Integrated Thermal Aero Propulsion (ITAP) Engine

John R. (Bob) Fagan*, Scott C. Morris † and Joshua D. Cameron ‡

Notre Dame Turbomachinery Laboratory, South Bend, IN, 46601

A novel gas turbine architecture is proposed that integrates a conventional air-breathing cycle for propulsion with a closed loop supercritical CO2 cycle. The approach leverages the advantages of the conventional architecture of a gas turbine engine, while integrating thermal management and power generation in a manner that radically changes the engine configuration and system efficiency. In the proposed architecture, an open, air-breathing Brayton cycle is augmented with a closed sCO2 cycle that provides simultaneous power transport and thermal management of hot-section components. Detailed cycle analyses have demonstrated the potential for a 9% to 18% reduction in fuel burn and emissions for a single aisle commercial transport aircraft. The engine also has the potential to eliminate much of the complexity and materials limitations of current engines.

I. Introduction

Commercial and military aircraft are almost exclusively powered by gas-turbine engines. This is a result of the significant power-to-weight advantage compared with other power generation cycles[1]. Modern aircraft engines have evolved to include a high pressure-ratio and high-temperature core that provides power to a high-mass flow fan system for efficient production of thrust. The most recent generation of engines has included a variety of architectural and component technology improvements to reduce fuel burn and associate environmental impacts as well as to increase reliability and safety.

While the progress over the recent decades has been substantial, the maturity of the relevant technologies with the conventional engine architecture suggests that there is limited opportunity for major future improvements. Disruptive changes to engine efficiency thus will require non-conventional aero-propulsion engine architecture. This has inspired a variety of new, novel, and potentially revolutionary alternatives to the typical turbofan architecture. Electric propulsion, for example, has received significant attention in recent years.

An all-electric system would have myriad advantages, with truly zero emissions during flight. However, there is a significant technology gap between current capability and the requirements to support a single-aisle mission [2], [3].

Boeing 737-900 MTOW	165000 lbs (75000 kg)
Boeing 737-900 Dry Weight	94000 lbs (42500 kg)
Fuel Burn for a Typical Two Hour Flight Segment (Each Engine)	5050 lbs (2300 kg)
Energy Equivalent for 5050 lbs (2300 kg)	93 MBTU's (27.3 MW-hr)
Usable Energy Storage Capacity for Automotive Batteries (Current Generation)	250 W-hr/kg
Energy Storage Increase Required for Single-Aisle Application	20 - 30x

Fig. 1 Weights and Energies for a Single Aisle Aircraft Engine.

The shortfall in battery capacity (figure 1) is significant but is likely not the biggest challenge. Modern hub airports support between 500 and 2000 flights per day with turn around times less than one hour in length. Neither the infrastructure to produce and deliver that amount of power nor the technology to charge the batteries to support those turn-around times exists today. With the investments being made in electric propulsion and energy storage, there will certainly be breakthroughs lessening these challenges, but they are unlikely to impact the next generation of commercial aircraft.

An alternative approach to increasing engine efficiency is to utilize a closed-loop working fluid in a Brayton cycle. The use of supercritical carbon dioxide (sCO2), for example, has gained significant attention in recent years

*Associate Director, Notre Dame Turbomachinery Laboratory

†Professor, Department of Aerospace and Mechanical Engineering, University of Notre Dame

‡Director, Notre Dame Turbomachinery Laboratory

for land-based electricity production[4]. This includes system designs for stand-alone power operations [5] as well as systems for waste heat recovery [6]. Applications for space propulsion have been proposed [7]. In addition to the potential for increased thermodynamic efficiency, sCO2 turbomachinery is extremely compact [8]. However, the size of the heat exchangers required for a closed-loop system presents a significant challenge [9] for many applications.

The use of closed-loop systems for aircraft propulsion has been considered. However, the concepts have typically been used for thermal management as opposed to a direct power conversion process [10].

