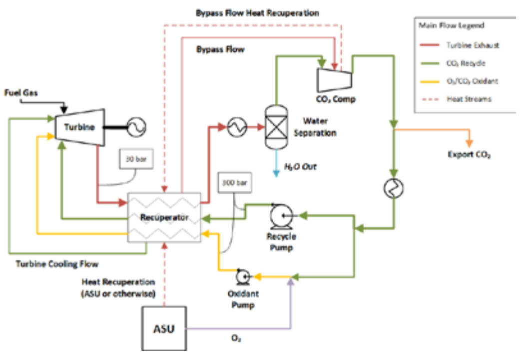
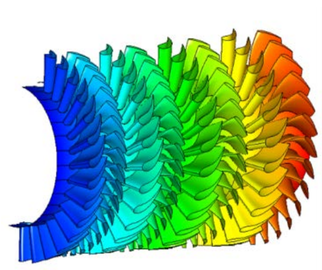
Development of Oxy-Fuel Combustion Turbines with CO2 Dilution for Supercritical Carbon Dioxide Based Power Cycles



Kick-off Meeting

Jeff Moore, Ph.D.
Institute Engineer
Southwest Research Institute



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SwRI Project 23916

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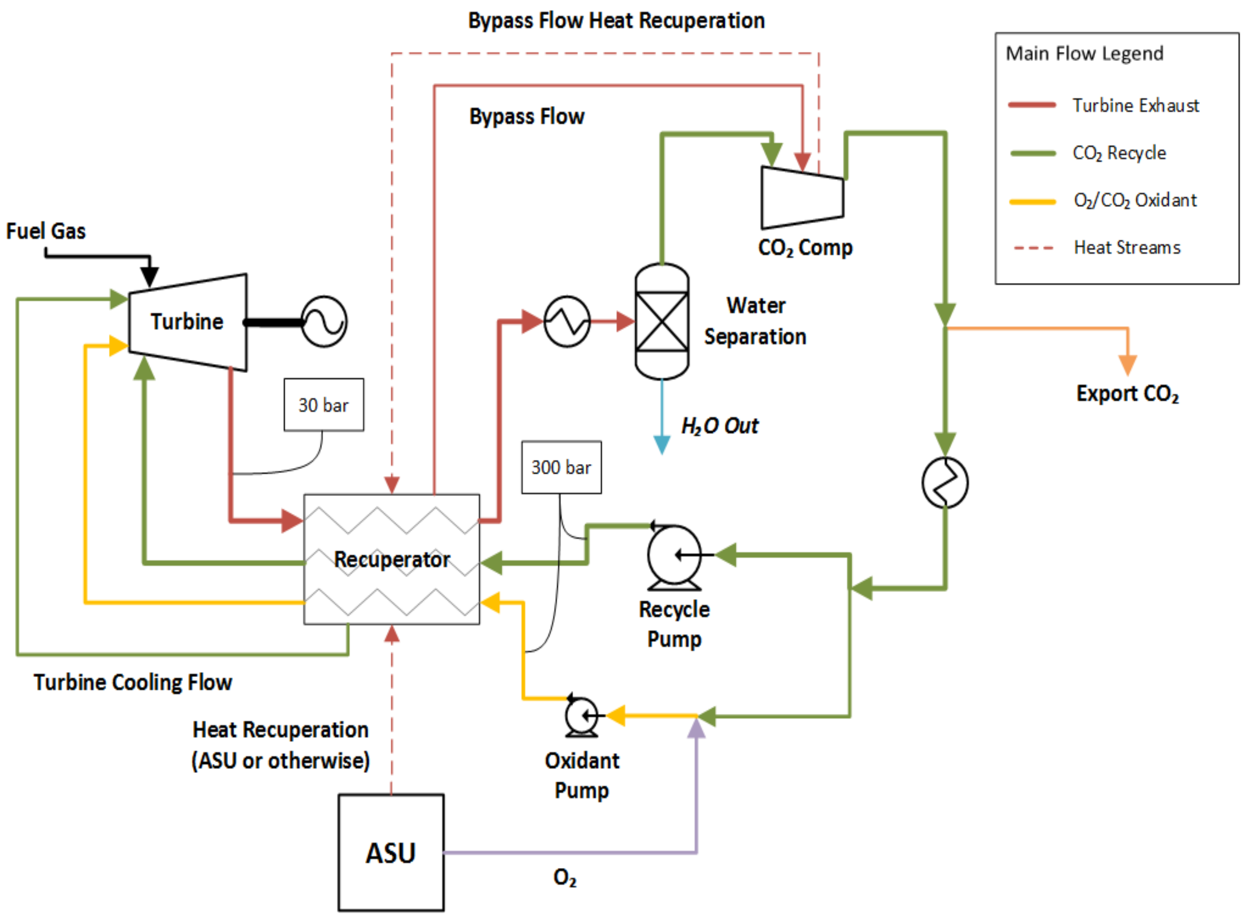
Project Objectives

