High-Temperature Reactors

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Russian Delegation Visit to ORNL

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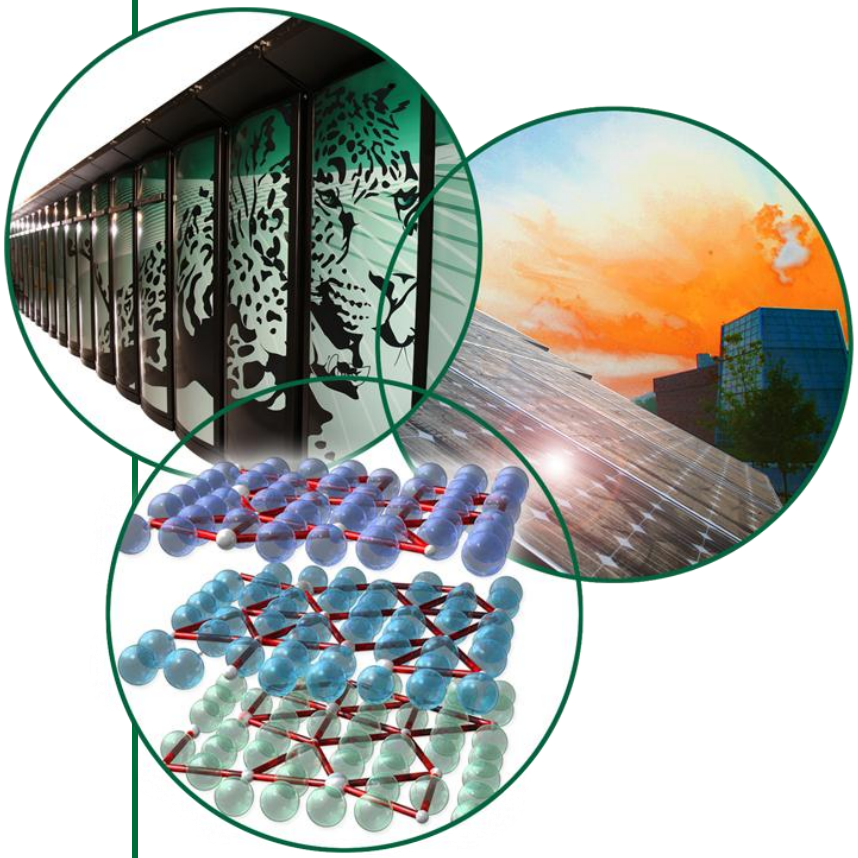

U.S. DEPARTMENT OF ENERGY

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Outline

- ORNL's role in High Temperature Gas-cooled Reactor (HTGR) technology programs
- Modular HTGRs background: how they differ from light-water reactors (LWRs)
- Prospects for near-term modular HTGR deployment
- Summary

Modular HTGR—Defined by IAEA—Specific Design and Inherent Safety Features

- High-temperature: process heat or efficient electrical output
- High-quality ceramic coated-particle fuel
- Single-phase coolant (helium)
- Post-shutdown decay heat removal achievable via a passive system—the reactor cavity cooling system (RCCS)
- Combination of low core power density + large heat capacity + high thermal conductivity + large temperature margins → long-time response to all loss-of-forced-circulation (LOFC) accidents
- Negative reactivity coefficients + large temperature margins → safely accommodate reactivity insertions

Why Bother with Modular HTGRs?

High temperature: process heat (large market potential)

For Brayton cycle: electrical efficiency ~50% vs LWR ~33%
(that's like 30 vs 20 mpg fuel use!)

reduced fuel use and high-level waste (~33%)

reduced waste heat reject rate (~50%)

heat reject temperature ideal for (flash) desalination

Passive safety: reduced (active) safety systems, benefits to licensing

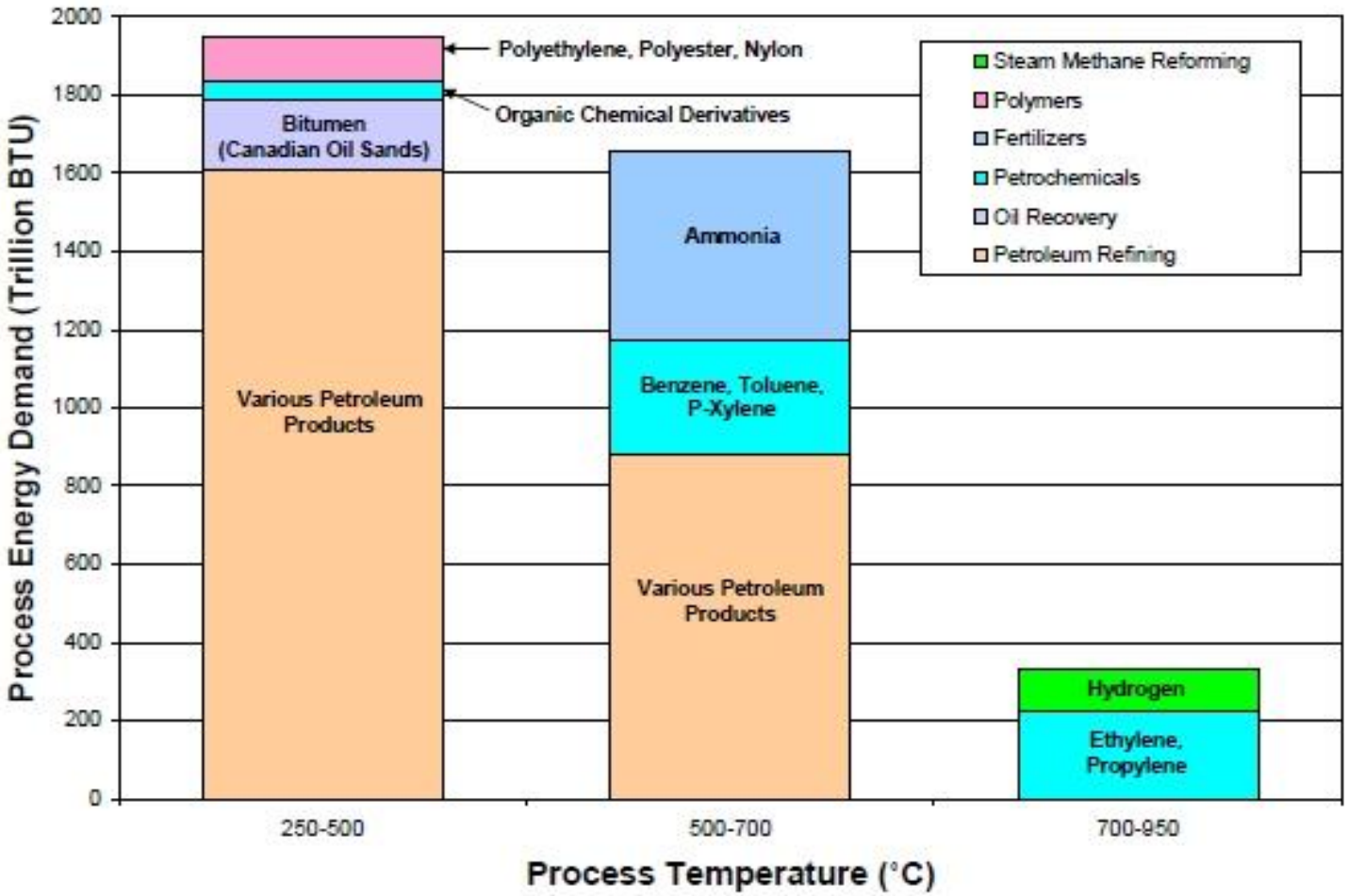
no need for auxiliary power for cool-down

confinement (vs containment) building

Fuel flexibility: uranium or actinides (or thorium); "deep burn"

