DOE FE0031617 KICKOFF MEETING

Novel Modular Heat Engines with sCO2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery

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TOPICS

- Background
- Project objective(s)
- Technical approach
- Project structure
- Project schedule
- Project budget
- Project Management Plan, including Risk Management

BACKGROUND

TARGET APPLICATION & MOTIVATION

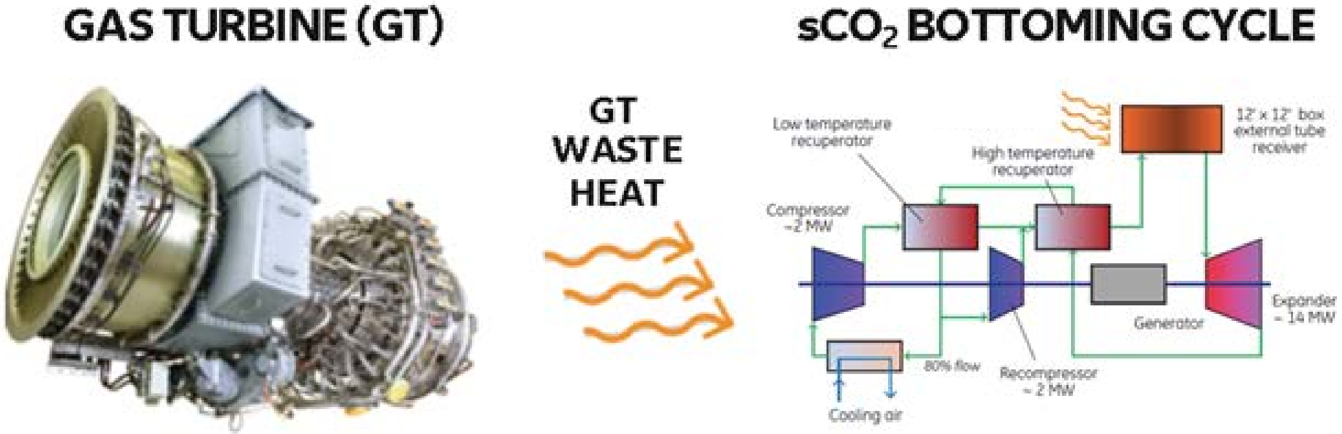
- Target application→ heat engines for pipeline compression (PC); currently not using WHR
  - 20% upgraded using bottoming cycle natural gas savings of 42 billion cubic feet/year
  - 120M in annual fuel costs
  - 2.5M ton reduction in annual CO_2 emissions

- General simple cycle gas turbine cycles yield ~25-35% efficiency

- Combined cycle (GT + bottoming cycle) yield >50% cycle efficiencies

- In power plants→ steam turbine bottoming cycle

- Steam turbine packages impractical for PC
  - Complex operation
  - Make-up water
  - On-site operator
  - Large system components (LPT/H2O condenser)