- Develop a conceptual design for a sCO2, coal syngas or natural gas-fired oxy-fuel turbine in the 150-300 MWe size range capable of 1200°C turbine inlet temperature at 30 MPa and exhaust temperatures in the 725-775°C range.
- Significantly improve the state-of-the-art for thermal efficiency and results in a high-pressure stream of CO_2 simplifying carbon capture, making the power plant emission-free.

sCO_2-based, semi-closed recuperated Brayton (Allam) cycle Process Flow Diagram



From the FOA

- The Phase I development effort must conceptually address the full oxy-combustion turbine design. This includes the combustor, turbine stage count, airfoil design, airfoil cooling, hot gas path, exhaust thermal management, seals, bearings, machine housing/casing, machine/rotor dynamics, thrust management, instrumentation and controls and all other major subsystems.
- Designs of the key turbine technology features should consider design requirements for commercial scale systems, even if they may not normally be required at a smaller pre-commercial scale.

From the FOA

- Phase I work will identify technology gaps and a detailed test plan to address these gaps through bench scale testing in a potential subsequent Phase II project.
- The test plan, and associated Phase II testing, should resolve key technical uncertainties to support a Phase II preliminary design.

Phase 1: Technical Approach

- Develop a thermodynamic cycle analysis (heat, mass, and energy balance) for a sCO_2 semi-closed recuperated Brayton cycle based on natural gas as the fuel and the proposed sCO_2 turbine: 8 Rivers.
- Consistent with the conceptual design and cycle analysis, develop nominal engine component boundary conditions in terms of pressures, temperatures, mass flows, heat flux etc.: 8 Rivers/GE/SwRI.
- Develop a conceptual oxy-fuel sCO_2 combustion turbine design: SwRI and GE (Aero, mechanical, thermal management), Air Liquide (combustion system), EPRI (materials), and Georgia Tech (combustion kinetics).

Phase 1: Technical Approach

- Consistent with the conceptual design and cycle analysis, develop and evaluate overall engine thermal management options and concepts including engine cooling fluids, airfoil thermal management, exhaust thermal management, etc.: GE, SwRI, and Air Liquide.
- Develop a technology maturation plan leading to pre-commercial testing of the proposed oxy-fuel sCO_2 combustion turbine: Team with 8 Rivers leading.
- Develop a test plan with cost, schedule, and resources required to resolve identified technology gaps and that supports the advancement of a potential Phase 2 preliminary design: Team with SwRI leading.
- Evaluate and recommend hot-section materials: EPRI.

Phase 2: Project Objectives

- Execute Phase I test plan to resolve technology gaps
- Develop a detailed design of the oxy-fuel sCO_2 combustion turbine system
- Develop a cost estimate for the oxy-fuel sCO_2 combustion turbine system
- Define a Demonstration and Scale-up Program
- Update the Technology Maturation Plan.

