2011 National Physics Teachers Workshop

The Next Generation Nuclear Plant – Nuclear Beyond the Grid

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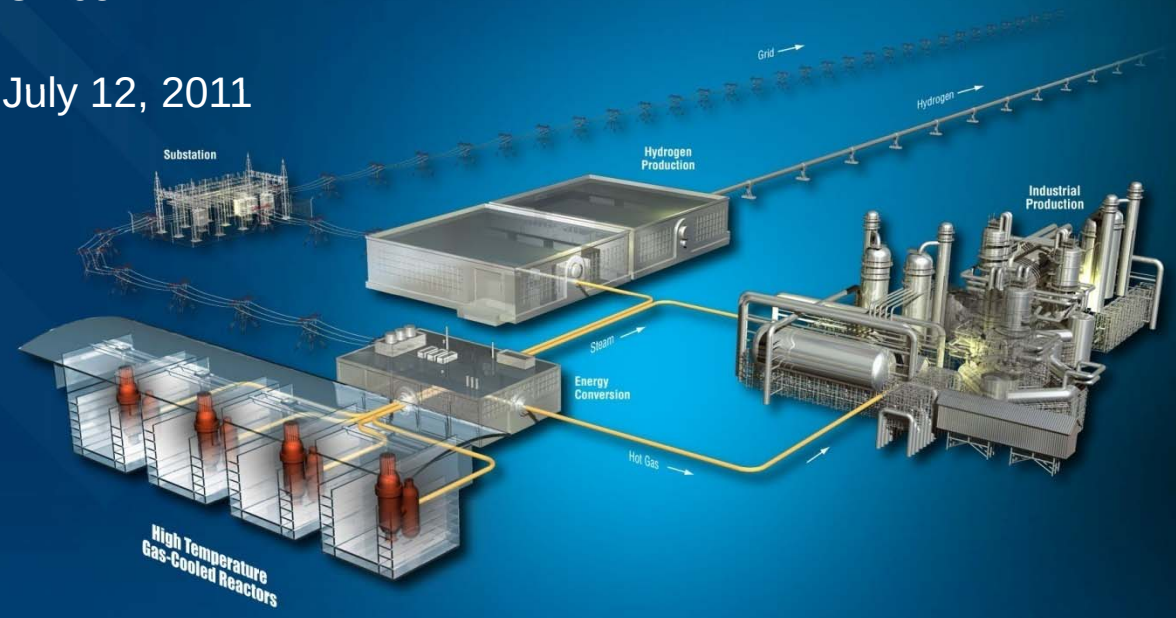

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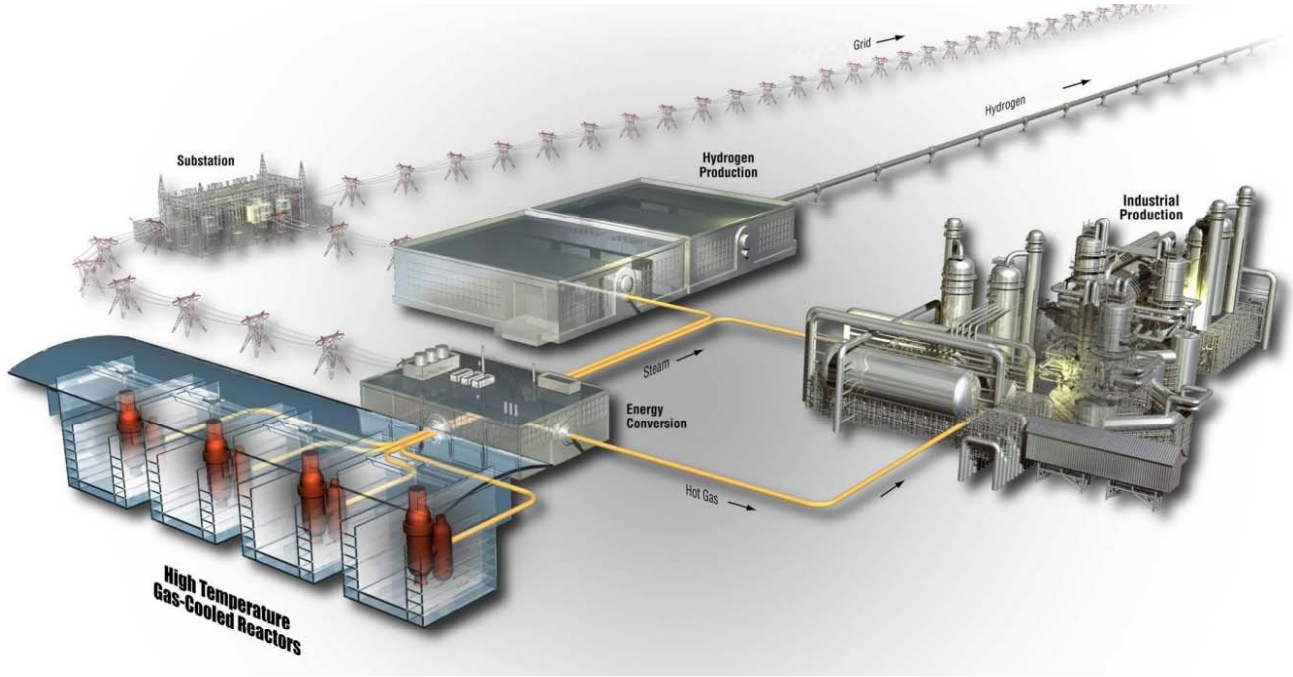
Idaho National Laboratory

Discussion Points

- The Energy Challenge - demand, supply, risks & opportunities
- Role for high temperature gas reactors (HTGR) and potential impact
- Current state and areas of development

