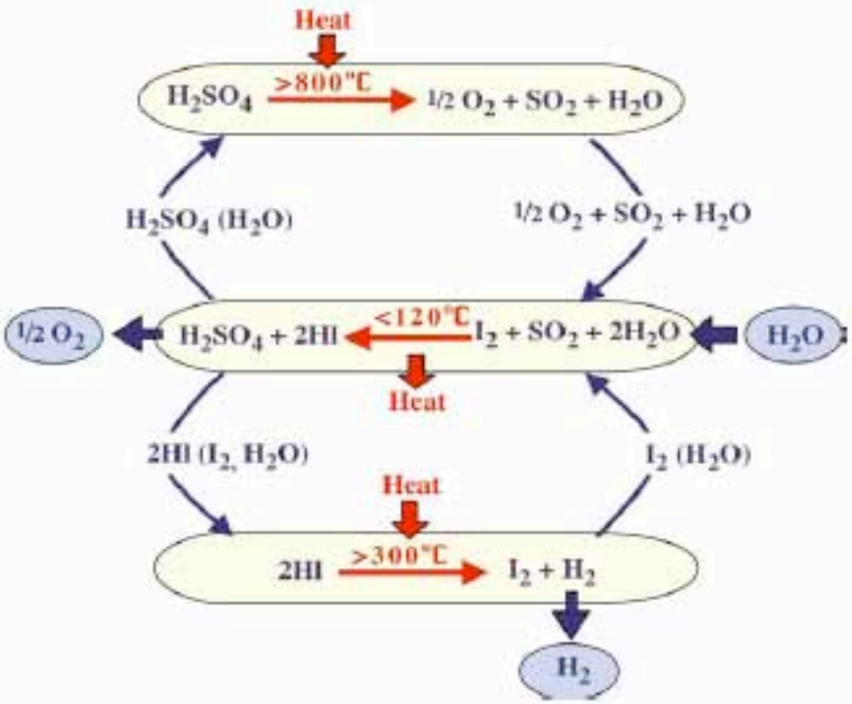
- *Either fan power or cooling-tower cost*
- *Modestly reduced efficiency*
- *Noise pollution*

Economic optimum looks like a mix of wet and dry cooling, depending on electricity and water costs

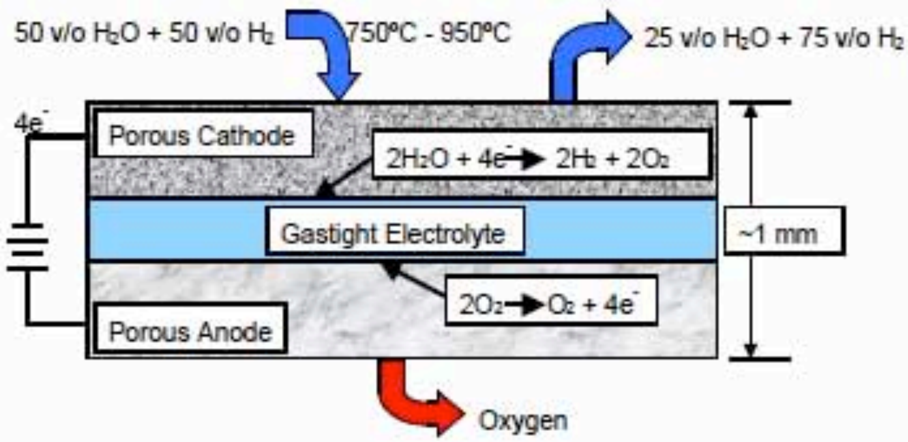
As Efficiency Increases, Normal Electrolysis Becomes Increasingly Attractive for H_2 Production

- **Well-established technology**
- **Operational flexibility**
- **Amenable to co-generation (day-night)**
- **Permits separation of facilities**

Nonetheless, High-T is Well-Suited for Centralized H_2 Production by S-I or HTE



Sulfur-Iodine (S-I)
Thermochemical Process



High Temperature Electrolysis
(HTE) Process

Both very much in the R&D stage

Could a Thermal MHR Reactor Burn Transuranics (TRU)? . . . Yes, Using Unique Features of the MHR