Project Structure: SwRI

- SwRI will be prime
- Coordinate conceptual design of turbine, combustor
- Perform finite element analysis and conjugate heat transfer of 1^{st} stage 3D blade
- Evaluate overall engine thermal management options and concepts including engine cooling fluids, air foil thermal management, exhaust thermal management
- Help develop case thermal management
- Incorporate aero and combustor design to generate 2-D layout
- Perform preliminary rotordynamics analysis
- Develop a test plan with cost, schedule, and resources of a potential Phase II preliminary design.

Project Structure: 8 Rivers

- Develop a thermodynamic cycle analysis (heat, mass, and energy balance) and boundary conditions for a sCO_2 semi-closed recuperated Brayton cycle
  - Consider natural gas (and coal synthesis gas
- Work with GE/SwRI to develop nominal engine component boundary conditions in terms of pressures, temperatures, mass flows, heat flux.
- Help develop a test plan with cost, schedule, and resources of a potential Phase II preliminary design.

Project Structure: General Electric

- Consistent with the cycle analysis, develop nominal engine component boundary conditions
- Develop a conceptual oxy-fuel sCO_2 combustion turbine design working with SwRI and Air Liquide including aero, mechanical, and thermal management.
- Evaluate overall engine thermal management options and concepts including engine cooling fluids, air foil thermal management, exhaust thermal management
- Develop the turbine aerodynamic blade (stator and rotor pair) for the turbine first stage.
- Develop seal conceptual designs
- Help develop a test plan with cost, schedule, and resources required to resolve identified technology gaps and that supports the advancement of a potential Phase II preliminary design.

Project Structure: Air Liquide

- Develop a conceptual oxy-fuel sCO_2 combustor design and integrate into GE/SwRI turbine design.
- Develop and evaluate overall engine thermal management options and concepts for the combustor including engine cooling fluids, air foil thermal management, exhaust thermal management in collaboration with Georgia tech utilizing combustion kinetic model for oxy-fuel sCO2 system
- Develop a test plan with cost, schedule, and resources required to resolve identified technology gaps and that supports the advancement of a potential Phase II preliminary design.

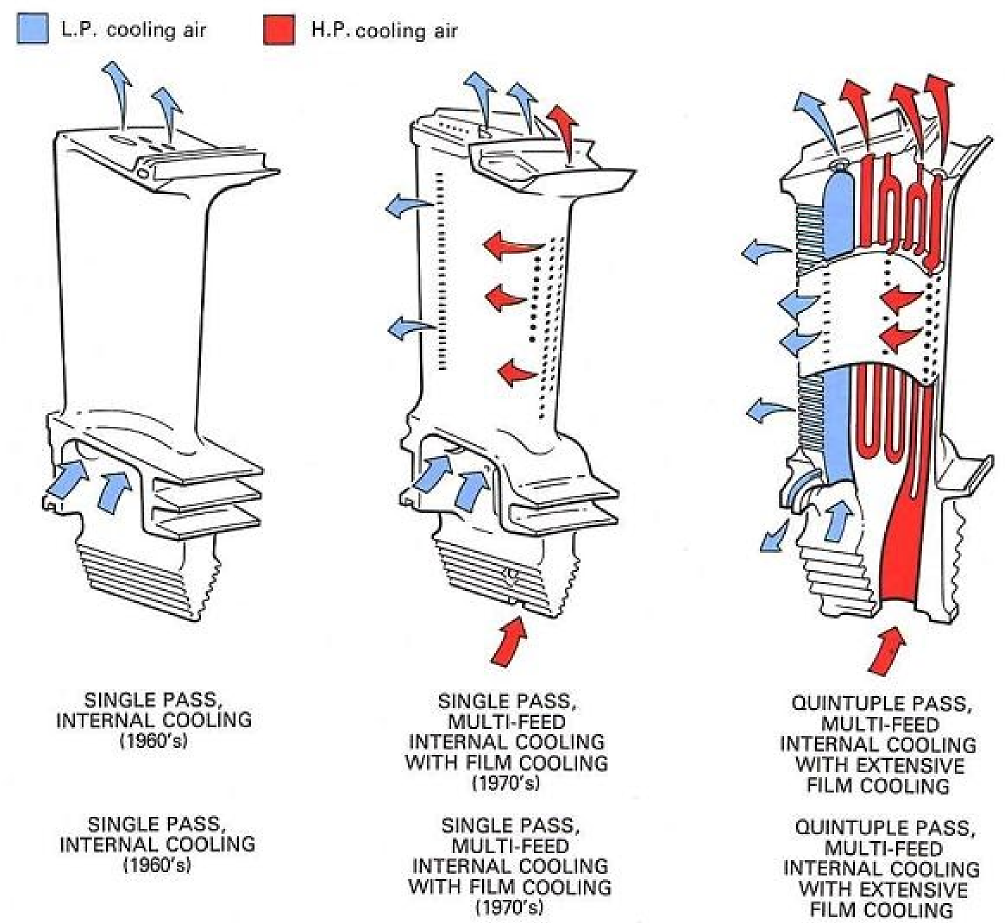
Project Structure: Georgia Tech University

