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UPDATE ON UNITED STATES ADVANCED ULTRA-SUPERCRITICAL COMPONENT TEST PROJECT FOR 760°C STEAM CONDITIONS

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ABSTRACT

Following the successful completion of a 15-year effort to develop and test materials that would allow advanced ultra-supercritical (A-USC) coal-fired power plants to be operated at steam temperatures up to 760°C, a United States-based consortium has been working on a project (A-USC ComTest) to help achieve technical readiness to allow the construction of a commercial scale A-USC demonstration power plant. Among the goals of the ComTest project are to validate that components made from the advanced alloys can be designed and fabricated to perform under A-USC conditions, to accelerate the development of a U.S.-based supply chain for key A-USC components, and to decrease the uncertainty for cost estimates of future commercial-scale A-USC power plants. This project is intended to bring A-USC technology to the commercial scale demonstration level of readiness by completing the manufacturing R&D of A-USC components by fabricating commercial scale nickel-based alloy components and sub-assemblies that would be needed in a coal fired power plant of approximately 800 megawatts (MWe) generation capacity operating at a steam temperature of 760°C (1400°F) and steam pressure of at least 238 bar (3500 psia).

The A-USC ComTest project scope includes fabrication of full scale superheater / reheater components and subassemblies (including tubes and headers), furnace membrane walls, steam turbine forged rotor, steam turbine nozzle carrier casting, and high temperature steam transfer piping. Materials of construction include Inconel 740H and Haynes 282 alloys for the high temperature sections. The project team will also conduct testing and seek to obtain ASME Code Stamp approval for nickel-based alloy pressure relief valve designs that would be used in A-USC power plants up to approximately 800 MWe size.

The U.S. consortium, principally funded by the U.S. Department of Energy and the Ohio Coal Development Office under a prime contract with the Energy Industries of Ohio, with co-funding from the power industry participants, General Electric, and the Electric Power Research Institute, has completed the detailed engineering phase of the A-USC ComTest project, and is currently engaged in the procurement and fabrication phase of the work.

This paper will outline the motivation for the effort, summarize work completed to date, and detail future plans for the remainder of the A-USC ComTest project.

INTRODUCTION

Coal has been used extensively as a primary fuel source for electric power generation, both in the United States and throughout much of the world. As recently as 2007, more than 50% of all electric power in the U.S. was derived from coal- fired power plants. [1] Historically low natural gas prices, and declining costs of renewable generation in recent years, have been driving factors in the reduction of coal-fired power generation in the U.S., however, coal is expected to remain a significant factor for power generation in the U.S. through 2050. [2] Globally, coal remains the largest source of electricity generation in 2018 (at 38%), but competition from solar photo voltaic, wind and natural gas is projected to reduce the fraction of electricity generated by coal through 2040. [3] These market pressures, combined with the traditionally higher emissions of greenhouse gases and other pollutants (per unit of energy production) than other fuels such as natural gas, have driven initiatives to seek higher cycle efficiency for advanced coal-fired power generation options. The amount of CO_2 produced when a fuel is burned is a function of the carbon content of the fuel. The heat content is mainly determined by the carbon and hydrogen content of the fuel. Heat is produced when carbon and hydrogen combine with oxygen during combustion. Natural gas is primarily methane (CH4), which has a higher energy content per carbon atom, due to the higher hydrogen content, relative to coal. Thus, natural gas has a relatively lower CO_2 mass emissions rate, on a per unit of energy basis, compared to coal. This inherent flue characteristic, combined with more stringent air quality regulations, poses a unique set of challenges for the future of coal as a sustainable and viable fuel source. Since the cycle efficiency of a steam power plant is directly related to the steam temperature and pressure, advanced ultra-supercritical (A-USC) steam cycles have the potential to improve cycle efficiency, reduce fuel costs, and significantly reduce greenhouse gas emissions. Current research, development, and demonstration efforts are focused on enabling the construction of advanced ultra-supercritical plants, operating with steam temperatures as high as 1400°F (760°C) and steam pressures up to 5000 psi (35 MPa), which can potentially increase cycle efficiencies to greater than 47% percent HHV (higher heating value), and reduce CO_2 emissions by roughly 25%, compared to that of the existing U.S. fleet. [4]

