Advanced Gas Turbine and sCO2 Combined Cycle Power System

Kickoff Meeting

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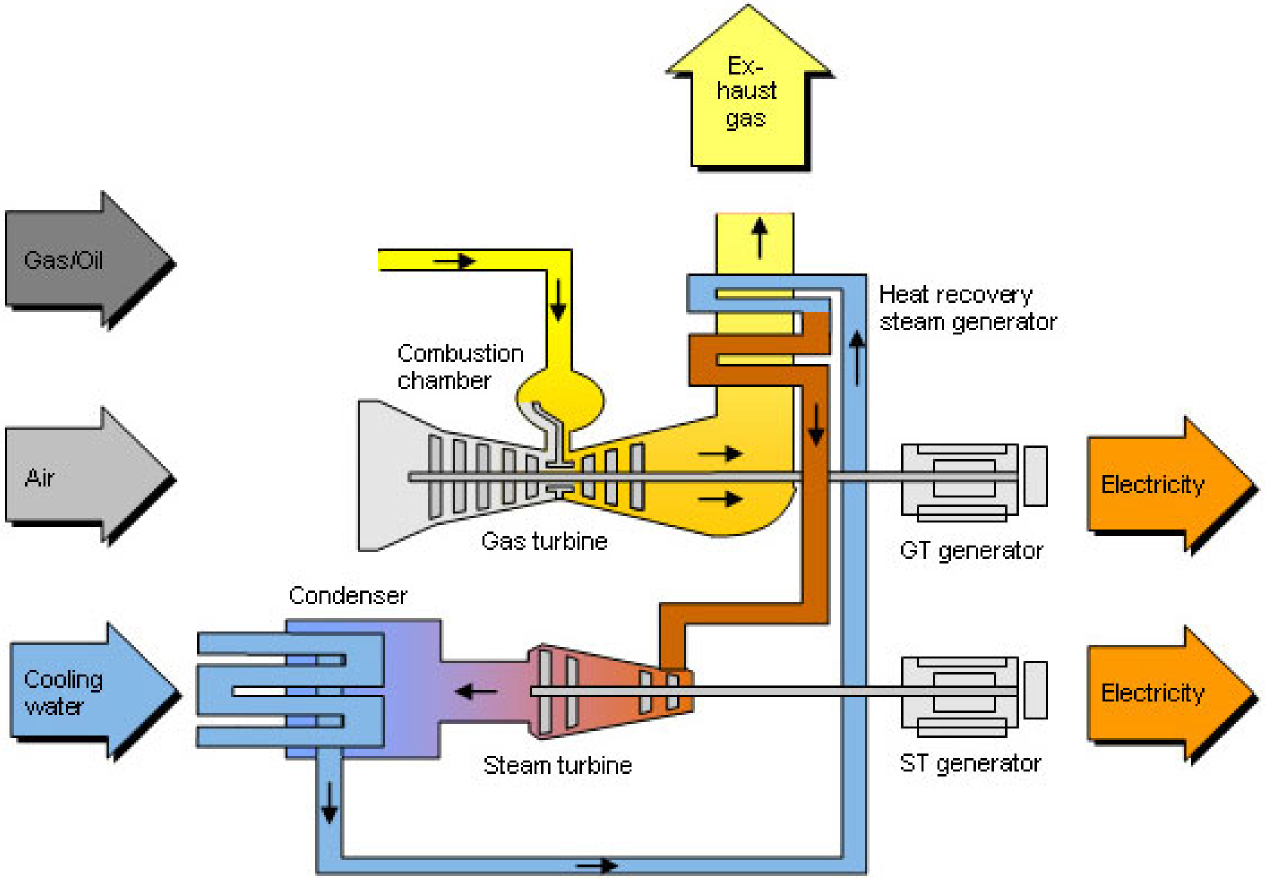
Presentation Outline

- ❑ Background and Motivation
- ❑ Technical Approach
- ❑ Project Objectives
- ❑ Project Risks
- ❑ Project Schedule
- ❑ Project Budget
- ❑ Summary

Project background and motivation: Large scale combined cycles



Schematic of large scale Combined Cycle Gas Turbine power plant from Siemens. Large scale plants of this type can be upwards of 300 MWe.