- Develop combustion kinetics model for the conceptual oxy-fuel sCO_2 combustion turbine design using agreed to process conditions and fuel types.

Project Structure: EPRI

- Identify materials suitable for a conceptual oxy-fuel sCO_2 combustion turbine environment.
- Provide data on material properties and corrosion performance.
- Recommend future testing to evaluate performance of the materials in an oxy-fuel combustion environment.

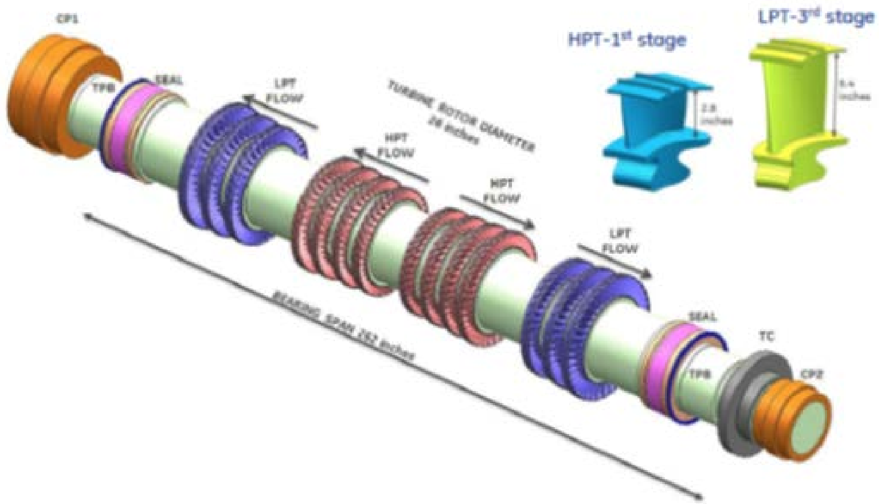
Turbine Blade Cooling



http://aeromodelbasic.blogspot.com/2012/01/bearing-chamber-cooling-development-of.html

