Title of Grant / Cooperative Agreement:	Hybrid Wave-Rotor Electric Aero-Propulsion (HyWREAP)
Type of Report:	Summary of Research
Name of Principal Investigator:	M. Razi Nalim
Period Covered by Report:	11/15/2012-11/14/2014
Name and Address of recipient's institution:	Indiana University- Purdue University Indianapolis, Trustees of Indiana University
NASA Grant / Cooperative Agreement Number:	NNX13AB87A

Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

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Hybrid Wave Rotor Electric Aero Propulsion

NASA Award Number: NNX13AB87A

NARI LEARN Fund – Final Report

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1 Project Overview

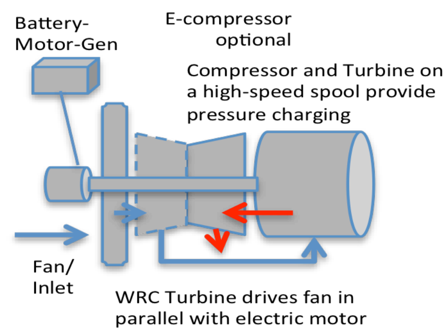

Fig 1. Schematic of HyWREAP with WRCT

Purpose: The goal of this project was to investigate the proposed hybrid wave-rotor electric aero-propulsion concept (HyWREAP, Fig. 1). The tasks were to perform flow and combustion analysis of the pressure-gain, wave-rotor combustor (WRC) turbine concept, and investigate benefits for the most likely flight application of HyWREAP.

Hybrid propulsion for future airplanes could integrate light-weight energy storage and electric drive with more efficient combustion engines. Electric technology advancements include high-power batteries and possibly light-weight cryo-cooled motors and superconductors. Electrical energy converts efficiently for cruise thrust and for taxiing thrust in congested airports, but unlike combustion fuel, stored battery weight remains for the flight duration. This project focused on a highly efficient combustion turbine engine with low-speed drive output for integration with batteries and electric drive. It is based on prior work on wave rotor combustors (WRC), which combines constant-volume combustion (CVC) thermodynamics with the high power density and full expansion of turbines. With a further 'twist', the wave rotor combustion *turbine* (WRCT) with *curved passages* merges compressor, combustor, and turbine functions into a single rotating component. The internal processes in a WRCT are illustrated in the 'developed' or unwrapped view of passages in the Fig. 2 (left). HyWREAP uses WRCT for substantially more efficient propulsion to drive a large low-speed propeller or ducted fan directly without gearing. A target of 70-90% fuel burn reduction is set for subsonic regional jets over 2010 technology, combining WRCT with electric drive.

WRCT technology can accomplish CVC in an efficiently flowing, mechanically elegant, and tightly integrable component. Following earlier work with NASA on pressure-exchanger designs, self-sustaining re-ignition and fast propagating deflagration was demonstrated in a self-cooled wave rotor rig. This straight-channel ambient-pressure rig operated for short times as predicted. Scalable ignition and combustion physics, thermal management, and long-life

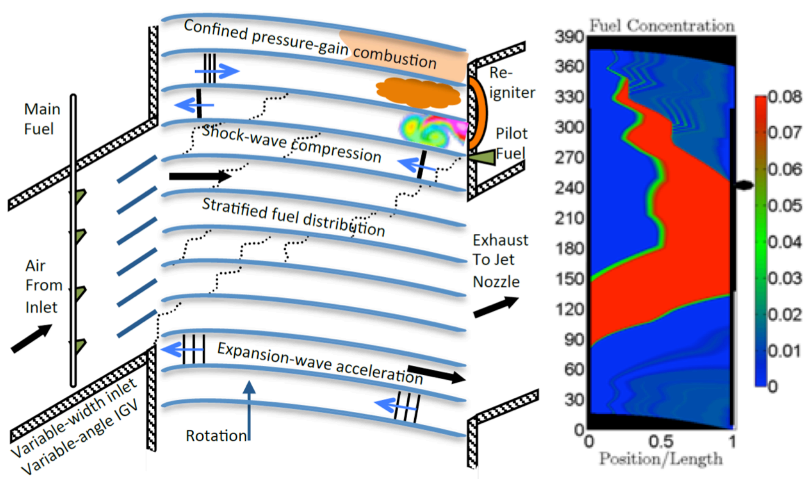

Fig 2. Schematic of internal processes (left) and computed fuel mass fraction over a cycle

sealing are being addressed. Using shock compression, fast deflagration, and gas expansion in multiple chambers within one pressure casing, that rig validated a design and modeling code and provided insight into ignition and combustion feasibility. With shaft torque and work output by using curved chambers, specific work is increased for a given turbine inlet temperature.

