ELECTRIC POWER RESEARCH INSTITUTE

Evaluation of Steam Cycle Upgrades to Improve the Competitiveness of US Coal Power Plants

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Project Description and Objectives

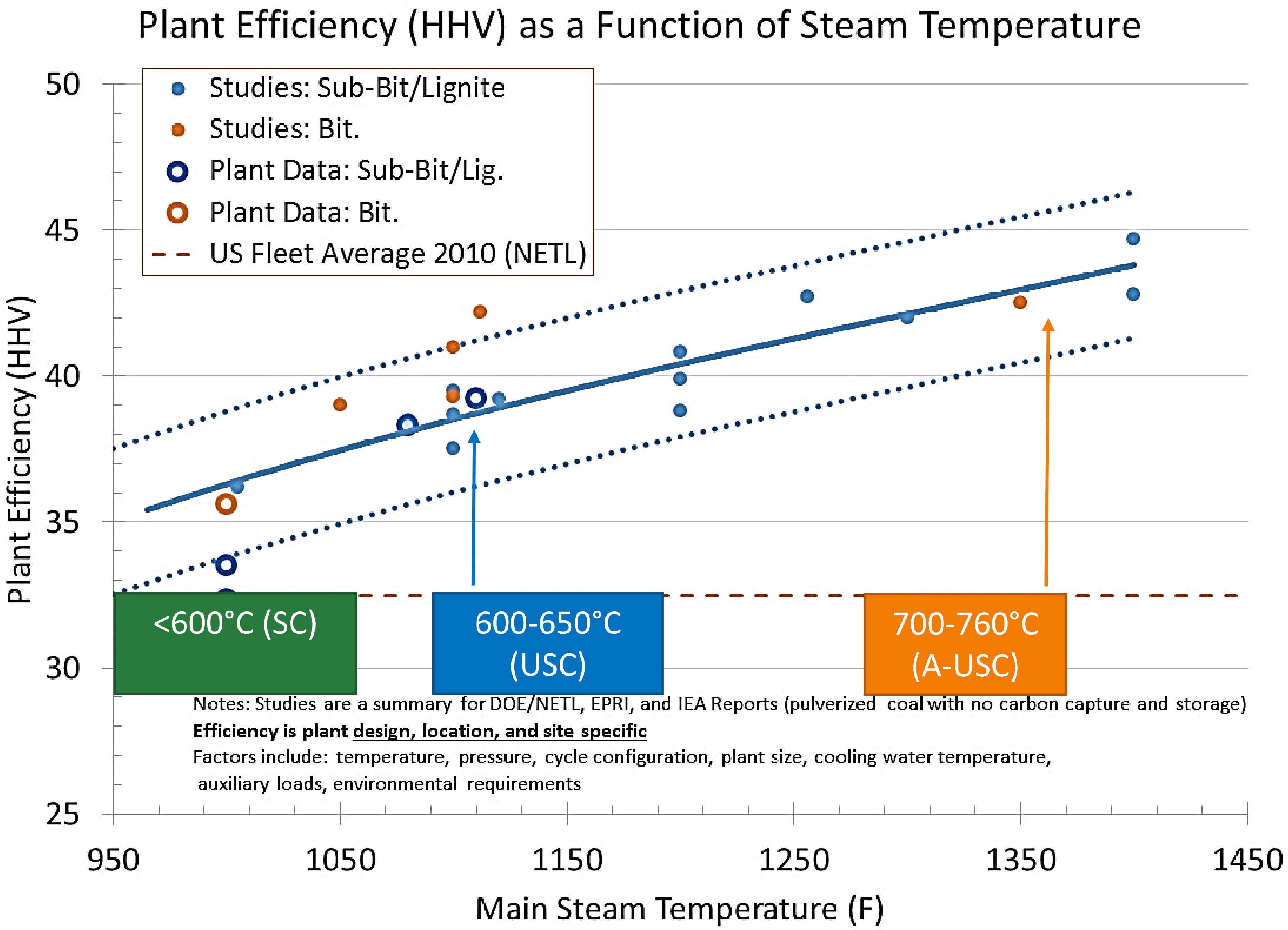
- Examine the feasibility of retrofitting advanced materials to improve heat rate, while minimizing plant modifications
- Reduce coal consumption of existing utility fleet by increasing steam cycle efficiency
- Increase steam temperatures to Advanced Ultra-supercritical (AUSC), or USC conditions – while maintaining original pressure
- Employ advanced nickel-based high-temperature materials
  - Result of DOE-funded materials R&D
- Estimate improved capacity factor, and economic benefit from higher plant efficiency

Strategic Alignment with DOE Fossil Energy Objectives

Power Plant Efficiency Improvements – Develop cost-effective, reliable technologies to improve the efficiency of new and existing coal-fired power plants.