No void reactivity transients

- Fixed Graphite Moderator
- He coolant transparent to neutrons

  ⇨ Pure TRU or LEU-boosted cores

Good neutron utilization

- Low interaction with fuel containment & low radiation damage
- High probability of interaction with fuel content (kernel)

  ⇨ Large specific destruction rates

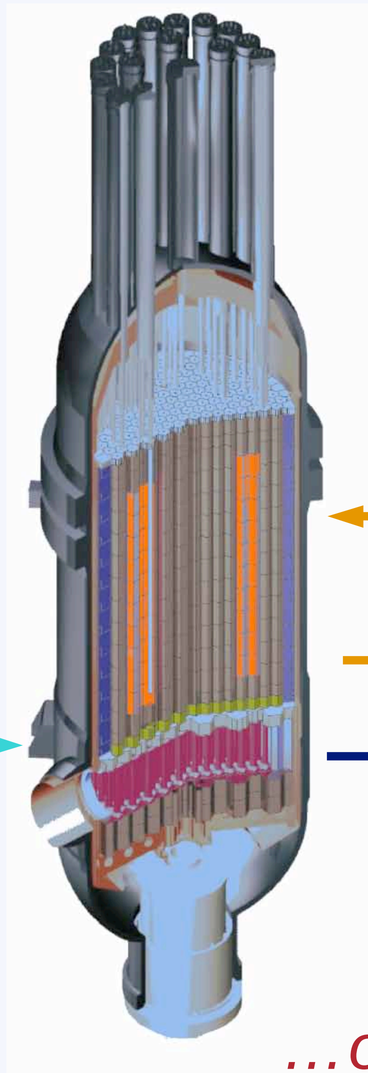
TRISO

Full containment to high burn-up

- Small-scale, encapsulated fuel with strong, long-lived enclosure
- High burn-up without multiple fuel re-cycling ⇨ >60% fuel utilization

Flexibility of MHRs Provides Both LWR TRU Destruction and Steady-State Self-Processing

LEU + Spent Fuel (TRU)



With "Deep Burn," mixed-core MHRs can be used as the base reactor for future sustained nuclear power growth

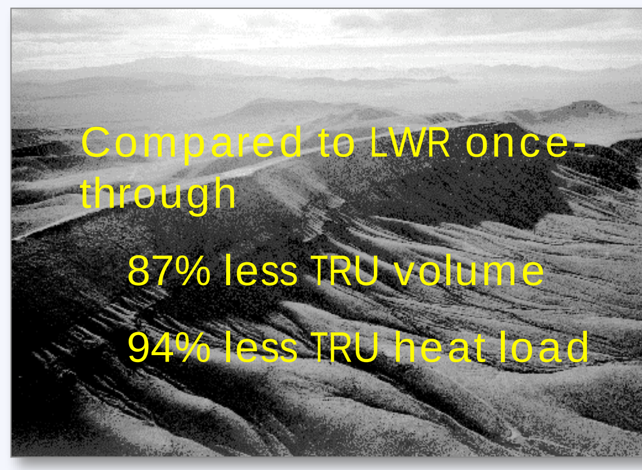
High temperature, high efficiency, passive safety, low waste production, attractive waste-form

Pu, TRU

Single loop

TRISO Process +Refab.

