



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Nuclear Energy University Programs (NEUP) Fiscal Year (FY) 2016 Annual Planning Webinar

**Advanced Reactor Components
(Subtopics RC-2.1 & 2.3)**

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August 11, 2015

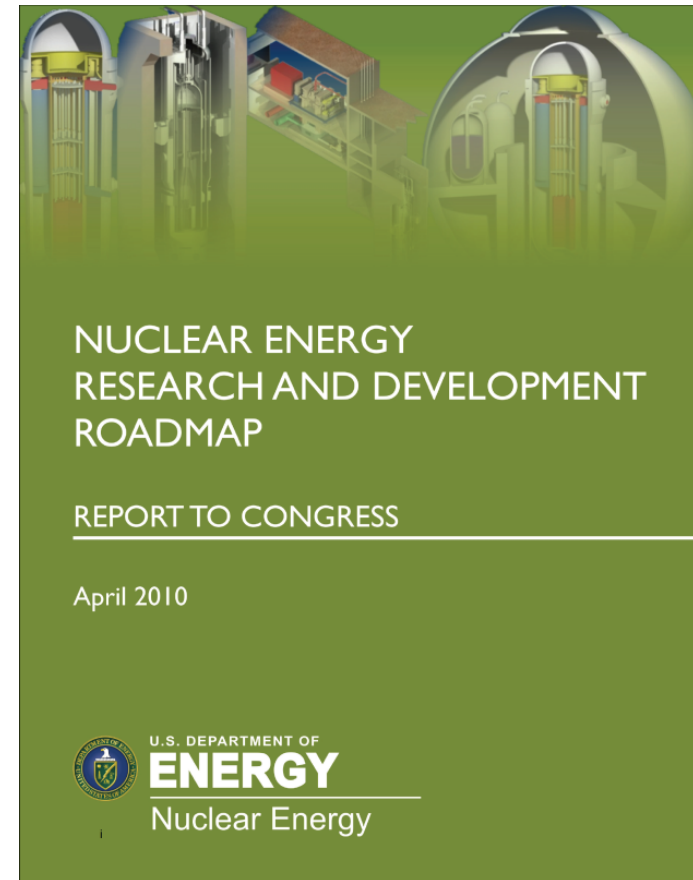
Structural Materials Are Critical for Advanced Nuclear Reactors

- **Development and qualification of advanced structural materials are critical to the design and deployment of the advanced nuclear reactor systems that DOE is developing**
 - **High and Very High Temperature Gas Cooled Reactors (HTGRs and VHTRs)**
 - **Sodium Cooled Fast Reactors (SFRs)**
 - **Fluoride Salt Cooled High Temperature Reactors (FHRs)**
- **Structural materials must perform over design lifetimes for pressure boundaries, reactor internals, heat transfer components, etc.**
- **Performance of metallic alloys for the long times and high operating temperatures required is being examined under the Advanced Reactor Technologies (ART) Program**



ART Program Supports Advanced Reactor Development

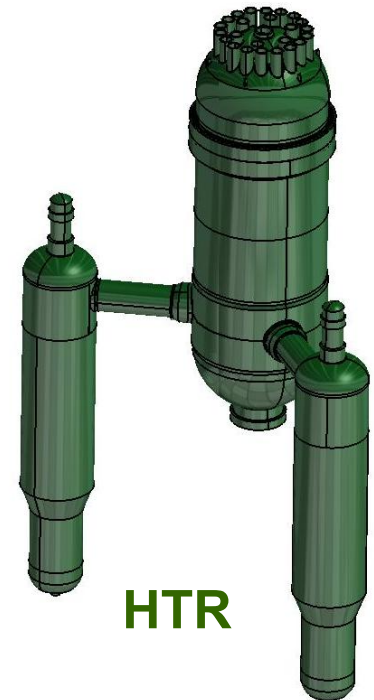
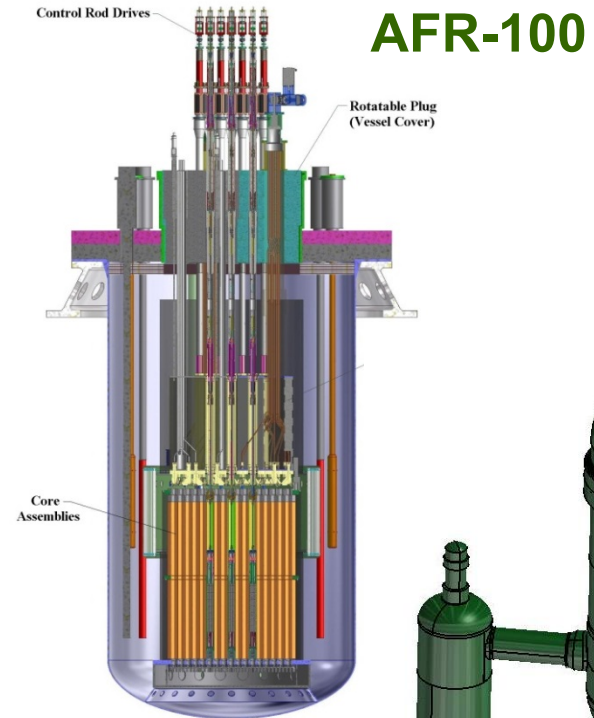
- **ART R&D supports multiple high-level objectives identified in the 2010 Nuclear Energy R&D Roadmap (2 & 3)**
 - (2) Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals
 - (3) Develop sustainable nuclear fuel cycles
...overall goal is to have demonstrated the technologies necessary to allow commercial deployment of solution(s) for the sustainable management of used nuclear fuel that is safe, economic, and secure and widely acceptable to American society by 2050.”