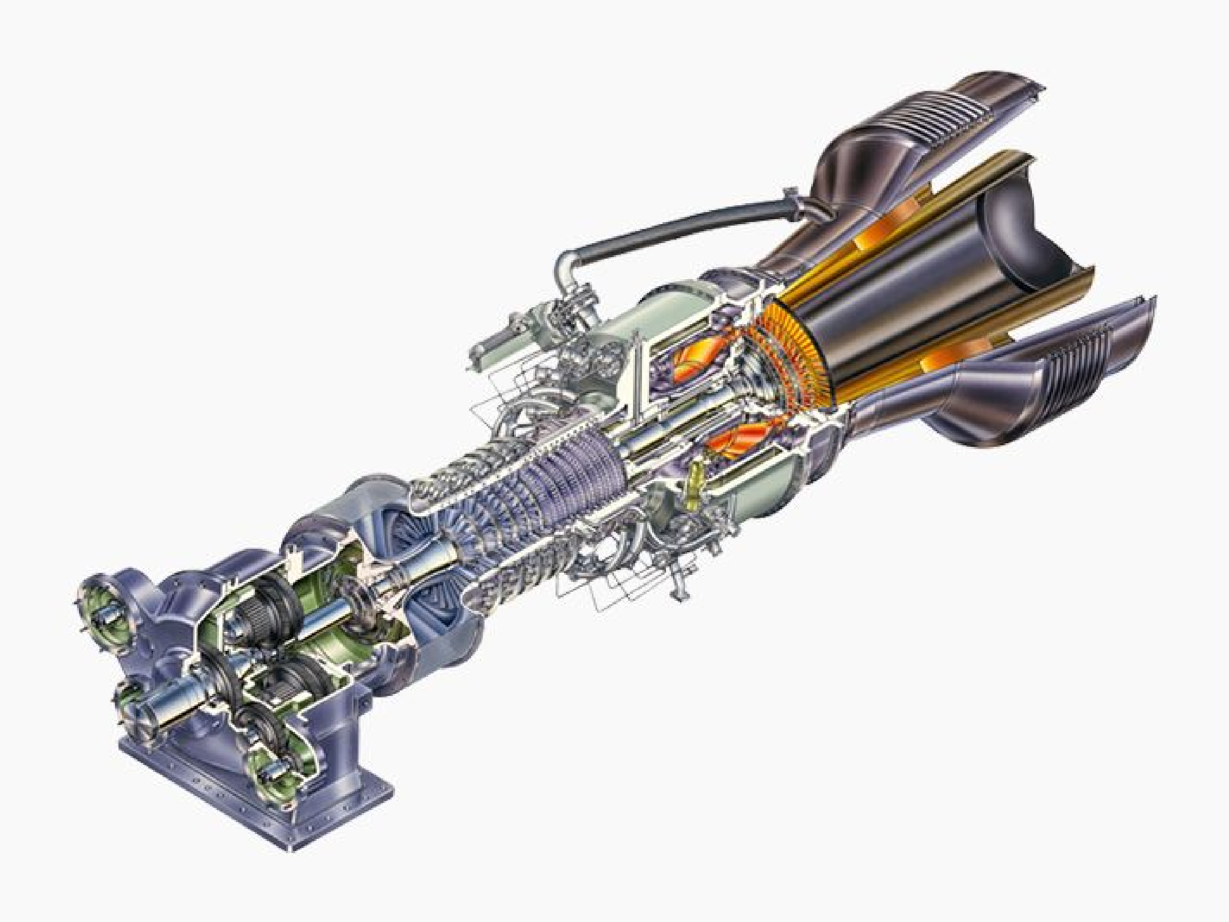
Modern gas turbines are highly efficient with thermal efficiencies between 30 and 45%.

To drive overall efficiency even higher, large gas turbine power plants use a Waste Heat Recovery System (WHRS), also called a bottoming cycle, to extract heat from the gas turbine exhaust.

This combination of primary and bottoming cycles is called a Combined Cycle Gas Turbine or CCGT.

For large CCGT plants a steam Rankine WHRS is traditionally used. The addition of this WHRS allows for overall plant thermal efficiency to reach nearly 65% in large, utility scale plants.

Project background and motivation: sCO2 small scale combined cycle



Schematic of a Solar Turbines Titan 130 which is often used at natural gas compression stations. A Titan 130 produces 16.5 MWe

WHR systems are not typically added to smaller gas turbines of the type used at natural gas compression stations due to:

- Size
- Complexity
- Initial capital cost
- On site water requirements

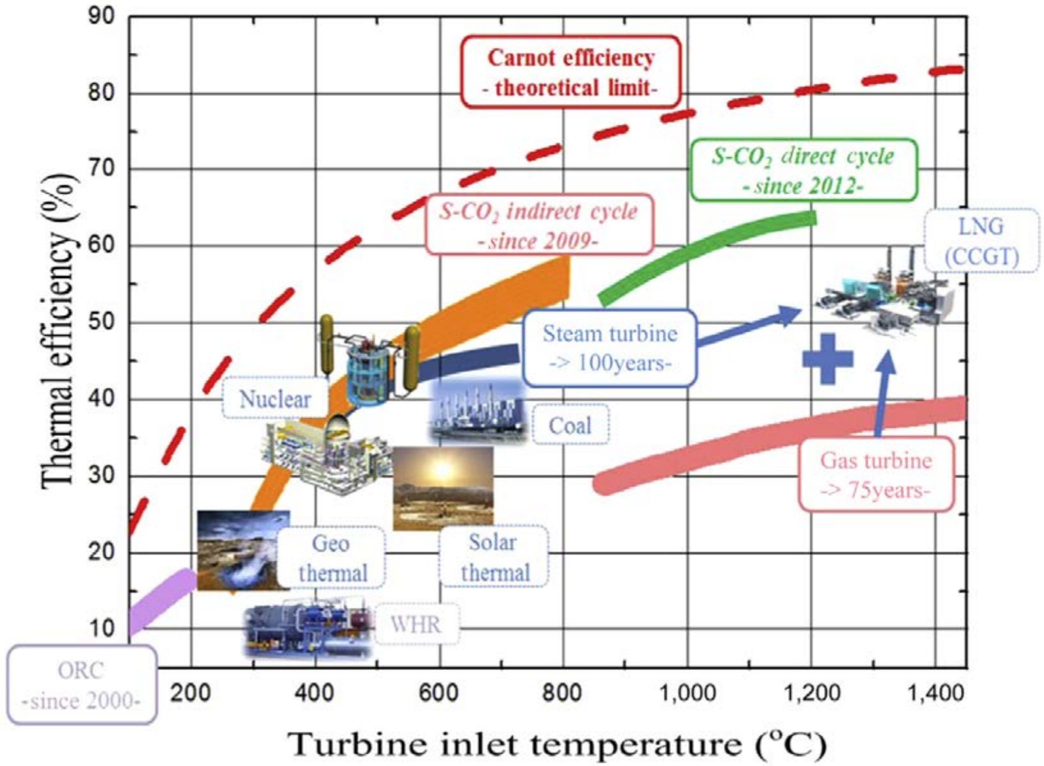
A WHR system based on super critical CO2 as a working fluid could address all of these issues.