In the U.S., advanced materials research has been conducted by a consortium of boiler and turbine manufacturers, the U.S. Department of Energy (DOE) Albany Research Center, and Oak Ridge National Laboratory, through the “Boiler Materials for Ultra-Supercritical Coal Power Plant”, and “Materials for Advanced Ultra-supercritical Steam Turbines” projects, which have been co-funded by the DOE, through the National Energy Technology Laboratory (NETL), along with the Ohio Coal Development Office (OCDO), managed by Energy Industries of Ohio (EIO), and technically directed by the Electric Power Research Institute (EPRI). [5, 6] Figure 1 provides a summary of the history of the A-USC materials program in the United States. Since 2001, this effort has been aimed at evaluating the high temperature mechanical properties and oxidation/corrosion behavior of advanced alloy systems, and developing fabrication practices for use of these materials in an A-USC plant. In 2015, the focus shifted from materials testing to component testing (ComTest Project). In 2018, Phase II of ComTest was initiated, which is focused on facilitating the fabrication, testing, and supply chain validation for key full-scale A-USC components, needed to support commercial scale demonstration of the technology, with steam temperatures up to 1400°F (760°C), yielding efficiency up to 47% based upon higher heating value (HHV). The HHV efficiency depends on coal moisture content, while efficiency based upon lower heating value (LHV) is independent of coal moisture content. Therefore, efficiency based upon HHV can be 3-10 percentage points lower than efficiency based upon LHV, as coal moisture can vary from less than 5% to over 50%, depending on coal type.

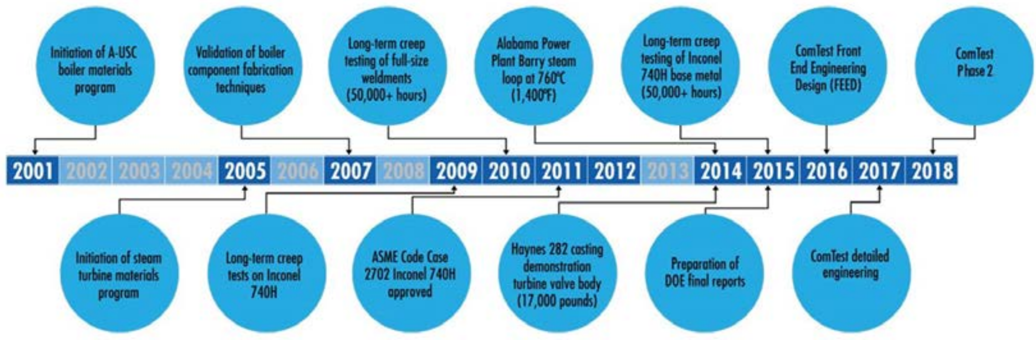

Figure 1: History of the U.S. A-USC Materials Program

The current ComTest project supports the A-USC commercialization roadmap, leading to the design of a commercial scale A-USC demonstration plant in the 2023 timeframe. The earlier DOE-funded A-USC projects have achieved Technology Readiness Levels (TRL) of 5. Completion of the ComTest project will achieve TRL 7, allowing A-USC technology to be ready for full-scale demonstration. [7]

DISCUSSION

Project Objectives

As summarized above, the work by the U.S.-based A-USC consortium through 2015 comprised laboratory scale and pilot scale materials testing. [8] This included installation of air-cooled probes and steam-cooled loops, both of which operated within existing coal-fired utility-scale boilers to evaluate fire side corrosion resistance, and steam side oxidation of candidate material alloys and coatings, under realistic exposure to high temperatures and corrosive coal ash constituents. The consortium also gained American Society of Mechanical Engineers (ASME) Code approval of the Inconel 740 material, successfully cast and extruded the largest high nickel precipitation hardened alloys and developed unique welding techniques. Successful research and development resulted in the selection of high-temperature nickel-based alloy materials and fabrication processes that are suited for power generation applications, with working fluids up to approximately 1472°F (800°C). [5, 6]