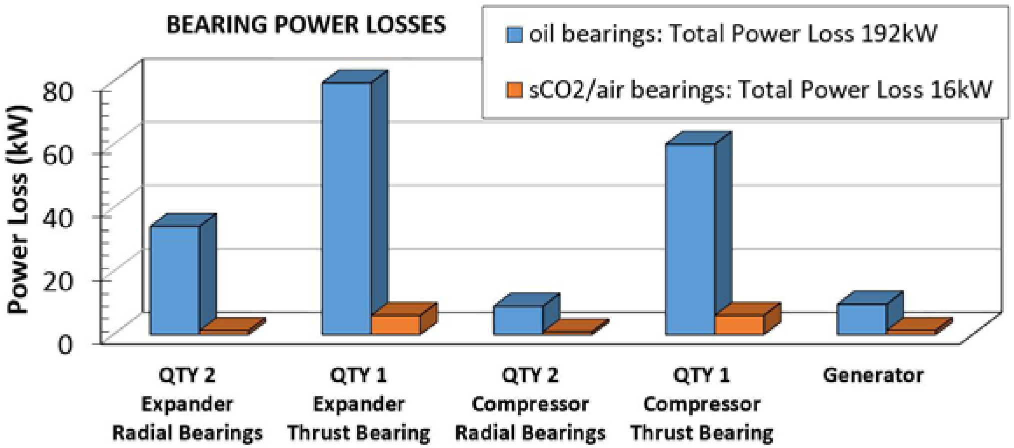


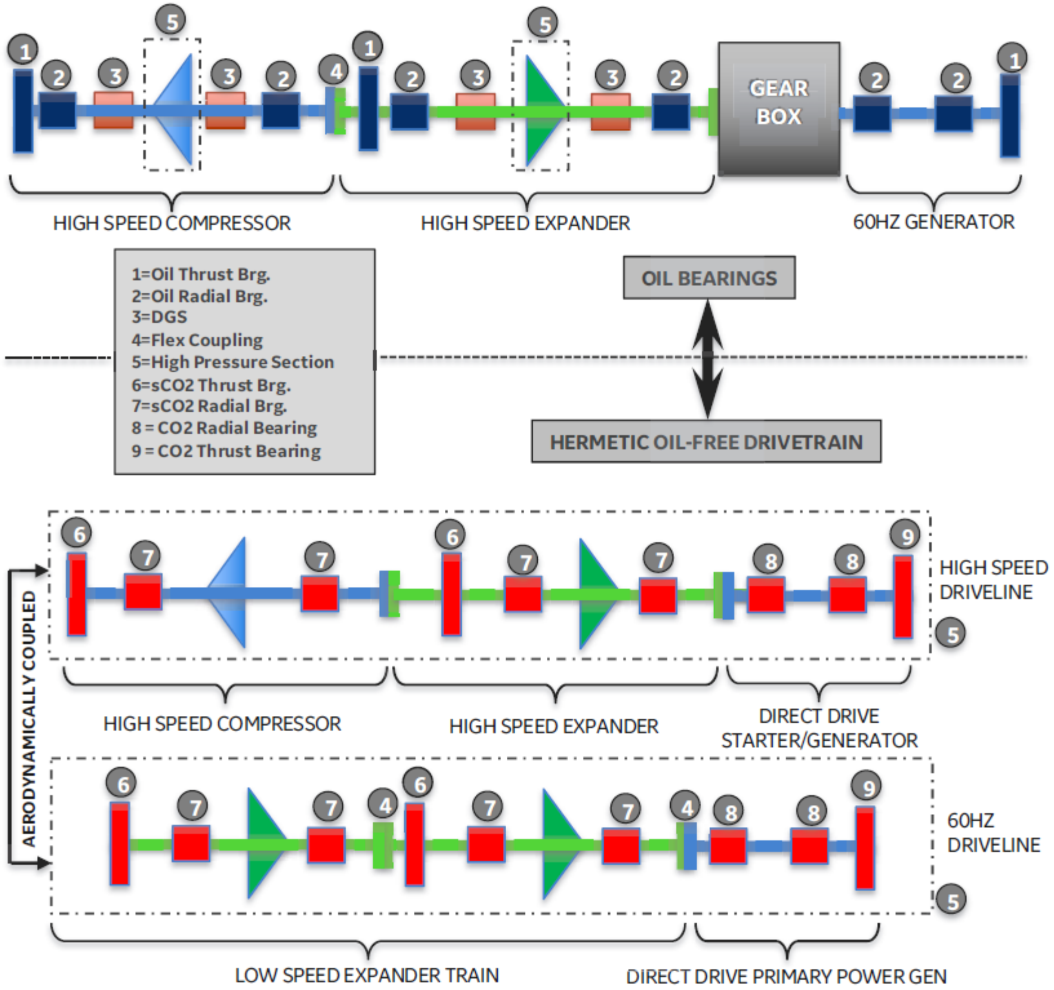
NEED A MODULAR & REMOTELY DEPLOAYABLE BOTTOMING CYCLE FOR PIPELINE COMPRESSION HEAT ENGINES

Advanced sCO_2 Cycle using Hermetic Oil-Free Drivetrain

- Current high power >10MW sCO2 cycles utilize oil-bearings
  - Requires sealing
  - Loss of CO2 overtime (recharging needed)
  - Power loss of bearings is high (high speed)

- Concept → replace oil bearing with CO2 bearings
  - CAPEX cost savings → ~400K
    - No gearbox/oil skid/dry gas seals
  - Hermetic system = no CO2 recharging
  - Lower bearing power loss ~2 cycle points





SIGNIFICANT CAPEX AND OPEX REDUCTION OPPORTUNITY

PROJECT OBJECTIVES/STRUCTURE

PROJECT OBJECTIVE & STRUCTURE

- Project objective
  - Conceptual design of a hermetic oil-free sCO2 drivetrain for a bottoming cycle
  - Commercial assessment and viability of the concept

- Program structure
  - GE
    - Drivetrain layout/design
    - Aero-design
    - Bearing design
    - Electric machine design
  - Southwest Research Institute
    - Commercial assessment
    - Market evaluation
    - Cycle analysis/definition

Program Team

GE Global Research

- Drivetrain Layout & Configuration
- Turbomachinery Design
- sCO_2 Bearing Design/Modeling
- Risk Reduction Planning Phase II

SwRI SOUTHWEST RESEARCH INSTITUTE

- Cycle Analysis
- Market and Application Evaluation
- Commercial Risk Assessment
- Risk Reduction Planning Phase II

Relevant Prior Work

- Gas bearing design/ test/modeling expertise
- 14MW Sunshot Expander Design
- Apollo Compressor Design
- Film-riding component design/testing/ modeling expertise

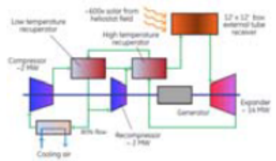
1.5 Year, $625K Program. Development of Hermetic Oil-Free sCO_2 Turbomachinery for Bottoming Cycles

