



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Nuclear Energy University Programs (NEUP) Fiscal Year (FY) 2017 Annual Planning Webinar

**Advanced Reactor Components
Integrated Research Project**

**Codification of Compact Heat Exchanger Usage for
Nuclear Systems**

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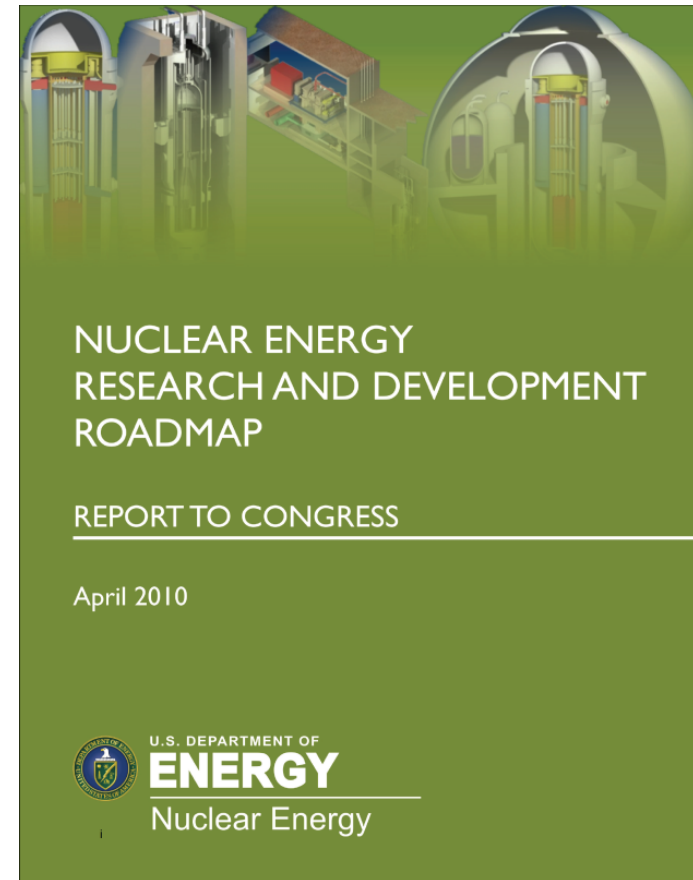
Structural Materials Are Critical for Advanced Nuclear Reactors

- **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)**
 - **Salt Cooled High Temperature Reactors (MSR & FHRs)**
 - **Lead and Lead-Bismuth Cooled Reactors (LFRs)**
- **Structural materials must perform over design lifetimes for pressure boundaries, reactor internals, heat transfer components, etc.**
- **Performance of structural materials for the long times, high operating temperatures, and environments required is being examined under the Advanced Reactor Technologies (ART) Program**



ART Program Supports Advanced Reactor Development

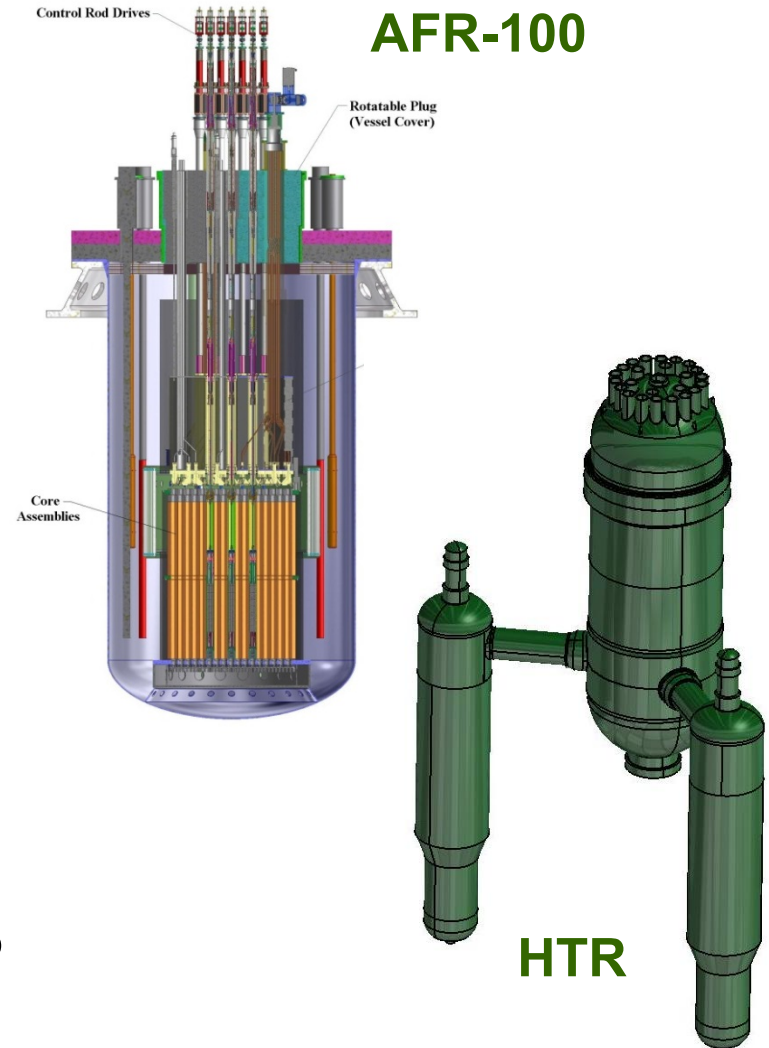
- **ART R&D supports multiple high-level objectives identified in the 2010 Nuclear Energy R&D Roadmap (2 & 3)**
 - (2) Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals
 - (3) Develop sustainable 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**
 - 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**
 - 625MWt/315MWe, 750°C outlet temperature to steam generator, plant life (60 years)
- **Advanced high temperature reactors cooled by liquid lead and salt are also being considered**