The project started with an aircraft mission and system modeling using a simplified approach to calculate the overall fuel burn with different load sharing between electric and gas turbine engine. It was not intended in this project to address battery technologies or other features of electric power generation, storage, or transfer. Plausible projections for battery energy density are made from other work. This guided the design of the WRCT, the pressure ratio and blade angle required to provide the necessary fuel consumption benefit compared to present day gas turbine engines. Utilizing the first-order estimate for the WRCT, a thermodynamic analysis and a quasi-1d model was developed to predict the gas dynamics and work output from the combustor. The current work has provided fuel burn estimates, thermodynamic analysis and numerical model of the WRCT, allowing its for preliminary design and optimization.

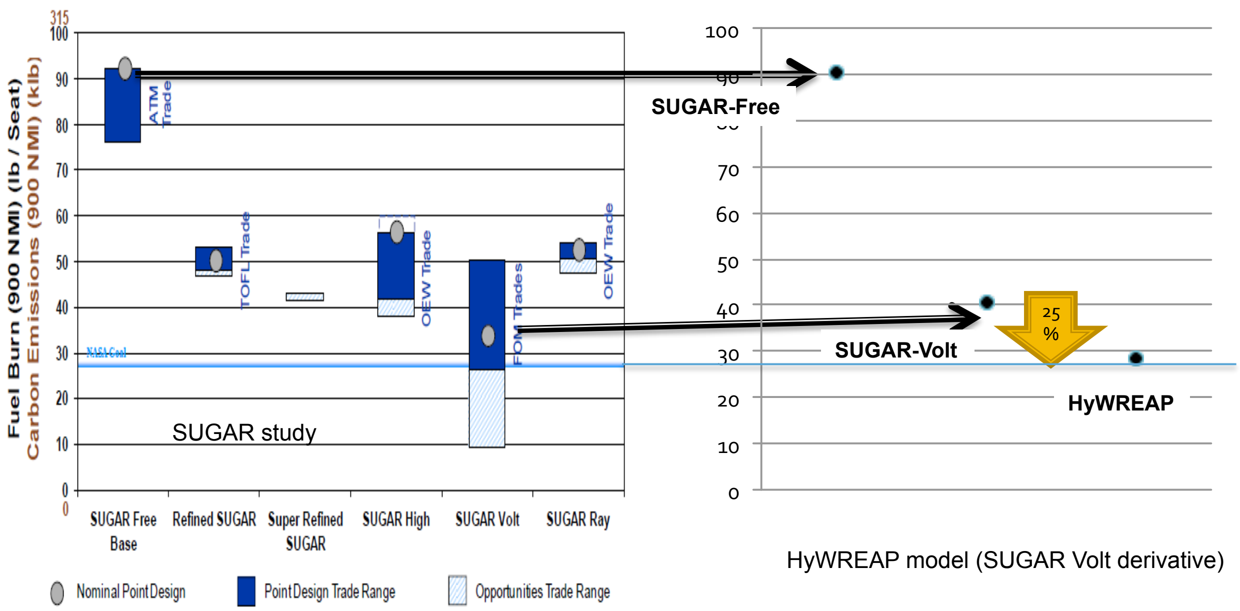

Fig 3. Validation of methodology against Boeing SUGAR study and estimate of fuel-burn and CO2 reduction with WRCT

2 Hybrid Electric Propulsion System Design

A methodology was developed for a first-order estimate of battery weight and fuel burnt over the range of an aircraft mission, for fixed empty weight (including electric system) and payload of general parallel-hybrid transport aircraft. The method demonstrates the impact of hybridization choices for a typical mission of 900 nautical miles, but could be applied to any particular range. Levels of hybrid power can be varied to evaluate different scenarios of battery energy density, electric motor weight, gas turbine efficiency, and other parameters. The present work studied the performance of a regional jet. The method revealed trends in fuel burn and aircraft take off gross weight with any discontinuous stepwise variation of electric load share for climb and cruise phases. Future work will include more accurate iterative calculation of battery weight and thrust during climb by using the energy change and rate of climb. The Boeing-led SUGAR-Volt h-fan engine was modeled, and when modified for WRCT performance based on thermodynamic analysis, an overall mission fuel burn reduction of at least 70% appears possible with the WRCT estimated to be 25% lower in specific fuel consumption than considered by this SUGAR case. Short-range flights (a few hours) between busy large airports can most benefit from hybrid or all electric aircraft using substantive stored electric energy and aggressive electrochemical battery discharge rates.