Project Objectives: Deliver the conceptual design of a hermetic oil-free sCO_2 turbomachinery drivetrain for application as a bottoming cycle for high efficient heat engines using sCO_2 lubricated bearing systems

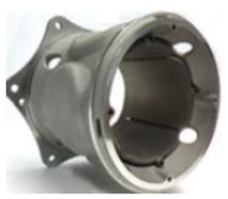
GAS TURBINE (GT)

GT WASTE HEAT

sCO_2 BOTTOMING CYCLE



RADIAL sCO2 BEARING



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THRUST sCO_2 BEARING

Technical Approach

- Drivetrain layout & config.
- System trade-offs
- Bearing system design
- Phase II risk mitigation anchored on Phase I concept design work
  - * Plan/design sCO_2 BRG tests
  - * Plan/design full scale rotor tests

Technical Challenges

- Thrust load management
- Radial bearing damping
- Thermal runaway & thin-film clr. management

Program Deliverables

- Hermetic oil-free drivetrain config.
- Turbomachinery conceptual design
- Bearing requirements and config.
- Bearing design readiness for Phase II
- Test facility and hardware design for Phase II

Anticipated Benefits

- Heat engine cycle efficiencies >50%
- Hermetic 0 leakage sCO_2 system. Enables remote operation with minimal oversight.
- Cycle performance to (+) 2% improvement over systembusing oil-lubricated bearings
- System cost reduction compared to conventional oil-bearing-based drivetrain architectures

TECHNICAL APPROACH

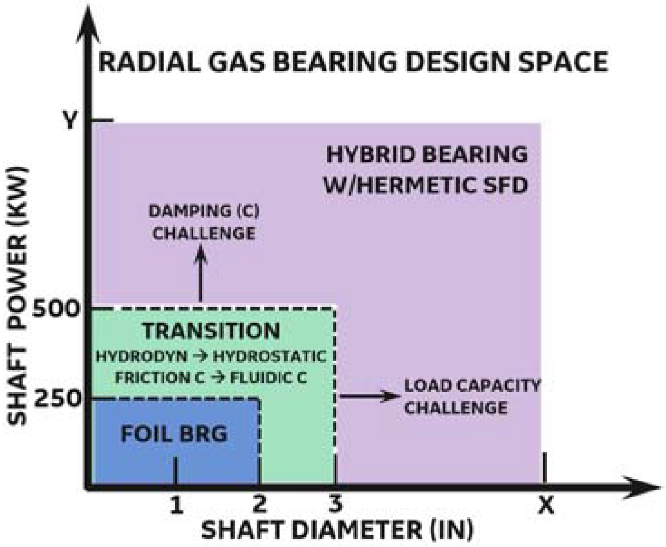
KEY ENABLING TECHNOLOGY

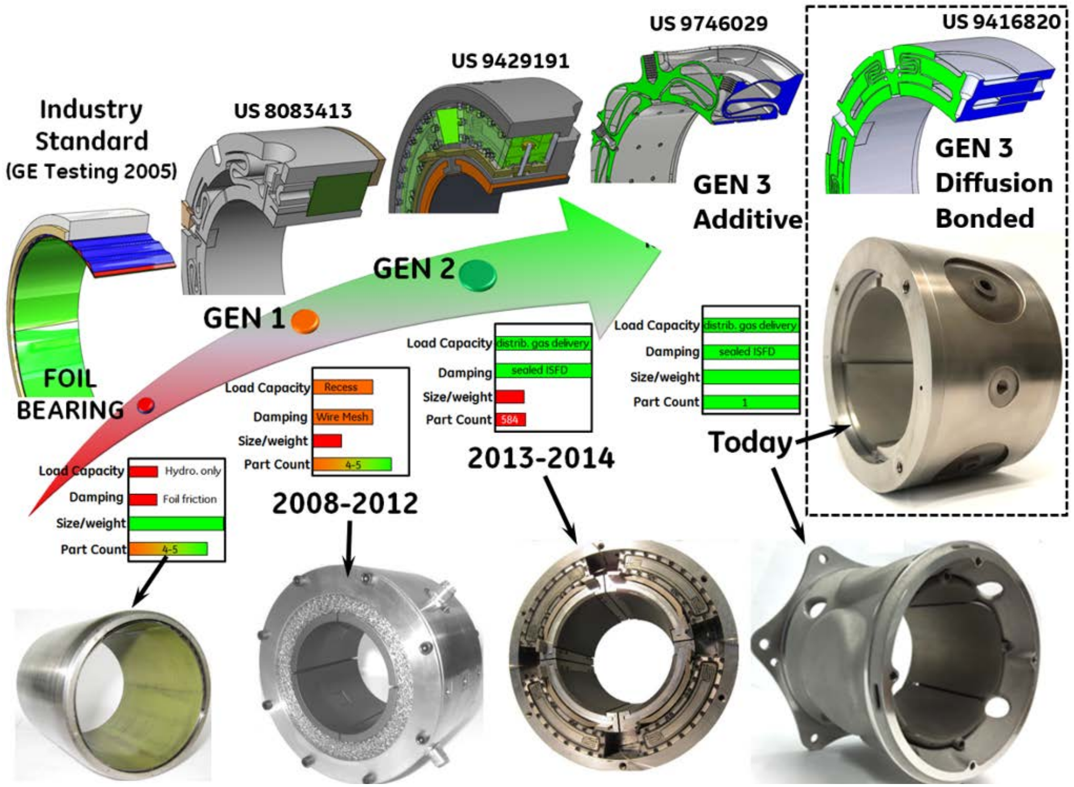
- Current state of the art mainstream gas bearing → foil bearings