ART Program Includes Advanced Materials R&D Activities

- **Development and qualification of graphite, improved high-temperature alloys, and ceramic composites for advanced reactor systems**
- **Advanced Fast Reactor-100 is an example of fast reactor systems**
 - Targets local small grids with limited needs for on-site refueling
 - 250MWt/100MWe, sodium-cooled, core life (30 years), plant life (60 years)
- **AREVA's High Temperature Reactor is an example of a He-cooled system**
 - TRISO fueled, graphite moderated
 - 625MWt/315MWe, 750°C outlet temperature to steam generator, plant life (60 years)



Advanced Reactor Components Addresses Two Significantly Different Structural Materials Research Topics in FY16

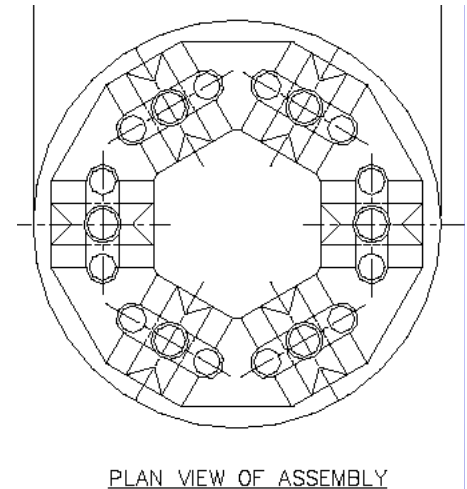
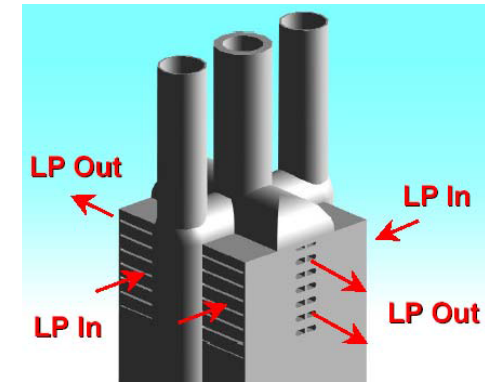
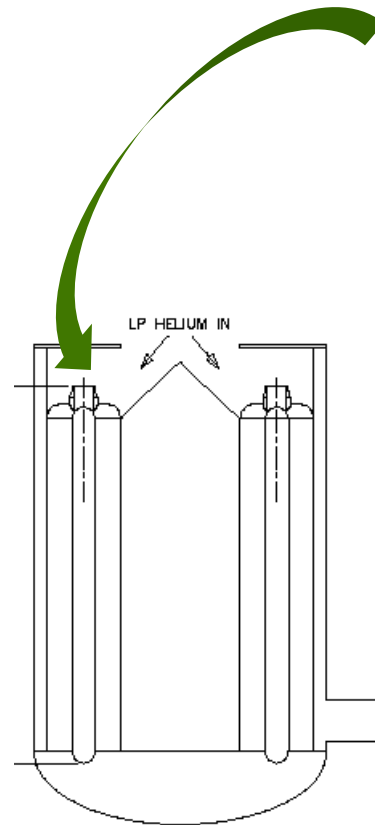
- **RC-2.1 Compact Heat Exchangers (CHXs)**
 - **Advanced nuclear reactor systems may utilize CHXs as part of high efficiency, Brayton cycle energy conversion systems for improved cost and efficiency. SFRs and FHRs may utilize a supercritical carbon dioxide (sCO₂) secondary loop, and HTGRs may incorporate CHXs. Numerous ASME Codification issues must be addressed before CHXs can be used in nuclear systems**

- **RC-2.3 Helium Tribology in Gas Cooled Reactors**
 - **HTGRs and VHTRs use helium as a reactor coolant to transfer heat from the core to either a primary-to-secondary heat exchanger or to a steam generator. Metallic components will likely consist of Alloy 800H or Inconel 617. Friction, wear, and self-welding of metallic surfaces in the typical He environment of such reactors is of concern.**

RC-2.1 CHXs for Advanced Reactor Systems Require ASME Nuclear Code Qualification

- High efficiency Brayton cycle systems based on $s\text{CO}_2$ improve cost and efficiency
 - Minimize material cost and reactor and plant footprint
- CHX for SFR Brayton cycle operates at moderate high temperature – about 550°C
 - Nominal $s\text{CO}_2$ pressure about 20MPa (2900psi)
 - Nominal sodium pressure about 2MPa (300psi)
- Potential HTGR and VHTR applications at higher temperature ($800 - 950^\circ\text{C}$)