Spent fuel storage & proliferation: better ways; high resistance to diversion

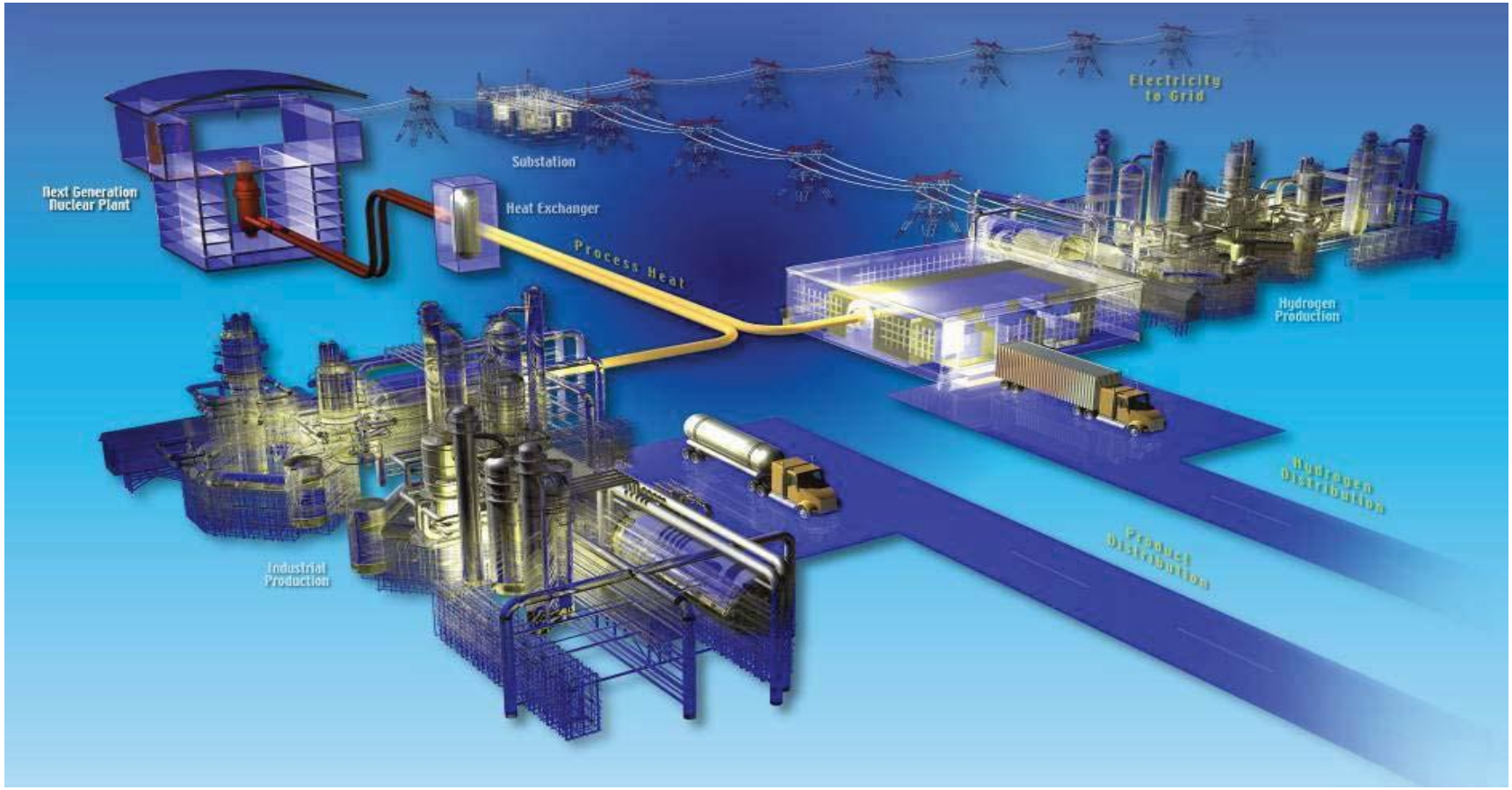
Survey of U.S. Industrial Needs for High-Temperature Process Heat



ORNL – Areas of HTGR contributions

- **U.S. Department of Energy (DOE), Office of Nuclear Energy (NE), support for the Next Generation Nuclear Plant (NGNP)**
  - TRISO fuel development and testing
  - Graphite and high-temperature metals
  - Russian/US Gas Reactor Technology Development (Medvedev/Obama Bilateral Presidential Commission)
- **DOE - National Nuclear Security Administration (NNSA)**
  - RF/US Gas-Turbine Modular Helium Reactor (GT-MHR) for disposition of excess weapons plutonium
- **U.S. Nuclear Regulatory Commission (NRC)**
  - Safety and licensing issues for NGNP
- **Participation in IAEA HTGR programs**

An NGNP providing high-temperature process heat and electricity to its appreciative neighbors