- Foil bearing traits
  - Suitable for small turbomachinery ~300KW
  - Operates on principle of hydrodynamics
    - Rubbing occurs at low speeds
    - Low load capacity at low speeds
  - Significantly lower damping vs. to oil bearings
  - Foil structure compliance a key trait for reliable operation

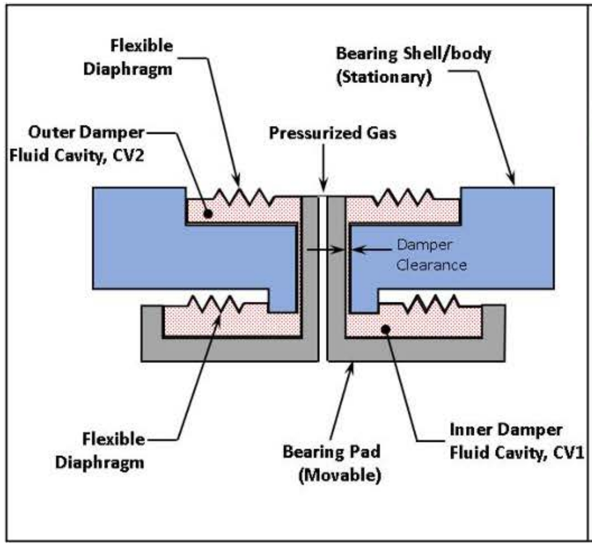
- Desired traits for next gen gas bearing for large turbomachinery
  - Leverage/translate key flexibility elements from foil bearing
  - Allow for external pressurization capability for high load capacity
  - Develop damping concept = to oil bearing dampers
  - Cost neutral concept vs. oil bearing