As valuable as these accomplishments have been to advance the state-of-the-art in A-USC technology, the scale of these earlier tests were below that required to minimize the risk associated for a U.S. utility to build a multi-billion-dollar A-USC power plant. Earlier plans, considered during Phase I of the ComTest project, had included operational testing at the 10-15 MW scale. [9] However, as the project team (with the help of a utility industry advisory committee) evaluated the needs of the A-USC technology roadmap, and in particular the needs of a commercial-scale A-USC demonstration plant, it became clear that the final risk barriers would be best addressed by conducting full-scale (800 MW) manufacturing and/or fabrication of components and sub-assemblies from an identified, capable U.S. domestic supplier base, rather than constructing a sub-scale operational testing facility. Components for the fabrication demonstration are designed to A-USC steam conditions of 1400°F and 3500 psig, and are full-scale as to pipe and tubing outside diameter and wall thickness, turbine rotor diameter and turbine nozzle carrier (inner shell) thickness.

Consequently, the scope of ComTest Phase II has been defined to meet the following objectives:

- Close the remaining gaps and reduce the risks for manufacturing components from advanced materials for commercial demonstration
- Fabricate full-scale versions of selected components made of nickel-based alloys
- Validate a qualified supply chain, to provide greater cost certainty for components
- Expand ASME code approvals required for A-USC materials and components

Additionally, the work scope of the current project will be applicable to the materials, component fabrication methods, and supply chain validation for other advanced generation high temperature cycles.

The work plan for ComTest Phase II includes fabrication of components that have been identified as being outside of the proven capabilities of the existing supply chain, including:

- Steam turbine rotor forging and nozzle carrier casting components
- Superheater and reheater header and tube assemblies
- Large diameter pipe extrusions and forgings
- Test valve articles to support ASME Code approval

Key fabrication steps required to maintain the components in the field will also be performed and validated, including boiler weld overlays and simulated field repairs. Extensive inspection and quality assurance testing of the components fabricated under this phase will included.

A summary of the key Phase II work scope, associated with each key area, is shown in Table 1.

Table 1. Key Work Scope Areas for ComTest Phase II

Item	**Scope of Work**
Boiler / Superheater	Build 800-MWe sized nickel-based alloy parts of superheater and steam piping system – steam headers, boiler tube assemblies, tube membrane panels and weld overlays, large diameter, thick-wall pipe and fittings up to 25 inch (63.5 cm) OD x 4 inch (10.16 cm) thick wall). Field erection and repair simulation.
Nickel-based Alloy Valves	National Board qualification of scale spring-loaded and power actuated pressure relief valve designs for conditions up to 760°C & 345 bar
ASME Code Cases	Alternate pressure-relief method, flanged fittings, shielded metal-arc weld materials for joining Inconel 740
Steam Turbine	Fabricate commercial-scale nozzle carrier casting (10 tons) and rotor disk forging (20 tons) – both from Haynes 282 alloy

Project Plan and Schedule

The ComTest project has been structured as a two-phase project, with a defined decision point at the end of the first phase. Phase 1, which began in November 2015, served to identify the technology gaps, as well as the scope and cost of required testing. Phase 2, which was awarded by the US DOE in December 2018, is designed to perform an advanced manufacturing effort to complete US-based supply chain validation for full commercial scale (800-850 MWe) A-USC components made of nickel-based alloys, operating at steam temperatures up to 760°C.