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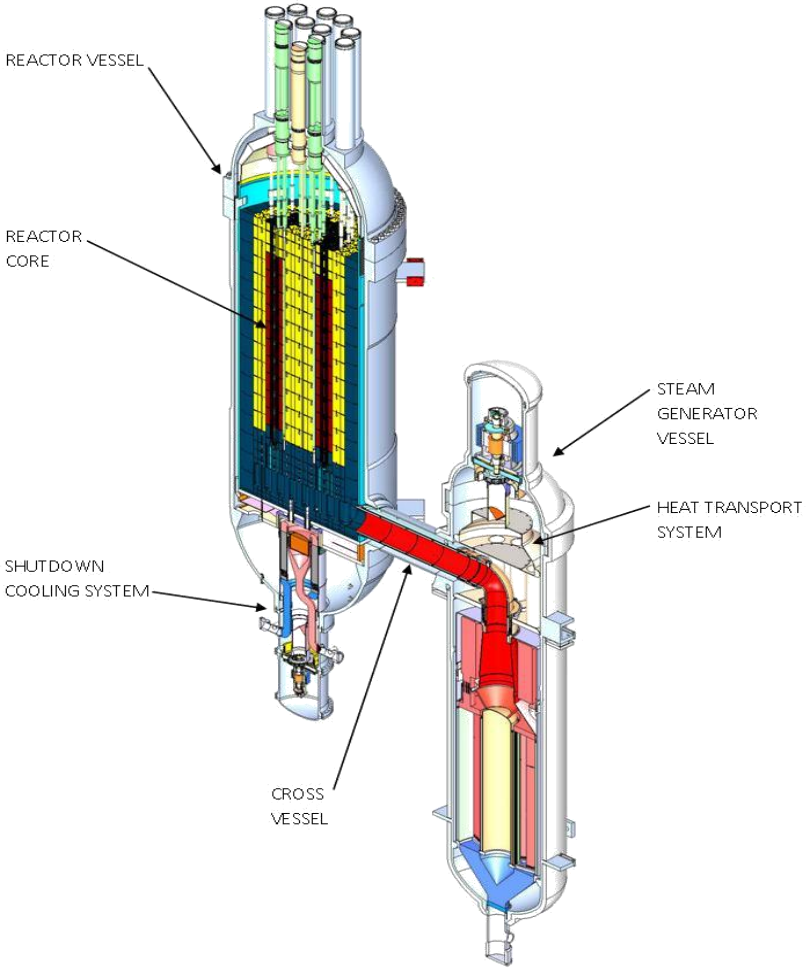
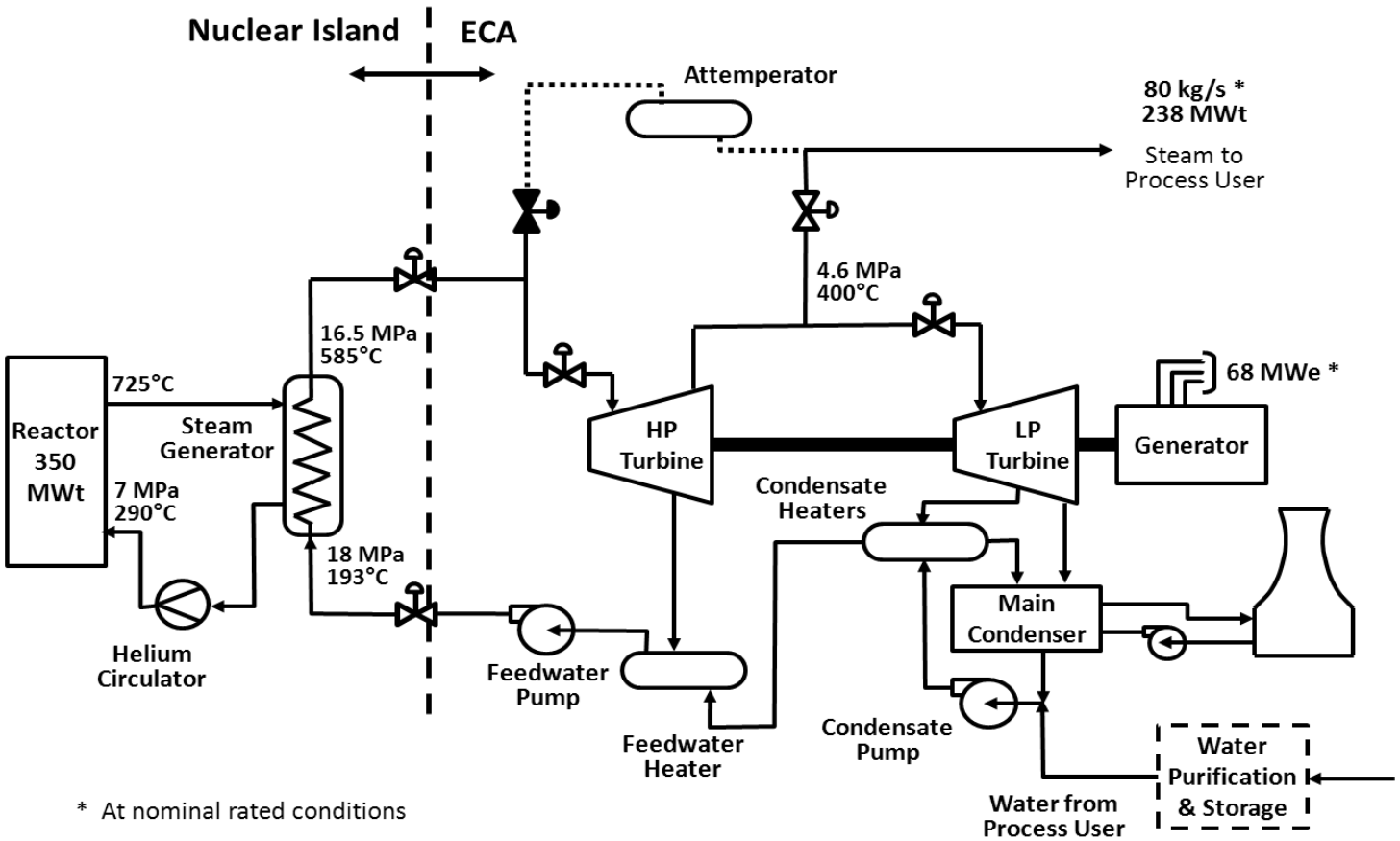
General Atomics (GA) NGNP concept demonstration plant: Steam-Cycle Modular Helium Reactor (SC-MHR)

- Reactor power level 350 MW(t)
- Reactor outlet temperature 725°C
- SC-MHR mission: cogeneration of process steam and electricity
- Nominal plant production and energy design parameters
  - Gross electricity: 68 MW(e)
  - Net electricity: 56 MW(e)
  - Steam export: 80 kg/s

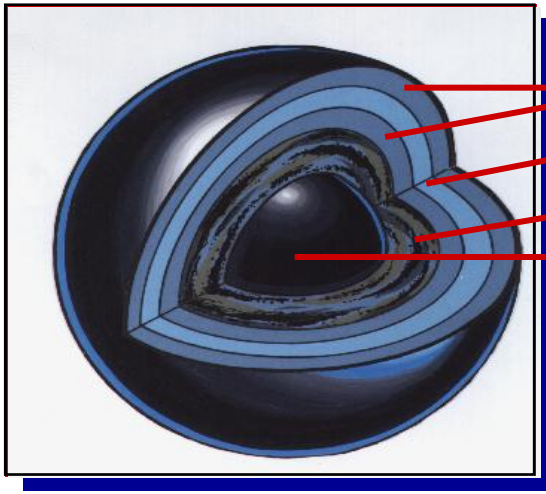


SC-MHR Demonstration Plant Configuration

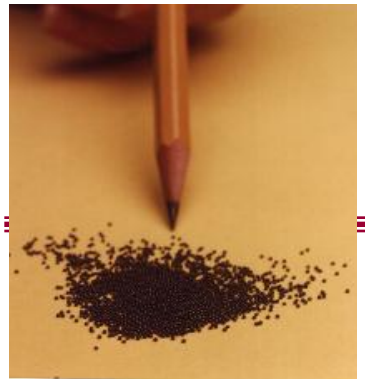


* At nominal rated conditions

Ceramic fuel retains its integrity under severe accident conditions



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).



PARTICLES

COMPACTS

FUEL ELEMENTS

GENERAL ATOMICS

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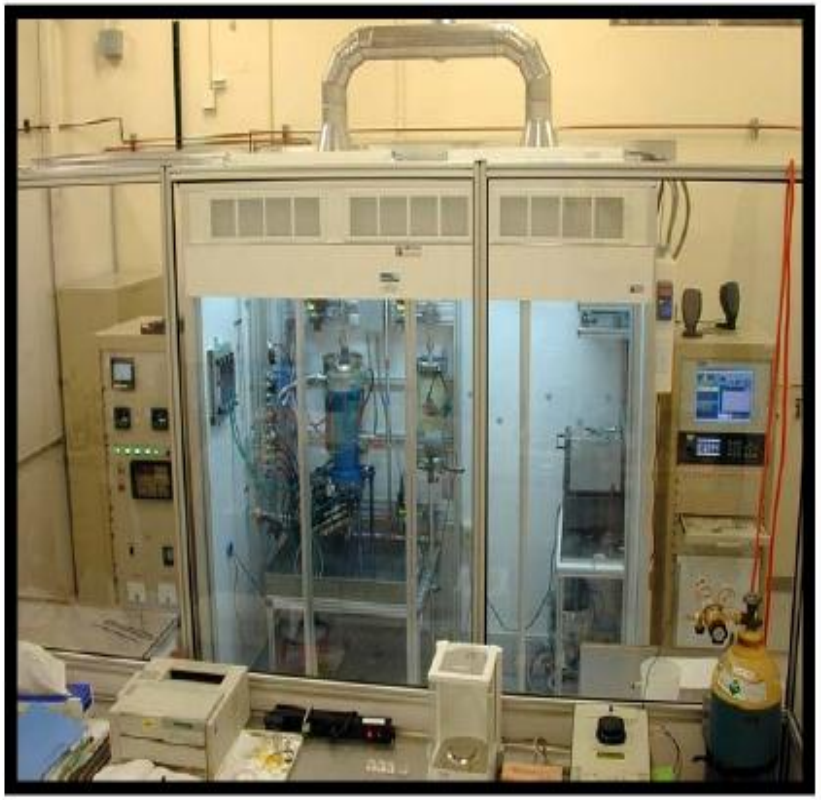
Elements of the ORNL fuels lab include kernel, coater, and compacting sectors Shown here are “push-button” coaters, shown to produce excellent TRISO fuel