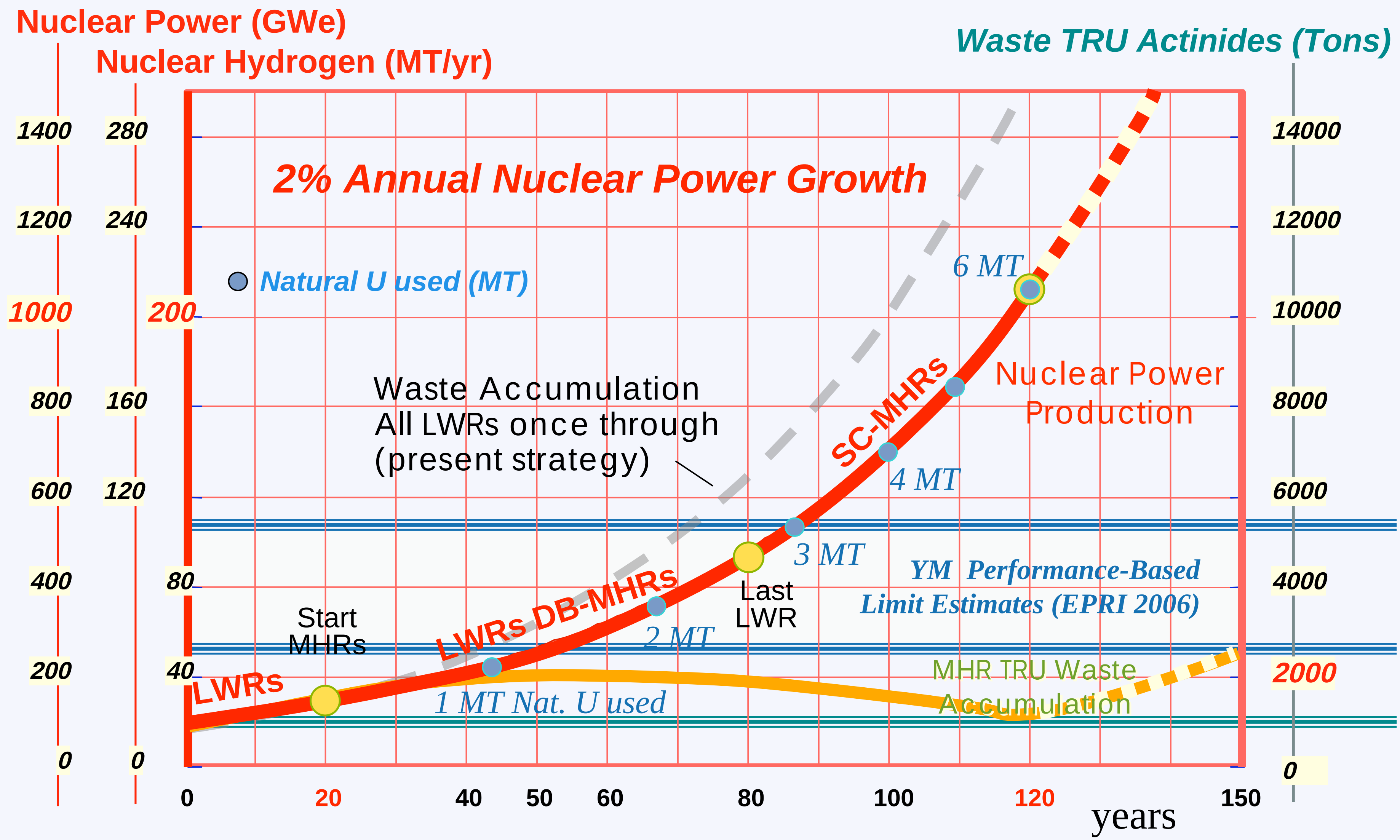
33 kg TRU/GW_e-yr of weapon-unsuitable "Dregs"



Repository limit dominated by short-lived fission products

...or burn "dregs" in fast reactors à la GNEP

Deep Burn MHR Strategy Could Extend U.S. Yucca Mtn. (or equivalent) for ~Century



In Summary, MHRs Go Far Towards Satisfying Multiple Advanced-Reactor Criteria

Gen IV

- Inherent Safety / Security √ √
- Proliferation resistance √
- Fuel-cycle sustainability √
- Competitive COE √ (√)

Additional

- Unit size flexibility / Modularity √ √
- Low water consumption √ √
- Process heat (H_2) √ √
- Manageable spent-fuel form √ √
- Low O&M requirements / Costs √ √

… but We Also Continue to Explore Improvements and New Applications

- Dry cooling
- Desalination
- Extended fueling duration
- TRU destruction
- Size and PCU flexibilities
- Dual-application / co-generation
- Hydrogen production for synfuels, etc.

And we remain open to requirements / suggestions of interested parties

Summary and Conclusions

- The MHR goes far towards satisfying the Gen IV, et al., goals
  - Inherently safe, simple and modular – well suited to small / medium grids
  - Flexible with regard to fuel cycle and type
  - Versatile in its heat applications
  - In its simplest form, ready for deployment today, albeit with a COE penalty relative to more advanced versions

- To meet the MHR's full potential, three issues remain
  - Completion of turbine PCU development
  - Creation of commercial TRISO fuel supply
  - Reactor-scale system demonstration