Example of CHX modules inside a Section III vessel

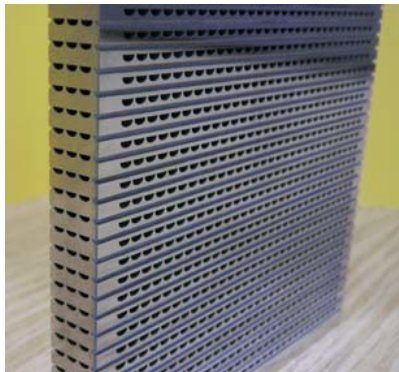




Micro Channel and Plate Fin Are Candidate CHX Types

■ Diffusion bonded micro channel

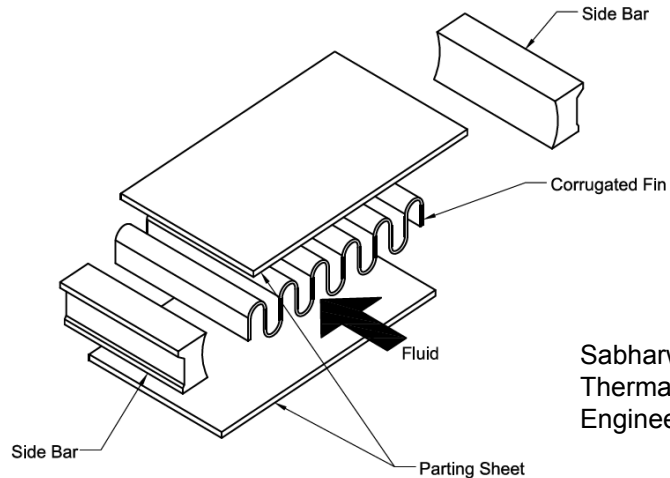
- Series of bonded thin plates or shims
- Chemically etched micro channels
- Integral flow distribution channels
- Good for high pressure



Southall et al., ICAPP '08

■ Diffusion bonded or brazed fin CHX

- Corrugated plate fin sandwiched between two flat plates or shims
- More efficient use of materials and larger flow passages



Sabharwall et al., Journal of Thermal Service and Engineering Applications, 2013

■ Composite of both types proposed for sCO₂ CHX

- High pressure sCO₂ in micro channels
- Low pressure sodium in plate fin configuration



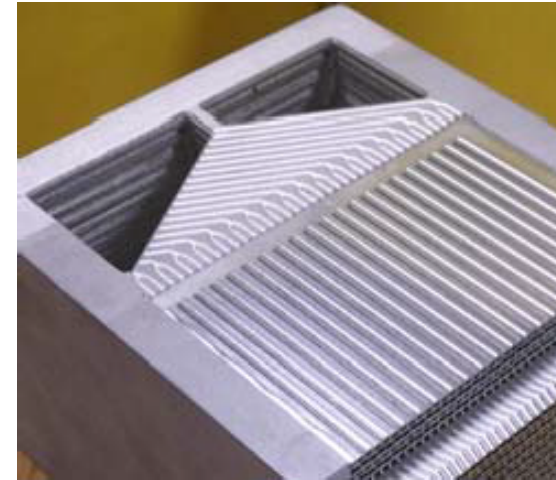
Southall et al., ICAPP '10



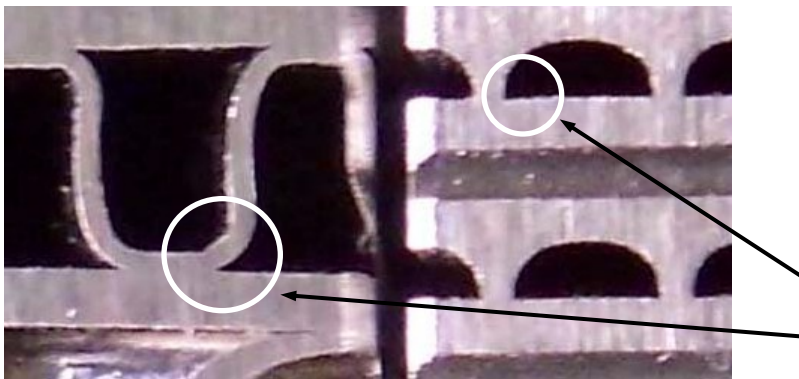
CHXs Have Complex Geometry at Micro- and Macro-Scales