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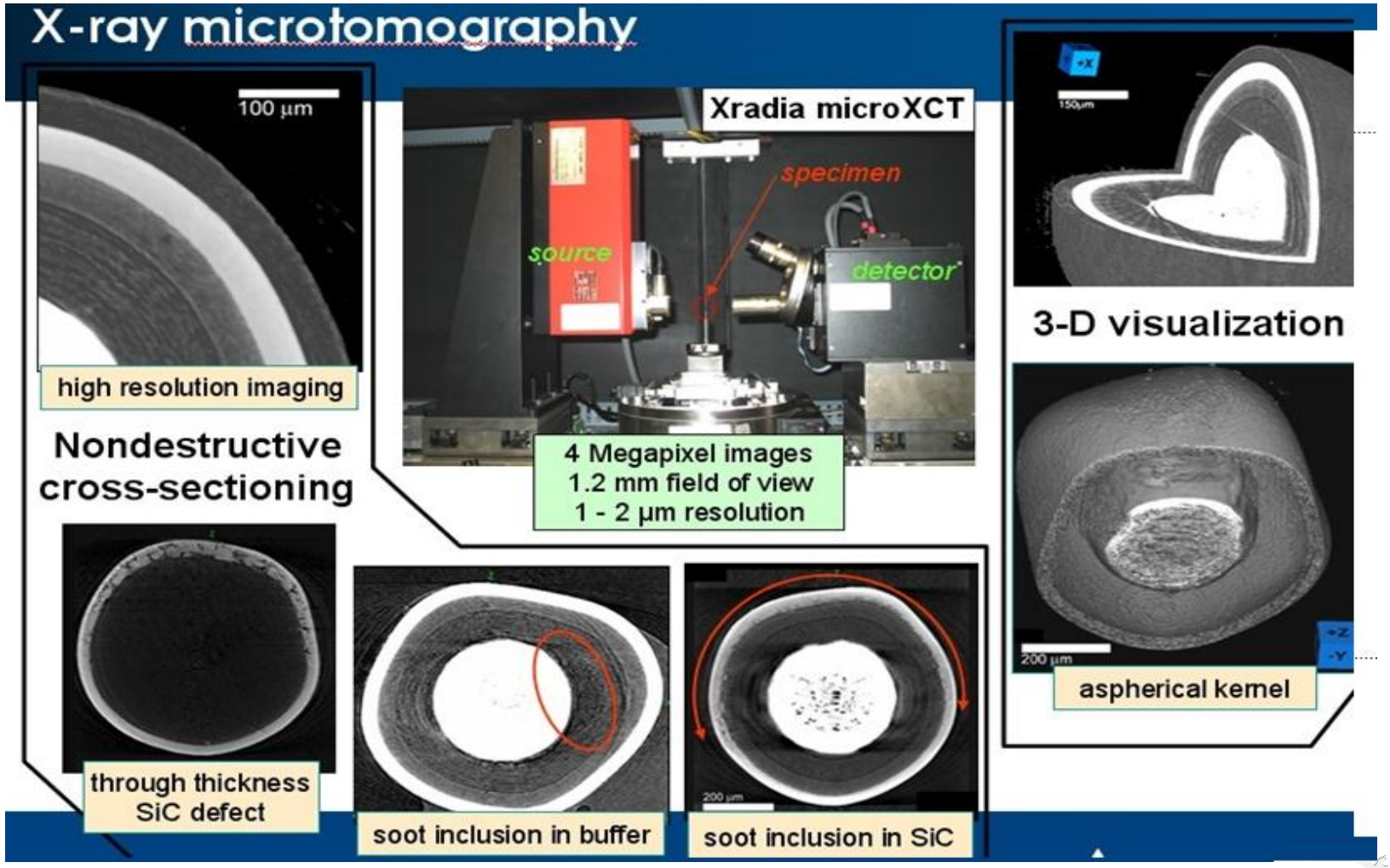
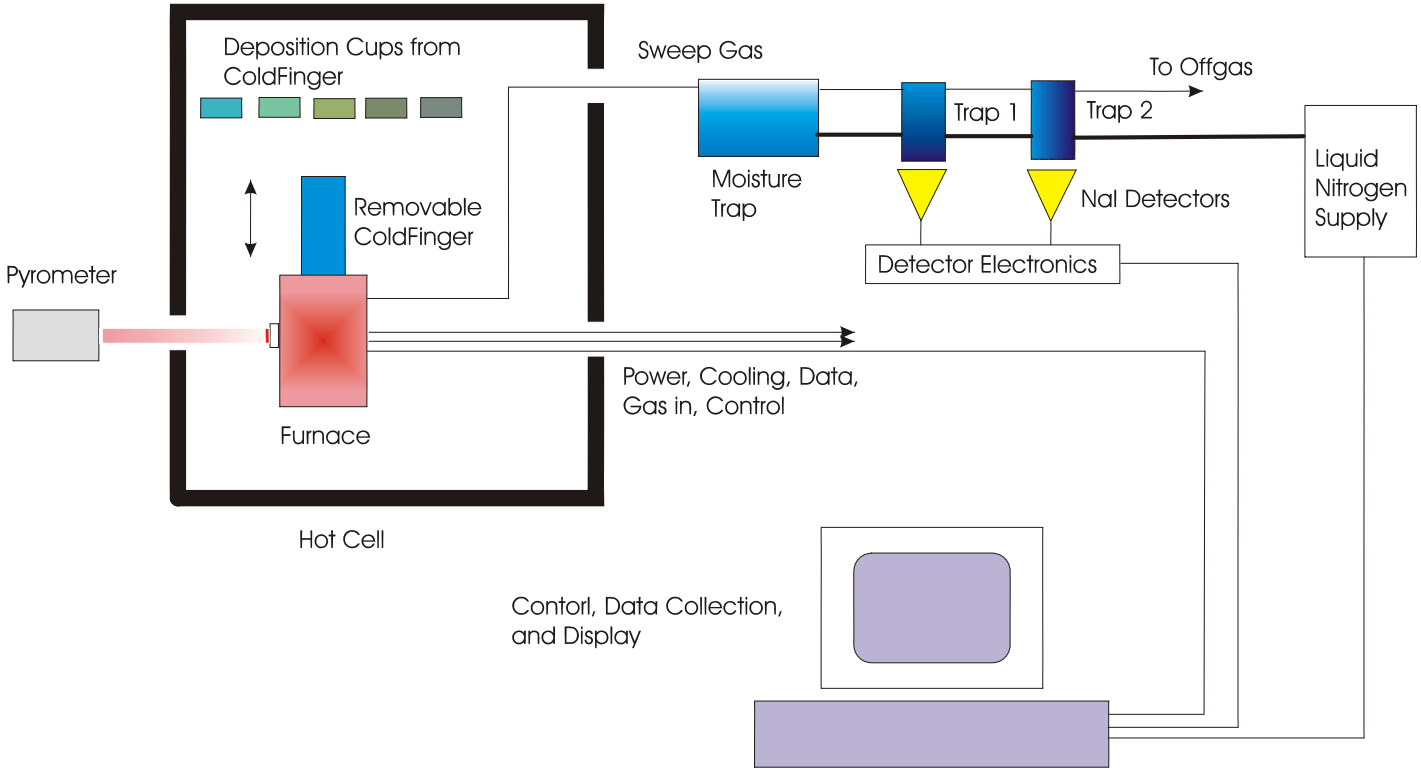
ORNL fuels lab has state-of-the-art characterization and inspection