The project activities for the current Phase II of the ComTest project have been grouped into six major technical tasks, in addition to project management activities, as follows:

- **Task 1** – Project management and planning
- **Tasks 2-6 –** Phase I activities Completed
- **Task 7** – Procure the A-USC materials that will be fabricated into AUSC components and sub-assemblies in Tasks 8 through 10.
- **Task 8 –** Fabricate A-USC boiler and superheater components and sub-assemblies.
- **Task 9** – Fabricate a cast nickel-based steam turbine nozzle carrier casing (Haynes 282).
- **Task 10** – Fabricate forged nickel-based components for an A-USC steam turbine (Haynes 282) and for an A-USC main and reheat steam piping system (Inconel 740).
- **Task 11 –** Conduct testing and obtain ASME Code Stamp approval for nickel-based pressure relief valve designs that would be used in A-USC power plants up to approximately 800 MWe size.
- **Task 12 –** Develop a testing matrix for more extensive mechanical properties testing and metallurgical examination of the fabricated components fabricated in Tasks 8, 9, and 10.

A variety of advanced materials, which have been technically validated by the earlier US-based A-USC materials research efforts, were selected for component manufacturing, and supply chain validation. The list of materials being used under Phase II, along with the associated component areas, is shown in Table 2.

Table 2. Materials used in ComTest Phase II

Material	**Component Area Used**
Grade 91/92	membrane panels
Haynes 282	tubes, castings, forgings
HR6W	tubes, pipe/header
Inconel 617	safe ends on various tubing
Inconel 740H	tubes, pipes, forgings
Sanicro 25	tubes
SAVE12AD	pipe/header
TP347H and Super 304H	lower temperature zones

The project team structure for ComTest Phase II is shown in Fig. 2. Energy Industries of Ohio (EIO) is the prime contractor, manages the overall project administration and has ultimate reporting responsibility to DOE. Electric Power Research Institute (EPRI) provides the technical project management and is responsible for planning long-term lab scale mechanical properties testing (creep, fatigue and creep-fatigue) on the components fabricated in Phase II. EPRI will also be responsible for ongoing communication with EPRI member organizations, the A-USC Utility Advisory Committee, and the utility industry in general. AECOM will provide engineering services and project schedule oversight to support the project. GE will fabricate and assemble various superheater/reheater components, construct a membrane panel, perform field erection trials (via Potts Welding and Boiler affiliate), and develop field weld procedures and oversee Pressure Relief Valve ASME Code approval activities at their affiliate, Baker Hughes. MetalTek will produce a 21,000-pound turbine nozzle carrier casting. Special Metals (Huntington Alloys Inc.) will provide Inconel 740H raw material for extrusion of pipes and tubes, and perform a triple-melt procedure for producing a Haynes 282 forging billet to be used in making a full scale steam turbine rotor step forging. Special Metals will also fabricate the wye fitting and perform pipe bends and evaluations. Riley Power will develop fabrication and testing methods to support the Procedure Qualification Record (PQR) and Weld Procedure Specification (WPS) of the materials needed for various boiler island components such as steam header stub welding, and will develop weld overlay processes and procedures for use on field weld repairs. The A-USC Utility Advisory Committee consists of representatives from key members of the utility industry who will provide technical oversight and input on the project direction.