■ Complex arrangement of flow channels and distribution manifolds

- Challenge to ensure external boundary conditions transfer to CHX internals



Southall et al., ICAPP '10



Southall et al., ICAPP '09

■ Sharp re-entrant corners result in stress concentrations

- Significant stress redistribution from pressure and thermal stresses



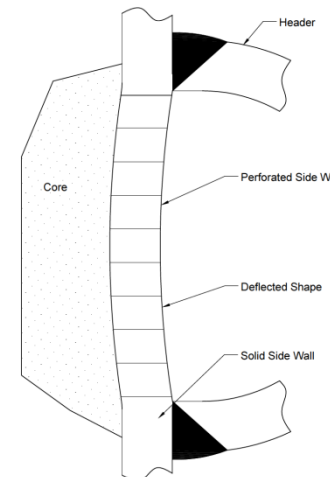
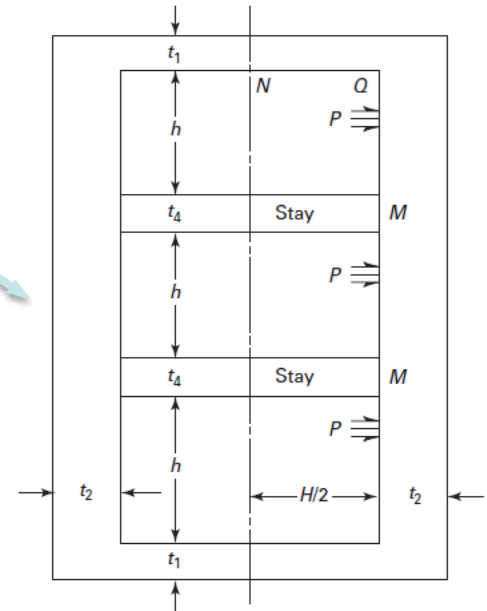
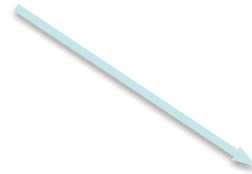
Complex CHX Structure Challenges Current ASME Nuclear Design Process

■ Non-nuclear Sec VIII, Div 1 provides micro channel sizing rules based on stayed rectangular vessels

- Does not consider thermal stresses or cyclic loading
- Does not adequately address elevated temperature bending stress/strain redistribution due to creep

■ Sec III elevated temperature design analysis (Subsec HBB) requires consideration of thermal stresses and cyclic loading based on stress classification

- Thermal stresses important for allowable cyclic life – particularly at elevated temperature
 - Interaction of core and manifold
 - Core thermal gradients – global and local
- Stress classification requires deconstruction of FEA results (primary, secondary and peak)
- Stress classification at sharp corner incompatible with current Section III, Subsection HBB methods



**Complex thermal
mechanical
interactions at
header location**



Potential Solutions Are Available to Develop Bases for ASME Sec III Rules

Substructuring

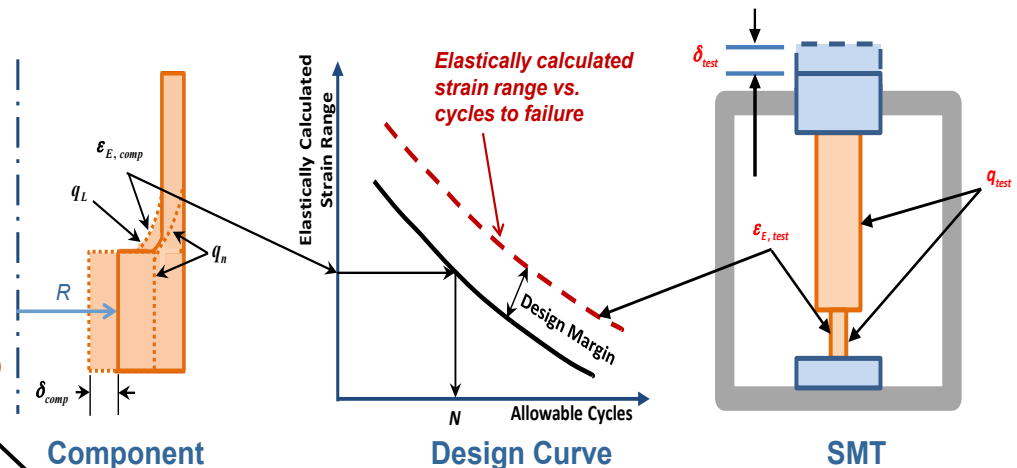
- Define equivalent smeared properties surrounding detailed representation of local area
- Still requires stress classification

Sec III Div 5 elastic-perfectly plastic (E-PP) draft Code Cases

- Uses elastic-perfectly plastic stress analysis based on pseudo yield stress that bounds response to allowable stress/strain values
- Doesn't use stress classification
- Models all details, thermal gradients and cyclic loading

Impact of sharp corner stress concentration

- Experimentally determine effective stress/strain concentration factor or effective corner radius
- Experimentally establish equivalent creep-fatigue curve analogous to **SMT** approach
- Creep and creep-fatigue crack growth methodologies



RC-2.1 Compact Heat Exchangers

- **Proposals are sought develop a structural design methodology to provides an assessment of elevated temperature failure modes of CHX under sustained and cyclic loading due to pressure and thermal gradients. The results will be used as the technical basis for developing a Section III, Division 5 Code Case for CHXs in nuclear systems. Input from industry would be considered valuable.**
- **Potential solution pathways could focus on the following areas to resolve the complex CHX structure challenges needed for current nuclear design procedures**
 - **Substructuring**
 - **Elastic-perfectly plastic design methodology**
 - **Experimental approach to deal with sharp stress concentrations at corners**