The present communication describes a novel, hybrid approach that incorporates both conventional air-breathing engine architecture and a closed-loop sCO2 cycle. This approach leverages the advancements associated with conventional gas turbine engine technologies while utilizing the sCO2 for both efficiency improvements and for thermal management. This new engine architecture addresses efficiency-limiting features of current turbofan engine design, while utilizing available and demonstrated technologies. The proposed architecture integrates the two cycles in a manner unique to previous implementations with compelling benefits. The emerging development of sCO2 power and thermal management cycles and the compact size of their associated turbomachinery are enabling for this architecture.

II. Baseline Engine

The baseline engine for this assessment is a notional representation of a modern 30,000 lb. thrust, high bypass ratio, commercial engine similar to the current generation of engines powering the Boeing 737 Max and Airbus A320NEO families of aircraft. The architecture is a two-spool engine with a direct connected fan module. The engine was modeled with the Numerical Propulsion Simulation System (NPSS) with component efficiencies, material technologies, and bypass ratios consistent with the latest generation of engines. The cycle calculations use the GasTbl thermodynamic property package included in the NPSS software.

The potential benefit of a thermal management cycle can best be analyzed by looking at the power usage in the baseline gas turbine engine for a takeoff power and cruise condition. This is illustrated in Figure 2. For the energy balance in the figure, the values are expressed with dimensions of power. The fuel burn values are calculated by multiplying the fuel lower heating value by its flow. The air streams values are calculated by multiplying the difference of the local specific total enthalpy minus that at the engine inlet multiplied by the local airflow. The difference between the energy input (fuel burn) and the net energy addition to the air exiting the engine in the fan and the core exhaust streams is due to the combustion efficiency, overboard leakage from the core and the fan streams, and the engine and aircraft accessory power requirements. Note that this is simply an energy balance and does not reflect the thermal efficiency of the cycle.

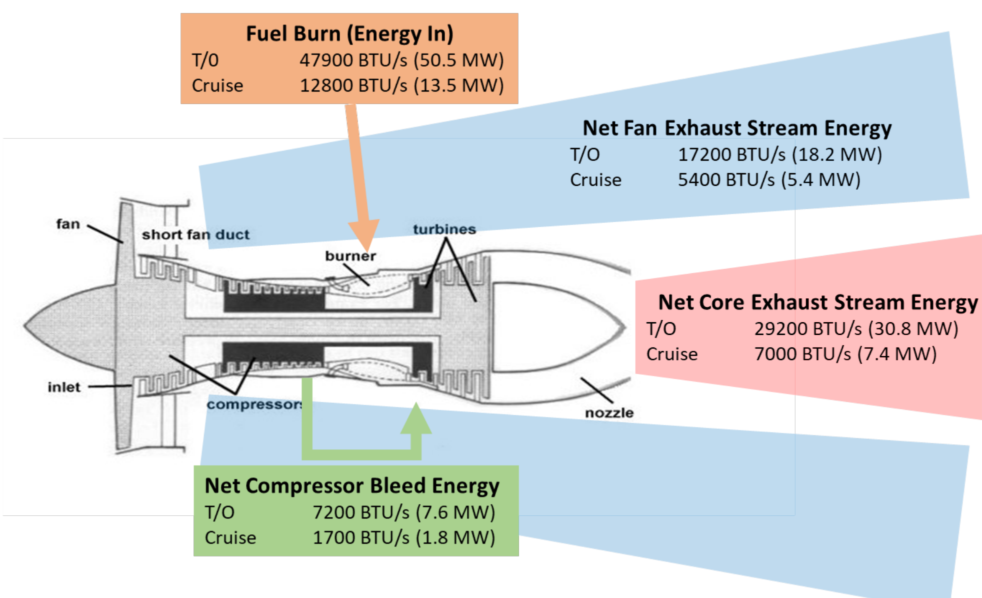

Fig. 2 Energy Balance in a Gas Turbine Engine.