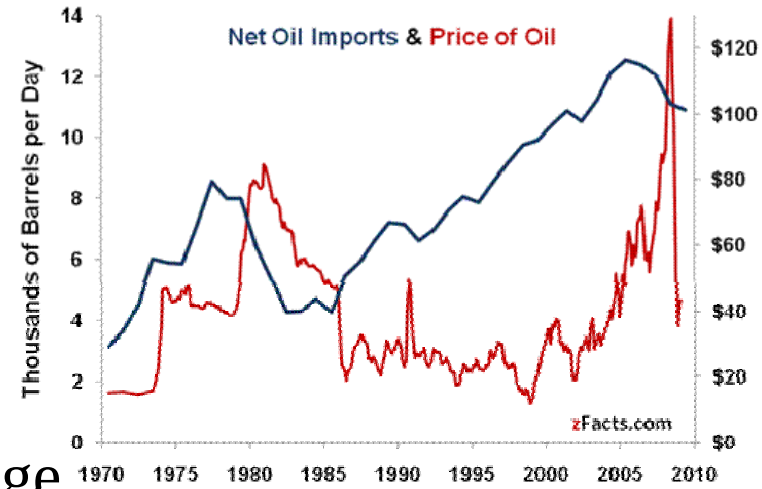


Next Generation Nuclear Plant

Addressing the Energy Challenge…

Dependence upon unfriendly sources

60% of oil used in U.S. is imported

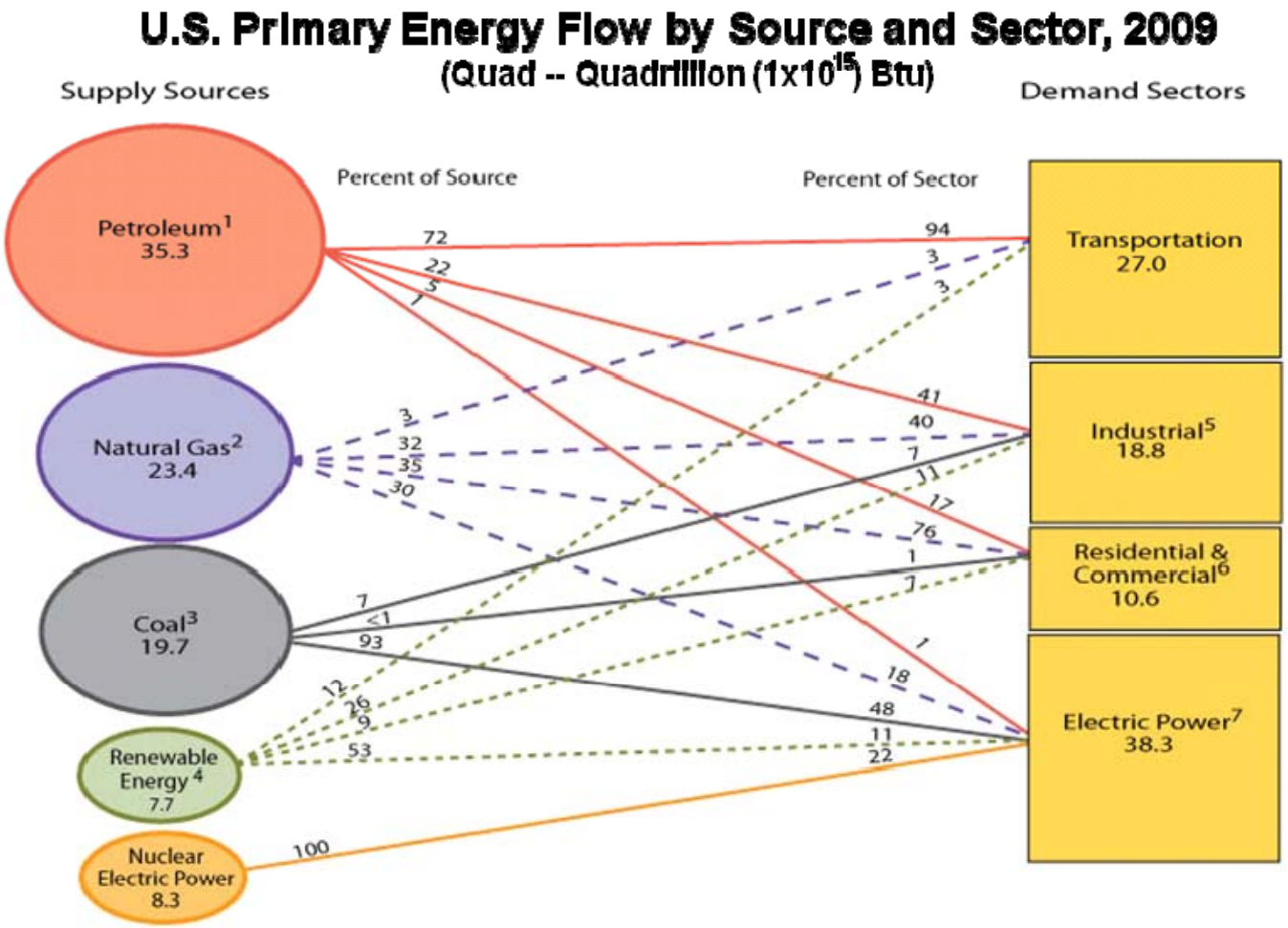


Increased risk of environmental damage from fossil fuel extraction and consumption

Volatile prices for oil and natural gas

Unpredictable tax and regulatory policy

Energy Production and Consumption in U.S. – the Potential Market

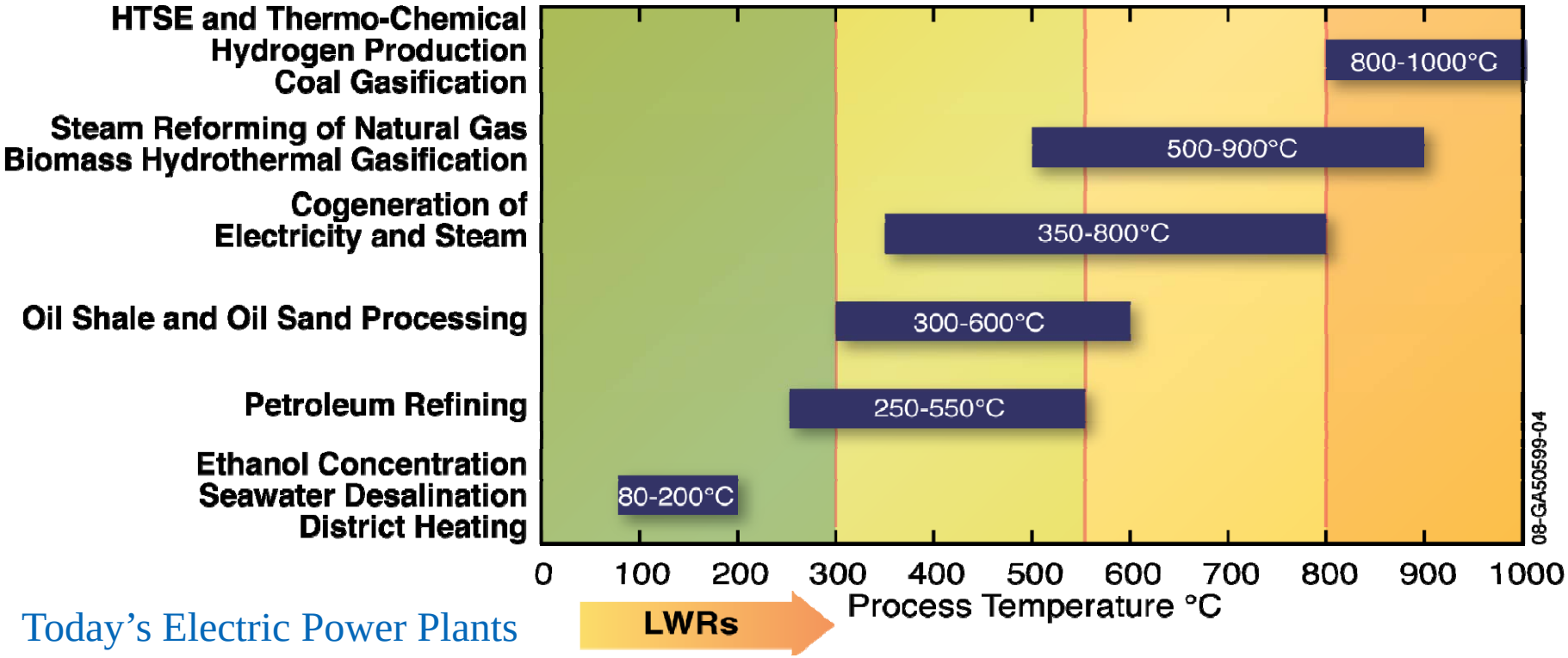


A growth opportunity for nuclear

What nukes supply now with Light Water Reactor (LWR) Technology

NGNP Next Generation Nuclear Plant

Industrial Heat Requirements (or why HTGRs are promising)



Today's Electric Power Plants

Electricity & Industrial Heat

HTGR VHTR

Next Generation Nuclear Plant

Industrial Applications and the number of HTGRs that would be needed to drive them

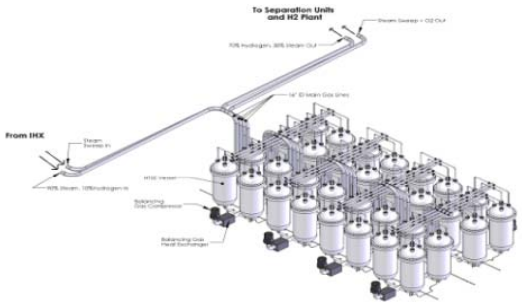
(these processes are driven by heat from fossil fuel combustion

Petrochemical (170 plants in U.S. – 6.7 quads*)

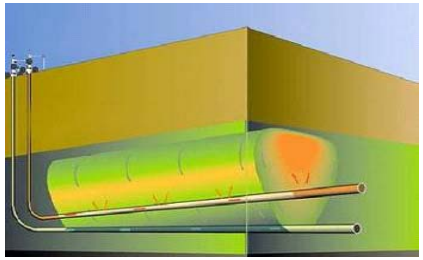
Petroleum Refining (137 plant in U.S. – 3.7 quads)

Fertilizers/Ammonia (23 plants in U.S. – 0.3 quads)

Coal-to-Liquids (24 600 MWt HTGRs for 100,000 bpd new plants)



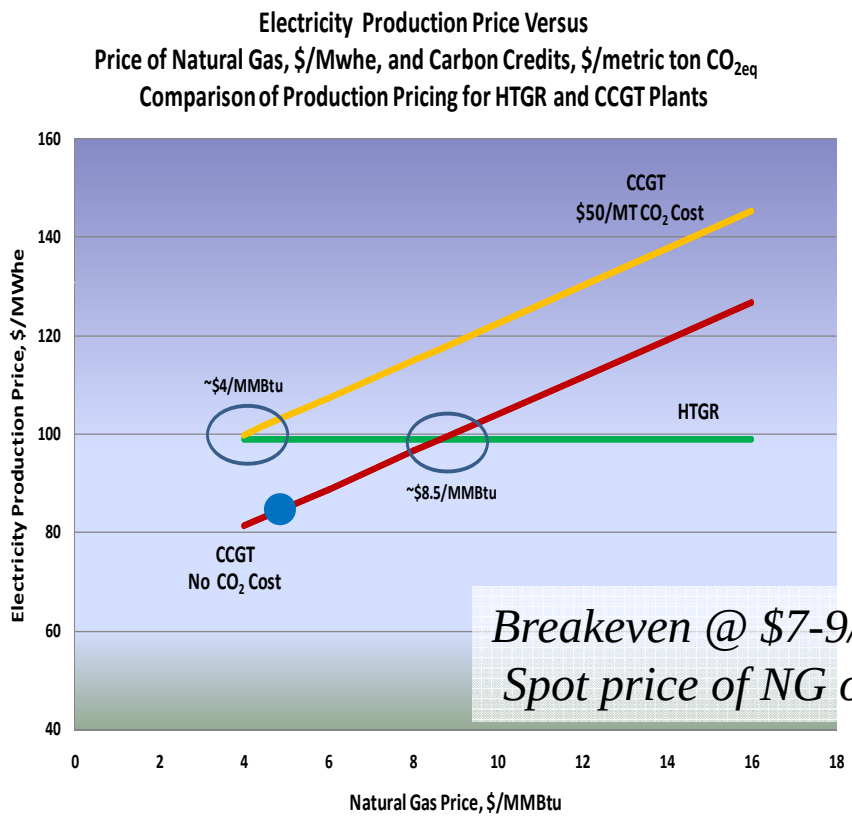
Hydrogen Production (60 – 600 MWt HTGRs)

