SAND2018-1877R

Advanced Reactor Technology/Energy Conversion Project FY17 Accomplishments

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Purpose: The purpose of the ART Energy Conversion (EC) Project is to provide solutions to convert the heat from an advanced reactor to useful products that support commercial application of the reactor designs.

Description: The EC project in FY17 was focused on the application of heat from a Sodium Fast Reactor (SFR) to a supercritical carbon dioxide (sCO_2) Brayton power cycle. Maximum turbine inlet temperature is 550° C and expected thermal efficiency is 45%. The current state of the sCO_2 technology is a laboratory scale demonstration of a sCO_2 Recompression Closed Brayton Cycle (RCBC) at 250 kWe. To achieve commercial interest, R&D is necessary to reduce the technological and economic risks for: materials that can handle the temperature and pressures without serious corrosion from the sCO_2; component technology that demonstrates scalability to commercial levels; system level testing to demonstrate performance and develop operating procedures; technology readiness level (TRL) risk management, systems engineering and economic models guided by a technology roadmap to support early engagement with industry to leverage knowledge and transfer technology.

Strategy: Perform basic and applied R&D to develop the sCO_2 RCBC to support the energy conversion of the SFR by 2030 at commercial off-the-shelf scale. To that end the EC projects are:

- Leading energy conversion collaboration efforts between the offices of NE, EE and FE; supporting concurrent engineering and integrated project management.
- Developing and testing materials suitable to supporting the sCO_2 RCBC for the SFR for the lifetime of the plant.
- Developing heat exchangers for the SFR coupling the sodium to the sCO_2 and understanding the consequences of sodium and sCO_2 interactions.
- Developing the sCO_2 components for the RCBC demonstration: including turbines, compressors, recuperators, seals, bearings, control valves, control systems, high speed electrical generators, and waterless heat rejection.
- Testing sCO_2 components within a complete system to investigate performance trades, assess effects of design features such as fluid additives, and develop operating procedures.
- Developing and maintaining technology roadmaps, system engineering and economic models, science based steady state and dynamic models for specifying requirements and developing operating procedures, tracking results, and planning futures.

Goal Setting: During FY14, Sandia National Laboratories set a goal to help establish a technology roadmap for the commercialization of the sCO_2 Power Cycle:

"By the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology."

This goal established a focus for the activities of the ART/EC Project and was implemented into the "sCO_2 Brayton Cycle: Roadmap to Product Commercialization" in FY16. The roadmap is a key deliverable of the Management and Integration work package, and is a living document that captures innovations and constantly evaluates technological readiness levels. The "systems engineering model for ART Energy Conversion" was developed to incorporate Project Management Planning, System Engineering Modeling, and Technology Readiness Assessment in a concurrent approach to the commercialization goal.

The Roadmap helped define the work packages of the ART/EC project, funded by a cross-cutting initiative Supercritical Transformational Electrical Production (STEP). The STEP program defined a 5-year plan for a 10 MWe Pilot Facility constructed by industry to fulfill the Goal. The facilities of the ART/EC program (at Sandia and Argonne) were transformed into Component Development Platforms to reduce the technical risks of the Pilot Facility.

The FY17 focus of the EC Project continued with the SFR application and the following activities:

- Technology Roadmap/Project Management Plan/System Engineering Model completed
  - Systematic Risk Identification and Retirement from components to system configuration.
- Commercialization of the sCO2 system components to a higher TRL level to support sCO2 system commercialization by 2030
- Operation Recompression Closed Brayton Cycle at a turbine inlet of 550C
  - Brayton Development Platform working with industry to achieve high TRL components for system integration.
- Development of Intermediate Sodium to CO2 Heat Exchanger (Primary Heat Exchanger)
  - Sodium Drain, Fill, Plug in PCHE
  - Sodium CO_2 interactions

These activities attempted to address and advance the TRL level of components of the RCBC to 550°C and begin to move to 750°C turbine inlet temperature by:

- Engaging in Federal Business Opportunities (FBO) to Cooperative Research and Development Agreement (CRADA) Processes, yielding Lab/Industry collaborations with patents, copyrights, and national awards
- Sandia procuring the world's first 1 MW turbo compressor at 750°C though Design/Build process
- Standing up 8 additional test configurations in addition to the RCBC Development Platform to address:

- Heat Exchanger (SEARCH© design tool), optimized Printed Circuit Heat Exchanger Design
    - Heat Exchanger test rig
    - Particle Imaging Velocimetry (PIV), flow distribution measurement
    - sCO_2 Seals test rig
    - sCO_2 Bearings,
    - Turbocompressor test rig
    - Dry Heat Rejection (Tall Loop), waterless power production
    - Parallel Compression, combining compressor fluid output under different conditions

Another key deliverable in FY17 was support of "Industry Days" workshop at Argonne. Workshop documentation identifies:

- There is a range of opportunity for collaboration in component development across a range of applications.
- The biggest challenge for technology development is in economics. Top research priorities were identified.
- The primary challenges towards commercialization are:
    - Proving reliability of the system.
    - Meeting standards of utility.
    - Understanding all the risks associated with writing a contract between vendor and utility.
- Industry interest is tangible, but engagement needs to be supported both financially and operationally. Some areas to consider include:
    - Easing collaborations between industry and the national laboratories,
    - Facilitating information sharing that protects commercial IP,
    - Supporting technology development economically and via policies and programs

The top R&D needs were identified and prioritized as shown in Figure 1.

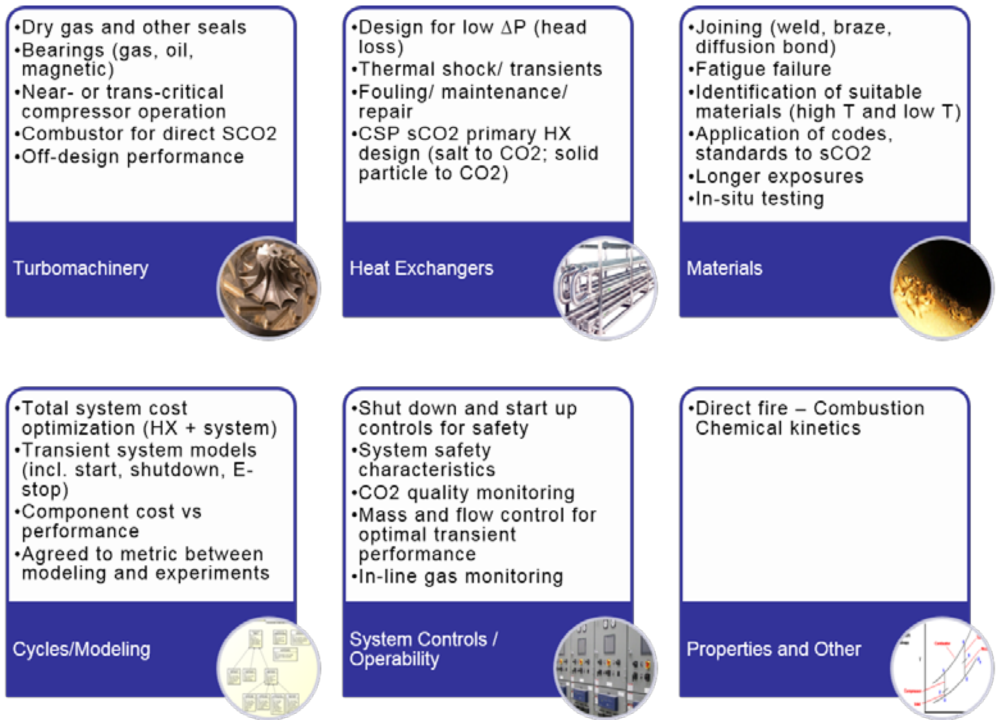

Figure 1. Industry Days Top R&D Needs.

Figures 2,3,4 summarize the technical findings in FY17 for the components of the RCBC.