- This project aims to evaluate options for existing plants to upgrade steam temperature for higher cycle efficiency
  - Average efficiency of US coal-fired fleet = 33% HHV
  - Efficiency increases to over 41% HHV at 1,350°F steam temperature
  - Base cases defined to represent 80% of existing coal-fired fleet

Motivation for AUSC Coal-Fired Power Plants



Project Status

- Worked with utility partner (Southern Company) to validate representative subcritical and supercritical base case models
- Developed thermodynamic performance models for the upgrade cases
- Evaluated technical feasibility (boiler & turbine) for upgrade cases
  - Nine original upgrade cases completed
  - Added three new cases
- Estimating capital costs associated with feasible upgrade options
- Preparing the unit dispatch model – impact on asset profitability

AUSC Retrofit Study – Work Scope

- Model technical feasibility of required modifications
- Generate capital cost estimates
    - GE – boiler and steam turbine
    - AECOM – balance-of-plant
- Estimate the value of the heat rate improvements by detailed modeling of the unit dispatch in several regional U.S. power markets (EPRI's US-REGEN model)
    – Compare revenue of upgraded units vs. non-upgraded units
- Prepare technical report

Improve heat rate while minimizing power plant modifications

Project Structure - Tasks

- 1 Project management and planning
- 2 Evaluation of technical feasibility
  - 2.1 Thermodynamic performance models of base case at full load
  - 2.2 Impact of upgrades to base cases at full load
  - 2.3 Part load performance for flexible operation scenarios
  - 2.4 Dynamic modeling of system for fluid circulation
- 3 Unit dispatch modeling (EPRI's US-REGEN model) to 2050
- 4 Capital cost estimation to AACE Class III (+/-30%)
- 5 Overall economic evaluation

Two-year project ends in January 2020

Background – Challenges for AUSC Technology

- Greenfield A-USC steam plants may not be cost effective
  - Conventional USC (1100°F or 593°C) power plants use lower cost materials
- Retrofits to higher temperature may be more cost effective option
  - Significant reuse of existing equipment – decreased capital cost
  - Increase only steam temperature – not steam pressure
    - Limit the scope of equipment replacement
      - Superheater and reheater panels
      - Steam turbine
      - Piping between the superheater/reheater and steam turbine

Technical Approach - Summary

- Maximize the applicability of the study results to existing fleet
  - 300+ units with ~2,400 psia (16.6 MPa) main steam (subcritical)
  - 100+ unit with ~3,500 psia (24.1 MPa) main steam (supercritical)
- Insure that results reflect actual situations in US fleet
  - Data from existing operating units supplied by Southern Company
- Evaluate a variety of temperature upgrade options
- Employ an experienced technical team that has worked together on prior DOE-funded AUSC project (ComTest)
  - EPRI, GE, AECOM, HES