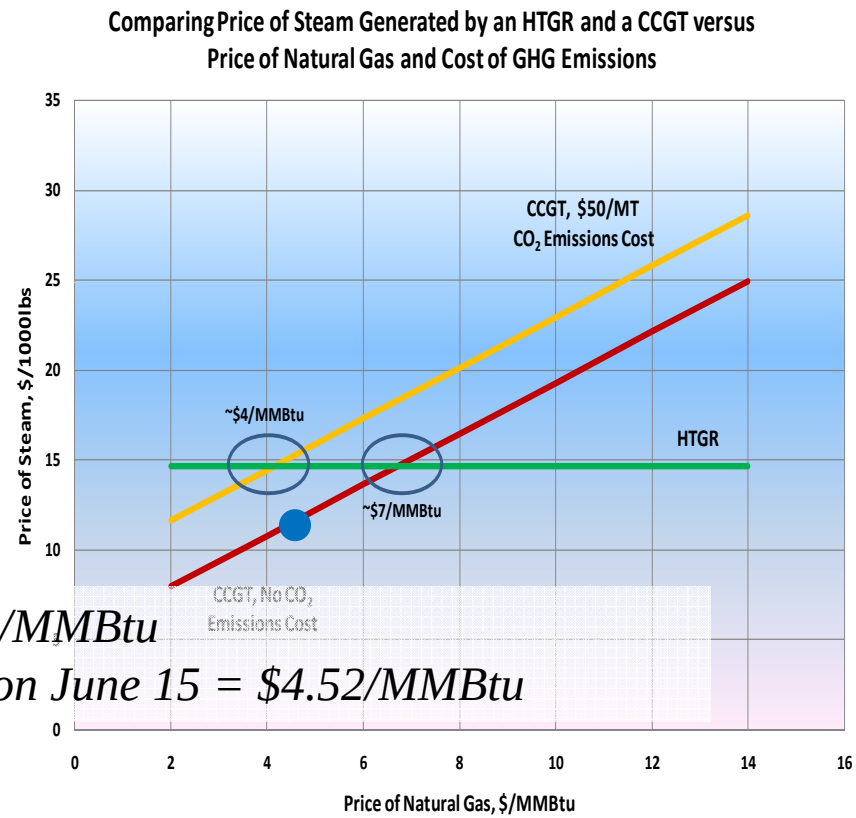


Oil Sands/Shale (43 – 600 MWt HTGRs)

*Quad = 1×10^{15} Btu (293 MM MWth) annual energy consumption

But can they compete?





Breakeven @ $7-9/MMBtu

Spot price of NG on June 15 = $4.52/MMBtu

Next Generation Nuclear Plant

Economic Factors

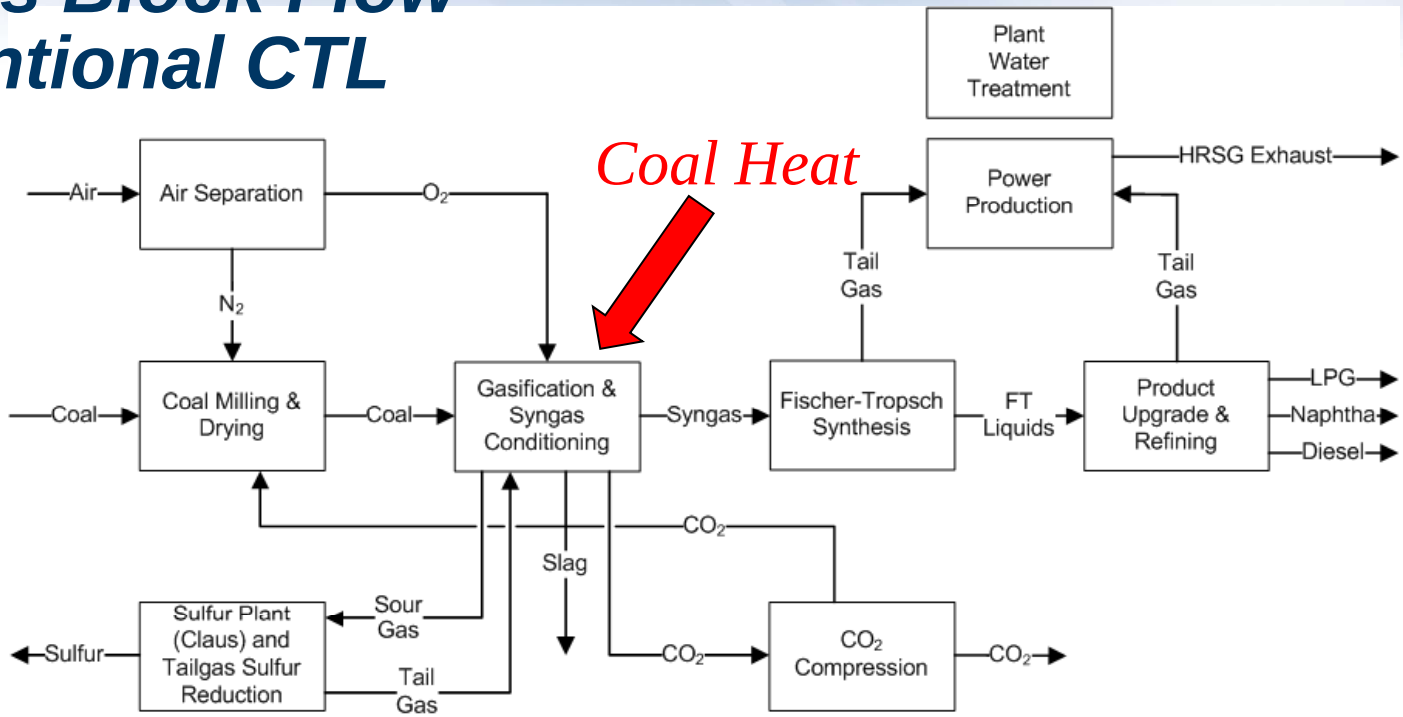
HTGR Plant Capital Cost	$1,700/KWt	Financing Interest	8%
CCGT Capital Cost	$625/KWt	Financing Term	20 years
Debt	80%	Tax Rate	38.9%
Internal Rate of Return	15%		

One possible approach – Nuclear-assisted Coal-to-Liquids Conversion (CTL)

- Fischer-Tropsch CTL process invented in Germany in the 1920's
  (coal-rich, oil-poor)
- Used in Germany and Japan during WWII
  (9% of war fuel, 25% of auto fuel)
- Used in South Africa since 1955
  (~30% of transportation fuel comes from coal)

Sasolburg CTL Plant (and world's largest single point source of CO_2)

Process Block Flow – Conventional CTL



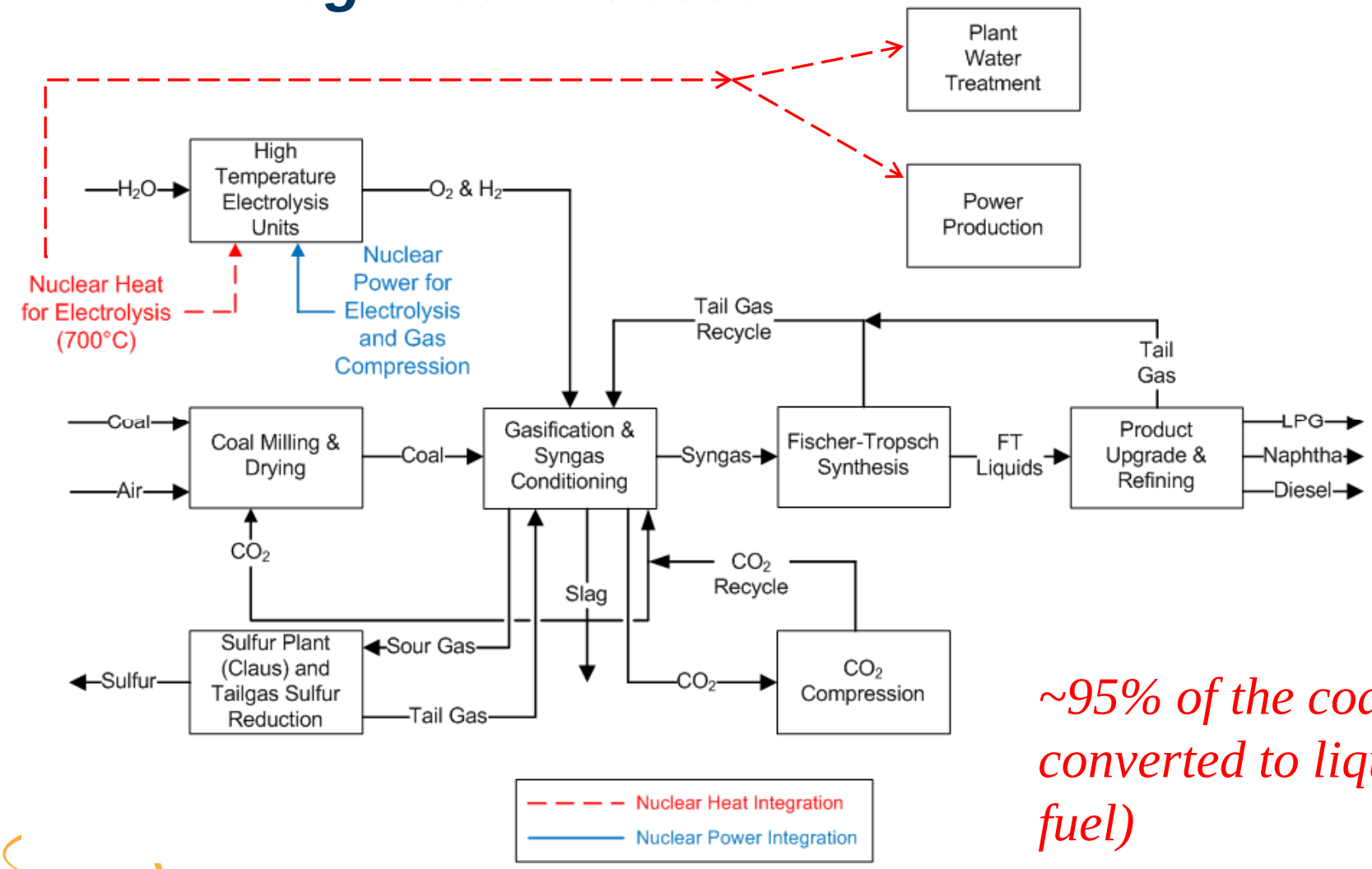
~30% of the coal is converted to liquid fuel (the rest to CO_2)