ORNL TRISO fuel heatup accident testing

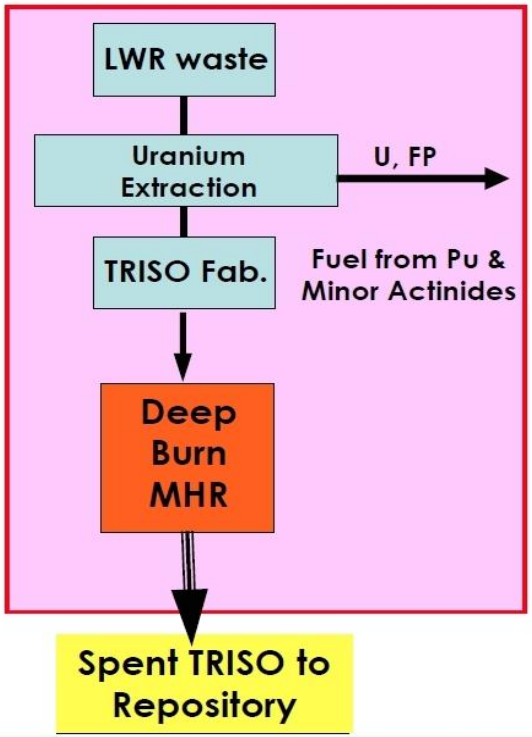
- General furnace configuration



Actinide burning ("deep burn" fuel) – part of NGNP program (with GA)

Deep Burn is a Promising Spent-Fuel Strategy, Based on MHR + TRISO Particle Fuel

- Spent fuel actinides made into TRISO fuel
- Fissile Pu destroyed & actinides reduced in the DB-MHR
- Spent TRISO elements placed in Repository
  - Coatings secure ~10^6 yrs.
- With once-through Deep Burn processing
  - Little fissile Pu in Repository
  - Radio-nuclides permanently confined in TRISO particles
  - YM capacity greatly increased



GENERAL ATOMICS

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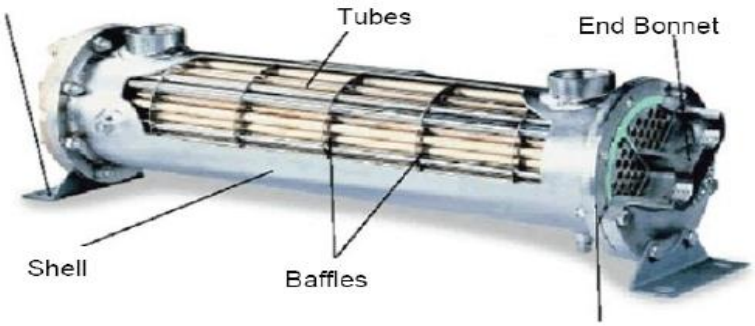
ORNL graphite program

- Wide-ranging advanced R&D in graphite technology, including carbon-carbon composite applications
- Example: Graphite furnace in oxidation lab:

ORNL: DOE's lead laboratory for NGNP's high-temperature materials

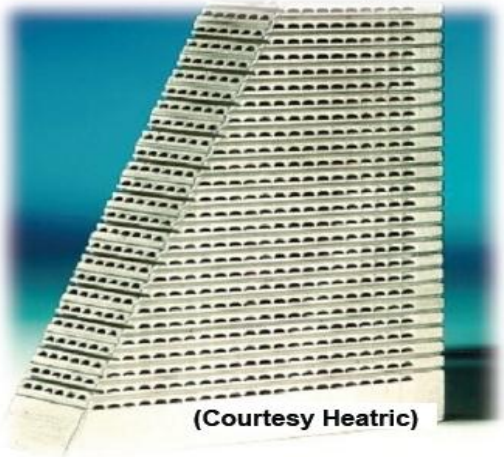
- Temperatures up to 950°C
- Expected principal damage mechanism: creep-fatigue
- Only one alloy, 800H, is ASME Code qualified and only to 762°C
- Alloys 617, 230 & X(R) suitable but not in nuclear section of the ASME Code



Straight-Tube HX

THTR-300 Steam Generator

Printed Circuit Board Heat Exchanger



(Courtesy Heatric)

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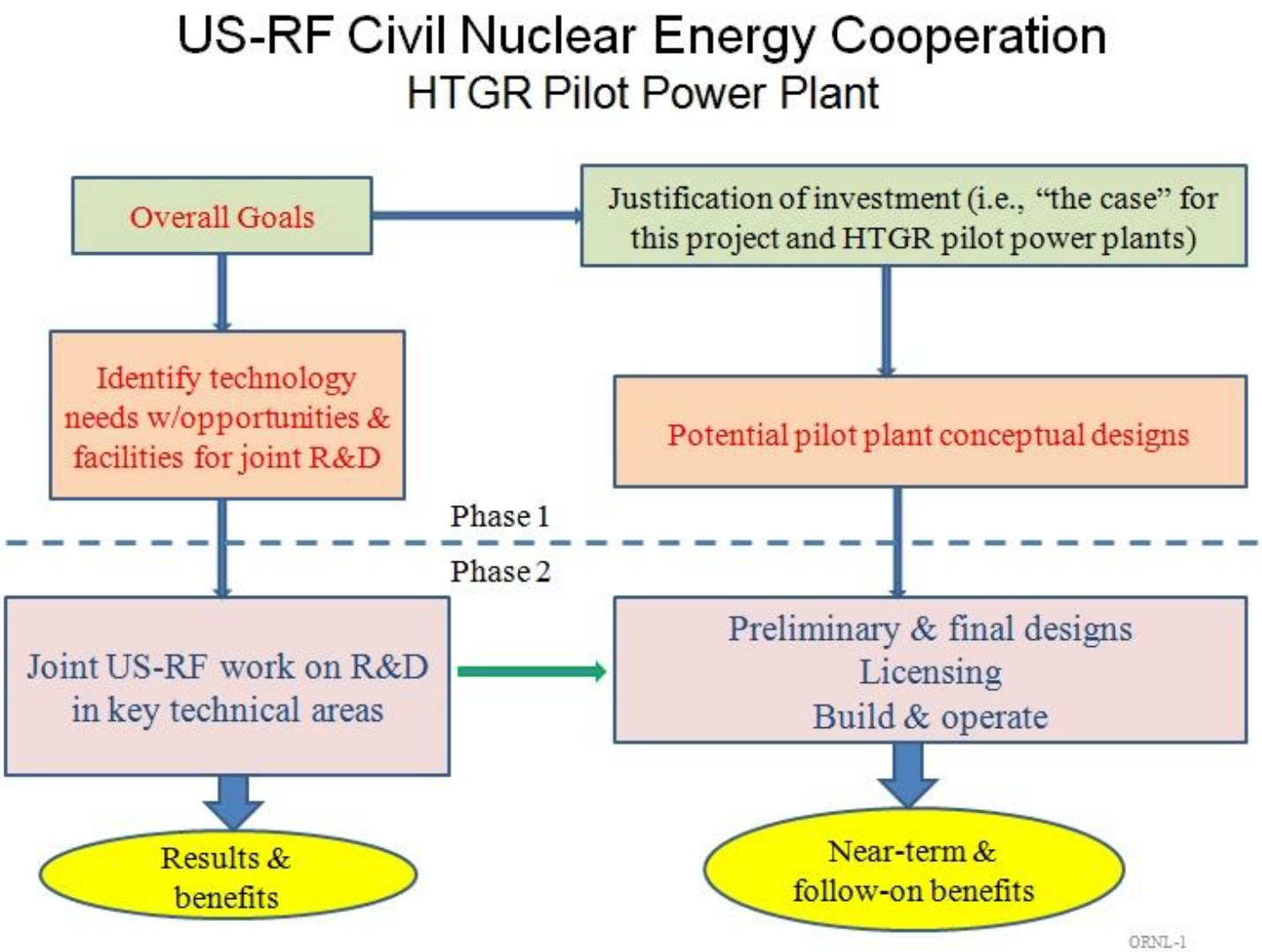
Presidential joint commission –