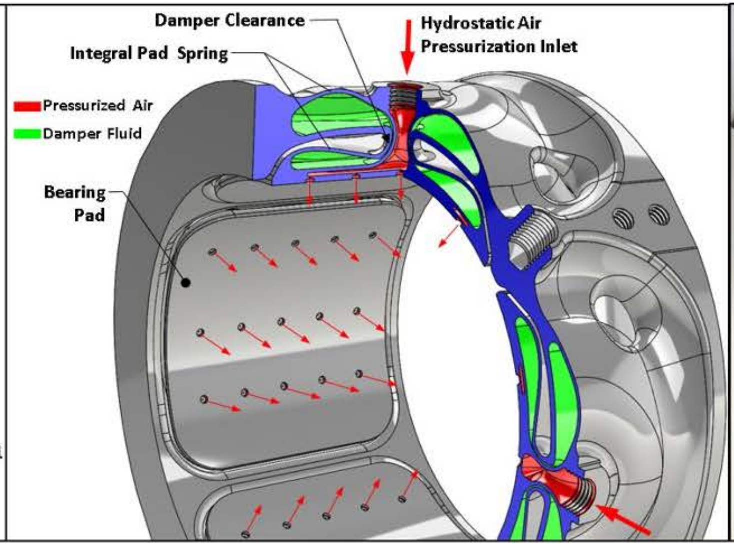
CONCEPT NECESSITATES COMPLEX FUNCTIONALITY AND LOW COST

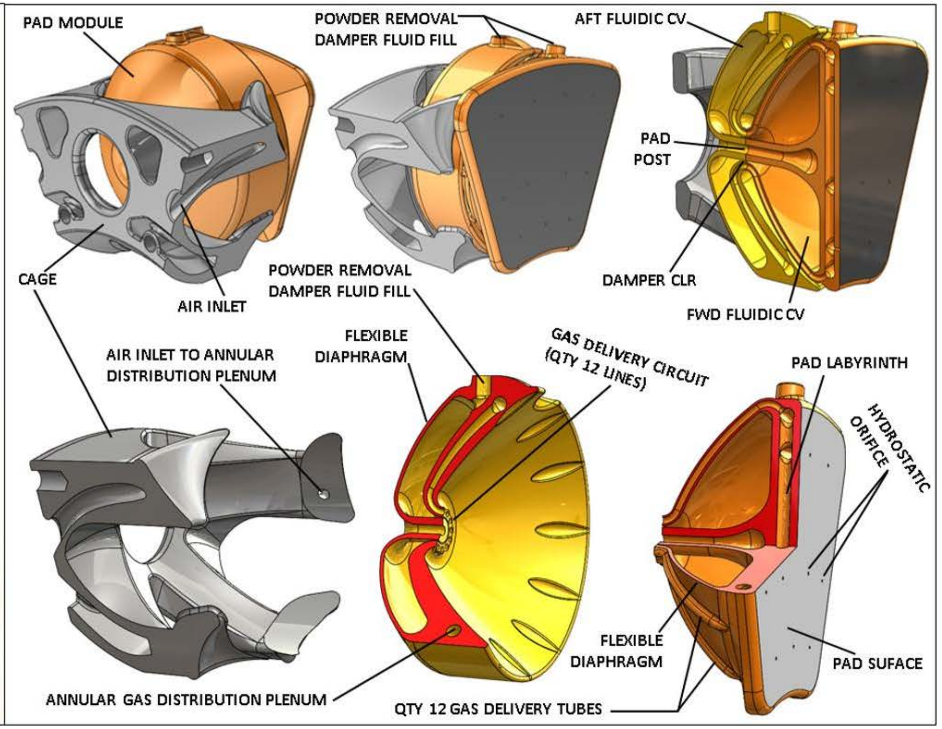




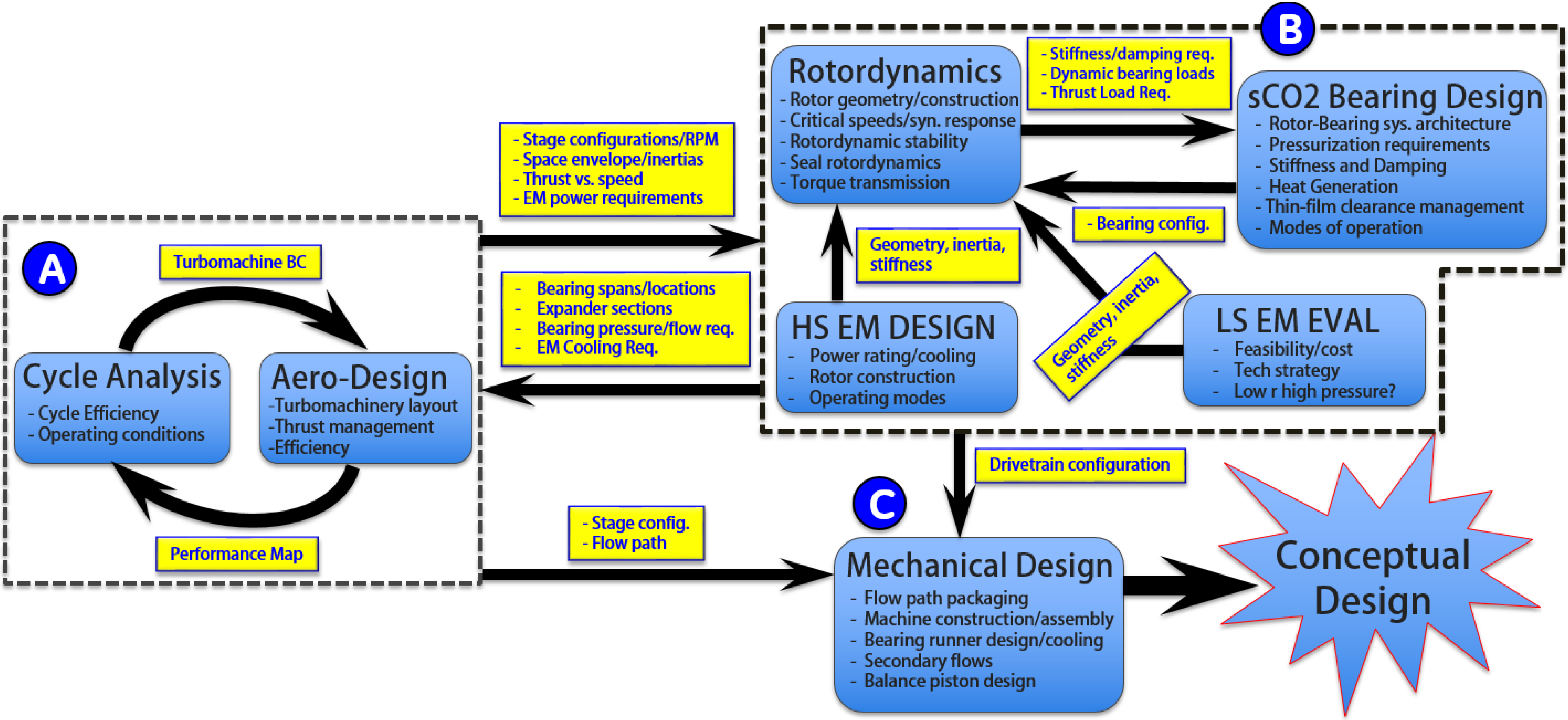
CANDIDATE BEARING CONCEPTS: ADDITVELY MANUFACTURED