Steps of Conventional* Synthetic Fuels Production

1. Syngas (CO and H_2)
Coal — Gasification (steam + oxygen + coal)
2. Synthesis (from CO and H_2)
Fischer-Tropsch reaction produces long chained hydrocarbons
3. Traditional Refining
50,000 barrels per day of diesel, naptha, and liquefied petroleum gas

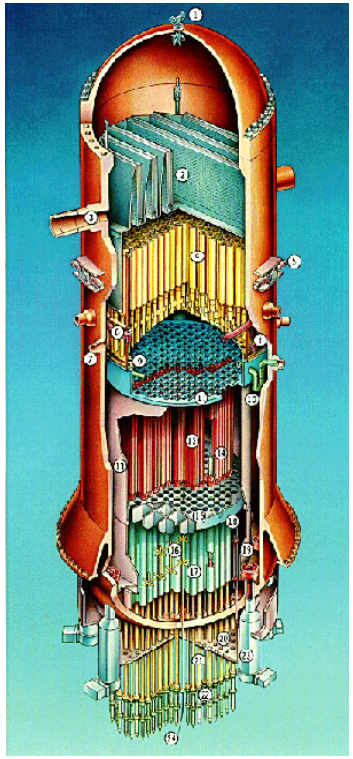
*Commercial installations in South Africa and China, but not in U.S.

Process Block Flow Diagram - HTGR-Integrated Process

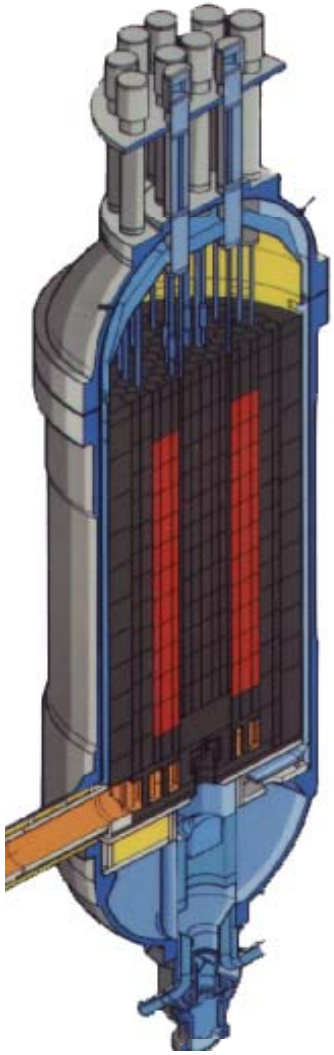


~95% of the coal is converted to liquid fuel)

Let's look at the Technology
LWRs vs HTGRs – Key differences



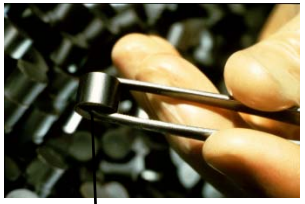
Neutron Moderator	Water	Graphite
Coolant	Water	Helium
Pressure (MPa)	15.5	7-9
Inlet/Outlet Temperature (C)	290/325	350/750
Typical Thermal Power(MW)	3000	300-600



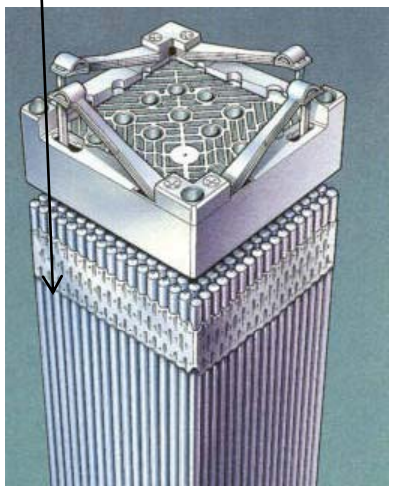
Next Generation Nuclear Plant

LWR safety

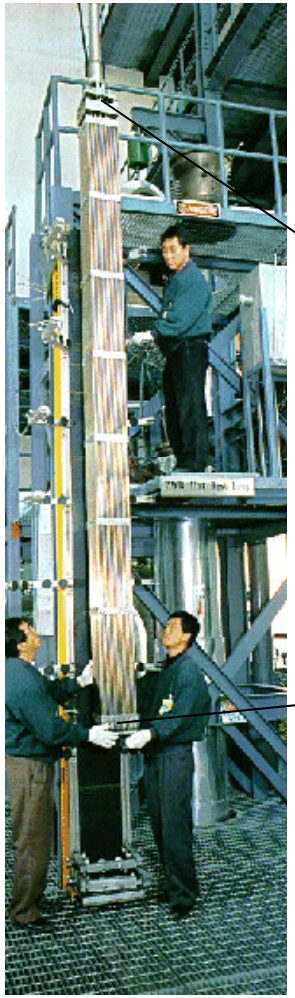
Among other limits, the cladding must be kept below ~1200C to prevent fuel damage, i.e. the rods must always be covered with water → active and redundant safety systems