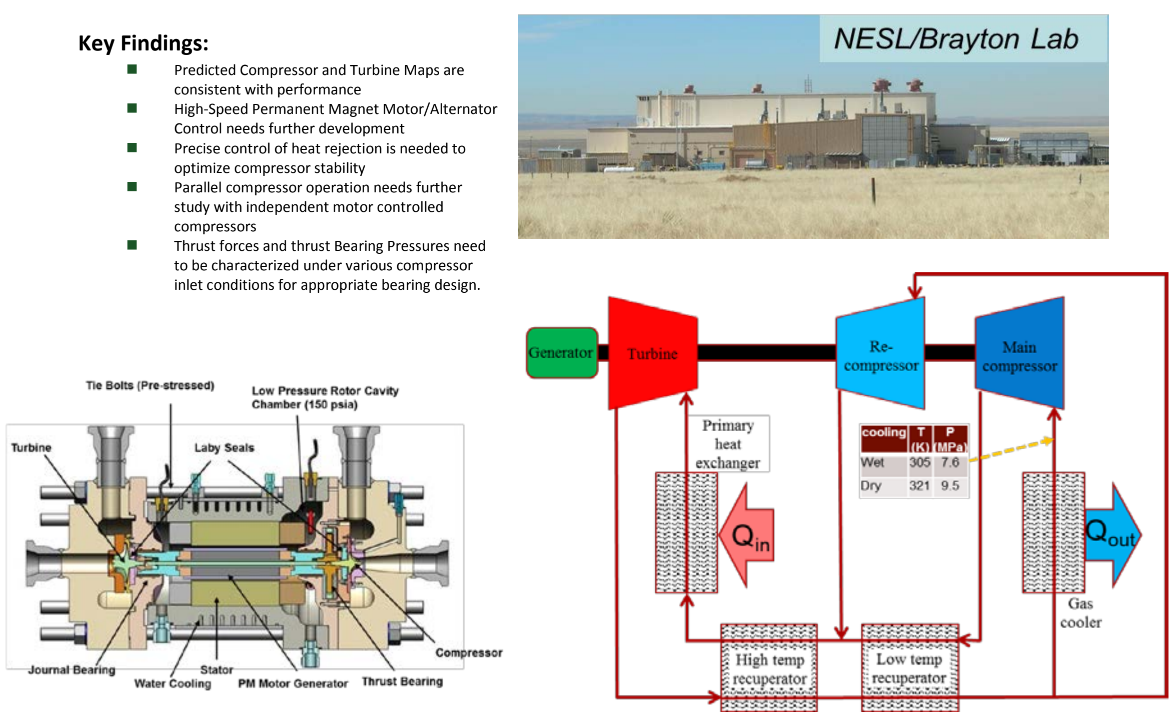

Figure 2. Key Findings of R&D on RCBC Testing.