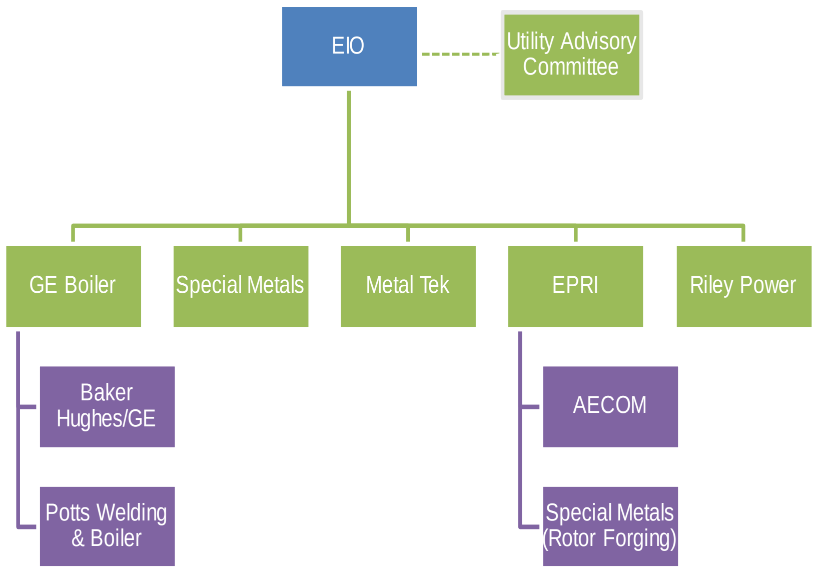

Figure 2. ComTest Phase II Organization Chart

A high-level schedule for the ComTest project is shown in Fig. 3. Project work commenced during late 2015 with Pre-FEED, environmental assessment, and preliminary site selection activities. The FEED study was performed in early 2016, and produced a project capital cost estimate, with an accuracy range of -20% to +30%. The subsequent detailed engineering effort produced a final Phase II cost estimate in early 2018, at which time Phase I concluded, and a decision point was reached. Phase II was officially awarded in December 2018, at which time subcontracts and purchase orders were initiated. The main Phase II fabrication tasks are all scheduled to be under way during 2019. The majority of component fabrication is scheduled for completion during 2020, with the exception of the nozzle carrier casting, which should be completed in 2021. Evaluation and reporting tasks, including the Final Report, are scheduled to be completed by September 31, 2021.

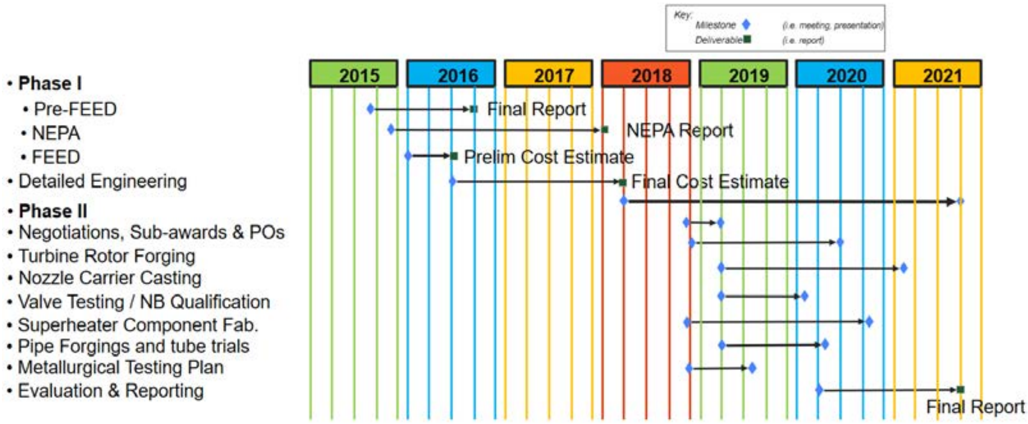

Figure 3: ComTest Project Schedule

Key Components Fabricated in Phase II

Under the current project work scope, key boiler components will be fabricated. These include the full-scale A-USC steam headers, superheater/reheater (SH/RH) subassemblies, and tube membrane panels. The arrangement of the SH/RH assembly, with headers, is shown in Fig. 4. Headers are being fabricated in sizes ranging from 40 cm (16-inch) outer diameter / 7.6 cm (3-inch) wall thicknesses up to 56 cm (22-inch) outer diameter / 9.4 cm (3.7-inch) wall thickness from the following alloys: Inconel 740H, HR6W and SAVE12AD. SH/RH subassemblies will be fabricated from the following alloys: Inconel 740H, H282, HR6W, Sanicro 25, TP347H, and Super 304H. Alloy 617 will be used as the safe end attachment on various tube combinations as needed for post weld heat treatment compatibility.