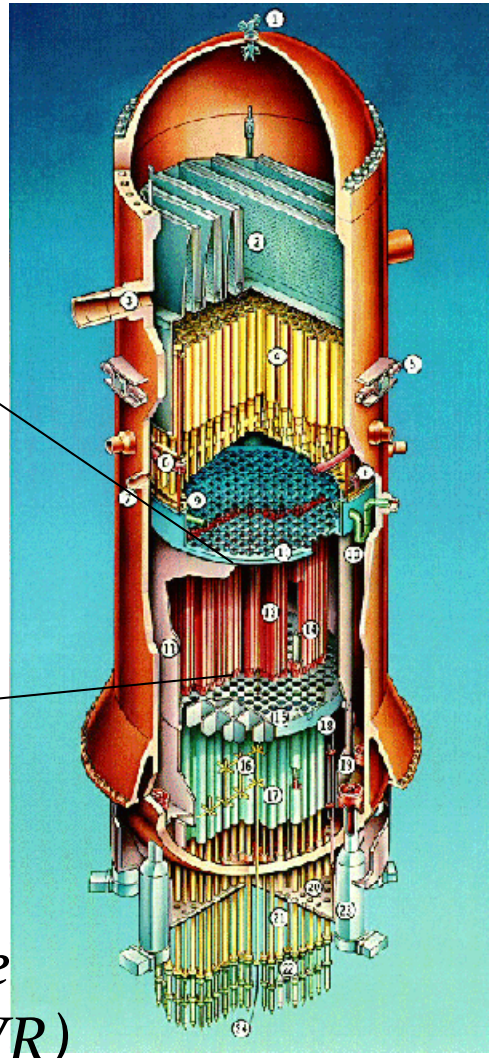


UO_2 pellet



Assembly

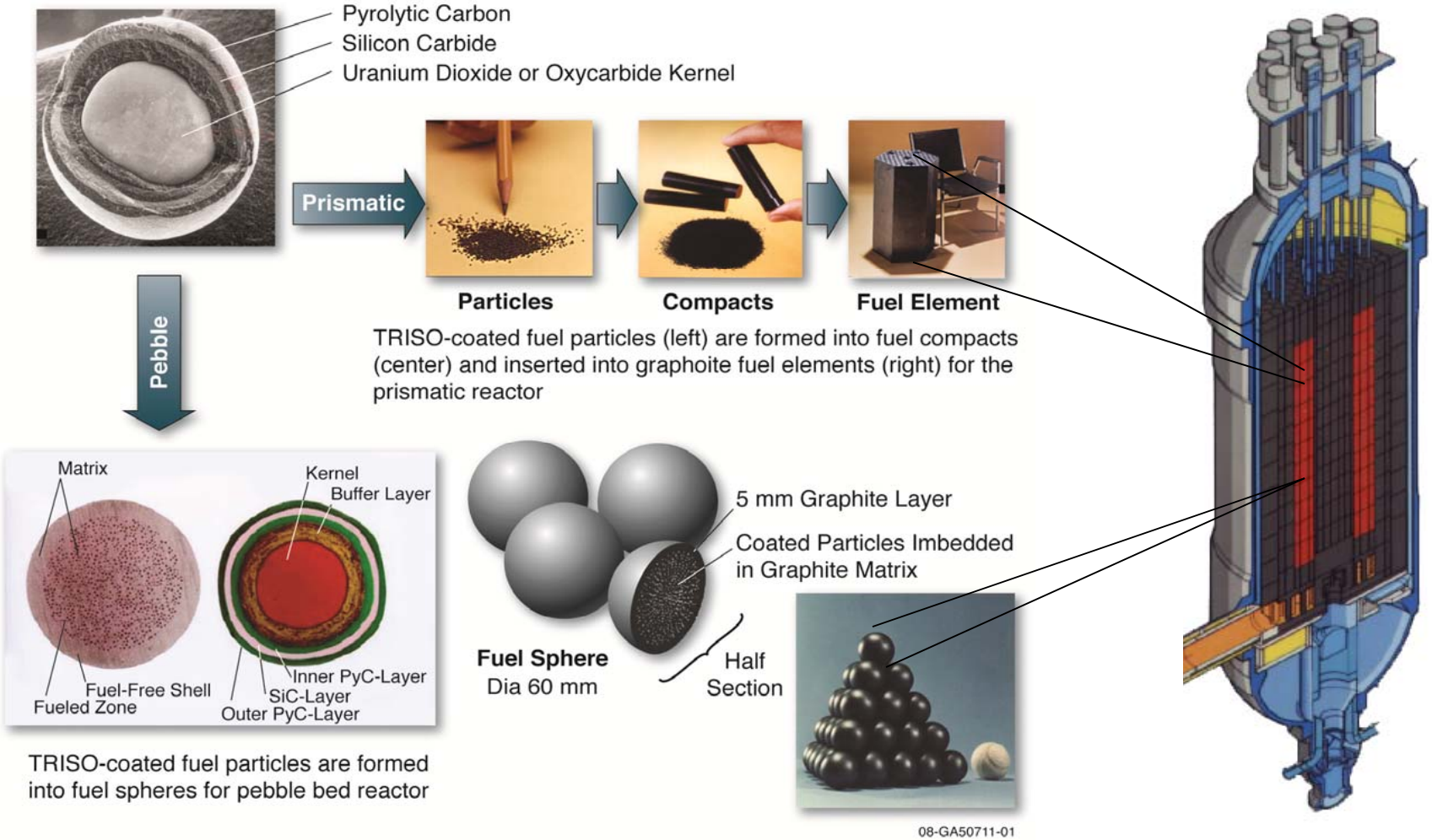




Core (BWR)

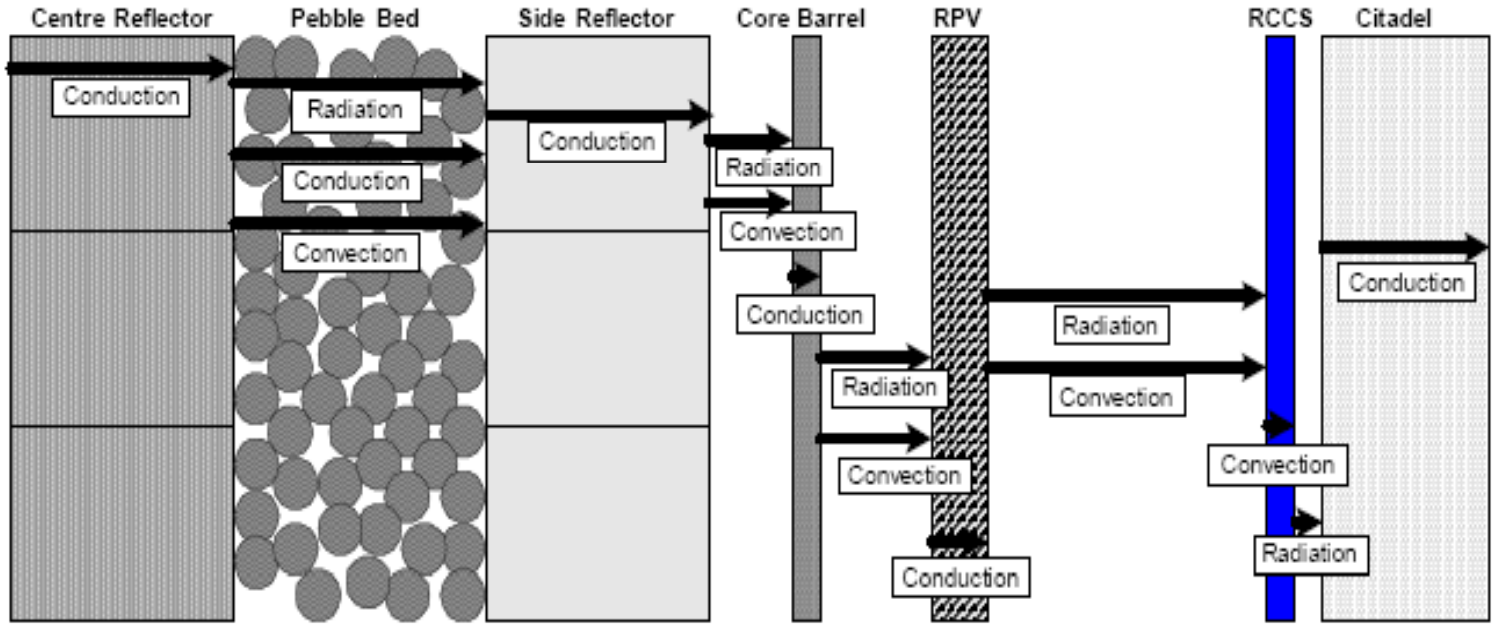
HTGR safety

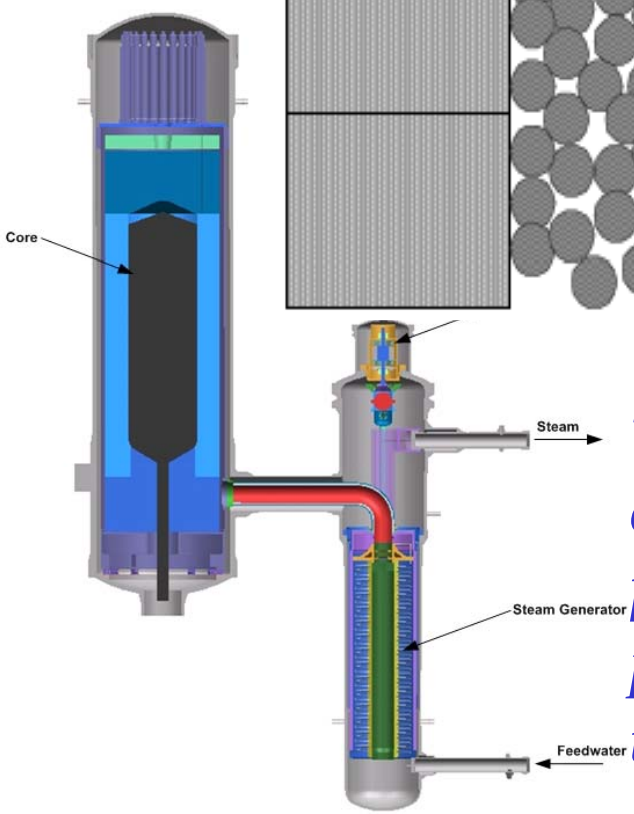
Ceramic fuel particles are encased in pyrolytic carbon layers that maintain integrity at temperatures in excess of 1600°C.



Next Generation Nuclear Plant

The Other Key to Safety – Core Design





Tall, thin graphite core with low power density enables decay heat to be removed from the core at a sufficiently high rate to prevent fuel from reaching failure temperature.

Wasn't Chernobyl a graphite-moderated reactor?
(and Windscale too!)

From the Wikipedia entry on Chernobyl "A sudden power output surge took place, and when an attempt was made at an emergency shutdown, a more extreme spike in power output occurred which led to the rupture of a reactor vessel as well as a series of explosions. This event exposed the graphite moderator components of the reactor to air and they ignited; the resulting fire sent a plume of radioactive fallout into the atmosphere …."

- What burned in Chernobyl and Windscale was the metal (cladding around the fueled pressure tubes or uranium fuel itself)
- Graphite oxidizes slowly but is very difficult to burn (Some Type D Fire Extinguishers use graphite. Finely powdered graphite is preferred for fires in fine powders of reactive metals, particularly at high temperature. Graphite both smothers the fire and conducts away heat.)

Graphite electrodes are used for making steel from iron ore

Next Generation Nuclear Plant

HTGR Technology is neither new ….

Demonstration Plants

FORT ST. VRAIN – 842 MWt
(U.S.A.)
1976 - 1989

THTR – 750 MWt
(FRG)
1986 - 1989

Prototype Plants

HTTR – 30 MWt
(Japan)
1999 - present

HTR-10 – 10 MWt
(China)
2000 - present

DRAGON – 20 MWt
(U.K.)
1964 – 1975

AVR – 46 MWt
(FRG)
1967 - 1988

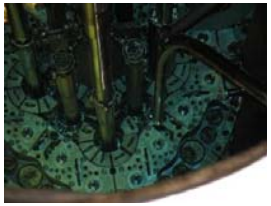
PEACH BOTTOM 1 – 115 MWt
(U.S.A.)
1967 - 1974

Next Generation Nuclear Plant

… nor mature; some development is needed.