This project will develop an advanced WHR cycle using sCO2 as a working fluid and create a conceptual design of a complete WHR package applicable to existing gas turbine installations. This WHRS will be:

- Highly efficient
- Modular and skidable
- Compatible with air cooling
- Allow for advanced load following

SwRI Hanwha Power Systems Solar Turbines A Caterpillar Company Williams

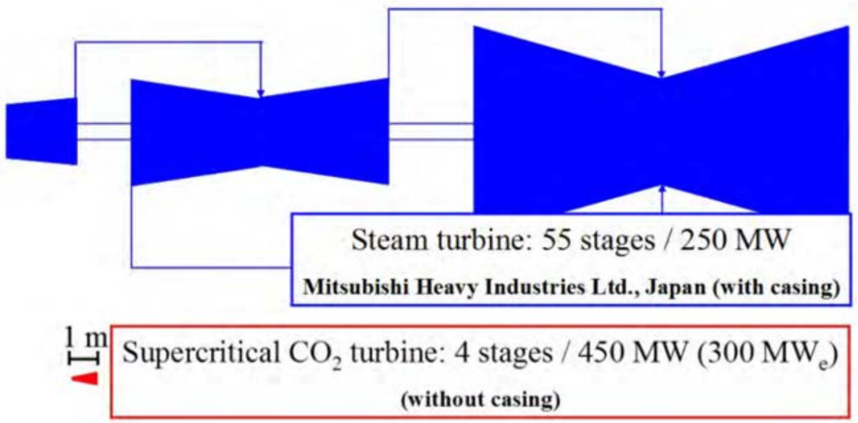
Project background and motivation: Benefits of sCO2



Cycle efficiencies vs Turbine Inlet Temperature from [5]

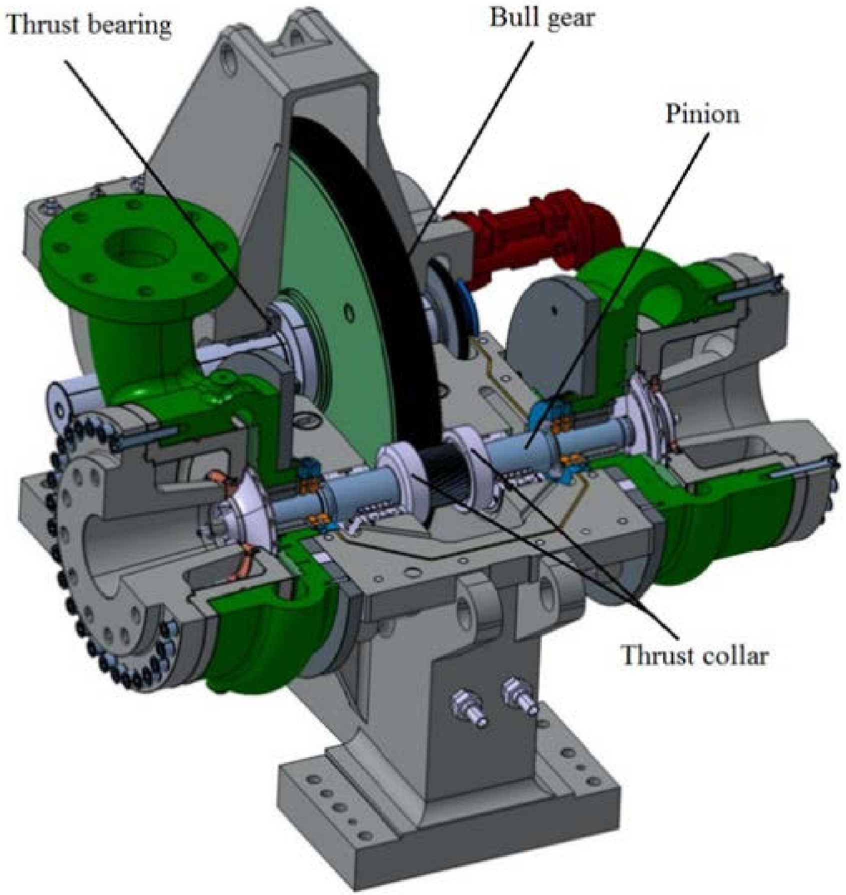
The exhaust temperature of a Solar Turbines Titan 130 is roughly 500C. Starting at this temperature the unique thermodynamic properties of sCO2 allow for increased cycle performance and decreased machinery size and complexity when compared to steam.

