COMPONENT TECHNOLOGY MATURITY & COST OF ELECTRICITY FOR SCO_2 BRAYTON POWER CYCLES IN NUCLEAR, SOLAR & FOSSIL HEAT SOURCES: DEVELOPMENT CHALLENGES AND MITIGATION APPROACHES

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ABSTRACT

Aerojet Rocketdyne (AR), in cooperation with the Department of Energy (DOE), has been evaluating supercritical CO_2 (SCO_2) based Brayton cycles and associated turbomachinery concepts for electric power production using fossil heat sources. The present work assesses the practical technology limits to increasing turbine inlet temperature in these cycles, and describes both component and system approaches to working around these technology constraints. Predicted performance penalties associated with these approaches, and the allowable increase in capital costs to provide the subsystems capable of mitigating the constraints while still delivering reductions in the Levelized Cost of Electricity (LCOE) are discussed.

INTRODUCTION

Both indirectly heated and directly heated sCO_2 based Brayton cycles are currently being investigated for thermal power generation. They are predicted to offer the potential of higher plant efficiencies, and less complex, lower cost turbomachinery than the current state-of–the-art steam Rankine and combined cycles. As in all thermodynamic cycles, efficiency increases with increasing peak cycle temperature (turbine inlet temperature for these cycles), but material capabilities limit these temperatures, and hence the efficiencies that can be achieved. Various approaches can be used to overcome these limitations, such as use of more capable, more expensive materials, turbine blade cooling, and cycle compromises to limit temperatures. These approaches decrease the potential efficiency gain of increasing turbine inlet temperature and/or increase the capital cost and complexity of the various components. The primary goal of assessing these cycles is to reduce LCOE while also meeting environmental constraints, and this paper presents predictions of the allowable increase in capital costs to maintain a reduction in LCOE as turbine inlet temperature is increased.

CYCLE DESCRIPTIONS AND INDIRECTLY FIRED CYCLE TEMPERATURE CONSTRAINTS

Simplified diagrams of the two Brayton cycles being considered are shown in Figure 1 and Figure 2. The indirectly fired cycle is suitable for solid fossil fuel, nuclear, solar and geothermal heat sources. Heat is transferred to the power generation cycle working fluid through a heat exchanger. Turbine inlet temperatures for this cycle are constrained by the material capability of the heat source heat exchanger and are limited to 1100°F for materials in common usage today, and 1300°F for materials recently certified for Advanced Ultra Supercritical steam cycles. To increase turbine inlet temperature beyond this constraint, direct combustion in the turbine working fluid is required (similar to the approach used in the high temperature section of combined cycles), and a closed power generation cycle is no longer possible. This direct combustion can be achieved either with duct firing downstream of an indirect heat source, or with a single natural gas or syngas combustor. The direct cycle considered here is a pre-combustion capture oxy-fired cycle using recirculated CO_2 as a diluent, and with a combustion pressure of 4000psi. In the baseline configuration for this cycle the working fluid stays above the critical pressure throughout the cycle.