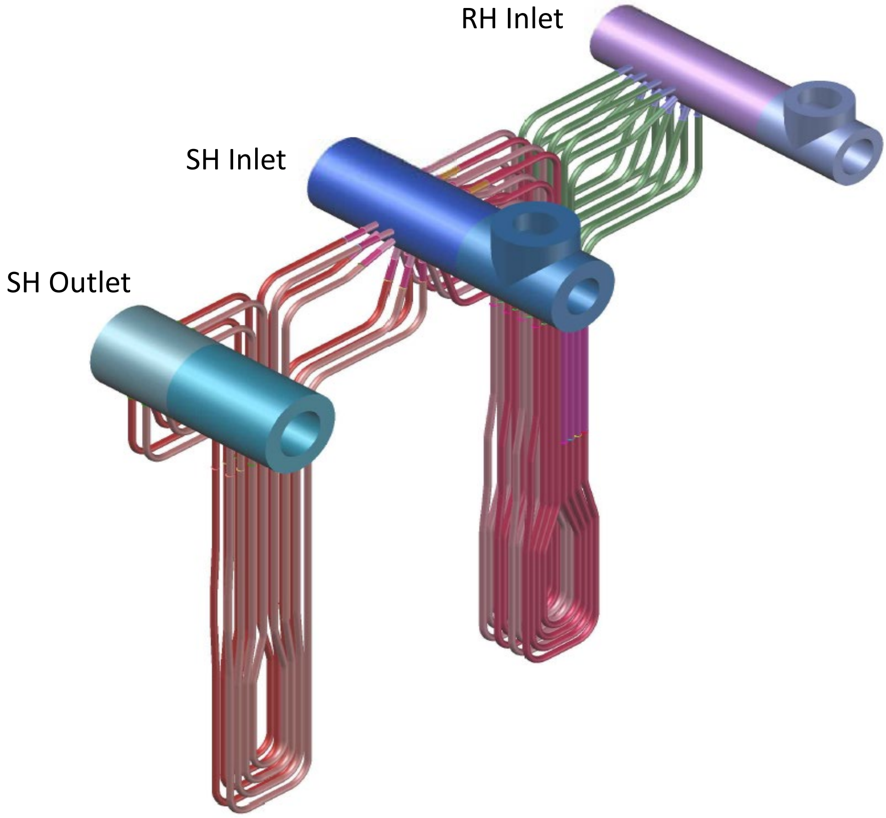

Figure 4: ComTest Superheater-Reheater Assembly (courtesy of GE)

The nozzle carrier has been identified as a key component of the steam turbine, as shown in Fig. 5. The complex nozzle carrier casting will be 10 tons of Haynes 282 alloy material, for only a representative half of the lower section, as identified in Fig. 6. This component will demonstrate the production readiness and capability of the U.S. foundry supply chain for producing large complex castings made from H282 alloy. Additionally, the team will produce a 91.4 cm (36-inch) diameter triple melt Haynes 282 alloy ingot of approximately 13,600 kg (30,000 lb.), This ingot will be used to fabricate a 305 cm (10-foot)-long A-USC steam turbine step rotor forging.

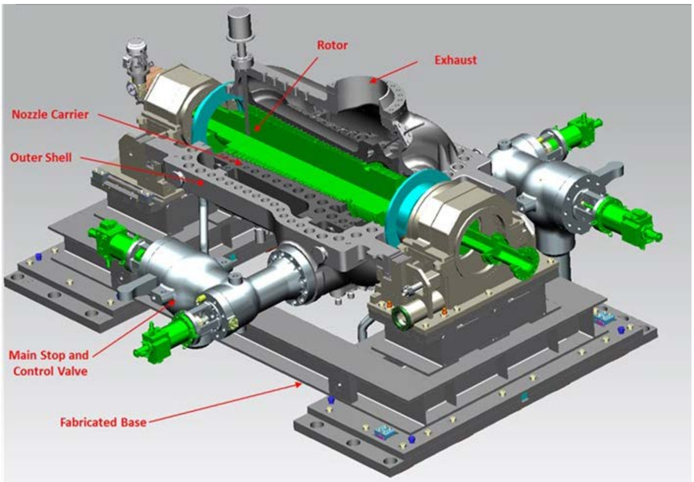

Figure 5: A-USC Steam Turbine - Showing Nozzle Carrier (courtesy of GE)