Nikolay Kodochigov (OKBM) – RF lead for HTGRs

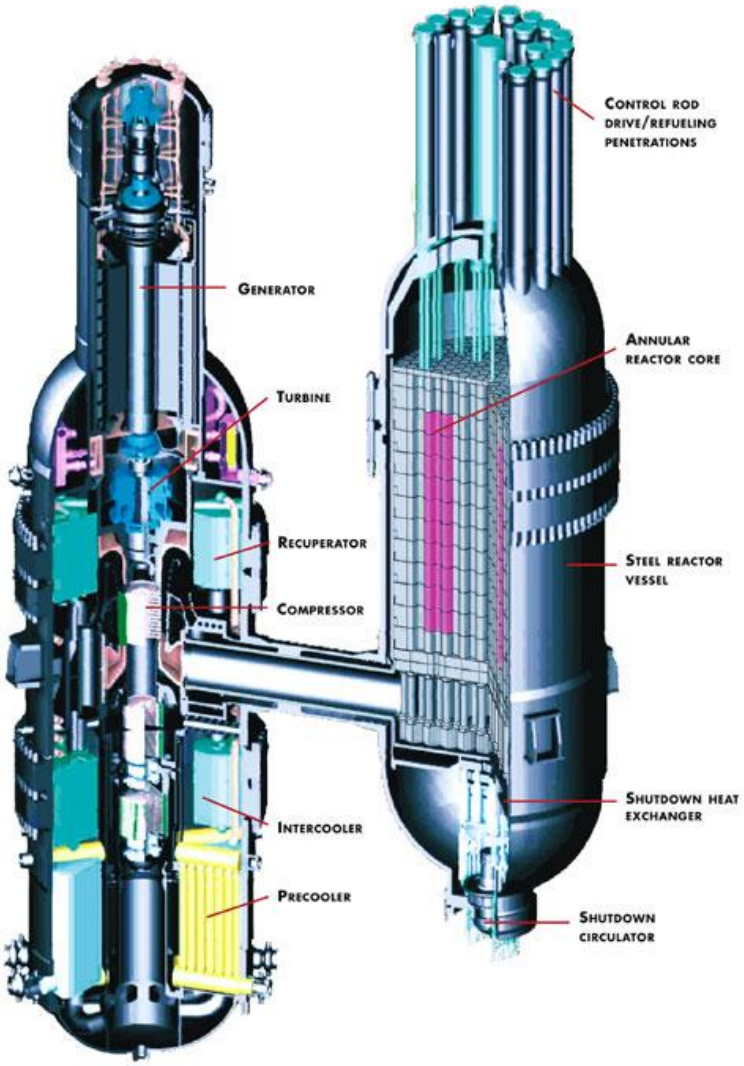


Selected US-RF program elements

- Seminar and facility exchange visits on high-temperature electrolysis for hydrogen production
- Proposal for joint TRISO fuel development at ORNL
- Pilot power plant configuration and conceptual design
- R&D in key technological areas
- Licensing issues for plants in US and Russia

ORNL supporting DOE/NNSA in joint U.S.-Russian GT-MHR Pu burner R&D

- OKBM – RF prime contractor (Nikolay Kodochigov)
- GA – US Industry lead
- ORNL – US-DOE lead lab
- Objective: R&D on Gas Turbine – Modular Helium Reactor (GT-MHR) technology to build prototype module(s) to accelerate disposition of 34-MT of RF excess W-Pu at ~270 kg-Pu/yr (PMDA)

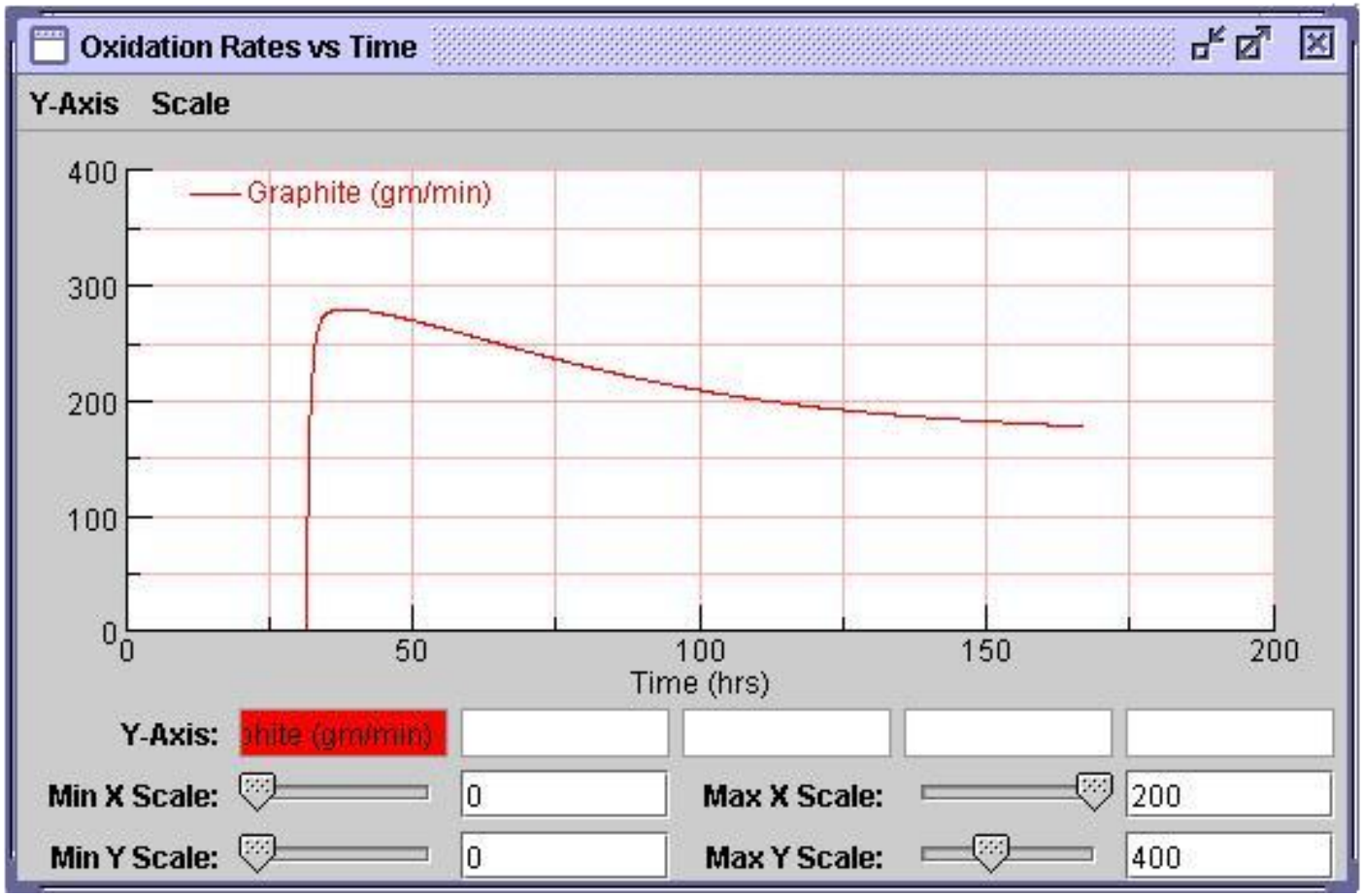


ORNL's NRC projects for HTGRs

- Confirmatory research on MHTGR licensing (1980s)
- Conducted PIRTs for fuel, FP transport, T/H and neutronics, graphite and other HT materials, process heat plant coupling
- Knowledge management support for NRC's HTGR evaluation model [EM] development, integration, testing, and utilization
- Advanced instrumentation – high-temperature sensors
- Advanced control (and control room) licensing issues
- Safety code development (confirmatory) – GRSAC example

Air ingress accidents present long-term accident mitigation challenges—example:

- Considering confinement gas (air, CO_2, CO, He, …), the oxidation rate declines even though gas ingress flow increases