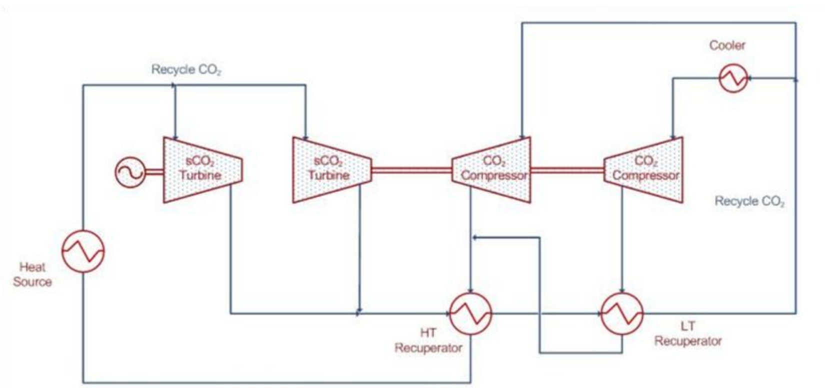

Figure 1: Indirectly Heated Recompression Brayton Cycle

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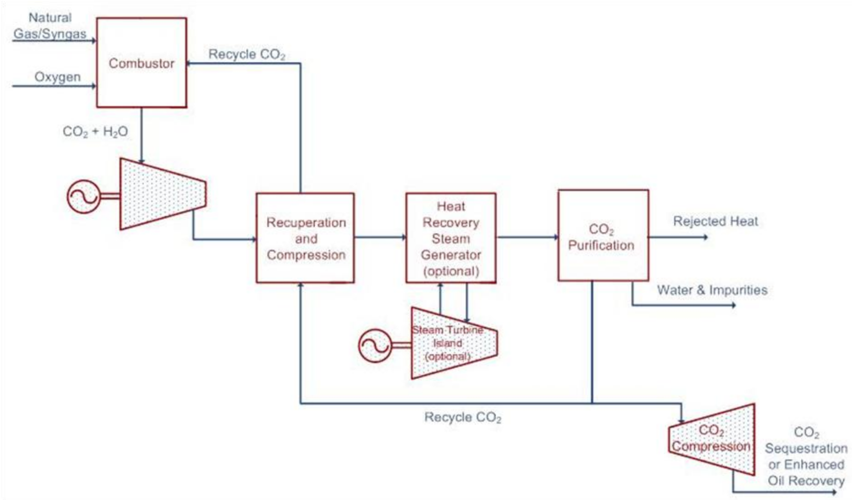

Figure 2: Directly Heated Recuperated Brayton cycle

DIRECTLY FIRED CYCLE TEMPERATURE CONSTRAINTS

Figure 3 shows calculated efficiencies for various cycles as a function of turbine inlet temperature, showing the relevant temperature constraints for the directly heated Brayton cycles being considered.

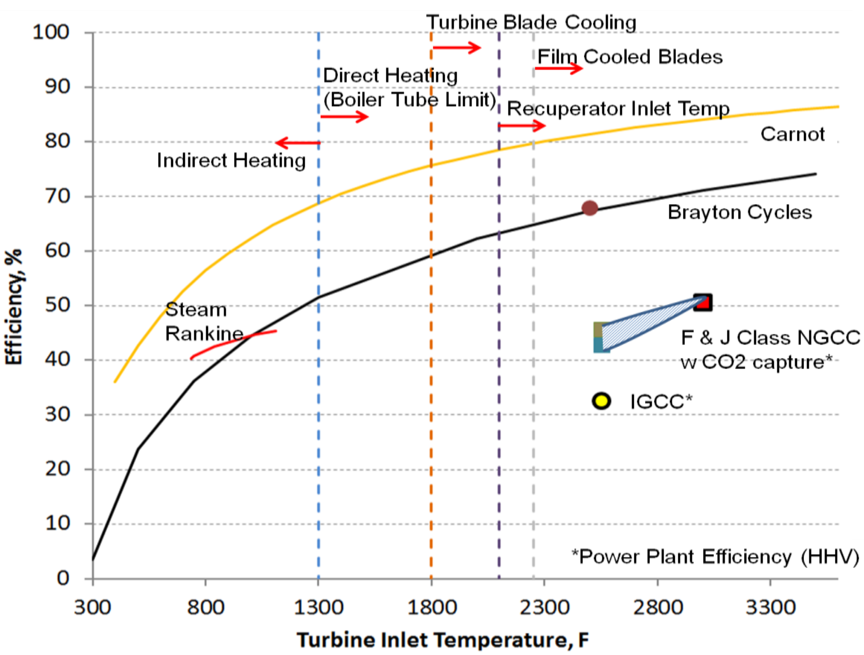

Figure 3: Gross Efficiency as a Function of Turbine Inlet Temperature

The first temperature limit reached is at 1800°F, after which turbine blade cooling is required to keep blade temperatures in an allowable range. Turbine blades can first be cooled regeneratively, where none of the coolant is injected into the turbine flowpath (which maintains turbine aerodynamic efficiency). The heat extracted by the coolant fluid is returned to the cycle, either to the recirculated CO_2 upstream of the combustor, or to a HRSG if a steam bottoming cycle is employed and steam used as the coolant, as shown in Figure 4.

The next temperature limit for this cycle occurs when the turbine exit temperature exceeds 1675°F, and is driven by the material capability of the high temperature recuperator. This corresponds to a turbine inlet temperature of 2100°F, and for turbine inlet temperatures higher than this the cycle must be compromised by taking a higher pressure ratio across the turbine. This reduces the turbine exit and compressor inlet pressure below critical, which lowers cycle efficiency because the compression load increases. Figure 5 shows a comparison of the T-S diagrams for the optimum cycle (where the turbine exit pressure equals the critical pressure) and the compromised cycle (where the turbine exit pressure is lower that the critical pressure).