Rotor Configuration

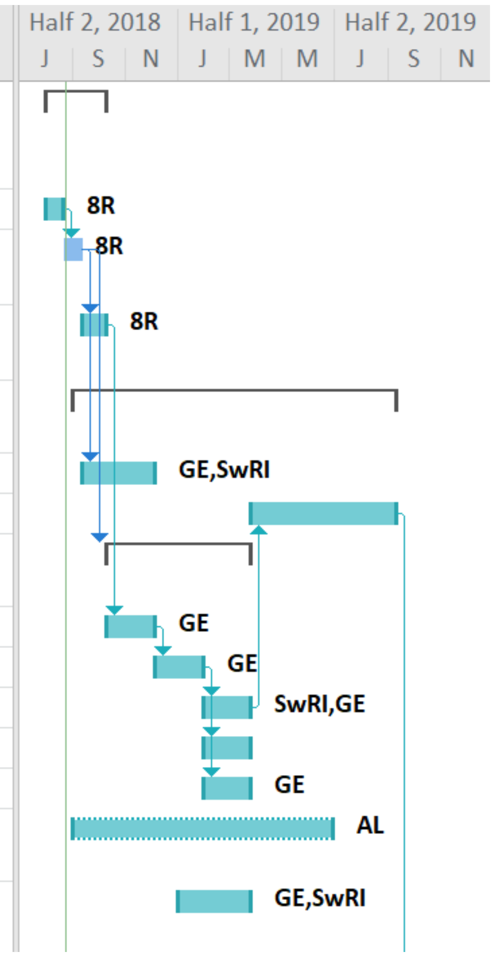
- Leverage previous work done on a 450MW turbine concept under the Utility Scale Seal Project (DE-FE0024007)



450 MWe sCO^2 Turbine Rotor Conceptual Design for Fossil Application

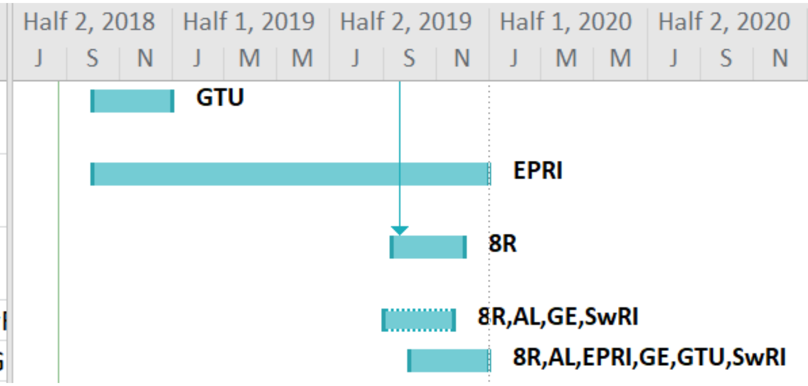
Schedule

	Task Name	Duration	Start	Finish	Resource Names
1	**Develop a thermodynamic cycle analysis**	**50 days**	**Wed 8/1/18**	**Tue 10/9/18**	**8R**
2	Overall Cycle Definition	15 days	Wed 8/1/18	Tue 8/21/18	8R
3	Thermodynamic Cycle Analysis	15 days	Wed 8/22/18	Tue 9/11/18	8R
4	Turbine Boundary Condition Development	20 days	Wed 9/12/18	Tue 10/9/18	8R
5	**Conceptual oxy-fuel SCO2 turbine design**	**267 days**	**Sat 9/1/18**	**Tue 9/10/19**	**AL,GE,SwRI**
6	Turbine Conceptual Design	60 days	Wed 9/12/18	Tue 12/4/18	GE,SwRI
7	2D Turbine Layout	120 days	Wed 3/27/19	Tue 9/10/19	
8	**Turbine Aero and Blade Cooling Design**	**120 days**	**Wed 10/10/18**	**Tue 3/26/19**	**GE,SwRI**
9	Aero 1D Design	40 days	Wed 10/10/18	Tue 12/4/18	GE
10	3D Aero Stg 1 Design	40 days	Wed 12/5/18	Tue 1/29/19	GE
11	Blade Cooling Design	40 days	Wed 1/30/19	Tue 3/26/19	SwRI,GE
12	Blade FEA/CHT Model	40 days	Wed 1/30/19	Tue 3/26/19	
13	Seal Conceptual Design	40 days	Wed 1/30/19	Tue 3/26/19	GE
14	Oxy-fuel Combustor Conceptual Design	216 days	Sat 9/1/18	Fri 6/28/19	AL
15	Develop thermal management concepts	61 days	Tue 1/1/19	Tue 3/26/19	GE,SwRI