TECHNICAL EXECUTION & APPROACH FOR CONCEPTUAL DESIGN



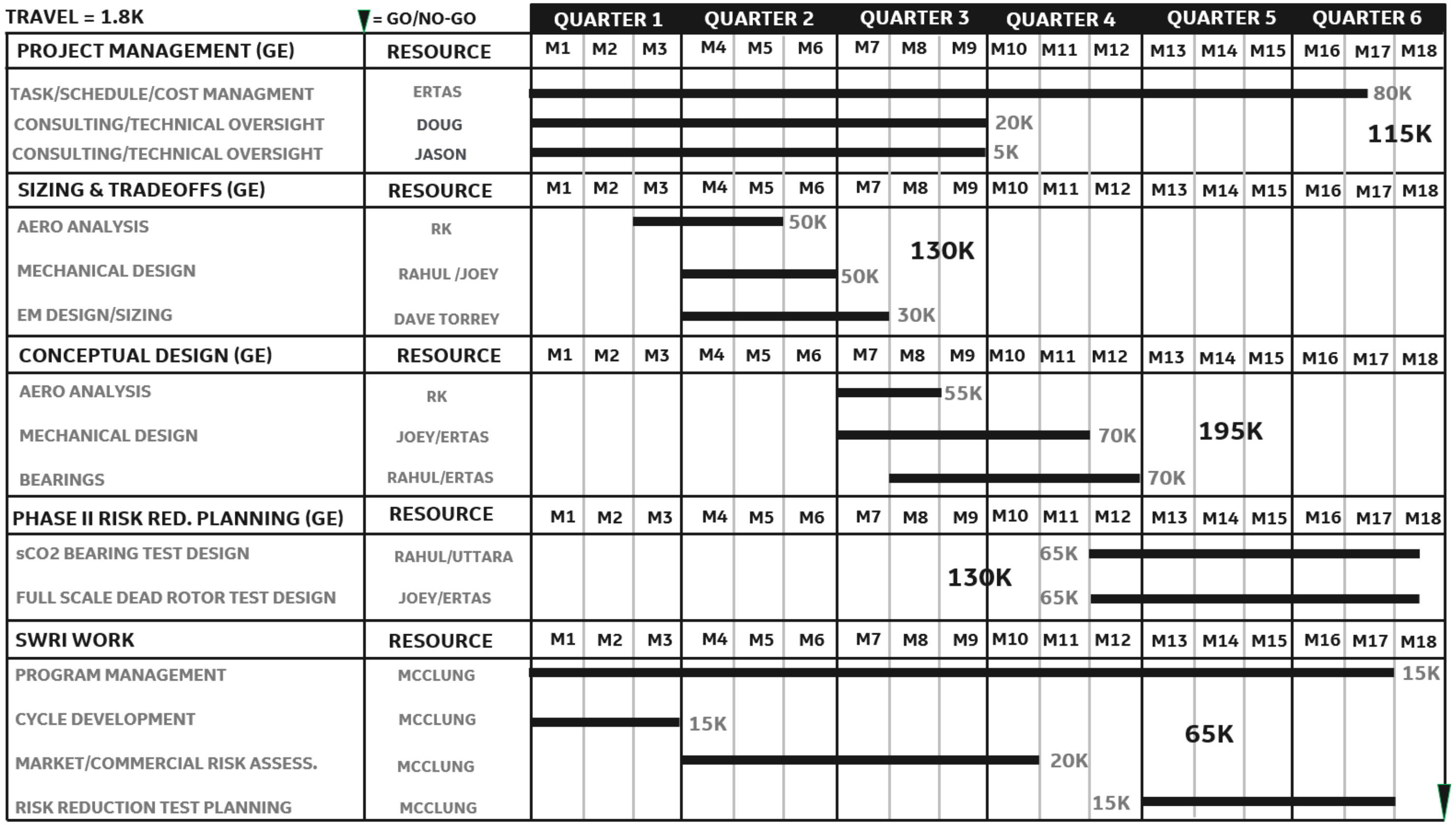
TECHNICAL RISKS & MITIGATION

- Three main high level risks in this project:
  - Gas Bearings
  - Electric Machines
  - Rotordynamics
- Bearings
  - Load capability
  - Damping
  - Thin film clr. Management
  - Thrust management
- Electric machine
  - Operation in pressurized CO2 environment
  - Cost
- Rotordynamics
  - Long 60Hz expander (many stages)