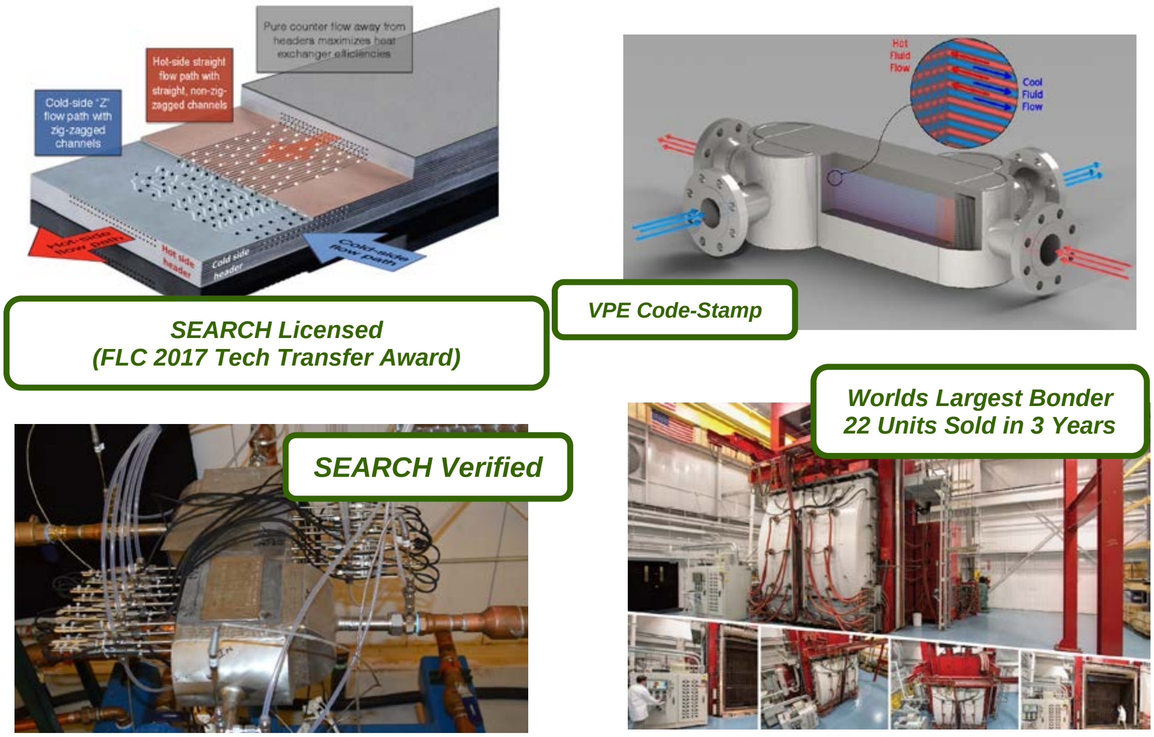

Figure 3. Key Results of PCHE R&D

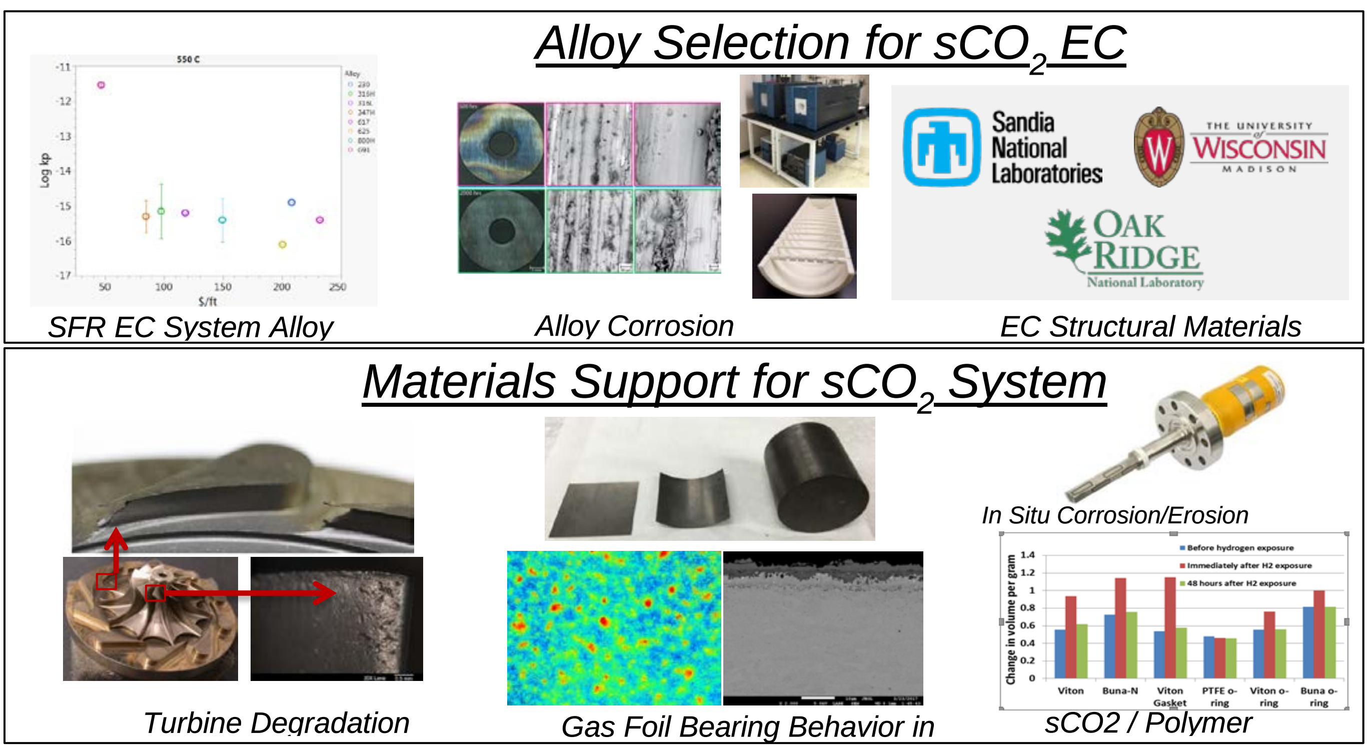

Figure 4. Key Results of sCO_2 Materials R&D

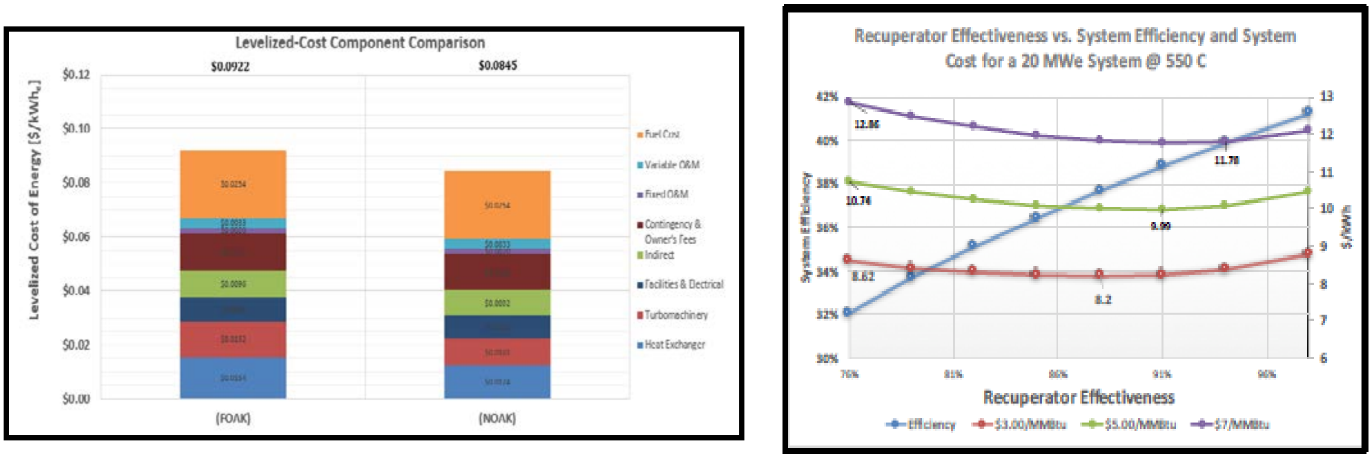

Figure 5. Results of Brayton LCOE Economics Model.

Figure 5 demonstrates the results of the Brayton LCOE Economics model. FY17 work is focused on the integration of an existing RCBC Evaluation and Trade Studies (RETS)© modeling tool with the Brayton LCOE economic tool to provide a much more rigorous estimation of the likely LCOE for Brayton systems. Preliminary results show how the new tool can provide insights. The example above shows the trade-offs between increased recuperator cost, system efficiency, and LCOE and suggests that optimal recuperator effectiveness varies based on fuel prices.

A schematic of the Plant Dynamics Code (PDC) being developed at Argonne National Laboratory in shown in Figure 6. This code has been specifically developed for both steady-state and transient performance analysis for sCO_2 cycles as well as cycle control strategy as well. The PDC targets specific features of the