The first takeaway from the figure is the magnitude of the energy associated with this engine cycle. At take-off, the power equivalent of the fuel burn rate is 50 MW for each of the two engines on the aircraft. Additionally, the core stream has had 30 - 70% more energy addition than the bypass stream, but only provides 10 - 13% of the total engine thrust. This indicates a waste heat recovery cycle for the core exhaust stream can provide significant benefit. It also demonstrates the advantage of a high bypass ratio cycle. Finally, a significant level of energy is expended to pressurize the air used for turbine cooling. An engine architecture that reduces the required level of cooling bleed flow will improve engine efficiency.

III. Integrated Thermal Aero Propulsion (ITAP) Engine

The proposed engine concept is illustrated schematically in Figure 3. The air system (shown in blue) follows from a typical application of the Brayton cycle, with the air inlet connected to a compressor, followed by a combustor and turbine. The air from the turbine is cooled through a heat exchange before exhausting to the atmosphere. In the application shown, the turbine is used to drive an electric generator (shown in grey) that is connected to both a battery and an electric motor to drive the propulsion system.

The integrated closed-loop cycle is shown in orange in Figure 3. Starting from the heat exchanger, the sCO2 temperature increases using the thermal energy recovered from the primary air flow exhaust and the working fluid is additionally heated as it passes through the hot section components. The sCO2 is then expanded through a turbine. The fluid then passes through a second heat-exchanger to reduce the temperature before moving through a sCO2 compressor to complete the closed cycle.

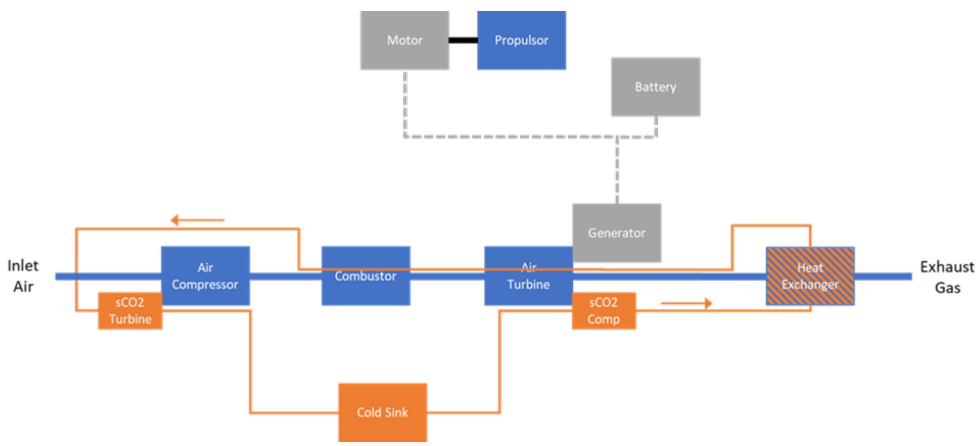

Fig. 3 Schematic of combined air-breathing and sCO2 cycles.

The integrated sCO2 thermal management system provides major benefit to the gas turbine engine. The cycle can be used to recover useful work from waste heat. Additionally, the working fluid can be utilized as a thermal sink for the high temperature structure of the air-breathing components. Both benefits contribute to an increased cycle thermal efficiency. Waste heat recovery cycles are well understood and, in this implementation, recover the waste heat not only from the engine exhaust, but also from the air-breathing hot section engine components.

The ITAP engine architecture uses the sCO2 rotating components to provide power transmission between the air-breathing compressor and turbine components. This is accomplished by integrating the air-breathing compressor and the sCO2 turbine into a single component as shown in figure 4. Similarly, the air-breathing turbine and sCO2 compressor are integrated into a single component. Employing the sCO2 system to transmit power between the components greatly simplifies the complex shafting, bearing, and lubrication system in conventional engine architectures. This architecture has the penalty of the reduced power transmission efficiency, but provides offsetting benefit at the system level.