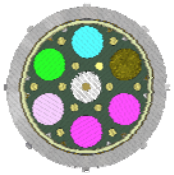
NGNP Technology Development and Qualification Needs

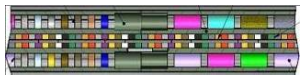
High Temperature Materials Characterization, Testing and Codification



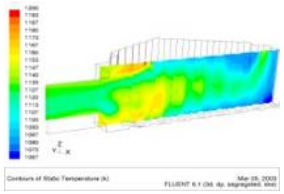
Fuel Fabrication, Irradiation, and Safety Testing

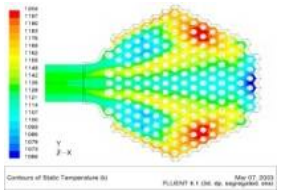
Graphite Characterization, Irradiation Testing, Modeling and Codification





Design and Safety Methods Development and Validation

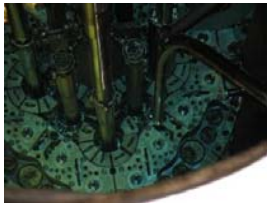




Next Generation Nuclear Plant

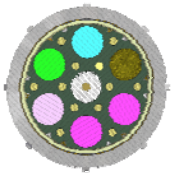
Major NGNP Technology Development and Qualification Needs

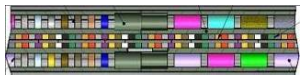
High Temperature Materials Characterization, Testing and Codification



Fuel Fabrication, Irradiation, and Safety Testing

Graphite Characterization, Irradiation Testing, Modeling and Codification





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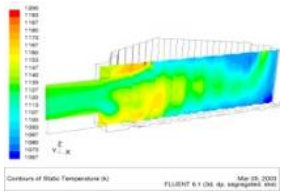
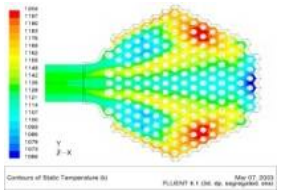
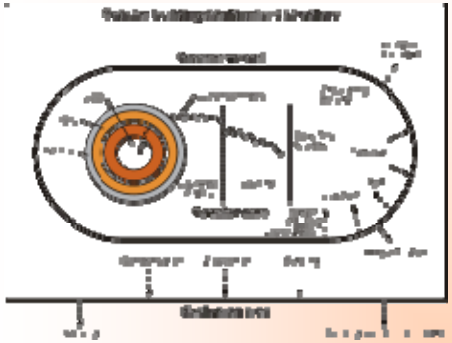


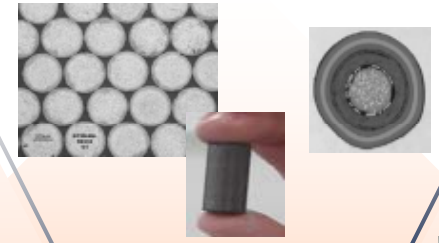


Next Generation Nuclear Plant

NGNP/AGR Fuel Program Elements



Fission Product Transport and Source Term

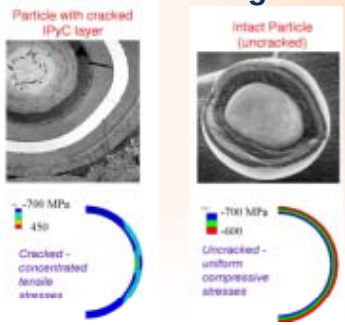


Fuel Supply

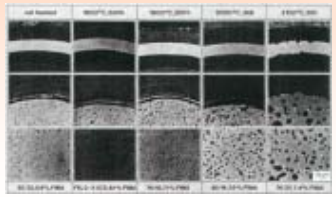
Fuel and Materials Irradiation

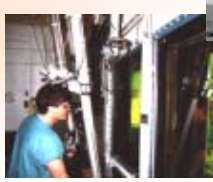
- Coated Particle Fuel Fabrication
- Fuel Qualification
- Analysis Methods Development and Validation

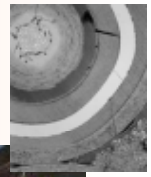
Fuel Performance Modeling



Post Irradiation Examination and Safety Testing



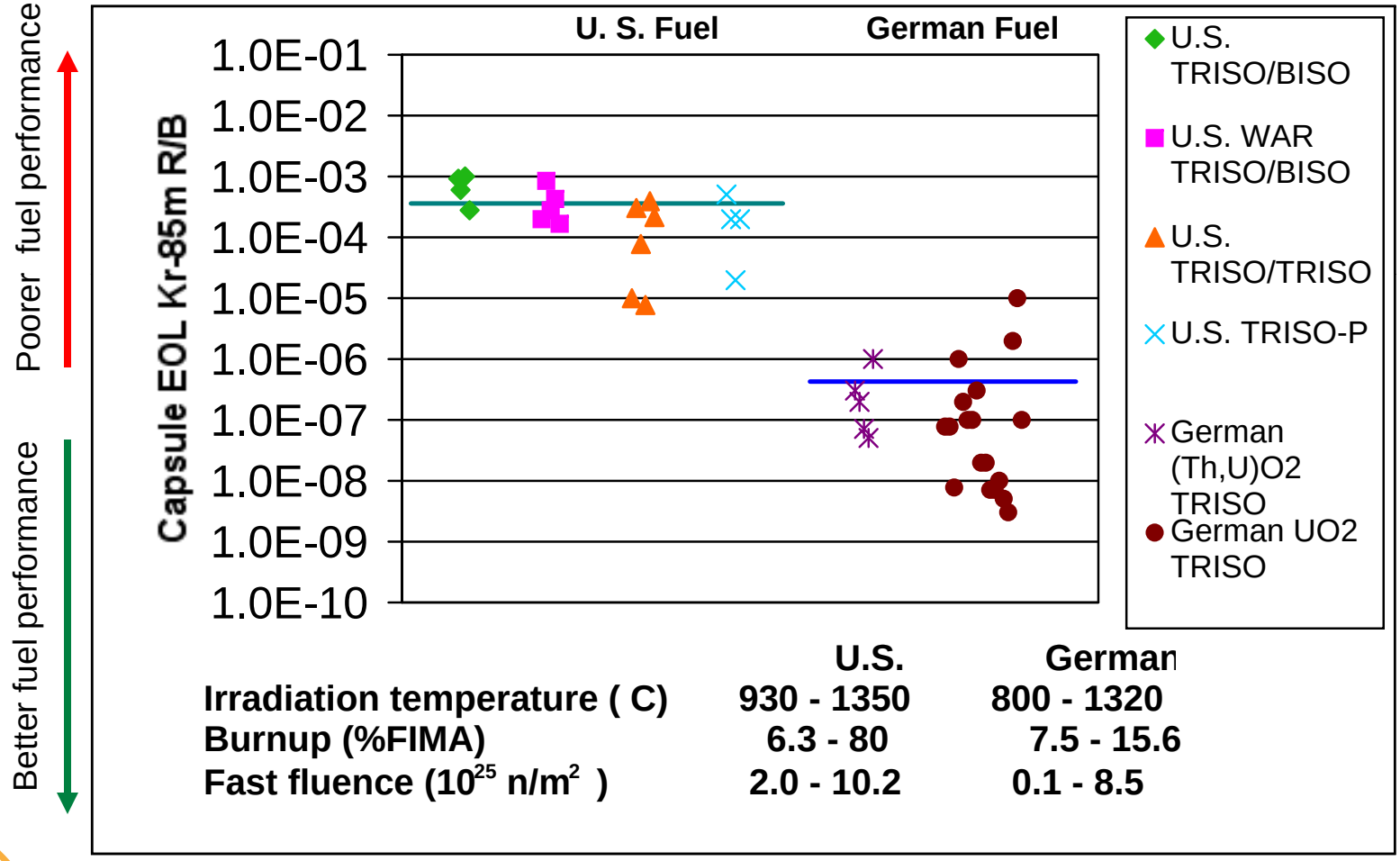




Program Participants INL, ORNL, B&W, GA

NGNP Next Generation Nuclear Plant

German Fuel has historically demonstrated 1000x better performance than US fuel. Art or Science?



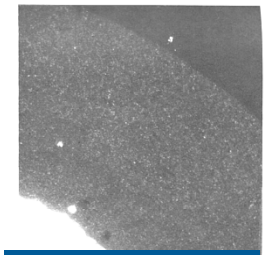
	U.S.	German
Irradiation temperature (C)	930 - 1350	800 - 1320
Burnup (%FIMA)	6.3 - 80	7.5 - 15.6
Fast fluence (10^{25} n/m^2)	2.0 - 10.2	0.1 - 8.5

Only German fuel performed adequately

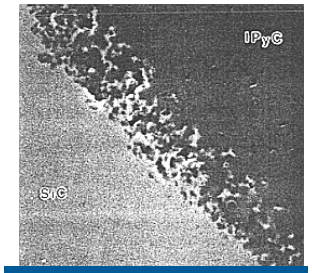
Detailed evaluation of German and US fuel fabrication processes and revealed important differences that impact performance

- Coating rate used to make PyC (affects permeability and anisotropy of layer; US is low which reduces permeability and increases anisotropy; German is high which reduces anisotropy and increases permeability)
- Nature of the coating process. US used interrupted coating. Germans used uninterrupted coating. Interrupted coating and tabling led to metallic inclusions (from the tabling screens) in the SiC layer creating weak particles
- Nature of the interface between SiC and IPyC (German fingered interface is strong and US is weak which causes debonding)
- Microstructure of SiC (German is small grained and US is large columnar grained; difference is largely due to temperature used during SiC coating step)
- US fuel had significant iron contamination of compact matrix which attacked the SiC and caused failures