sCO2 is also compatible with dry cooling which would allow a WHRS to be placed in a location without a ready supply of water which would be vital to a steam based WHRS.



Relative sizes of steam and sCO2 power cycle machinery from [2]

Project background and motivation: Integrally-Geared turbomachinery



Single pinion integrally-geared compressor from Hanwha Power Systems

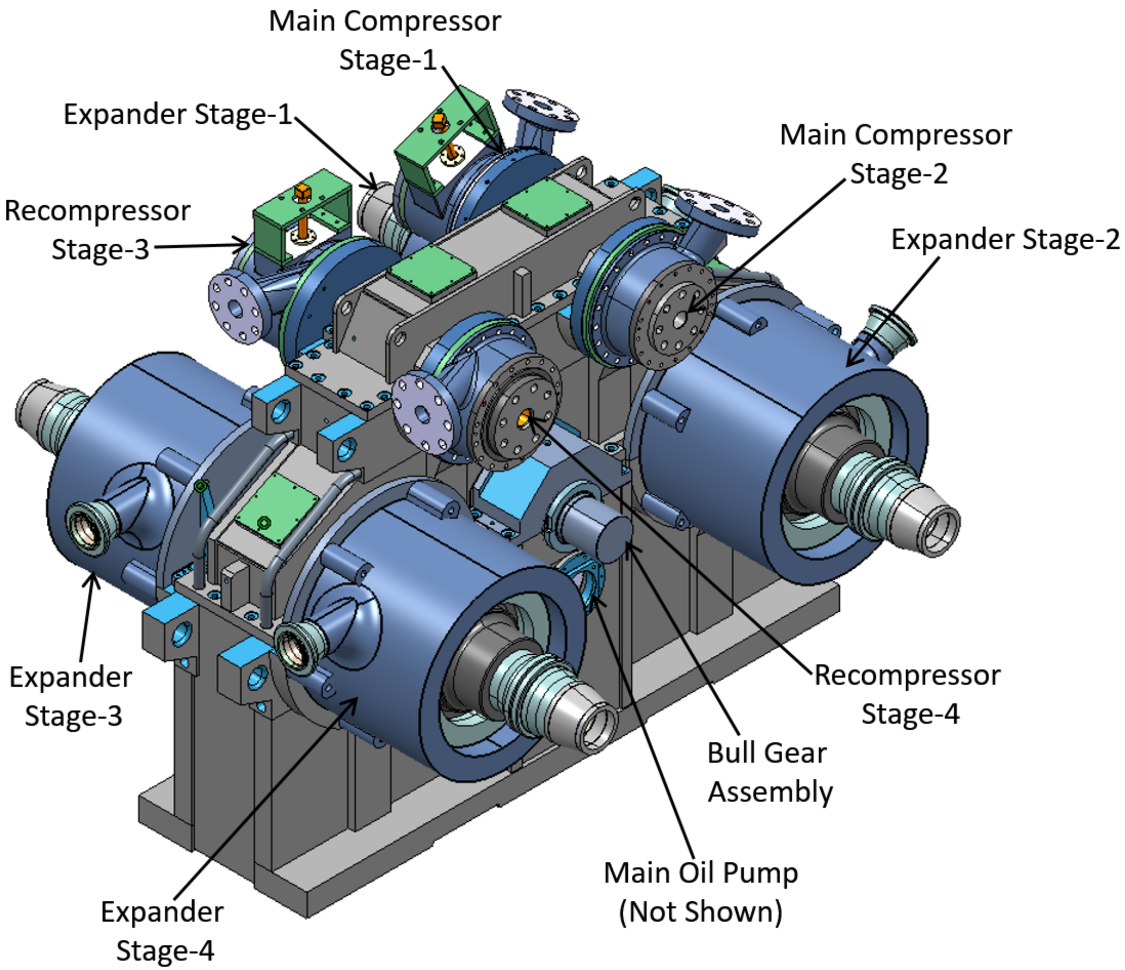
In order to further increase efficiency and compactness, the WHRS will use integrally-geared turbomachinery.

An integrally-geared machine consists of a central bull gear connected to one or more pinion shafts which contain one or two impellers each. These impellers can be radial compressors or radial turbines.