High Temperature Reactors May Use Advanced Energy Conversion Systems and Compact Heat Exchangers (CHXs)

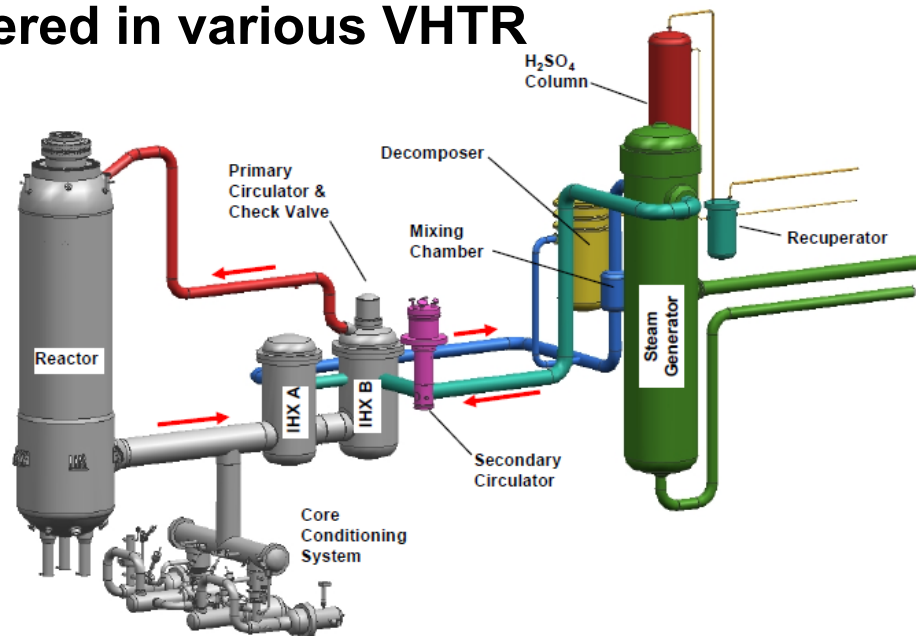
- **Brayton cycle systems based on $s\text{CO}_2$ improve thermal efficiency and operating economy**
- **Compact, high efficiency, $s\text{CO}_2$ recompression closed Brayton cycle energy conversion system that operates at a moderate high temperature (about 550°C) and 20MPa is being developed and demonstrated at Sandia National Laboratories**
- **Use of CHX to couple SFR plant to a Brayton cycle energy conversion system, instead of a steam generator, minimizes reactor and plant footprint and reduces capital costs**
 - e.g., AFR-100 design
- **Potential higher temperature applications ($\sim 750^\circ\text{C}$) could couple Brayton cycle system to salt-cooled or lead-bismuth-cooled reactor using CHXs**