Technical Approach – Original Upgrade Cases Planned

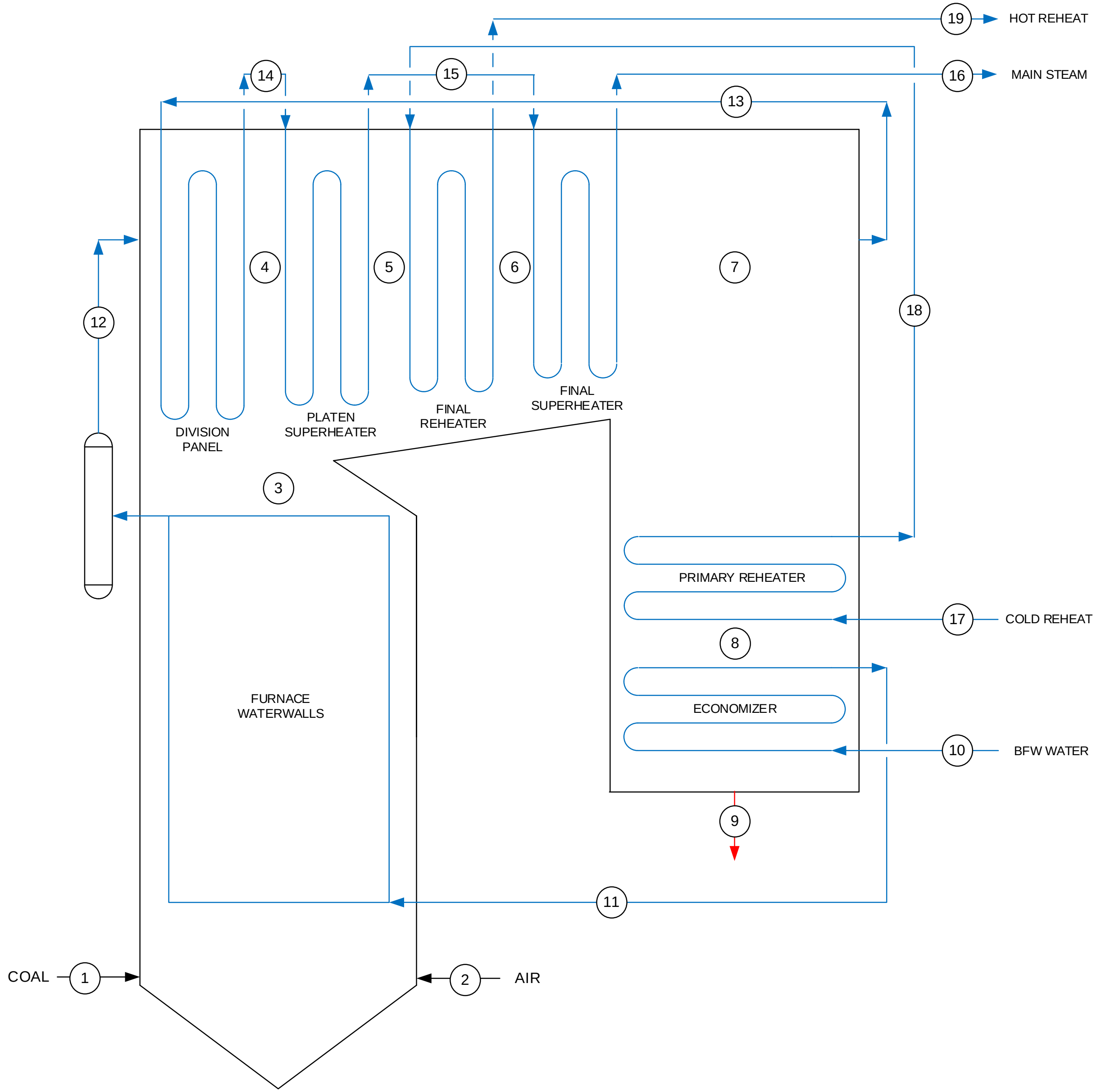
Case Name	Main Steam Pressure	Main Steam Temperature	Reheat Steam Temperature
Subcritical Base Case	2400 psi (16.6 MPa)	1000°F (538°C)	1000°F (538°C)
Subcritical USC Option	2400 psi (16.6 MPa)	1100°F (593°C)	1100°F (593°C)
Subcritical A-USC Option 1	2400 psi (16.6 MPa)	1200°F (649°C)	1200°F (649°C)
Subcritical A-USC Option 2	2400 psi (16.6 MPa)	1000°F (538°C)	1350°F (732°C)
Subcritical A-USC Option 3	2400 psi (16.6 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical Base Case	3500 psi (24.1 MPa)	1000°F (538°C)	1000°F (538°C)
Supercritical USC Option	3500 psi (24.1 MPa)	1100°F (593°C)	1100°F (593°C)
Supercritical A-USC Option 1	3500 psi (24.1 MPa)	1200°F (649°C)	1200°F (649°C)
Supercritical A-USC Option 2	3500 psi (24.1 MPa)	1000°F (538°C)	1350°F (732°C)
Supercritical A-USC Option 3	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical A-USC Molten Salt	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)