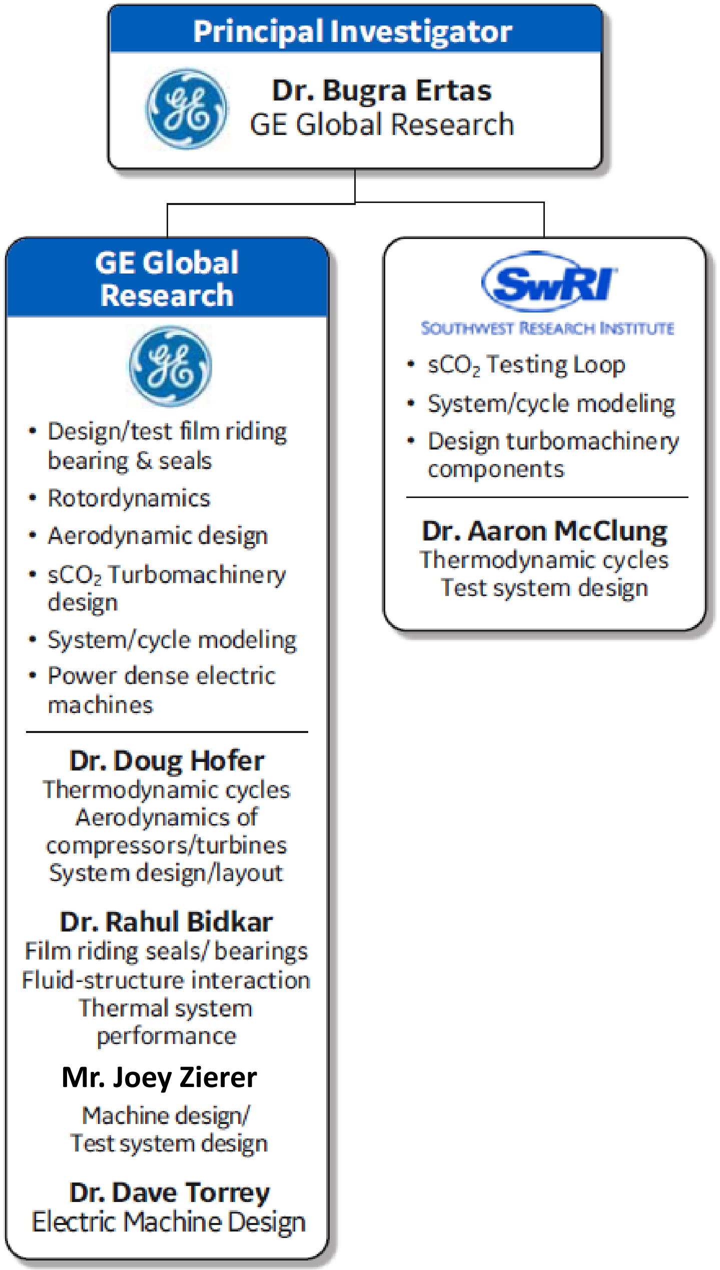
Description of Risk	Impact	Risk Management Mitigation and Response Strategies
Technical Risks		
Designing a high efficiency 60Hz expander	MED	Designing a configuration with a high number of turbine stages
Rotordynamics risk due to high number of turbine stages in 60Hz driveline	MED	Segmented expander configuration with multiple and flex couplings between segments
Defining bearing boundary conditions and requirements	HIGH	Successful expander design and Rotordynamics will dictate these boundary conditions and requirements.
Gas thrust bearing sustaining high thrust loads	HIGH	Careful design of balance piston sections anchored to appropriate stage pressures to mitigate thrust loads. Optimized thrust bearing design able to sustain mission cycle thrust loads through robust engineering of gas delivery system and fluid-film management.
Thermal runaway of the bearing fluid-film	HIGH	System level thermal-mechanical analysis addressing centrifugal shaft growth, thermal bearing-runner distortions due to film heating, misalignment, dynamic deflected mode shapes through critical speed transitions, and transient pressurization availability throughout the mission cycle. Analysis will drive flexibility of the bearing support and the gas delivery protocol to the flexible bearing pads aimed at ensuring safe and reliable fluid-film thickness values throughout the mission cycle.
Low damping of bearing system risking rotordynamic instability	HIGH	Design of a hermetically sealed squeeze film damper in the bearing support using an incompressible damper fluid. Implementation of annular gas damper seals at balance piston locations.
Bearing/shaft misalignment	MED	Designing flexibly mounted pads that absorb misalignment and protect the fluid-film
Inability of electric machine to operate in a high pressure sCO_2 environment	HIGH	Implement sealing system between turbomachinery and electric machine to reduce pressure in electric machine environment
Ability of sCO_2 radial bearings to support 10MW generator reaction loads	HIGH	Adequate design of pressurized gas delivery to the bearing pad while optimizing bearing pad geometry and projected area.