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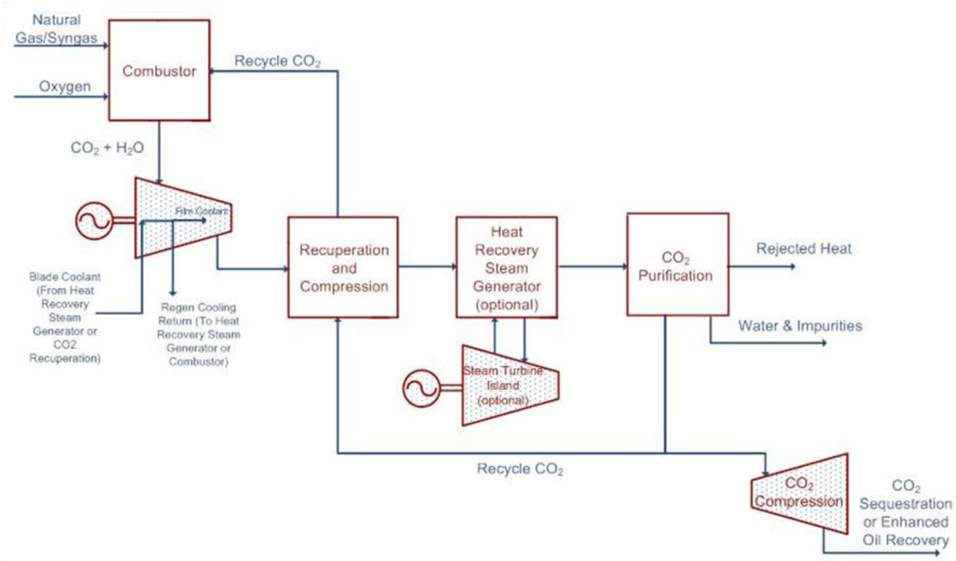

Figure 4: Directly Heated Cycle with Turbine Blade Cooling

The final temperature limit reached is the Thermal Barrier Coating (TBC) on the turbine blade at about 2250°F. At this point film cooling must be used to keep the TBC surface temperature below allowable limits. This reduces turbine aerodynamic efficiency because of the mixing of the coolant fluid into the primary turbine flowpath, and because of the additional heat that must be extracted from the turbine flowpath to maintain the TBC surface temperature.

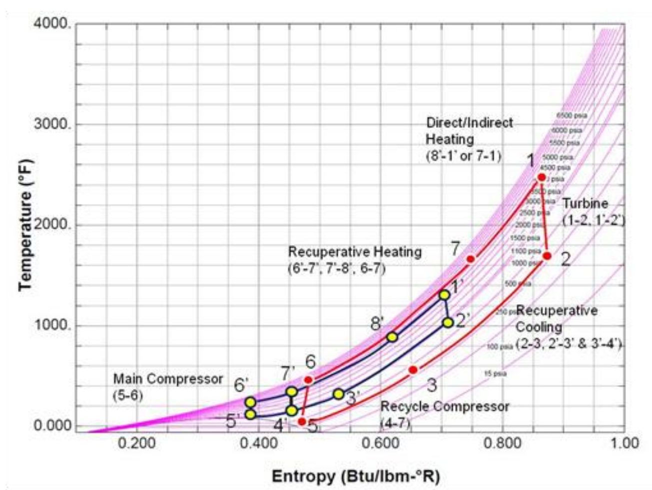

Figure 5: T-S Diagram for Cycle with Constrained Turbine Exit Temperature

ANALYSIS METHODOLOGY

Cycle and plant performance predictions were made using ASPEN process modeling software. LCOE predictions were made with a simplified spreadsheet derived from and validated against the DOE Power System Financial Modeling (PSFM) spreadsheet (References 3 and 4), with capital costs calculated using ASPEN capital cost estimation software or scaled from appropriate data in Reference 1 using the QGESS guidelines (Reference 2).