Integrally-geared machines have the following benefits:

- Independent pinion speeds increase overall machine efficiency
- Easy access between stages for intercooling and or reheating
- Stage access allows for each stage to have IGVs for better control
- Compactness
- Extra process compression pinions can be added to use energy recovered by WHRS directly

Project background and motivation: DOE APOLLO Compander



Case of APOLLO Compander from SwRI/Hanwha

SwRI and Hanwha are currently developing a 10MWe integrally-geared compander for an above 700°C sCO2 recompression cycle for concentrating solar power applications under the APOLLO funding opportunity from the DOE.

The detailed design of the compander was completed in 2017 and the machine is presently being manufactured with full speed, full temperature, commissioning and testing expected to begin at SwRI in 2019.

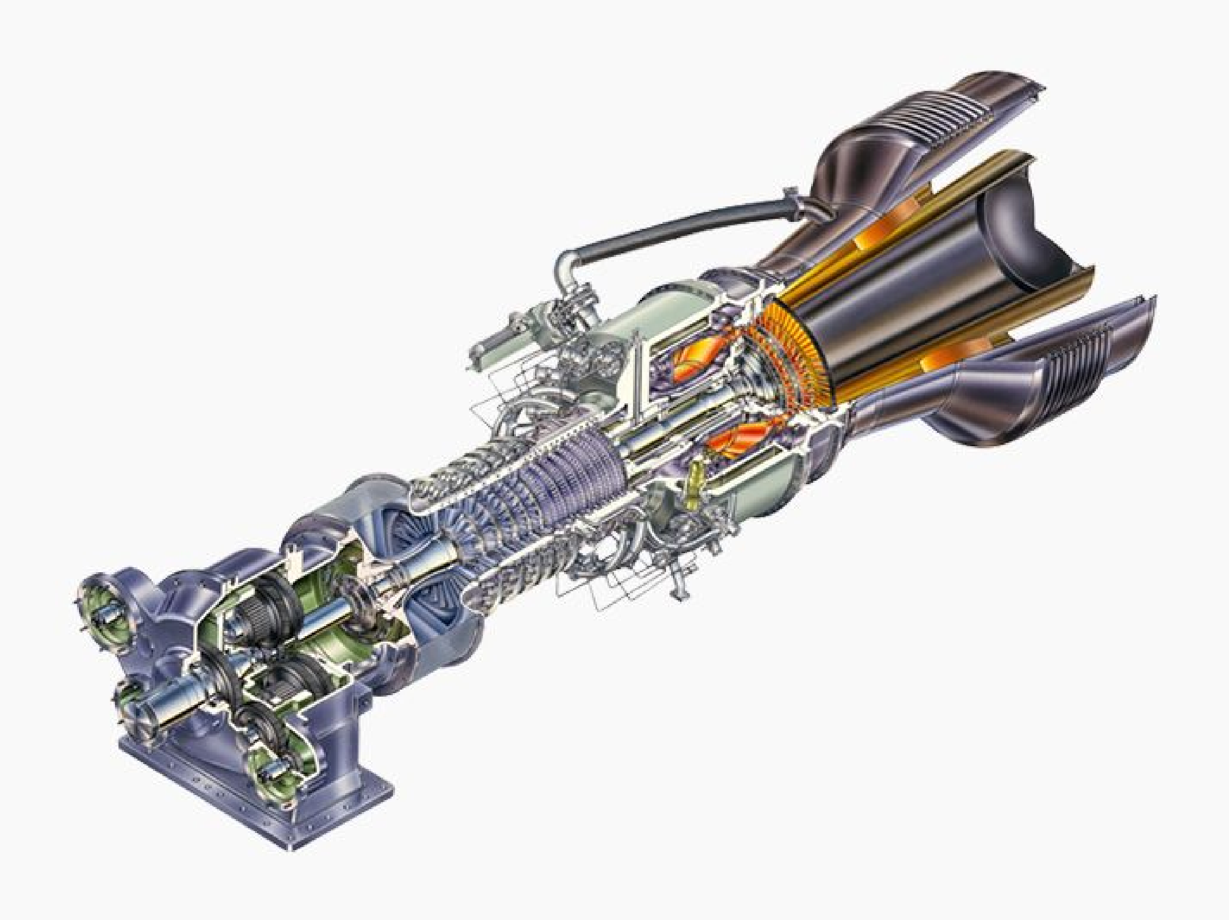
Most of the technical gaps associated with the APOLLO compander come from its high turbine inlet temperature. The WHRS will be lower temperature and use a different Brayton cycle variation, but the approach is similar.