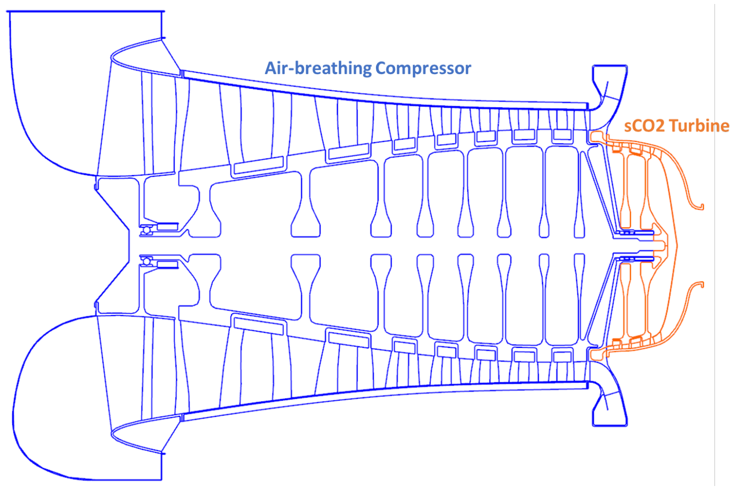

Fig. 4 Integrated air-breathing compressor and sCO2 turbine.

Numerical simulations of the ITAP engine were conducted to assess the feasibility and potential impact of the concept. The NPSS software was used to model the both the air-breathing components as well as the sCO2 power and thermal management cycle. The air-breathing cycle calculations used the GasTbl thermodynamic property package included in the NPSS software. The sCO2 cycle calculations used the Reference Fluid Properties (REFPROP) thermodynamic property package from NIST.

IV. Cycle Modeling Results

Cycle modeling was executed with both the baseline and the ITAP engines for several critical mission points. Each mission point was run to the same turbine inlet temperature for both engines. For the ITAP engine, each mission point was run over a range of pressure ratios for the air-breathing Brayton cycle. The same 4.5 pressure ratio sCO2 closed cycle was used for all the ITAP engine results with heat addition from the core exhaust heat exchanger and the thermal load of the hot section components. As a result of the heat transfer between the hot section components and the working fluid, the air-breathing cycle cooling flow is reduced by an associated amount. The closed cycle is shown on a pressure enthalpy diagram in figure 5.

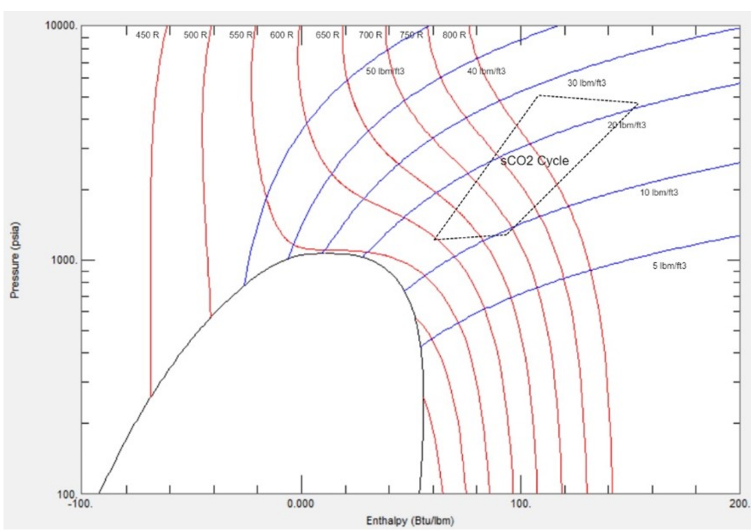

Fig. 5 sCO2 cycle used for the ITAP engine.

The ITAP engine used in this modeling is configured for an electrically driven propulsor with the "power generator" locally or remotely mounted. The ITAP fan module has the same propulsive efficiency as the baseline fan and accounts for losses in the electrical system. The air-breathing components for each engine have efficiencies representing the same level of technology. It does not include any benefit from "power load leveling" associated with hybrid electric systems, nor from thrust produced by the core exhaust stream. Benefit from both of these could be captured with appropriate system considerations. Consequently, the results quantify the difference in thermal efficiency between the two engines and specifically the cycle advantages of the ITAP engine.

The results for three important mission points are shown in figure 6. The figures show the net fuel burn as a function of the air-breathing cycle pressure ratio for Take-off, Climb, and Cruise conditions. The fuel burn reduction is between 9.1% and 18.0% for these mission points with climb and cruise the portions of the mission that consume most of the fuel.