Sandia National Laboratories

CHX Applications for VHTR and Hydrogen Production

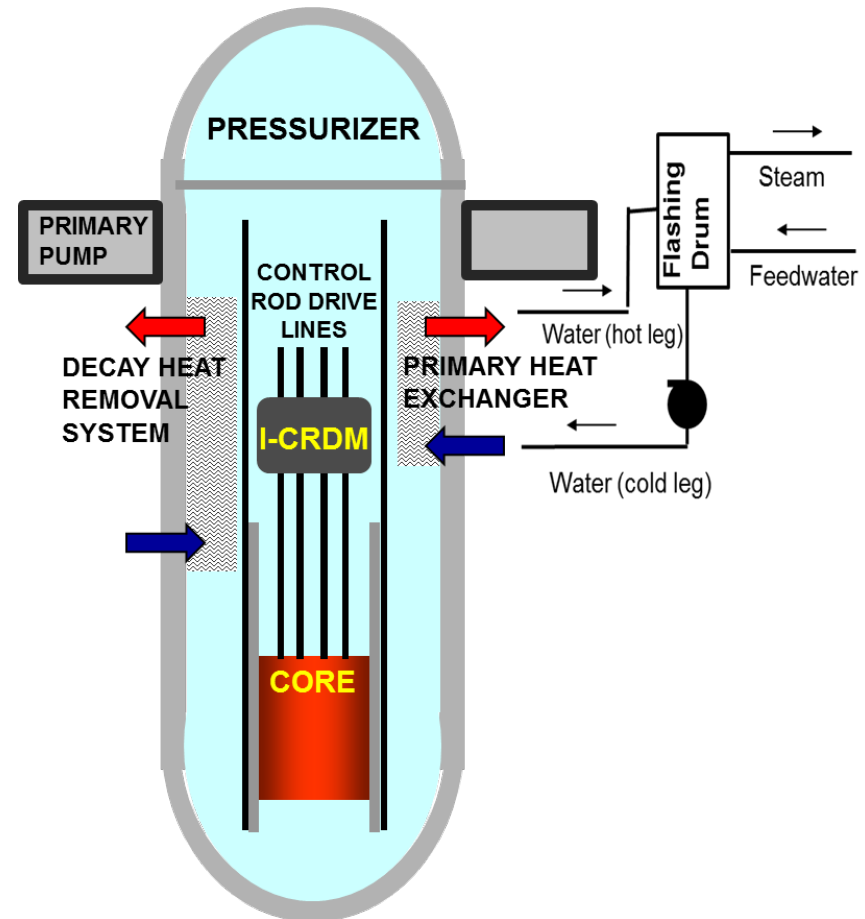
- Due to its compactness, the use of CHXs to transfer heat between primary and secondary heat transport systems, instead of traditional shell-and-tube intermediate heat exchanger, also reduces capital cost in VHTR systems
- Use of CHX to transfer reactor heat from the secondary heat transport system to the hydrogen loop for hydrogen production has also been considered in various VHTR design concepts
- Temperatures are higher, around 900 to 950°C but pressure differential across the CHX is low



CHXs Are Also Critical to Some Advanced, Integral LWR Designs, e.g., I²S-LWR Reactor Integral Configuration

Integral Inherently Safe Light Water Reactor (I²S-LWR)* Layout contains all primary circuit components located within the RPV

- Core
- Internals
- Control rods & drive mechanism
- Pressurizer integrated in the upper vessel head
- Primary and decay heat removal heat exchangers
- **Requires high power density (micro-channel type) primary HX (mC-PHX) plus external steam flashing drum**



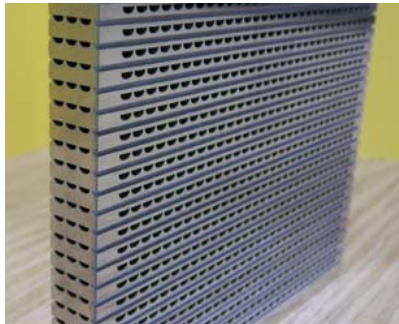
*Developed as part of Georgia Tech IRP 2013-2016



Micro Channel and Plate Fin Are Candidate CHX Types

■ Diffusion bonded micro channel

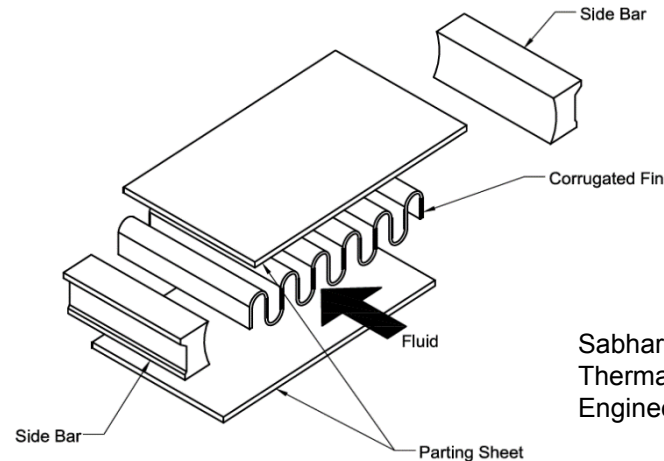
- Series of bonded thin plates or shims
- Chemically etched micro channels
- Integral flow distribution channels
- Good for high pressure