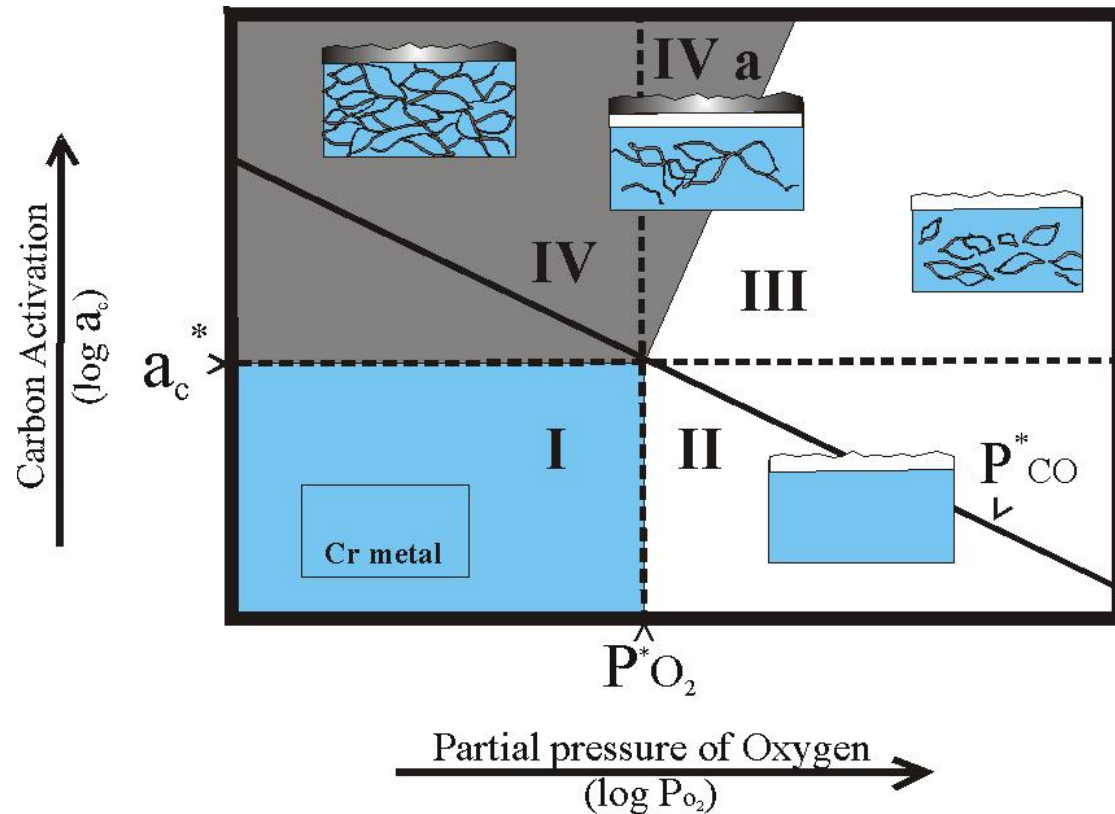
[Draft Report on CHX Nuclear Code Needs Being Finalized—Late August?](#)

J. Nestell and T.-L. Sham, “ASME Code Considerations for the Compact Heat Exchanger,” ORNL/TM-2015/401, Oak Ridge National Laboratory, Oak Ridge, TN (to be available from osti.gov)



RC-2.3 Tribology Performance of Metallic Alloys in High Temperature Helium Environments Needs to Be Examined

- High temperature strength and environmental compatibility in HTGR helium coolant is critical
- Creep and fatigue of ASME approved alloys appear to be relatively unaffected by HTGR helium
- Impact of HTGR helium on tribology of metallic components is less clear
 - Friction
 - Wear/Fretting
 - Self Welding



Nominal composition & potential ranges for HTGR He (μatm)

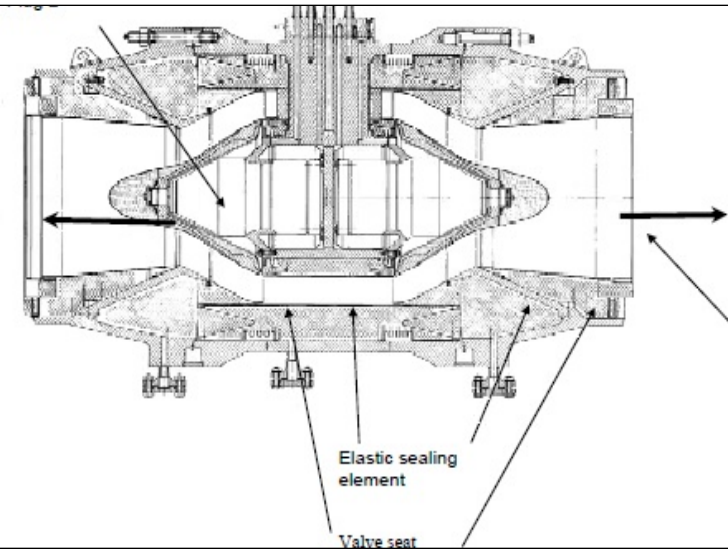
	H ₂	H ₂ O	CO	CO ₂	CH ₄	N ₂
Nominal	400	2.0	40	0.20	20	6
Range	300-500	1.0-4.0	30-50	0.05-0.40	10-30	2-10