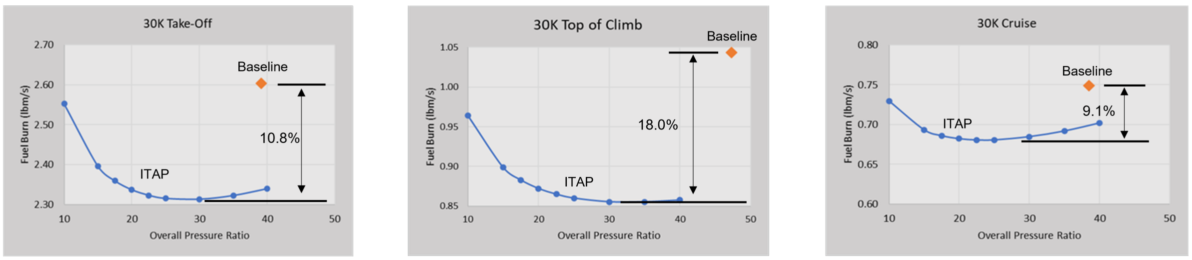

Fig. 6 Fuel burn for ITAP engine compared to the baseline.

V. Additional Benefits

While the potential fuel burn savings is very compelling, there are other advantages of the ITAP engine that are more difficult to quantify providing significant value.

From Figure 6, note that the optimal overall pressure ratio for the air-breathing cycle in the ITAP engine is between 25 and 30 compared overall pressure ratios between 40 and 50 for the various mission points of the baseline engine. At a given turbine inlet temperature, the lower pressure ratio cycle results in a higher turbine exit temperature and thus more waste heat recovery with the sCO2 cycle. This offsets the cycle advantage as the higher overall pressure ratio and results in a lower pressure ratio cycle for optimum fuel burn. The lower pressure ratio cycle provides two significant benefits. Potentially, the ITAP cycle could be supported with a single compressor rather than the two-compressor configuration in the baseline engine, reducing the number of components and the associated complexity. Additionally, the compressor exit temperature is reduced mitigating a materials / cooling issue at the rear end of compressors in high overall pressure ratio engines, where temperatures exceed the capabilities of conventional compressor material systems and there is no available cooling air supply without a secondary cooling system.

The ITAP architecture also supports a modular system where the major airbreathing components (compressor, combustor, turbine) are exclusively interconnected with fluid ducting and piping. This provides extensive freedom in the packaging of the engine within the aircraft and would support vibration and shock isolation for the rotating components allowing tighter clearances that could be preserved throughout the life of the engine. Additionally, a modular system would have great impact for the aftermarket, particularly if turbine modules could be swapped without engine removals.

VI. Challenges

We do not propose that an ITAP engine could currently replace the engine on today's aircraft. While much of the technology associated with the ITAP engine is in place today, there remain engineering challenges that will require an investment in time and money to ready a product for commercial flight. The biggest challenges associated with the ITAP engine are turbomachinery component efficiencies, sealing of the high-pressure sCO2 system, and heat exchanger design. While none of those problems are simple, they are each engineering challenges which can be addressed with the proper resourcing. History has shown that the cost benefit ratio for improvements in aero-propulsion engines justifies significant investments in new technologies. To address one of these issues, NDTL is currently executing sponsored research to improve the efficiency of sCO2 compressors.

VII. Additional Considerations

As stated, this study was executed based on distributed propulsion engine with an electrically driven propulsor. An alternative realization of an ITAP engine would use the sCO2 cycle for power transmission to the propulsor. This would eliminate the need for the high-power electrical system. This schematic for this configuration is shown in figure 7.