cycle: operation near the critical point of sCO_2 in the compressor and incorporated real CO_2 properties in the heat exchangers and turbomachinery without ideal gas assumptions.

In FY17, the PDC was used to characterize innovative features of the cycle with dry heat rejection, and cascaded cycles. The code was validated using the ANL PCHE heat transfer testing facility, the SNL Simple Brayton Loop, the SNL RCBC, and the Bechtel Marine Integrated Small-scale Test.

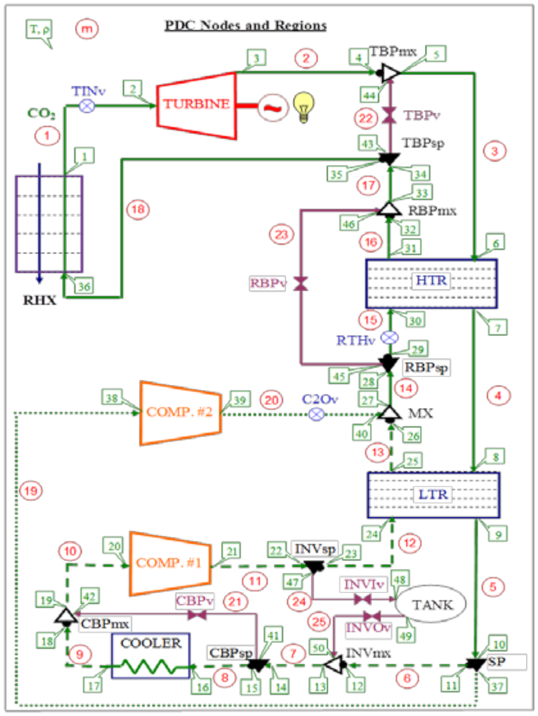

Figure 6. Schematic of the Argonne Plant Dynamics Code

sCO_2-Na reaction experiments continued in FY17 in open pool and in a semi-circular channel mock-up to investigate the self-sealing phenomena previously observed. At temperatures above 300°C, a small leak of high temperature sCO_2 into liquid sodium self-plugs in a very short time. The onset of the leak can be detected acoustically and stops when the leak plugs. Twelve sCO_2-Na tests were conducted, including in open pool and the channel mock-up. Prototypic bounding temperatures and pressures were recorded to support self-plugging model development.