LCOE CONSIDERATIONS FOR THE INDIRECTLY FIRED CYCLE

LCOE has two primary components – fuel cost and capital recovery charges. Figure 6 shows the predicted LCOE for 3 indirectly fired plants - two supercritical steam PC plants running at 1100°F turbine inlet temperature, one with and one without CO_2 capture, and an RCBC plant running at 1300°F with a pressurized oxy-fired coal combustor for the heat source. Data for the two PC plants is taken from cases 11 and 12 in Reference 1, and LCOE is normalized to that of the PC plant without capture.

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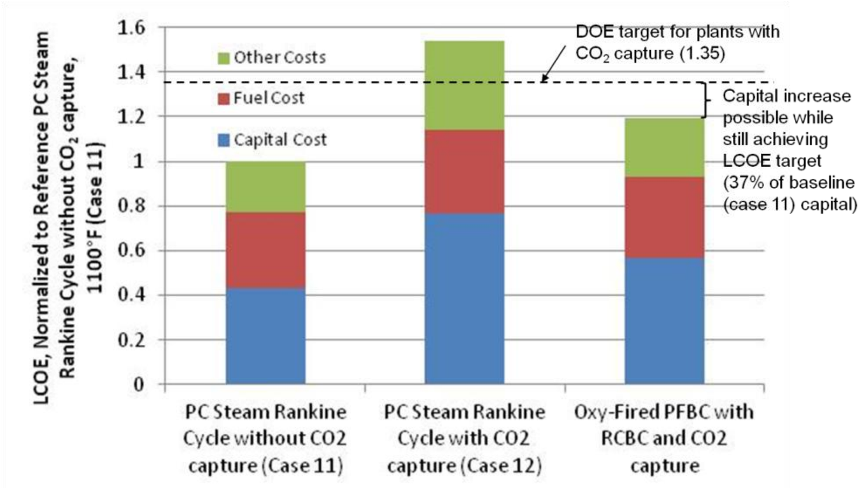

Figure 6: LCOE for Indirectly Fired Cycles

The differences in efficiency, and hence fuel costs, are small between the three cases, but the capital cost for the carbon capture equipment is large, significantly so for the post-combustion capture case. An RCBC plant is predicted to increase LCOE over a PC plant without CO_2 capture by only 18%, which is significantly less than the current DOE targets of 35%. It is also predicted that capital costs could increase by a further 37% over the baseline capital cost, or 26% over the current predictions for the RCBC capital cost without exceeding the current DOE target.

EFFICIENCY AND LEVELIZED COST OF ELECTRICITY FOR THE DIRECTLY FIRED CYCLE

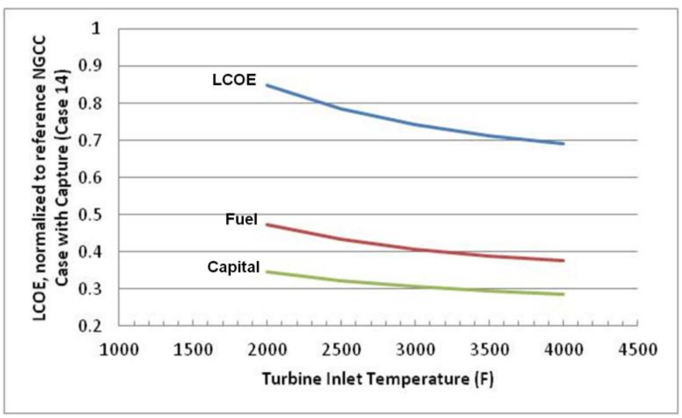

Figure 7: Idealized Decrease in LCOE as a Function of TIT – Directly Heated Cycle

Figure 7 shows predictions of LCOE as a function of turbine inlet temperature for directly fired cycles in an idealized case where there are no material driven temperature constraints. In other words, these predictions do not take into account any efficiency penalties due to turbine blade cooling or cycle compromises. The reference case for this comparison is an NGCC cycle with CO_2 capture (case 14 in reference 1). As expected, there is a decrease in LCOE as the predicted increase in efficiency reduces both fuel consumption and equipment size.

Figure 8 shows the calculated efficiency penalty for the approaches used to allow turbine inlet temperature to increase despite reaching the various material temperature limits. The blade cooling penalty curve combines the effects of regenerative and film cooling as required.