Technical Approach: Overall approach

In order to develop the WHRS the following overall approach will be used:

1. Define turbine exhaust conditions
2. Conceptual design of WHRS
   - -Cycle design and optimization
   - -Aerodynamic design
   - -Mechanical design
   - -Rotordynamic design
4. Create technology maturation plan
5. Explore alternative fuels
6. Develop phase 2 test plan and schedule

Technical Approach: Define turbine outlet stream boundary conditions



Schematic of a Solar Turbines Titan 130 which is often used at natural gas compression stations. A Titan 130 produces 16.5 MWe

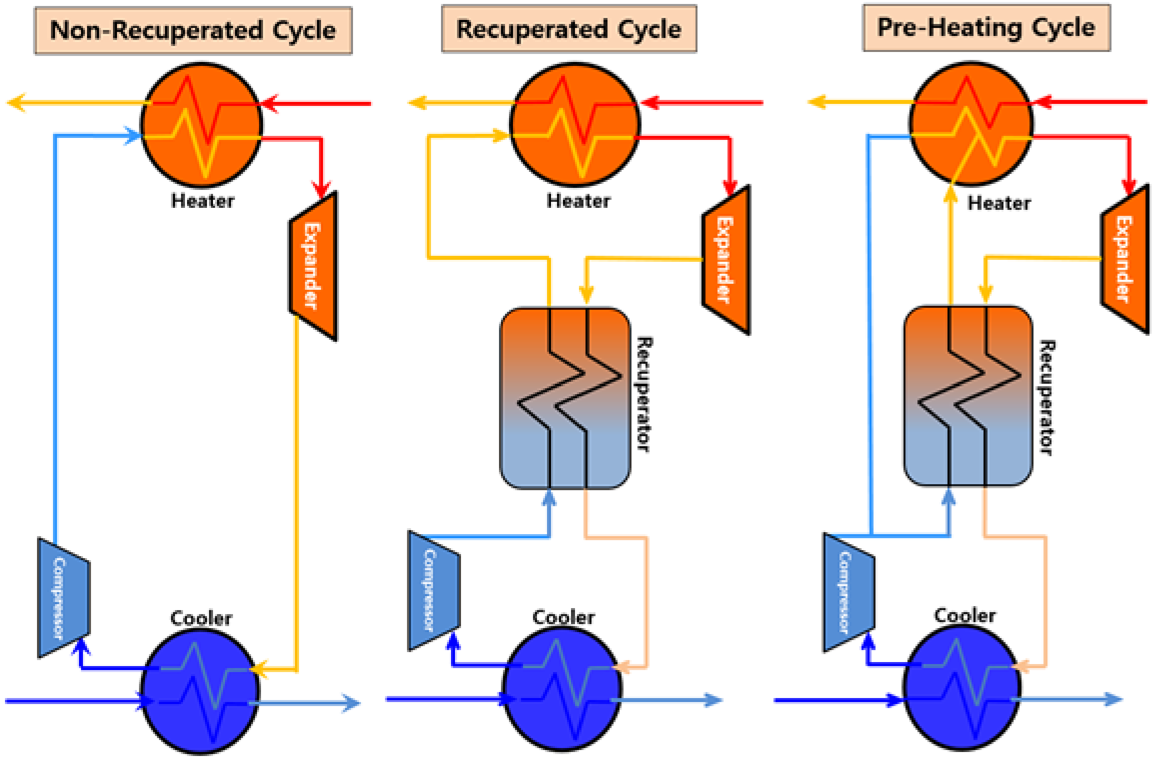
Market research will be conducted to determine which existing gas turbine to target for WHRS development.

Solar will provide detailed turbine outlet stream boundary conditions for use in cycle modeling.

Solar and Williams will provide detailed compression station operating experience such as:

- How often does a gas turbine typically run?
- How often are starts/stops?
- What load is typical?
- What are typical ambient air conditions?
- Is electrical power needed or would direct mechanical coupling be more appropriate?
- What size/weight/portability requirements are there for easy WHRS installation in existing compression stations?

Technical Approach: WHRS Conceptual Design (cycle)



Several cycles explored in preliminary analysis by Hanwha

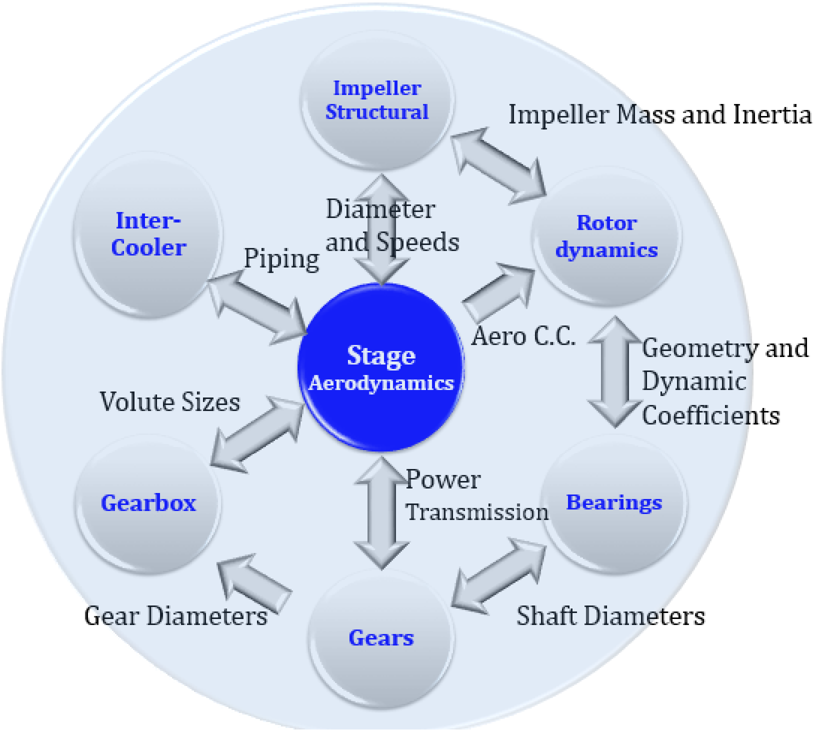
With boundary conditions defined, the WHRS cycle can be designed and optimized.