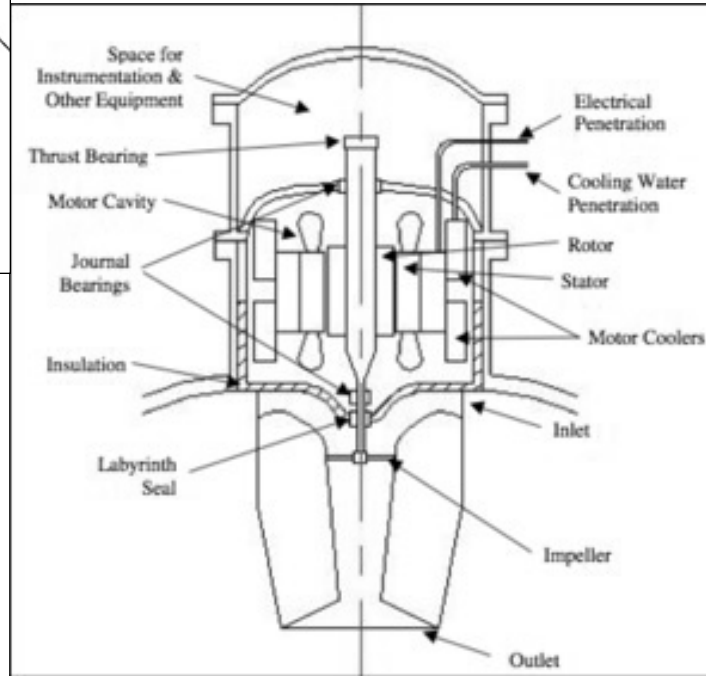
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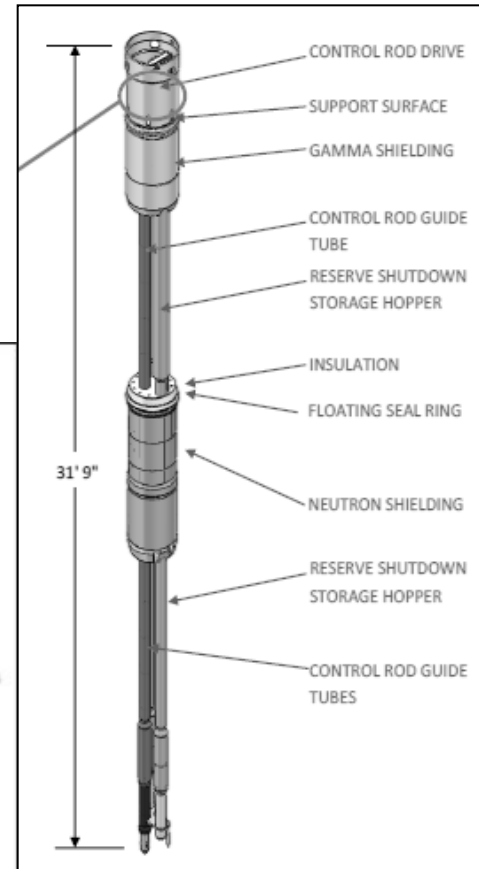
Metallic Components in HTGR Helium that Undergo Relative Motion Are Susceptible to Adverse Tribology Effects



German HTR He Isolation Valve Prototype



Simplified Helium Circulator



HTGR Control Rod

ASME Code-Approved Alloys for High Temperature Nuclear Construction Should Be Evaluated for He Tribology

- High temperature alloys 800H and Alloy 617 (soon to be added to ASME III Div 5) are of greatest interest
- Multiple mechanisms need to be evaluated
 - Friction and wear of sliding parts
 - Quasi-static situations (thermal expansion)
 - Vibrations and translations
 - Self-welding
- Example components
 - Control rod drive mechanisms
 - Fuel handling mechanisms for prismatic designs
 - Pneumatic systems for pebble bed fuel
 - Valves stems and seats (may be hardfaced)
 - Helium circulators

RC-2.3 Effects of HTGR Helium Coolant on Metallic Component Tribology

- **Proposals are sought to develop an improved understanding of the potential for enhanced tribological damage to Alloy 800H and 617 in simulated HTGR helium at relevant reactor operating temperatures. Input from industry involved in the design or manufacture of primary circuit components subject to helium tribology issues would be considered valuable.**
- **The proposed research should focus on**
 - **Experimental studies to compare the friction, wear, and self welding of the similar and dissimilar metal alloy couples in HTGR helium compared to that in air as functions of time, load, rate, environment, etc.**
 - **Conditions under which significant enhancement of deteriorated behavior in helium is observed should be identified and quantified.**
 - **Mitigation approaches should be developed and described, if possible.**



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**Electromechanical Pumps
(Subtopic RC-2.2)**