NRC: Unique licensing issues associated with modular HTGRs

- Critical dependence of safety case on TRISO fuel performance
- Reduced dependence on active safety systems due to
  - Design objective of “no fuel failures for P- and D-LOFC accidents”
  - Inherent (passive) safety characteristics
  - Inherently slow response and large safety margins
- Use of confinement (vs leak-tight containment) building
- Smaller EPZ (with no public evacuation planning)
- Concern for radioactive release from a D-LOFC due to dust in the primary system
  - Mainly a concern for pebble bed reactors (PBRs)
- Graphite core oxidation in a long-term air ingress accident
- Chemical and reactivity response to a steam ingress accident
  - Mainly a concern for primary system steam generator designs

ORNL supports IAEA's HTGR projects:

- Global nuclear and global warming:
  - Global cooperation is required!
- Support of Coordinated Research Projects (CRPs)
  - Fuel, physics, afterheat removal, reactor operation
- Consultancy support
  - Unique licensing characteristics, safety code reviews and validation
  - Prototype reactor design reviews
  - International HTGR design and safety seminars
- Effective collaborations with major participants:
  - Russia, Japan, China, South Africa, Korea, Germany…

IAEA CRP-3 GT-MHR-Pu code-to-code benchmark—(plus Framatome) peak fuel

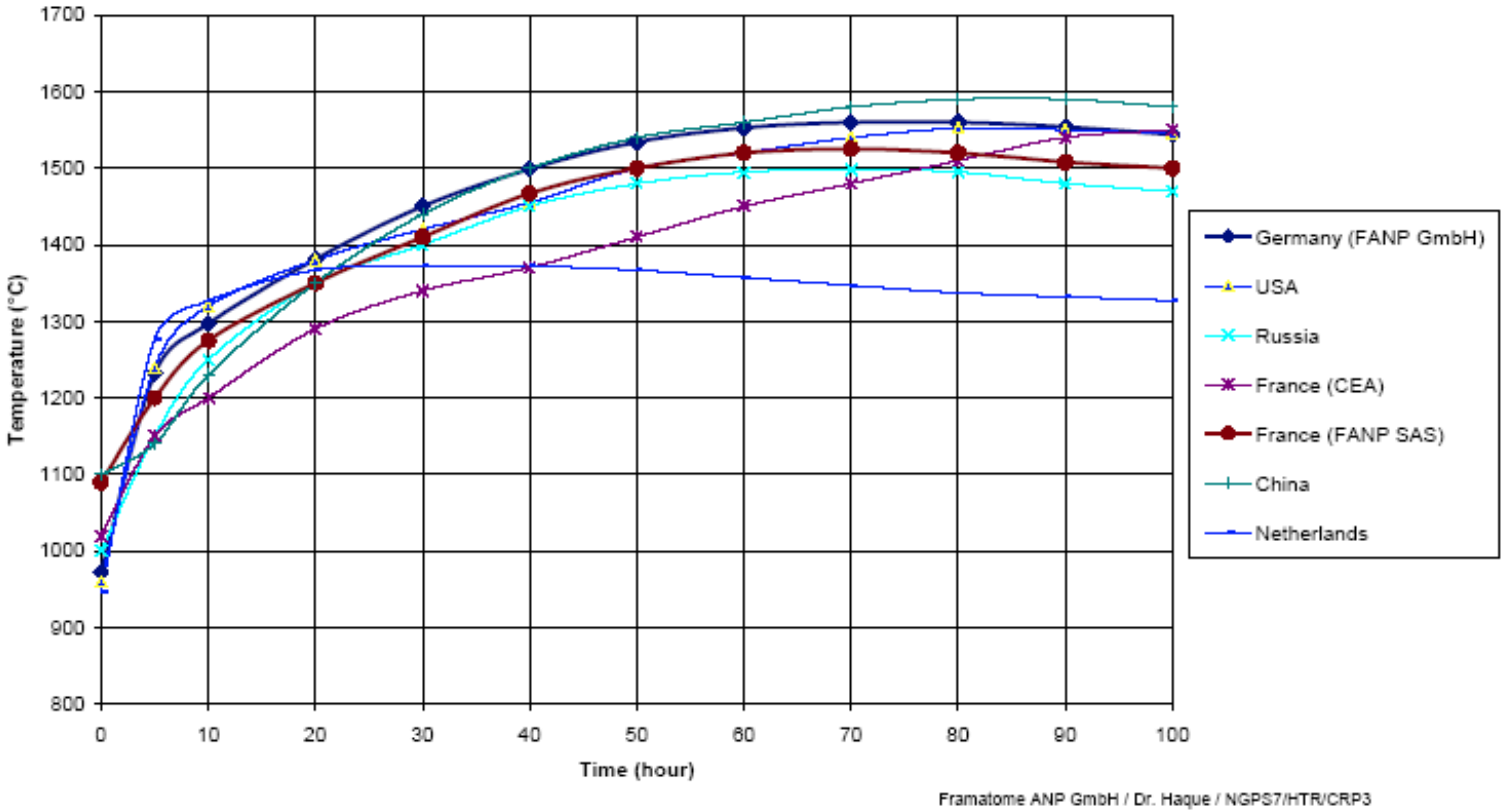
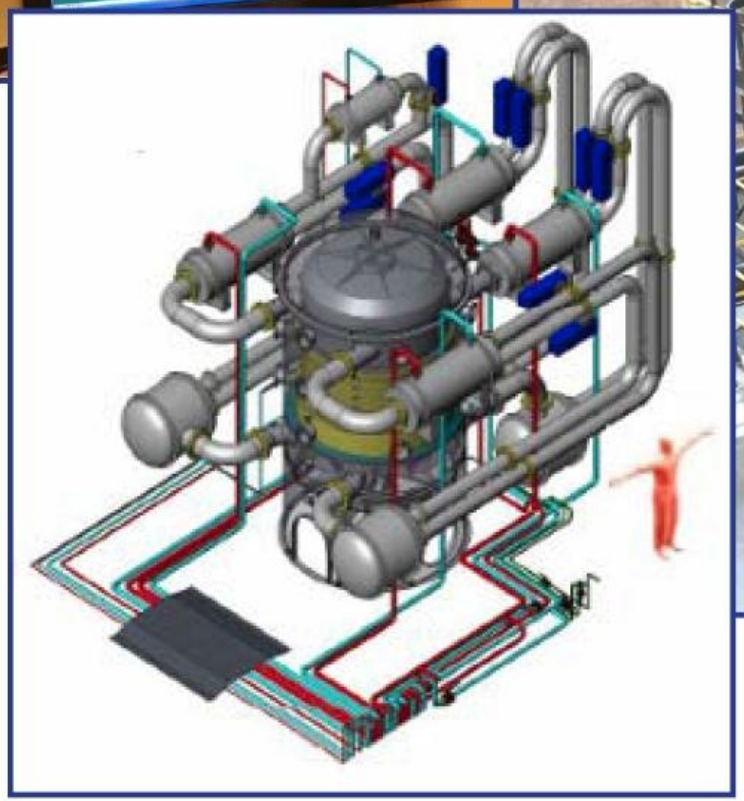


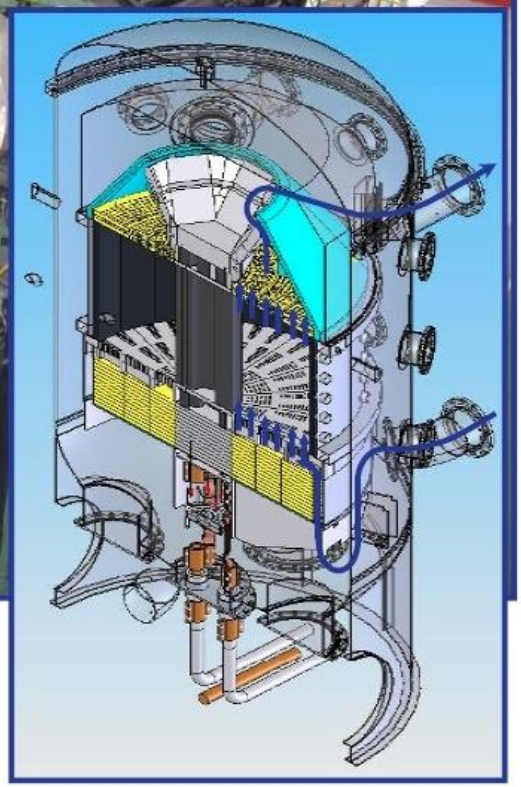
Fig.4: CRP-3 benchmark, Comparison of the code results of various countries for the peak fuel temperature during depressurized cooldown