Base Case Model Development

- Base cases were intended to be realistic, based on information from existing power plants
- These are not intended to be identical representations of existing units
- Allowed a more direct comparison, and matching parameters
  - Fuel (PRB coal)
  - Output (750 MW)
  - Steam turbine efficiency (identical)
  - Feedwater heater configuration (identical)
  - Site location and ambient conditions (Kenosha, Wisconsin)

Supercritical PC Boiler Base Case Preliminary Sizing

Furnace				**Roof, Walls, Screen Tubes**		
Duty	2,650	MMBTU/hr		Duty	252	MMBTU/hr
Total Surface Area	75,648	ft^2		Total Surface Area	35790	ft^2
Furnace Width	98	ft		Materials		
Furnace Depth	49	ft		CS	916	tons
Wall Height Below Nose	170	ft				
Hopper Height	25	ft		**Final Superheater**		
Height Wall Above Nose	21	ft		Duty	464	MMBTU/hr
Overall Boiler Height	216	ft		Total Surface Area	37810	ft^2
Materials				Number Panels	138	
CS	1131	tons		Panel Width	7.7	ft
				Panel Length	18	ft
Division Panels				Materials		
Duty	346	MMBTU/hr		T91	191	tons
Total Surface Area	9962	ft^2				
Number Panels	8			**Primary Reheater**		
Panel Width	29	ft		Duty	632	MMBTU/hr
Panel Length	16	ft		Total Surface Area	54466	ft^2
Materials				Number Panels	186	
T91	53	tons		Panel Width	8.2	ft
				Panel Length	18	ft
Platen Superheater				Materials		
Duty	475	MMBTU/hr		CS	68	tons
Total Surface Area	14693	ft^2				
Number Panels	113			**Economizer**		
Panel Width	3.2	ft		Duty	626	MMBTU/hr
Panel Length	20	ft		Total Surface Area	92407.9408	ft^2
Materials				Number Panels	253	
T91	64	tons		Panel Width	10.2	ft
				Panel Length	17.5	ft
Finishing Reheater				Materials		
Duty	509	MMBTU/hr		CS	410	tons
Total Surface Area	21085	ft^2				
Number Panels	113					
Panel Width	4.9	ft				
Panel Length	18	ft				
Materials						
T91	23	tons				