Southall et al., ICAPP '08

■ Diffusion bonded or brazed fin CHX

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



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

■ Composite of both types proposed for sCO₂ CHX

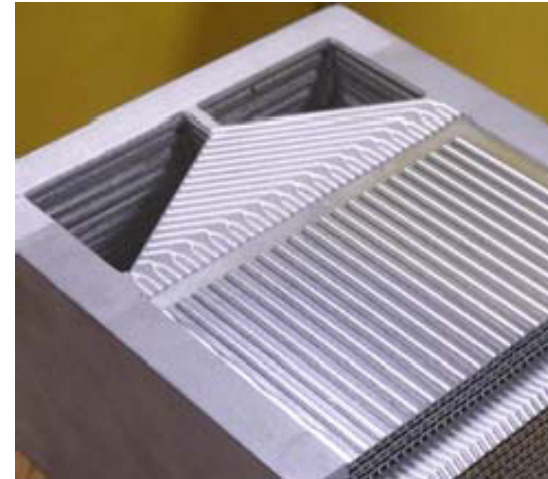
- High pressure sCO₂ in micro channels
- Low pressure sodium in plate fin configuration



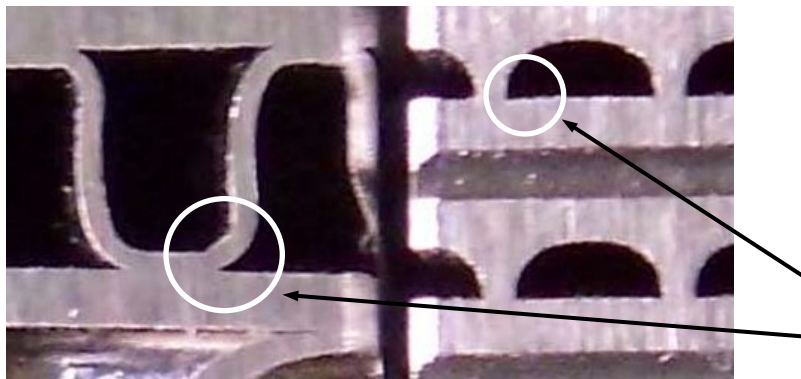
Southall et al., ICAPP '10

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



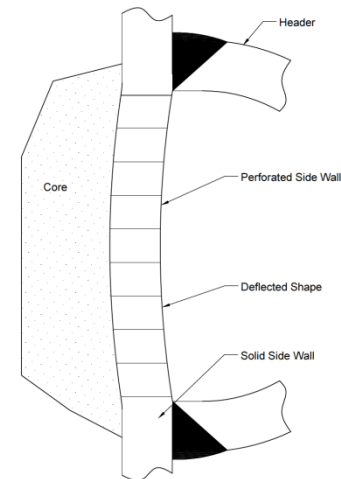
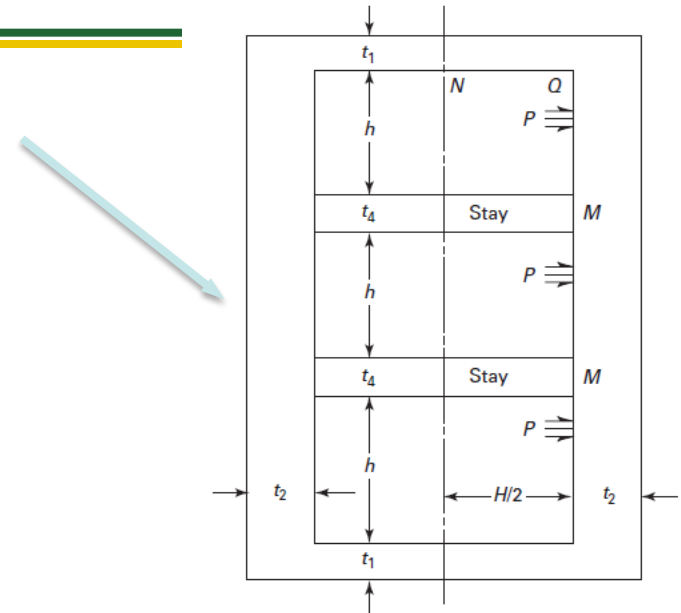
Southall et al., ICAPP '09

- **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 or cyclic loading
 - Does not adequately address elevated temperature bending stress/strain redistribution due to creep
- **Sec III elevated temperature design analysis (Div 5, Subsec HB, Subpart B) 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 HBB methods