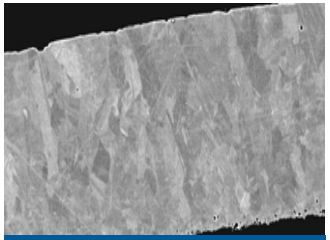
German



Isotropic PyC

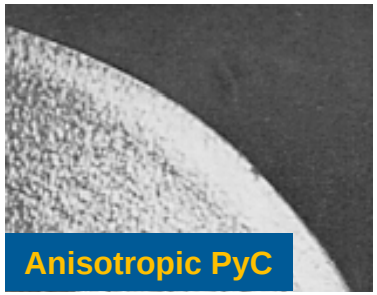


Strong interface

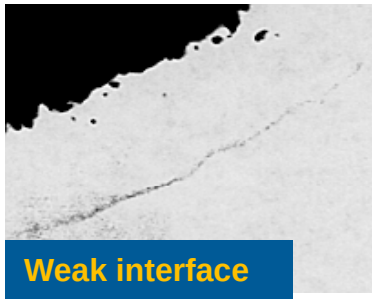


Small grained SiC

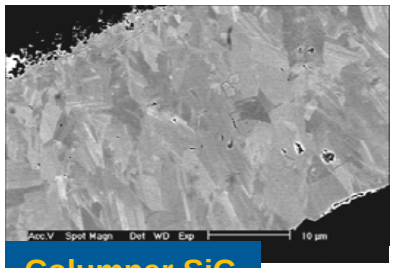
US



Anisotropic PyC



Weak interface

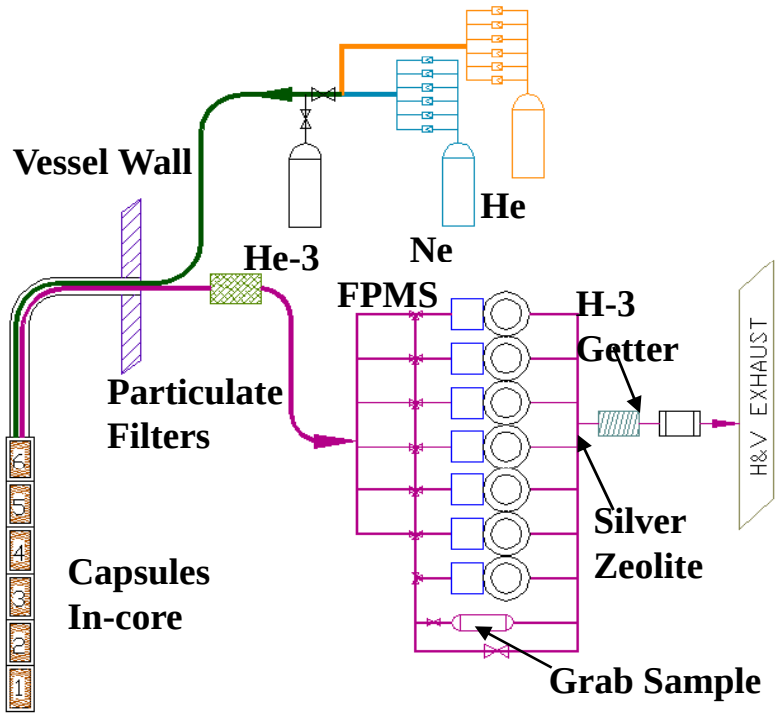


Columnar SiC

It was science and not art!

Under the NGNP fuel development program, the US has demonstrated outstanding performance

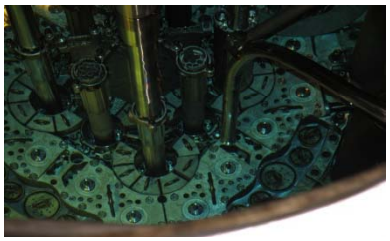
- First irradiation test completed in 2009
- Goal burnup ~ 18-19% FIMA (LWR fuel typically is burned to 5% FIMA)
- T_{max} < 1250°C, T_{avg} ~ 1150°C
- Fast fluence < 5×10^{25} n/m^2
- *No failures out of 300,000 particles*



Individual capsule assembly with fuel compacts

Completed Test Train

Insertion into INL ATR

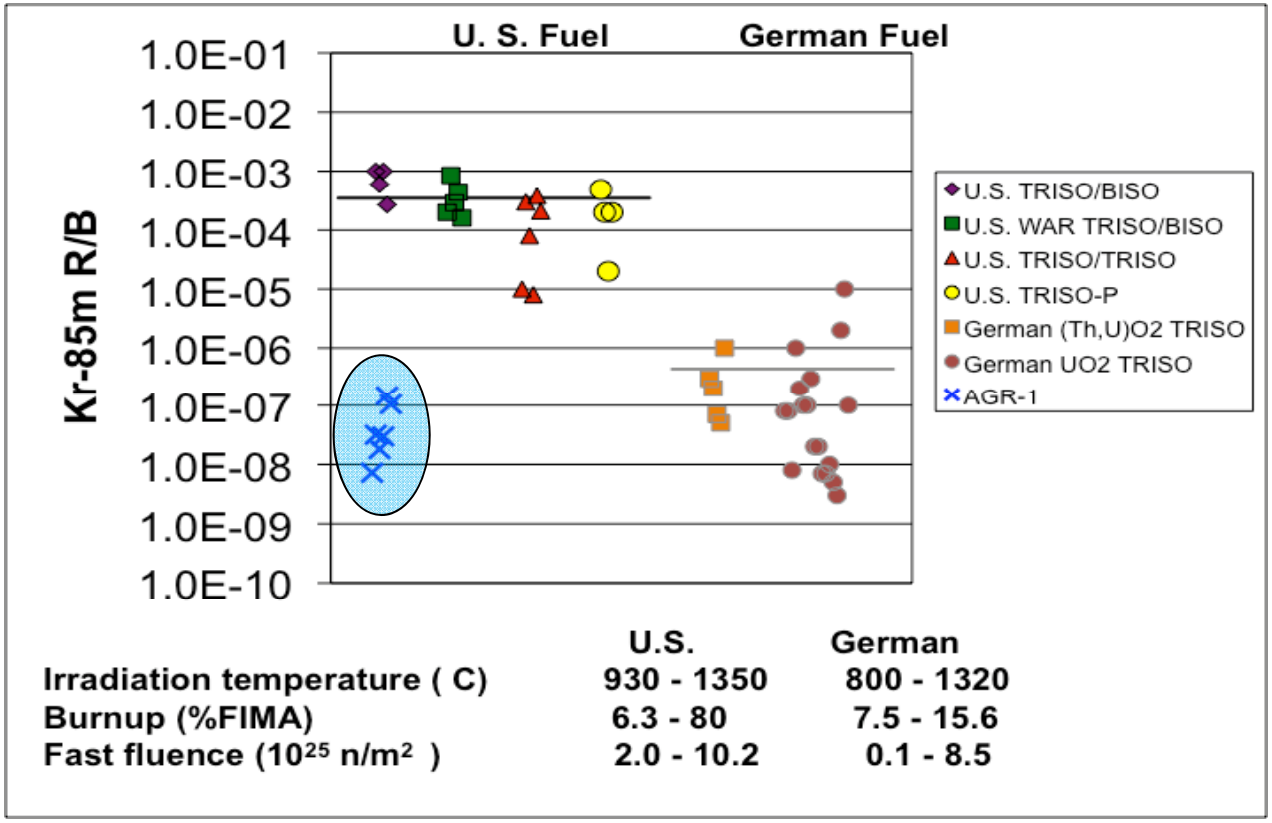


FPMS System

Next Generation Nuclear Plant

NGNP Fuel Performance

First test results show zero defects at twice the burnup attained in German fuel



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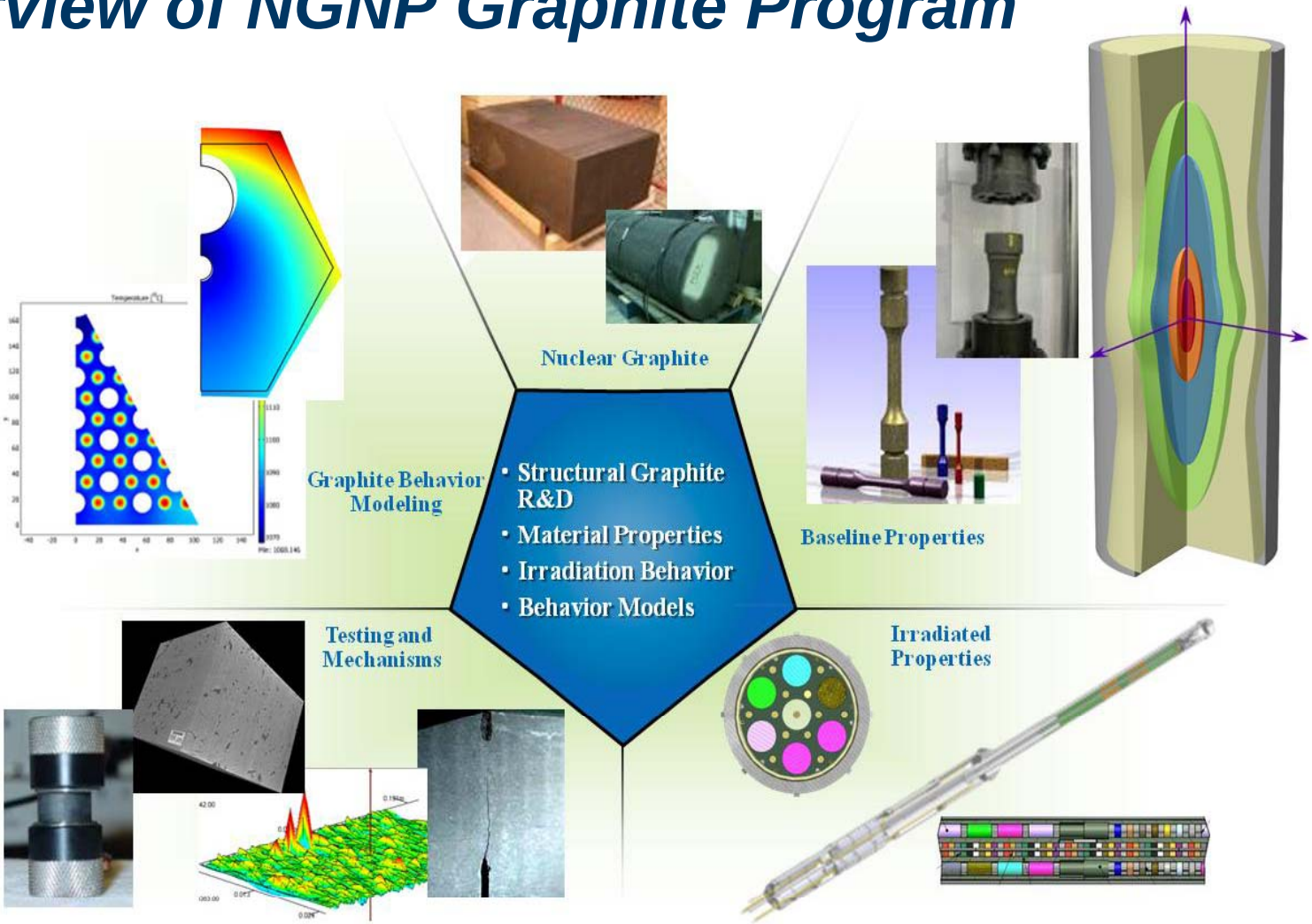
Fast fluence (10^{25} n/m^2)	2.0 - 10.2	0.1 - 8.5