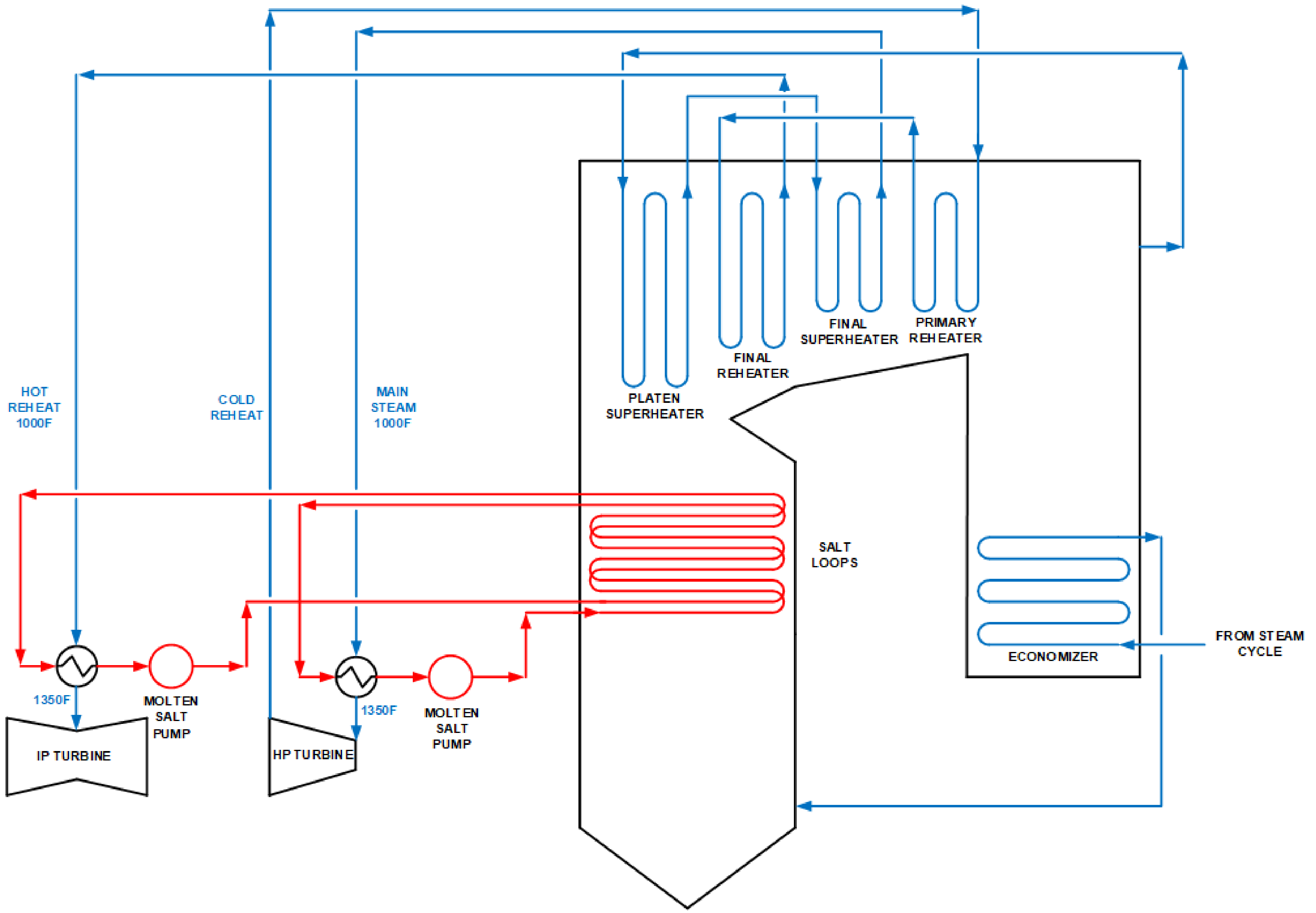
Model Details for Steam Cases

- Nine original upgrade options evaluated using
  - EPRI's PC-Cost for preliminary boiler sizing, and
  - AspenPlus™ for heat and material balance for boiler and steam cycle
- Net power output set to match applicable base case
  - Avoid upgrades to the switchyard and transmission lines
- Technical feasibility of boiler and steam turbine sections evaluated

Model Details for Molten Salt Case

- Evaluate molten salt option – goal to reduce costs associated with nickel alloy steam transfer piping from boiler to steam turbine
- Existing main and reheat steam piping will be used to carry 1000°F (538°C) steam from the superheat and reheat headers down to the level of the steam turbine.
- Separate low pressure molten salt system installed in the furnace
  - Extract heat at high temperature (up to 1400°F or 760°C)
  - Deliver the molten salt to a heat exchanger at the steam turbine level where the 1000°F (760°C) superheat and reheat steam flows will be heated to 1350°F (732°C) before entering the steam turbine.

Molten Salt Case Configuration



Full Load and Part Load Evaluation for Each Case

- Evaluate the thermodynamic performance
- Calculate the amount of heat transfer surface required
- Determine impact upon piping and steam turbine
- Model the performance at 75% load and 50% load

Conclusions from Evaluation of Original Upgrade Cases

- Steam cases at 1,100°F / 1,100°F (SH/RH) are feasible for both subcritical and supercritical configurations
- The 1,350°F steam temperature cases are not feasible
  - Insufficient space in existing boiler for needed heat exchanger surface
- Some 1,200°F steam temperature may be feasible – at least under some conditions

Technical Feasibility Results – Original Upgrade Cases

Case Name	Main Steam Pressure	Main Steam Temp.	Reheat Steam Temp.
Subcritical Base Case	2400 psi (16.6 MPa)	1000°F (538°C)	1000°F (538°C)
Subcritical USC Option	2400 psi (16.6 MPa)	1100°F (593°C)	1100°F (593°C)
Subcritical A-USC Option 1	2400 psi (16.6 MPa)	1200°F (649°C)	1200°F (649°C)
Subcritical A-USC Option 2	2400 psi (16.6 MPa)	1000°F (538°C)	1350°F (732°C)
Subcritical A-USC Option 3	2400 psi (16.6 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical Base Case	3500 psi (24.1 MPa)	1000°F (538°C)	1000°F (538°C)
Supercritical USC Option	3500 psi (24.1 MPa)	1100°F (593°C)	1100°F (593°C)
Supercritical A-USC Option 1	3500 psi (24.1 MPa)	1200°F (649°C)	1200°F (649°C)
Supercritical A-USC Option 2	3500 psi (24.1 MPa)	1000°F (538°C)	1350°F (732°C)
Supercritical A-USC Option 3	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical A-USC Molten Salt	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)