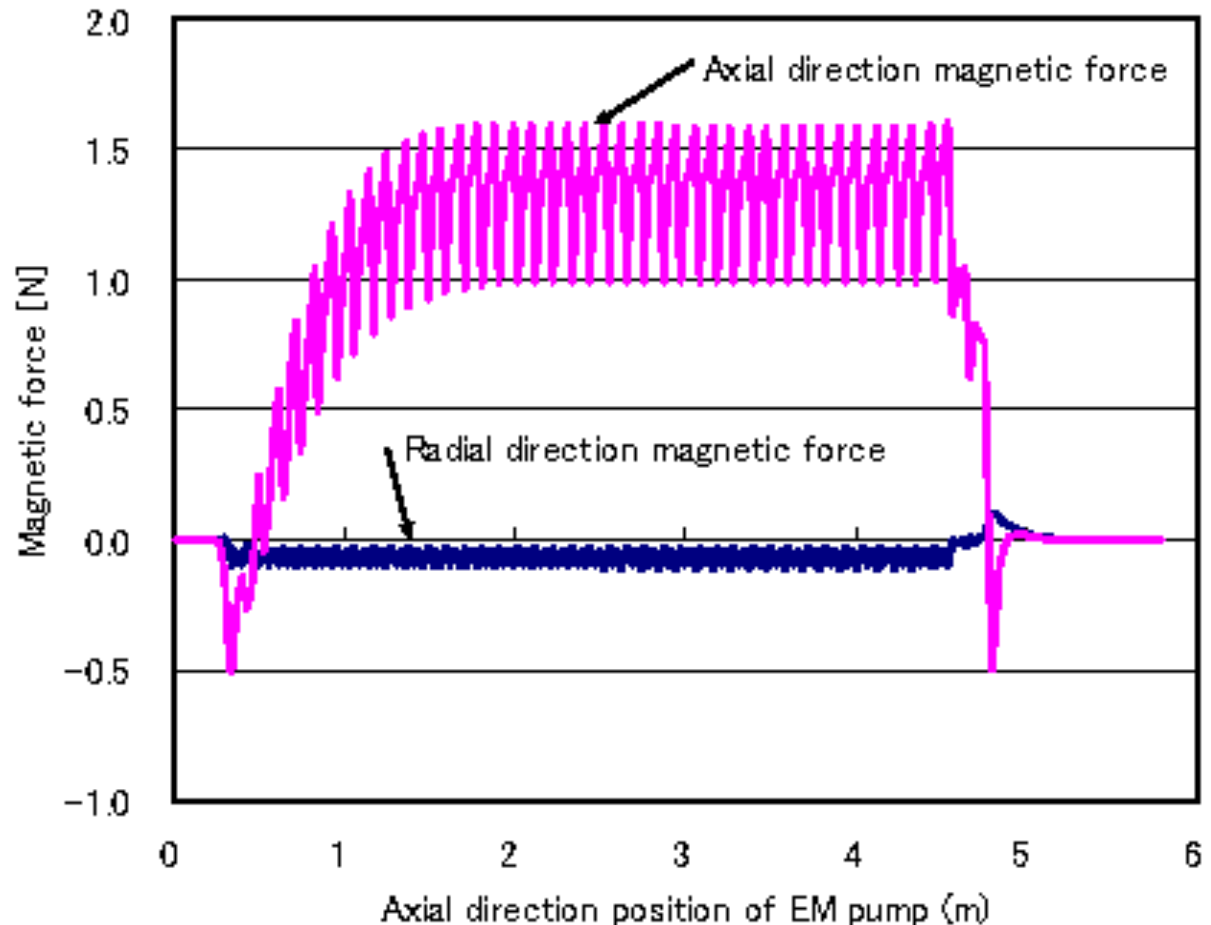
**Carl Sink
Office of Advanced Reactor Technologies
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August 11, 2015

Evaluating End Effects in EM Pumps

In an Annular Linear Induction EM Pump (ALIP), the traveling magnetic field of the stator induces a current in the fluid; the resultant axial force on the fluid induces a directional flow.

ASTRID uses “matrix method” to solve Maxwell’s equations in a series of mesh calculations. But correction factors for various fringing fluxes and stator ends result in an empirical outcome that requires improvement.





End effects in EM Pumps

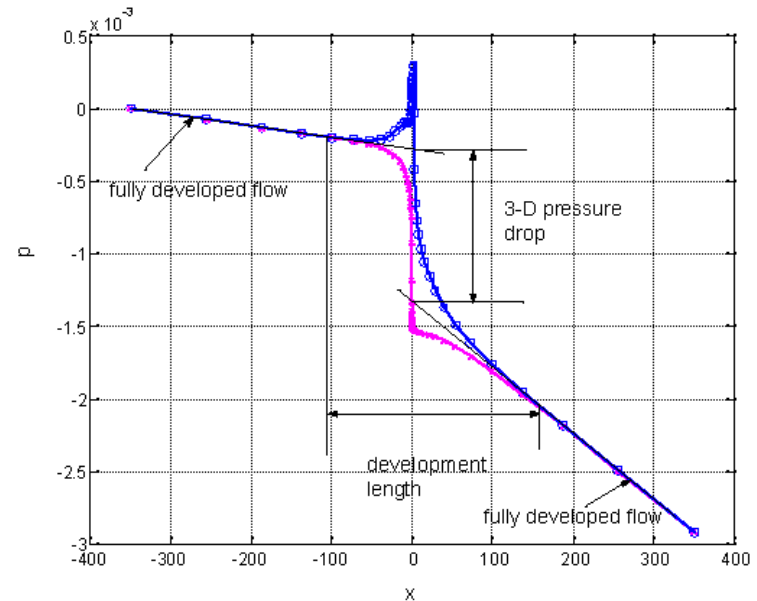
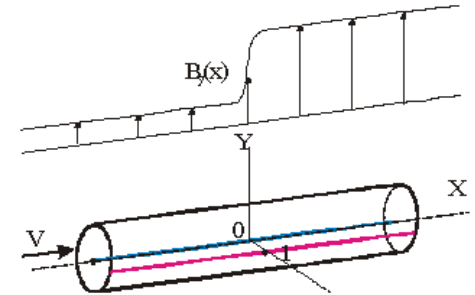
Three dimensional currents are generated in regions where conducting fluids flow through spatially varying magnetic fields