Many cycle configurations are possible. Preliminary analysis points towards a pre-heating cycle as being able to recover the most energy from the waste heat stream.

Cycle design and optimization will be done to optimize the cycle for the given boundary conditions and operating profile taking into account capital expense and machine complexity.

Auxiliary components to be purchased from outside vendors such as heaters and coolers and recuperators will be defined and explored.

Technical Approach: Aerodynamic/Mechanical/Rotordynamic design



Once the cycle has been defined, conceptual aerodynamic, mechanical, and rotordynamic design can begin. These three design phases will be highly iterative and build on each other.

Aerodynamic

Advanced meanline codes and correlations as well as Hanwha design experience will be used to define the impellers.

Mechanical

Mechanical design of the rotating and stationary components will be carried out using reduced order models and correlations. The design task will include gear design to maximize life, structural assessment to ensure maximum strength, and that the resulting design is serviceable.

Rotordynamic

Rotordynamic design will determine the optimal bearing and seal arrangements for the WHRS. The design will minimize shaft motions at critical clearances, such as impeller tips and seal locations.

Technical Approach: Other items

After conceptual design, other items will be explored such as:

Technology Maturation Plan

A technology maturation plan will be developed leading to pre-commercial testing of the WHRS. This will include a cost benefit analysis of compander, heat exchanger, and installation.

Alternative fuels

Solar Turbines has a long history of operating using alternative fuels. While there should be minimal impact on WHRS design due to the use of alternative fuels, this impact will be explored.

Phase 2 test plan and schedule

During the design of the WHRS, technical gaps will be identified. A test plan for phase 2 will be developed to close those technical gaps and experimentally prove out the WHRS.

Project Objectives

<u>Develop a Combined Cycle Gas Turbine and sCO2 Waste Heat Engine with an Overall Efficiency greater than 65%</u>

The overall cycle efficiency will depend on the efficiency of the gas turbine as well as the WHRS. A gas turbine will be chosen based on maximum potential WHRS market. WHRS cycle optimization will provide an optimal sCO2 WHRS cycle for the chosen gas turbine. This cycle could be adapted to more efficient gas turbines in the future.

<u>Develop a Commercially Competitive Waste Heat Recovery System with a Cost lower than $1,000/kW</u>

During cycle and conceptual WHRS design the capital cost of the WHRS will be considered to ensure a commercially viable solution.

<u>Demonstrate the Performance Advantage of a sCO2 Bottom Cycle Relative to a Conventional Steam Cycle</u>

The resulting WHR cycle and system will be compared to existing conventional technologies to ensure that it is optimal for the intended gas turbine.

Project Risks

Technical Risks

Preheat cycle does not provide adequate WHRS cycle performance
A wide range of cycles will be considered and detailed numerical modeling and optimization will be carried out to ensure that the cycle is optimized

Excessive heat exchanger cost
Heat exchanger vendors will be engaged prior to cycle optimization to develop guidelines for heat exchanger effectiveness, pressure drop and cost.

Turbomachinery components unavailable at speed pressure size combinations required by the cycle
Cycle operating point limits will be created prior to cycle optimization to ensure that the machinery required by the resultant cycle is realistic

Conceptual design indicated large thrust imbalances and or rotordynamic instabilities
Pinions will be designed for thrust balance. Data from the APOLLO project will be used to calibrate thrust and rotordynamic predictions.

Project Management Risks

Miscommunication and duplication of work
Regular meetings with functional groups, monthly status updates, and quarterly reports will ensure that good communication is maintained between all members of the research team.

Overspending
SwRI uses a computerized project reporting system that is integrated into all aspects of project management. Daily reporting of hours worked, real time project cost tracking, and projected resource availability is included in the software.

Shortage of resources
SwRI has access to a vast body of resources which not only include physical resources but human resources from several scientific disciplines. With over two million square feet of lab space and over 3,000 employees on site at San Antonio, shortage of resources is a rare occurrence.

Loss of cost share support
Hanwha Power Systems Americas has provided a signed letter of commitment to demonstrate that they are committed to providing technical and engineering support throughout the project.