Path Forward on Technical Feasibility Evaluations

- Expand upgrade options to include three new cases
  - Steam case at 1,000°F / 1,200°F (SH/RH) for subcritical
  - Steam case at 1,000°F / 1,200°F (SH/RH) for supercritical
  - Molten salt case at 1,200°F / 1,200°F (SH/RH)

Summary of Current Cases – Three Additional Cases

Case Name	Main Steam Pressure	Main Steam Temp.	Reheat Steam Temp.
Subcritical Base Case	2400 psi (16.6 MPa)	1000°F (538°C)	1000°F (538°C)
Subcritical USC Option	2400 psi (16.6 MPa)	1100°F (593°C)	1100°F (593°C)
Subcritical A-USC Option 1	2400 psi (16.6 MPa)	1200°F (649°C)	1200°F (649°C)
Subcritical A-USC Option 2	2400 psi (16.6 MPa)	1000°F (538°C)	1350°F (732°C)
Subcritical A-USC Option 2A	2400 psi (16.6 MPa)	1000°F (538°C)	1200°F (732°C)
Subcritical A-USC Option 3	2400 psi (16.6 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical Base Case	3500 psi (24.1 MPa)	1000°F (538°C)	1000°F (538°C)
Supercritical USC Option	3500 psi (24.1 MPa)	1100°F (593°C)	1100°F (593°C)
Supercritical A-USC Option 1	3500 psi (24.1 MPa)	1200°F (649°C)	1200°F (649°C)
Supercritical A-USC Option 2	3500 psi (24.1 MPa)	1000°F (538°C)	1350°F (732°C)
Supercritical A-USC Option 2A	3500 psi (24.1 MPa)	1000°F (538°C)	1200°F (732°C)
Supercritical A-USC Option 3	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical A-USC Molten Salt	3500 psi (24.1 MPa)	1350°F (732°C)	1350°F (732°C)
Supercritical A-USC Molten Salt A	3500 psi (24.1 MPa)	1200°F (732°C)	1200°F (732°C)

A-USC Retrofit Study – Current Status / Work Completed

- Completed thermodynamic performance models – two base cases
- Upgrade cases have been modeled
  - Full-load and part-load evaluations for original steam cases
  - Original molten salt upgrade option configuration
  - Evaluated technical feasibility of original upgrade options
- Calculated sizing of heat exchanger banks
- Certain high-temperature options for the supercritical case have been determined to technically non-feasible
- Added three additional upgrade options – being evaluated

Design and performance work done; costs underway

Market Benefits/Assessment

- The average efficiency of the US coal-fired fleet is approximately 33% (HHV)
- Capacity factor of existing coal-fired power plants is limited by efficiency
- Steam temperature increases to AUSC conditions, have the potential to increase efficiency to over 41% (HHV)
- This AUSC upgrade path is applicable to 80% of existing fleet
  - Technically feasible options could be widely deployed
  - Present project intends to quantify potential economic benefits of increased efficiency (temperature increase to AUSC conditions)

Technology-to-Market Path

- Plant upgrades to USC or AUSC steam temperatures are compatible with DOE's goals to achieve power plant efficiency improvements
- Candidate demonstration plants for initial upgrades have been identified
- Primary technology challenges relate to the fabrication of full-scale AUSC components and supply chain development
  - Phase II of DOE-funded ComTest project (DE-FE0025064) addresses these
  - ComTest is scheduled to be completed in September 2021

Conclusions

- Upgrades to existing coal-fired plants have the potential to increase the steam temperature, and cycle efficiency
- Maintaining original pressure can minimize plant modifications
- Some technically feasible upgrade options have been identified
- Capital costs are being calculated for the feasible options
- Higher efficiency is expected to lead to increased capacity factor
- Unit dispatch models will help to evaluate the potential long-term return on investment for the plant upgrade

A-USC Retrofit Study Support Acknowledgement

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