Better fuel performance

Next Generation Nuclear Plant

Overview of NGNP Graphite Program



NGNP Next Generation Nuclear Plant

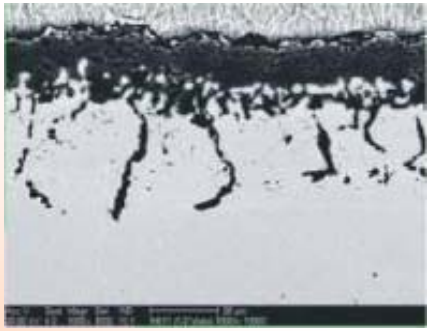
Goal: To characterize and qualify new grades of nuclear graphite for HTGR operation

Overview of NGNP High Temperature Materials Program

Development of Material Properties and Design Rules

and

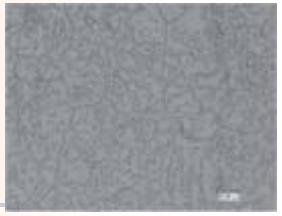
ASME Codification



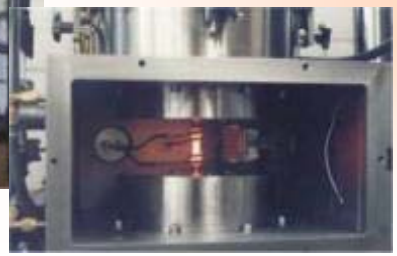
Materials:

- Pressure vessel steels
- Alloys for heat exchangers (up to 800°C)
- Control rod sleeves and other core internals

Material Characterization



Mechanical Testing

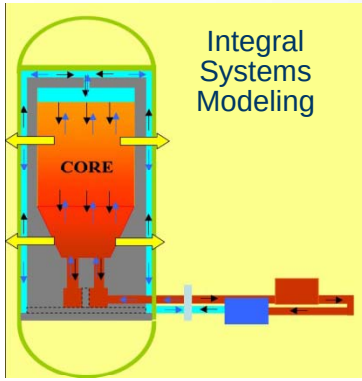


Environmental Testing

NGNP Next Generation Nuclear Plant

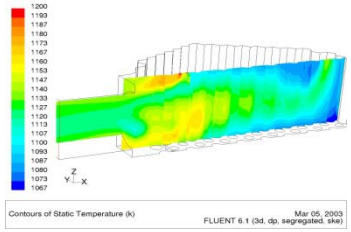
Goal: To qualify alloys for high temperature operation (pressure vessel, control rod sleeves, heat exchangers, etc.)

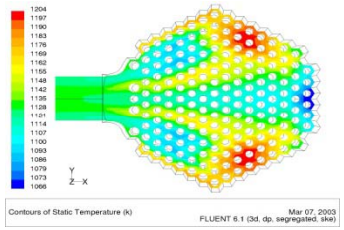
NGNP Methods Program Elements



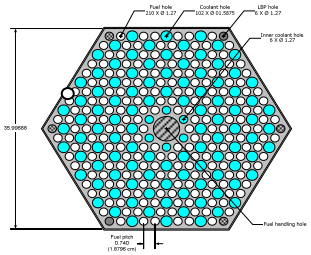
Integral Systems Modeling

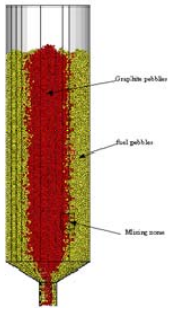
Multi-dimensional CFD Simulations





Pebble bed and Prismatic Neutronics





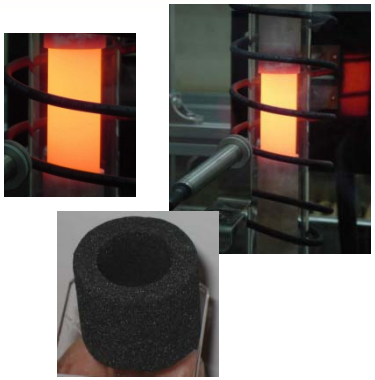
Physics, Thermal and System Safety Methods, Code Development and Application

Design Methods and Validation

Separate Effects and Integral Testing Under Normal and Off-Normal Conditions

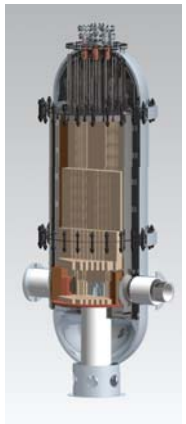
ANL Facility to Validate HTGR Cavity Cooling System Behavior

INL's Matched Index of Refraction Facility to Study 3-D Flow Effects



Graphite/Air Reaction Rate Testing

Scaled Vessel Testing

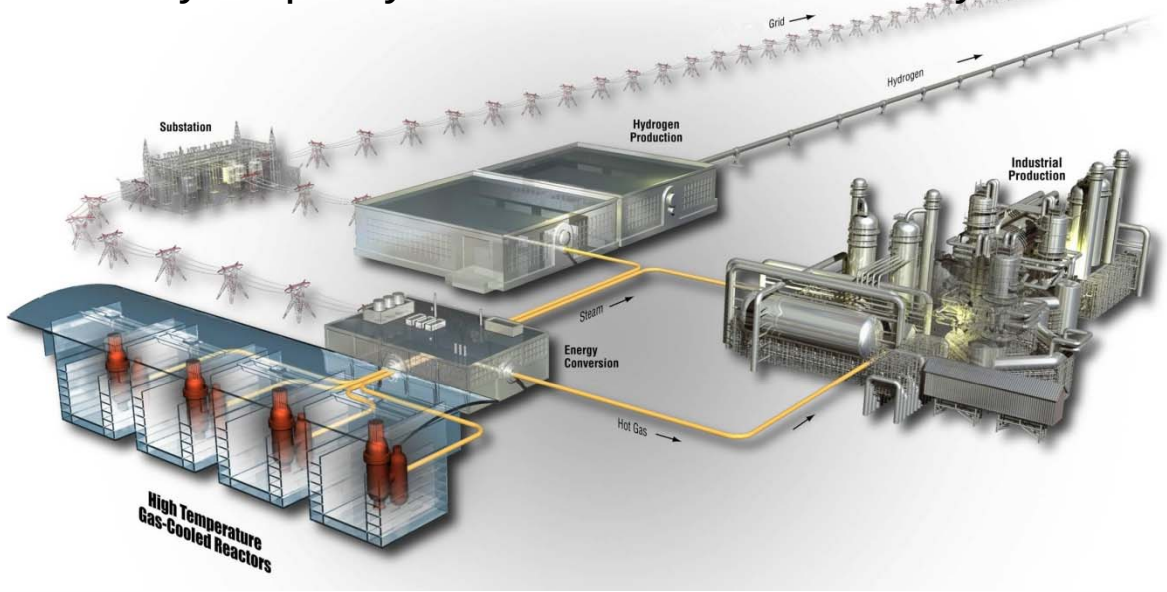


NGNP Next Generation Nuclear Plant

Goal: To develop and qualify core and plant analysis techniques to support design and licensing

Points to take away

- Volatile energy and feedstock prices (natural gas and petroleum) to the energy end-users – are currently passed through to the consumer
- The HTGR is the nuclear energy option to displace the use of petroleum for industrial process heat and reduce dependence on imported supplies
- HTGR fuel and core designs preclude core meltdown and eliminate the need for active core cooling systems
- The Next Generation Nuclear Plant Project is a partnership between the US Government and the energy industry (suppliers and users) with a goal to demonstrate commercial operation in the early 2020's
- Technology development is underway to qualify fuels, materials, and analysis methods



Next Generation Nuclear Plant

Thank you

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