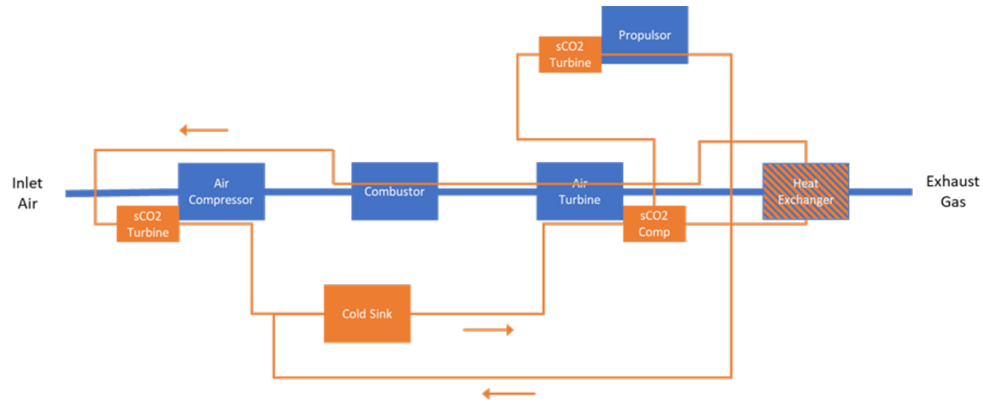

Fig. 7 ITAP engine schematic with an sCO2 driven propulsor.

This concept could be extended with a more complete integration with the aircraft and its sub-systems. The sCO2 system could be used for thermal management including waste heat recovery of the aircraft systems and for actuation of the aircraft flight control surfaces.

VIII. Summary

An alternative to a conventional gas turbine engine architecture based upon an sCO2 thermal and power management cycle highly integrated with an air-breathing gas turbine cycle is proposed. The ITAP engine builds off the decades of investment and experience in conventional gas turbine engines and leverages demonstrated technology for sCO2 thermal and power management cycles which has generated on-going development investment and commercial applications. The technology has the potential to provide a significant level of fuel burn reduction for propulsion applications coupled with a number of system benefits that provide value to the OEM's, operators, and their customers.

References

[1] Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

[2] Madonna, V., Giangrande, P., and Galea, M., "Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities," *IEEE Transactions on Transportation Electrification*, Vol. 4, No. 3, 2018, pp. 646–659. https://doi.org/10.1109/TTE.2018.2834142.

[3] Sarlioglu, B., and Morris, C. T., "More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft," *IEEE Transactions on Transportation Electrification*, Vol. 1, No. 1, 2015, pp. 54–64. https://doi.org/10.1109/TTE.2015.2426499.

[4] Brun, F. P., Klaus, and Dennis, R., *Fundamentals and Applications of Supercritical Carbon Dioxide (SCO2) Based Power Cycles*, Elsivier, 2017.

[5] McClung, S. N., S, Allison, T., and Tom, B., "Practical Considerations for the Conceptual Design of an sCO2 Cycle," *The 6th International Supercritical CO2 Power Cycles Symposium*, 2018.

[6] Chaudhary, M. A. D. P. M. V. T. Y. C. H., A, and Patel, J., "Feasibility Study of Supercritical CO2 Rankine Cycle for Waste Heat Recovery," *The 6th International Supercritical CO2 Power Cycles Symposium*, 2018.

[7] Sondelski, S. A. N. G. A. M., B, and Wilson, P., "Supercritical Brayton Power Conversion with a Direct Cooled Reactor for Space Power," *The 6th International Supercritical CO2 Power Cycles Symposium*, 2018.

[8] Cich, M. J. M. J. H. D., S, "DESIGN OF A SUPERCRITICAL CO2 COMPRESSOR FOR USE IN A 10 MWe POWER CYCLE," *The 6th International Supercritical CO2 Power Cycles Symposium*, 2018.

[9] Zada, K. R. W. A. S. C., K, "Analysis of Supercritical CO2 Brayton Cycle Recuperative Heat Exchanger Size and Capital Cost with Variation of Layout Design," *The 6th International Supercritical CO2 Power Cycles Symposium*, 2018.

[10] Stoia, E. G. B. K., M, and Needels, J., "Integrated Power and Thermal Management System for High Speed Aircraft," *AIAA Paper 2021–3531*, July 2021. https://doi.org/10.2514/6.2021-3531.