3 Thermodynamic Analysis

Thermodynamic modeling of a WRCT gas turbine engine was performed with real-gas properties using Cantera thermochemical data. The benefits in fuel efficiency and specific power estimated earlier with simpler models was confirmed (Fig. 4). Here, the WRCT is compared with conventional Brayton and pressure-gain Humphrey cycle engines for a fixed turbine inlet temperature limit, assuming sufficient work can be extracted in the WRCT.

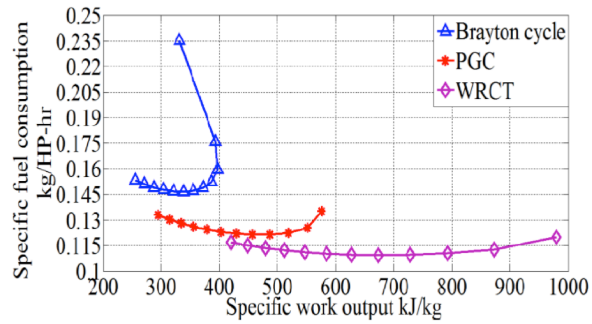

Fig. 4. Fuel consumption and power density (1600 K turbine)

4 WRCT Numerical Model

A time-dependent, one-dimensional gas dynamic and combustion code was extended to predict the unsteady gas dynamic flow features and combustion processes in a curved wave rotor combustor turbine channel, based on prior work. The model now includes the blockage effect of non-axial channels, rotation, and axial variation in channel height, blade thickness, and pitch line radius and azimuth. The model was exercised and validated against previous work on non-reacting flow in a wave turbine, as well as reacting flow in wave rotors. All previously used loss mechanisms, such as friction, heat transfer, partial opening, and incidence are retained. The change in angular momentum from inlet to exit provides the net rotor torque. The variation of fuel mass fraction in the operating cycle is shown alongside a schematic if the major gas dynamic and combustion processes in the WRCT channels (Fig. 2, right). Modeling suggests that there is a range of exit pressure for which combustion can be sustained, and it is feasible to operate without pressure gain.

5 Aircraft Design Exercise at Tuskegee University

An undergraduate senior design group at Tuskegee University's Aerospace Engineering department, conceptually designed a hybrid-propulsor aircraft for the AIAA 2013 undergraduate team aircraft competition on "Design of a 2030 Regional Airliner Considering Hybrid Electric Propulsion." Because of the Spring semester aircraft design course at Tuskegee, the undergraduate project was undertaken before significant research progress could be made by other partners. Using HyWREAP technology concept and unconventional body configuration, the team performed preliminary aircraft design.

6 Summary and Conclusions

Models of the HyWREAP system were created at three levels: a thermodynamic model of the combustion engine, a gas dynamic numerical model of the novel WRCT component, and a system model to estimate fuel burn in a hybrid electric aircraft with this technology. These three models enabled us to draw a roadmap for future work.

The hybrid-propulsion-system fuel burn model can examine the impact of combustion engine efficiency, energy storage density, and the thrust split during climb and cruise, depending on the aircraft type and mission. The thermodynamic cycle analysis provided a first-order estimate of the amount of improvement we can get with the use of a wave rotor combustion turbine cycle instead of a Brayton cycle. The analysis showed a large improvement in thermal efficiency, specific work and fuel consumption. The WRCT gas dynamic numerical model provided an estimate of torque and power output due to the curved channels from the change in angular momentum due to flow turning. The model also estimates flow velocities and the needed wave timing, which drives the optimal design the blade shapes, the ports and cycle time. The model includes many loss models, such as friction, heat transfer, partial opening, and incidence, but does not consider complex multidimensional effects such as boundary layer shock interaction, duct flow-channel interaction and shock refraction in a curved channel.

It is recommended to develop a map for the WRCT, to characterize operation of wave rotor based on compressor pressure ratio and turbine inlet temperature. This can be used to size the compressor and turbine based on the work output from the wave rotor combustor turbine. It is possible now to perform multi-disciplinary optimization and design the wave rotor combustor turbine with optimal blade angle and a propulsion system which will optimize aircraft performance over the N+3 time frame.

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