PROJECT SCHEDULE/BUDGET/MANAGEMENT

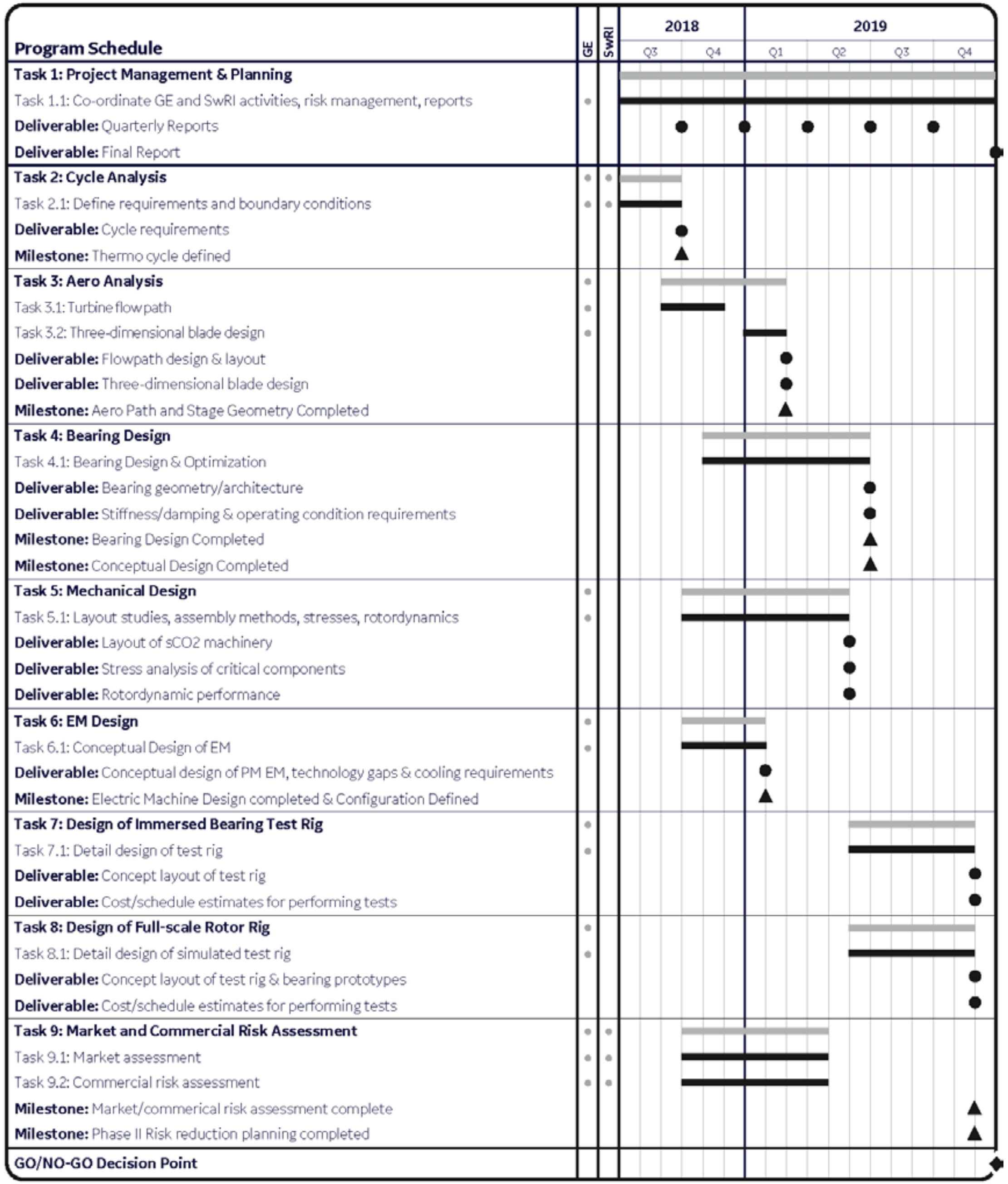
SCHEDULE & BUDGET BY DISCIPLINE AND INDIVIDUALS



Key Contributor and Role	Scientific Mastery of Technology	% Time
Dr. Bugra Ertas, GE, PI	Turbomachinery Rotordynamics, Gas Bearings, Machine Design	44
Dr. Doug Hofer, GE, Thermodynamic Cycle and Aerodynamics	Turbomachinery Aerodynamics, Thermodynamic Cycles, System Design	10
Dr. Rahul Bidkar, GE, Bearing Design	Film Riding Seals and Bearings, Thermal Performance, Machine Component Design, Fluid-Structure Interaction	26
Mr. Joey Zierer	Machine Design, Test Systems for Turbomachinery Components	17
Dr. David Torrey	Electric machines design	15
Dr. Aaron McClung, SwRI	Thermodynamic Cycles, sCO_2 Turbomachinery	10



SCHEDULE & BUDGET BY TASK/BUDGET PERIOD



Task	Go/No-Go Decision Point	Success Criteria
2 – 6	End of Phase I 12/31/2019	Conceptual design of oil-free hermetic sCO_2 bottoming cycle
9	End of Phase I 12/31/2019	Commercial and market viability
7, 8	End of Phase I 12/31/2019	Phase II risk mitigation planning and test design completion

Team Member	Budget Period 1	Budget Period 2	Total
GE Global Research	$327,057	$107,408	$434,465
SwRI	$49,630	$15,662	$65,292
TOTAL	$376,687	$123,070	$499,757

Task Number	Description	Planned Completion Date	Actual Completion Date (to be completed as part of the program)
2	Thermodynamic cycle defined	11/1/2018	
3	Aeropath and stage geometry completed	3/1/2019	
4	Bearing design completed	7/1/2019	
5	Mechanical design completed	5/1/2019	
6	Electric machine design completed and configuration defined	2/1/2019	
9	Market/commercial risk assessment complete	6/1/2019	
7, 8	Phase II risk reduction planning completed	8/1/2019	