Also studied in FY17 was nitrogen-sodium and inert gas-water tests in support of alternative power cycles. The apparatus is shown in Figure 7.

Figure 7. sCO2-Na Heat Exchanger Integrity R&D

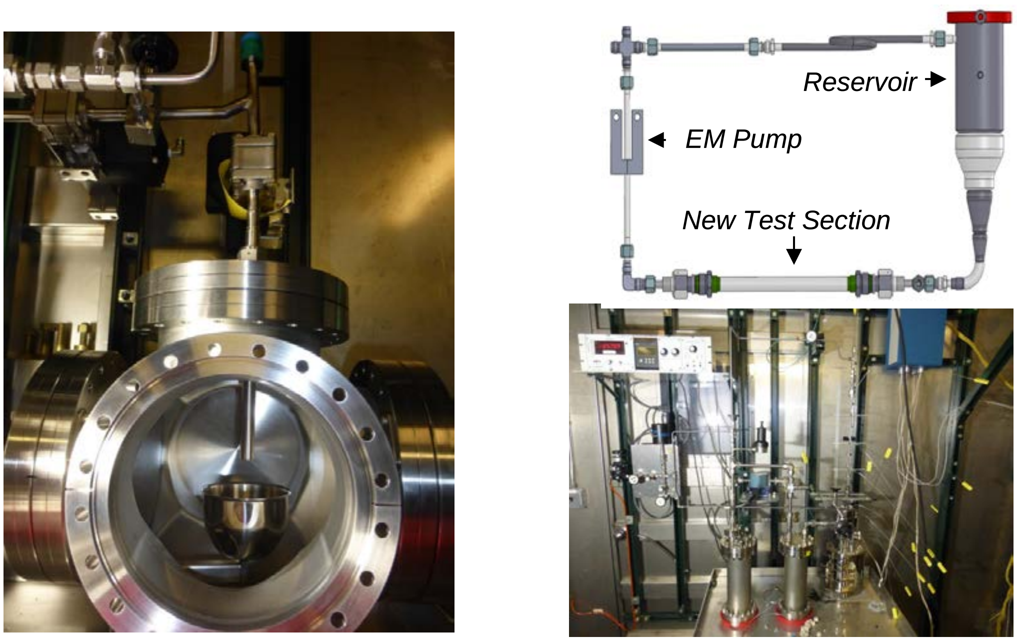

Figure 8. SFR Intermediate Heat Exchanger Development R&D

In FY17 three experiment facilities (Figure 8) were assembled to obtain data essential to the reliable design of intermediate sodium-to-CO_2 heat exchangers, a critical requirement for the sCO_2 Brayton cycle to be successfully deployed together with SFRs.

Complete assembly of sodium Draining and Refilling facility was needed to conduct sodium draining tests. The test aimed to determine lower limit on sodium channel size in compact heat exchangers to drain sodium in the required short timescale, prevent sodium bridges across the channel from being left inside of the sodium channels, and provide data for model validation. For the SFR, in the event of detection of sodium leakage or sodium fire, deliberate shutdown and draining of sodium -from intermediate sodium loop into dump tank- is required to minimize released sodium mass. The requirement is to drain intermediate sodium loop in fifteen minutes implying that sodium-to-CO_2 heat exchanger must be drained even more quickly. This requires orientation of the heat exchangers with sodium channels vertical or having significant vertical component.

If air ingresses the drained loop through the leakage site, then sodium remaining inside of the heat exchanger channels could be oxidized forming sodium oxide, Na_2O, which remains solid up to 1275°C. Worst case would be the retention of sodium bridges heat exchanger sodium channels and oxidizes forming solid plugs. Channels would be blocked and cannot be refilled with sodium. Sodium oxide plugs can be dissolved out by repetitively washing with hot purified sodium but that process can take a long time (weeks or months) making it impractical. Thus there is a need to assure that heat exchanger design promotes efficient draining, and precludes retention of sodium bridging heat exchanger sodium channels.

Activities in FY17 were limited to reconstruction of the apparatus to allow plugging to occur only in the test sections, control of oxygen content in the sodium using cold traps, and new electromagnetic pumps and flow meters to handle the larger non-test sections.

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