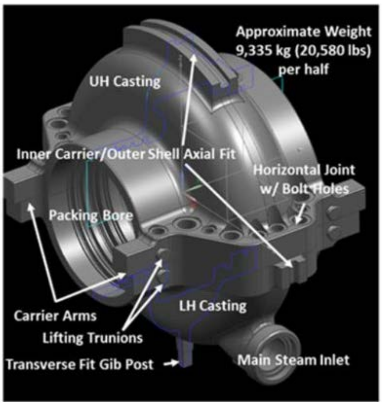

Figure 6: Trial Casting will be Lower Half of Nozzle Carrier (courtesy of GE)

Work Completed Under Phase I

Project activity under ComTest Phase I was executed in the period of November 2015, through March 2018. As Phase I progressed, data from other sources enabled the participating boiler and steam turbine equipment manufacturers to determine that it would not be necessary to build and operate a test facility to demonstrate sub-scale (10-15 MW size) A-USC components, including superheater and steam turbine. Instead, it was determined that a full-scale (800-850 MW size) component fabrication and supply chain development and validation project would be better suited to advance the A-USC technology, and close the gaps required to achieve commercial scale demonstration. Specific accomplishments during this phase included:

- Evaluated multiple potential host sites for test facility
- Identified viable host sites in the U.S. (Ohio and Alabama)

- Completed Pre-FEED and FEED tasks
- Optimized project scope – Closed project budget gap
- Prepared preliminary capital cost estimates for A-USC test facility
- Worked with suppliers to develop and validate U.S.-based supply chain
- Determined that operational testing of the steam turbine and the A-USC superheater was not required
- Revised scope of Phase II to focus on full-scale component manufacturing capability readiness
- Completed Detailed Engineering and cost estimate effort for revised Phase II scope

Current Status of Phase II Work

The Phase II work scope is designed to complete an advanced manufacturing and fabrication effort to complete US-based supply chain development and validation for full commercial scale (800-850 MWe) A-USC components made of nickel-based alloys, operating at steam temperatures up to 760°C. This work is scheduled to continue through September 2021. ComTest Phase II was officially awarded by DOE on December 12, 2018, and a Phase II kickoff meeting was held with DOE on March 4, 2019. The project team has submitted the final version of the Phase I Topical Report, which will be included as part of the overall project final report. An updated Project Management Plan has been completed and accepted by the DOE. Key subcontracts have been executed, including those between Energy Industries of Ohio, and sub-awardees Riley Power, General Electric, and the Electric Power Research Institute (EPRI). Purchase orders have been issued for the materials and consumables needed to complete the SH/RH assembly fabrication, and the component designs for the SH/RH assembly have been completed and submitted to the fabrication vendor. The work to develop the expanded metallurgical testing plan has been proceeding on-schedule

CONCLUSIONS

The technical goal of this project is to advance A-USC technology towards readiness for commercial scale demonstration (TRL 7), by designing, procuring, fabricating, constructing and evaluating key full-scale (800-850 MW) A-USC components, while demonstrating and validating the capabilities of the U.S. supply chain for large nickel-based alloy components. The capabilities validated by this project would serve to support both new-build (greenfield) and retrofit applications of A-USC technology. Additionally, the high strength of the nickel-based alloys evaluated under this project may help to facilitate enhanced flexible operation of new or existing power plants, even at lower temperature ranges, by allowing the design of thinner components, with lower thermal stress and thus greater fatigue resistance. The ComTest project is presently proceeding with the tasks under Phase II and is on-schedule to complete the defined effort by September 2021. The present project focus on full-scale manufacturing technology and supply chain development for advanced materials yields crosscutting benefits for a variety of high-temperature power generation options, which may include: supercritical CO_2 cycles, concentrated solar thermal, and nuclear power generation.

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