Prospects for near-term deployment

- PBMR (South Africa) – victim of financial downturn
- Japan – renewed interest due to Fukushima tsunami
- China – “on schedule” for HTR-PM – construction
  - As with PBMR, some additional R&D in progress
  - Cost estimate: with government support of design and R&D, construction and operational costs are equivalent to LWRs
- RF/US pilot plant project: “an opportunity”

High Temperature Test Unit





China's HTR-PM

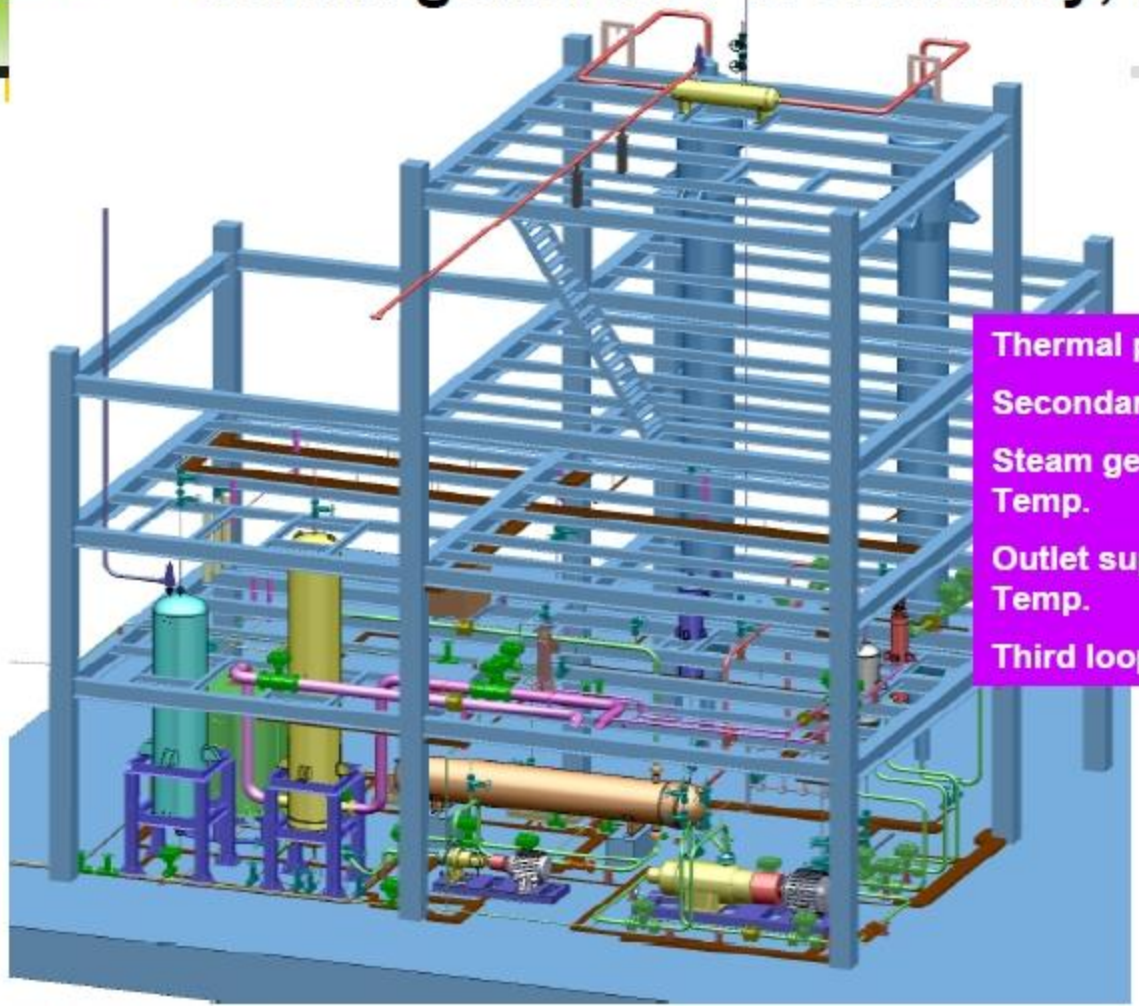
List of the key approved projects

- P1, Verification of helical once-through steam generator
- P2, Verification of fuel handling technology and the key component
- P3, Verification of small absorber ball shutdown system
- P4, Verification of digitalized protection system
- P5, Key components and technology of spherical fuel element fabrication
- P6, Verification of the control rod driven mechanism
- P7, Verification and research on helium purification and helium sealing

- P8, Verification for several technical problems of the demo project using HTR-10
- P9, Irradiation test of spherical fuel elements
- P10, Research and verification of important safety topics
- P11, Dynamic response and structural integrality of graphite internals
- P12, HTGR physics and thermal hydraulics and system simulation
- P13, HTGR fission products behavior
- P14, Key technology on hydrogen production by HTGR

China (INET) experiments in progress

Steam generator test facility, in P1



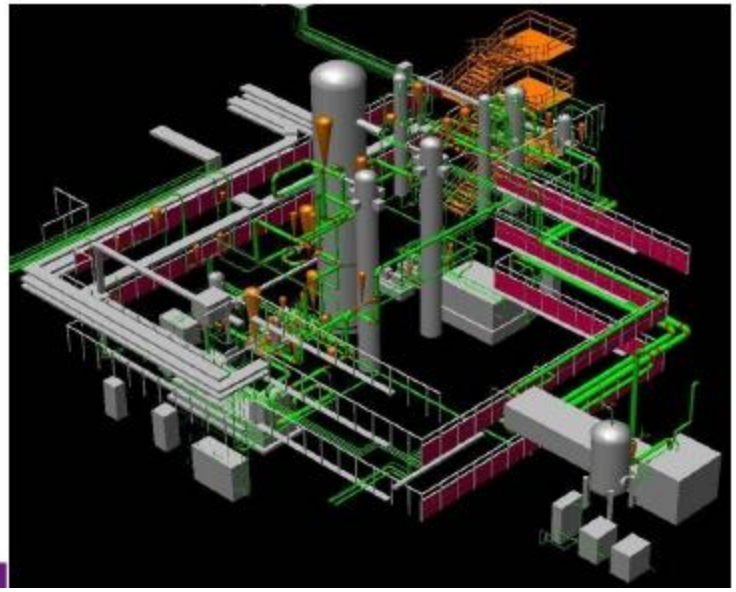
Thermal power	10MW
Secondary loop pressure	13.25 MPa
Steam generator inlet water Temp.	205℃
Outlet superheated steam Temp.	570℃
Third loop pressure	3MPa

China (INET) test loop similar to OKBM's

Helium Test Loop

Parameters of the facility

- Thermal power of SG: 10MW
- Temperature: 750 ℃
- Pressure: 7 MPa
- Working fluid: Helium



Experiments to be carried out:

- SG 1/19 test, steam 13.25MPa, 567℃
- Fuel handling system
- Small absorber sphere system
- Helium purification system

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SUMMARY

- ORNL has collaborated with Russia on wide ranges of modular HTGR R&D
- ORNL's interests, experience, and capabilities cover many modular HTGR topics
- Collaboration is desirable (and essential!) due to limitations in resources and the need to utilize international expertise (and facilities)

“spare”