These 3-D currents interact with the magnetic field, thus producing additional MHD pressure drop

Simple methods to account for the "end effects" or pressure losses at the ends of the pump, such as reducing the calculated value by a factor of $(N-1)/(N+1)$, where $N = \#$ of poles, are no longer adequate

Pressure at $y = 0$:

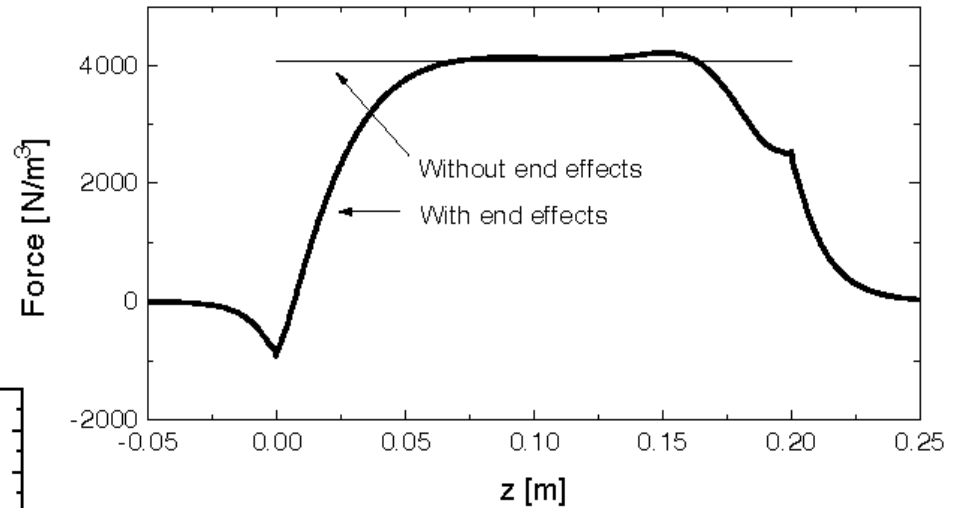
- along the duct axis (blue; circles)
- along the wall at $z=1$ (pink; crosses)



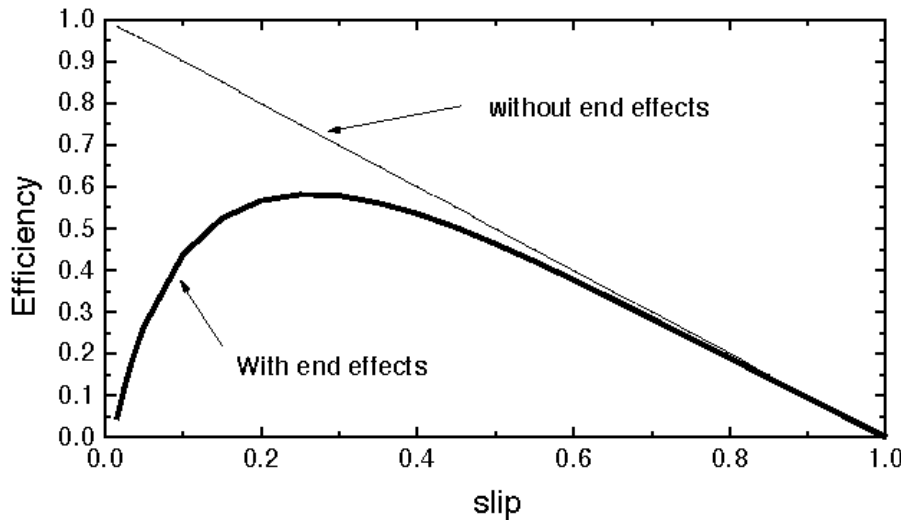


EM Pump End Effects

Ignoring end effects in ALIPs results in over-estimating pressure rise



Ignoring end effects in ALIPs results in over-estimating pumping efficiency



RC-2.2 Electromechanical Pumps

- **The objective of this project is to analyze the impact of end effects on the magnetic field and pump efficiency of current SFR EM pump designs. The project will also consider coupling results obtained from EM pump performance analyses with modern CFD modeling techniques.**