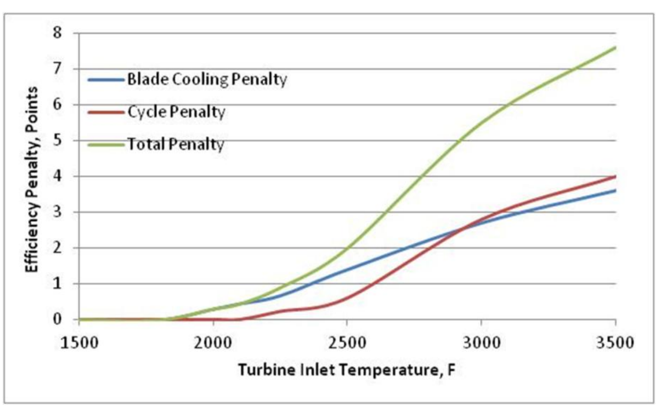

Figure 8: Efficiency Penalties to Mitigate Temperature Constraints

These decrements in efficiency increase the fuel cost portion of the LCOE over the idealized case, and also increase capital cost due to the need for higher cost materials and the higher fabrication, assembly and control system costs for configurations with blade cooling. The studies undertaken to date have not been in sufficient detail to make detailed bottoms-up estimates of equipment capital cost (and any increased installation costs to accommodate the additional coolant flows), however, it is possible to calculate what the allowable increase in capital cost is predicted to be to achieve target reductions in LCOE. This is presented in Figure 9.

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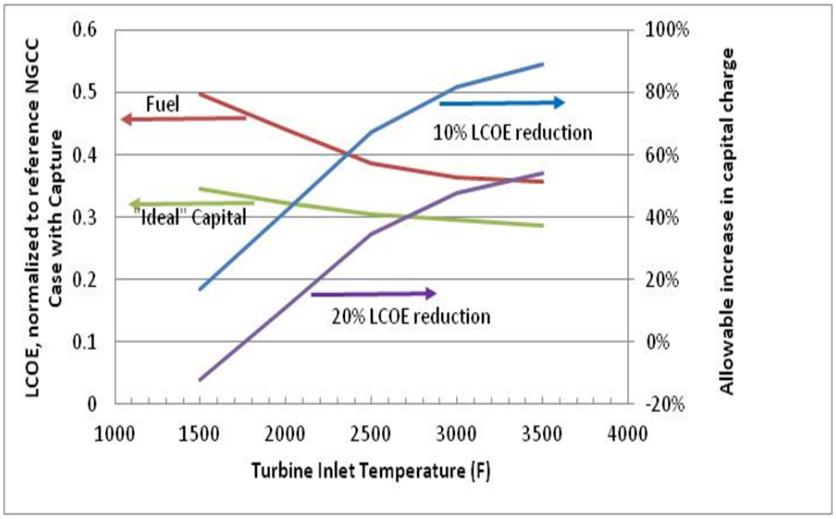

Figure 9: Allowable Capital Cost Increase to Reach Target LCOE Reductions for Directly Fired Cycle

The blue and purple curves show the increase in capital cost above that calculated for the idealized cycles in Figure 7 that will still reduce LCOE by 10% and 20% below the reference case. The reference case is the NGCC cycle with CO_2 capture presented in Reference 1 (case 14). The increase in capital is presented as a percentage of the predicted "ideal" capital at that temperature. These predictions suggest that that at 2500°F the equipment required to enable the turbine to operate at that temperature can cost up to 35% more than the current technology, and still achieve a reduction in LCOE of 20% over current NGCC cycles.

CONCLUSION

Brayton cycles are predicted to offer lower LCOE than current technology, especially when CO_2 capture is a consideration. There is also an incentive to develop technologies that allow higher turbine inlet temperatures than those currently targeted for indirectly heated cycles, as LCOE reductions are still viable after taking into account the efficiency penalties and associated capital increase of providing methods to keep component metal temperatures within acceptable limits.

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NOMENCLATURE

AR	=	Aerojet Rocketdyne
DOE	=	Department of Energy
HRSG	=	Heat Recovery Steam Generator
IGCC	=	Integrated Gasification Combined Cycle
LCOE	=	Levelized Cost of Electricity
NGCC	=	Natural Gas Combined Cycle
PC	=	Pulverized Coal
PSFM	=	Power Systems Financial Model
QGESS	=	Quality Guidelines for Energy System Studies
RCBC	=	Recompression Brayton Cycle
SCO_2	=	Supercritical CO_2
SCOT	=	Supercritical CO_2 Turbomachinery
TS	=	Temperature-Entropy

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