Project Schedule

	Year	2018					2019										
	Month	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
1	**Project Management and Planning**																
1.1	Coordination of Participants	1															30
1.2	Revise Project Management Plan	1															
1.3	Revise Risk Management Plan	1		1													
2	**Data collection / Market Research**																
2.1	Market Research		1		1												
2.2	Define Nominal Cycle Boundary Conditions			1		15											
3	**Conceptual Design**																
3.1	Thermodynamic Cycle Modeling					15			15								
3.2	Aerodynamic Design								15					15			
3.3	Mechanical Design								15					15			
3.4	Rotordynamic Design								15					15			
4	**Auxiliary Tasks**																
4.1	Detailed Technology Maturation Plan													15		31	
4.2	Explore Alternative Fuels													15		31	
4.3	Phase II Test Plan and Schedule													15		31	
	Milestones																
1	Finalization of Cycle Boundary Conditions					15											
2	Selection of WHRS Cycle								15								
3	Conceptual Design Complete													15			
4	Technology Maturation Plan and Phase II Test Plan Complete															1	

Work started in earnest in August 2018. We are still on schedule to meet all deadlines from the original project schedule.

Project Milestones

1. Finalization of Cycle Boundary Conditions. (12/15/2018)
2. Selection of WHRS Cycle. (5/15/2019)
3. Conceptual Design Complete. (8/15/2019)
4. Technology Maturation Plan and Phase II Test Plan Complete. (10/1/2019)

Project Budget

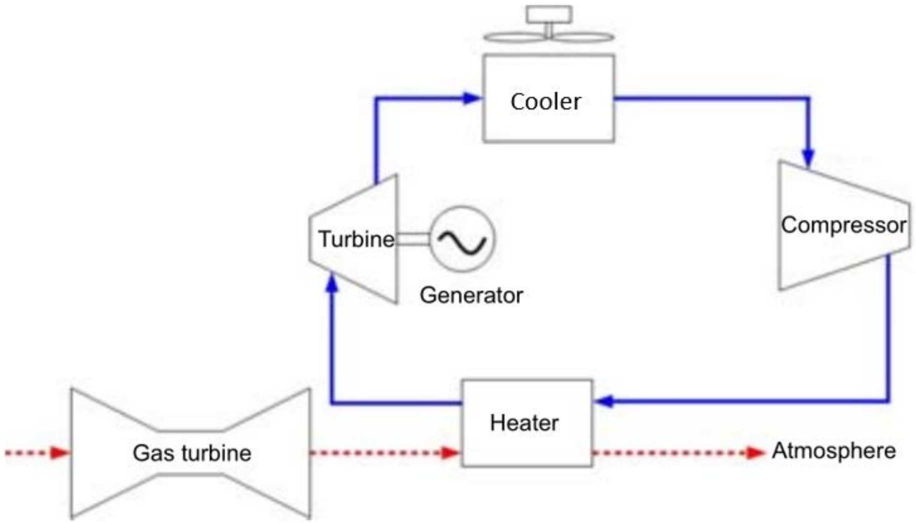
SUMMARY OF BUDGET CATEGORY COSTS PROPOSED The values in this summary table are from entries made in subsequent tabs, only blank white cells require data entry						
Section A - Budget Summary						
		Federal	Cost Share	Total Costs	Cost Share %	Proposed Budget Period Dates
	Budget Period 1	$500,000	$125,000	$625,000	20.00%	5/1/2018 - 11/1/2019
	Budget Period 2	$0	$0	$0	0.00%	
	Budget Period 3	$0	$0	$0	0.00%	
	Total	$500,000	$125,000	$625,000	20.00%	
Section B - Budget Categories						
CATEGORY	Budget Period 1	Budget Period 2	Budget Period 3	Total Costs	% of Project	Comments (as needed)
a. Personnel	$82,833	$0	$0	$82,833	13.25%	
b. Fringe Benefits	$41,417	$0	$0	$41,417	6.63%	
c. Travel	$9,329	$0	$0	$9,329	1.49%	
d. Equipment	$0	$0	$0	$0	0.00%	
e. Supplies	$0	$0	$0	$0	0.00%	
f. Contractual						
Sub-recipient	$300,000	$0	$0	$300,000	48.00%	
Vendor	$0	$0	$0	$0	0.00%	
FFRDC	$0	$0	$0	$0	0.00%	
Total Contractual	$300,000	$0	$0	$300,000	48.00%	
g. Construction	$0	$0	$0	$0	0.00%	
h. Other Direct Costs	$0	$0	$0	$0	0.00%	
Total Direct Costs	$433,579	$0	$0	$433,579	69.37%	
i. Indirect Charges	$191,421	$0	$0	$191,421	30.63%	
Total Costs	$625,000	$0	$0	$625,000	100.00%	

Work started in earnest in August 2018. We are still within our project budget.

After an initial discussion with Hanwha the travel expenditures may be adjusted going forward.

Instead of three site visits to compressor stations as well as a kickoff meeting in Morgantown, we are now planning a trip to Solar in San Diego and possibly a single site visit.

Summary



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- Highly efficient
- Modular and skidable
- Compatible with air cooling
- Allow for advanced load following

The overall goals of the project are to:

- Develop a Combined Cycle Gas Turbine and sCO2 Waste Heat Engine with an Overall Efficiency greater than 65%
- Develop a Commercially Competitive Waste Heat Recovery System with a Cost lower than $1,000/kW
- Demonstrate the Performance Advantage of a sCO2 Bottom Cycle Relative to a Conventional Steam Cycle

References

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