Schedule

	Task Name	Duration	Start	Finish	Resource Names
16	**Evaluation of Combustion Kinetics**	66 days	Mon 10/1/18	Mon 12/31/18	GTU
17	**Material Selection and Evaluation**	327 days	Mon 10/1/18	Tue 12/31/19	EPRI
18	**Develop a technology maturation plan**	60 days	Wed 9/11/19	Tue 12/3/19	8R
19	**Develop a test plan**	60 days	Sun 9/1/19	Thu 11/21/19	8R,AL,GE,SwI
20	**Final Reporting**	66 days	Tue 10/1/19	Tue 12/31/19	8R,AL,EPRI,G



Project Management Plan

- PMP complete
- Scope of work defined
- Milestones identified
- Schedule established
- Program risks identified and mitigation plan established

Milestones

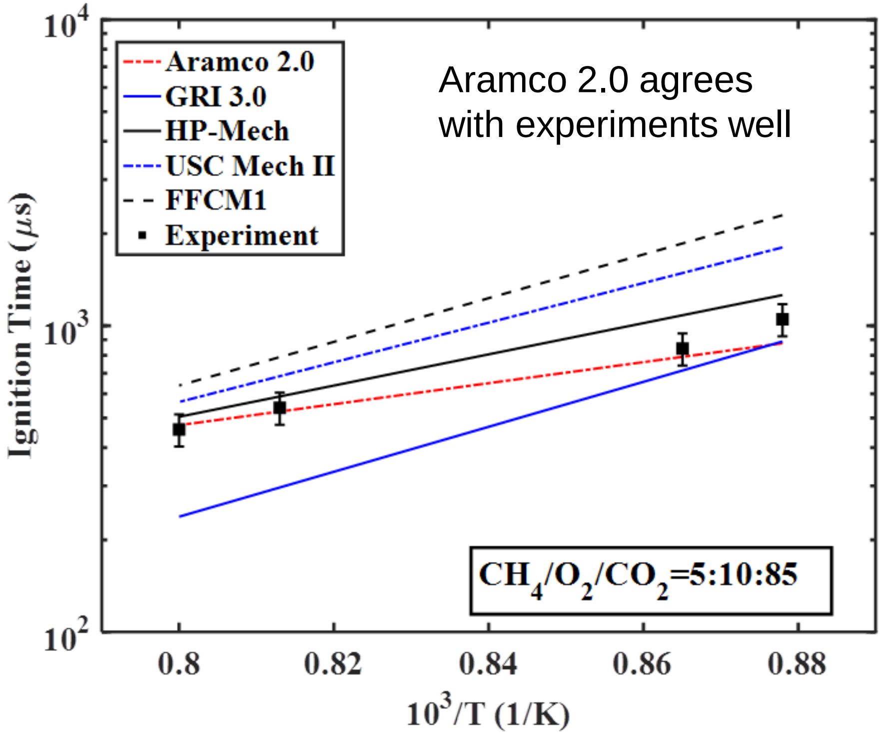
- Initial cycle definition and baseline thermodynamics analysis result.
- Definition of initial turbine boundary conditions.
- Develop aerodynamic design for the first-stage nozzle and blade with efficiency > 85%.
- Develop a cooled nozzle and turbine blade design with metal temperature in high-stress areas < 700°C.
- Develop a conceptual design for oxy-fuel combustor to achieve the firing temperature of 1,200°C.
- Develop a conceptual 2D layout for the turbine.
- Develop a conceptual design for the shaft end and interstage seals.
- Develop thermal management concepts with the pressure containing metal temperature < 700°C.
- Evaluate combustion kinetics by developing the model.
- Select preferred materials for hot-section components that provide 100,000 hours creep life.
- Update cycle thermodynamics analysis.
- Develop a Technology Maturation Plan.
- Develop a Detailed Design and Test Plan.

Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Financial Risks:				
Prime overrunning project.	Low	Med	Low	Earned value principals will be applied to track progress and financials.
Cost/Schedule Risks:				
Subcontractor not delivering on time.	Low	Med	Med	Periodic conference calls to monitor progress
Technical/Scope Risks:				
Subcontractor not delivering technical content.	Low	Med	Med	Periodic conference calls to monitor progress
Management Risks:				
Late on reporting deliverables.	Low	Low	Low	SwRI uses a tracking system that gets upper management attention, if any reports are late.
Planning and Oversight Risks:				
Unidentified technology gaps required for the development of the product.	Low	Med	Med	Phase 2 scope will be refined to close these technology gaps.
ES&H Risks:				
None identified. Paper study.				
External Factor Risks:				
None identified.				
Management Risks:				
A large number of subcontractors difficult to management.	Low	Med	Med	SwRI has worked directly with GE, EPRI, and Georgia Tech. Weekly conference calls will monitor progress and completion of action items.

Preliminary Technical Assessment

- Combustion kinetics

$CH_3+CH_3+M \rightarrow C_2H_6+M$ is the **elementary reaction** controlling kinetics at high pressure condition



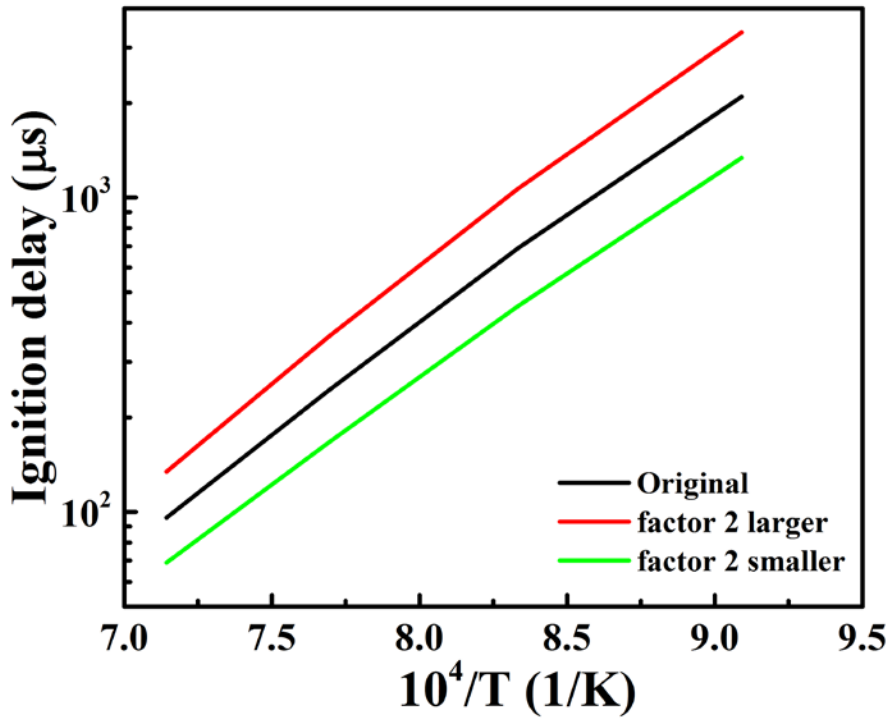


Figure 5. Comparison of Measured Auto-ignition Delays of $CH_4/O_2/CO_2$ Mixture (5:10:85) at 200 bar and Simulation Using Different Kinetic Models (USC II, Aramco 2.0, GRI 3.0, FFCM and Princeton HP-Mech) [4]

Figure 4. Prediction of Auto-ignition Delays Using (1) USC Mech II; (2) Doubling and (3) Halving the Reaction Rate Constant of $CH_3+CH_3+M \rightarrow C_2H_6+M$ at 105 bar for $CH_4/O_2/CO_2$ (5:10:85) Mixture

Preliminary Technical Assessment

- Literature Review Begun
  - 8 Rivers provided papers on NetPower project and Toshiba turbine development
- Cycle Modeling
  - Selected 300 MWe Frame Size
  - Compare against prior work done for future scaled NetPower project
  - Modeling will begin with pure methane with simplified model for turbine cooling