**Complex thermal
mechanical
interactions at
header location**



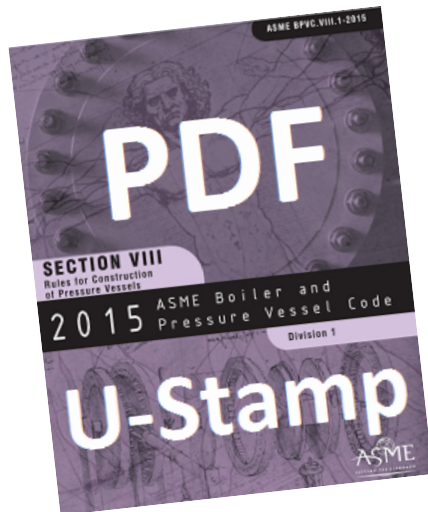
ASME Code Rules for CHXs Are in Sec VIII, but Not in Sec III for Nuclear Construction

- **Requirements for diffusion bonding (or diffusion welding) of microchannel heat exchangers in Section VIII, Div 1 in 2011 as Mandatory Appendix 42**
 - Appendix 42 specifies bonding procedures and performance qualification tests similar to requirements in Section IX
- **Design, fabrication and inspection requirements for diffusion bonded microchannel heat exchangers provided in 2009 in Code Case 2621-1**
 - Alloys for construction are limited to:
 - SA 240, Type 304L stainless steel
 - SA 240, Type 316L stainless steel
 - SA 240, 2205 stainless steel
 - Bi-metallic bond joints between dissimilar alloys are prohibited
 - The vessels cannot be used for “lethal service;” that is, in service containing lethal substances
- **The alloys listed in Code Case 2621-1 are not the same as those allowed for Class A construction in Section III, Div 5**

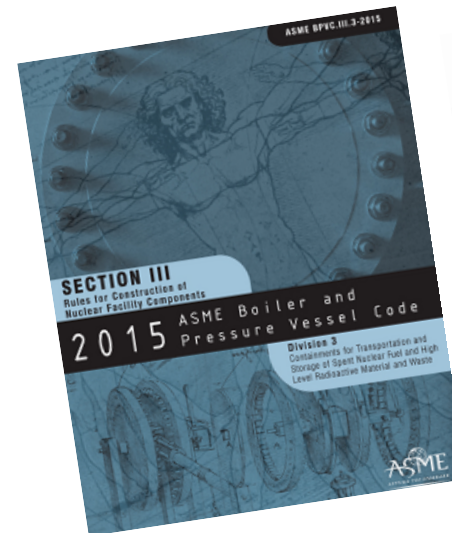


N-Stamping of CHX for Nuclear Service is Needed for Deployment

- Currently, CHX designed to the Section VIII Div 1 and Code Case 2621-1 can be code-stamped (U-stamp) by certificate holders
- However, nuclear code stamp (N-Stamp) is not available for CHXs due to a lack of Section III rules and procedures
- Establishing rules and procedures for Section III to allow N-stamping for CHXs is essential for the deployment of CHXs in advanced high temperature reactor systems



U Stamp



N-Stamp



Section III Rules and Procedures for CHXs Must Be Developed for Their Use in Nuclear Construction

- **Additional welding development for diffusion bonding (DFW) to establish details of the current and augmented welding procedures**
- **Development of design rules and design analysis methods for CHX in nuclear service (outside IRP scope, currently being considered by three current FY16 NEUP awards)**
- **Design and fabricate (i) representative CHX models, or a smaller than full-scale section of the CHX core, and (ii) selective scaled CHX system (including CHX core, sidewalls and headers)**
 - **Develop innovative testing methods to generate data to validate the design rules and design analysis methods under development by FY16 NEUP projects**
- **Develop innovative methods and technology as a basis for post-construction examination and testing of CHXs**

Section III Rules and Procedures for CHXs Must Be Developed for Their Use in Nuclear Construction (cont)

- **Develop innovative in-service inspection methodologies applicable to CHXs to support nuclear service operations**
- **Explore potential for fouling of microchannels based on service experience of current Section VIII vessels and on testing**
 - **Explore methods for cleaning microchannels and test the methods**
- **Address inspection issues during service life for clogging, leakage, and other conditions that are adverse to performance**
 - **Consideration during the design and construction process for methods for such inspections during service life should be explored and tested**

Interaction and Collaboration

- Interaction with ongoing NEUP projects on CHX design rules and design analysis methodologies development is important for test task
- Collaboration with ASME Code subject matter experts is highly encouraged
- Potential for interactions with existing CHX manufacturers is strong and would be considered very valuable to the overall IRP effort

Reference: 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
(<http://info.ornl.gov/sites/publications/Files/Pub57987.pdf>)

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