NASA/CR—2008-215226

Intelligent Propulsion System Foundation Technology

Summary of Research

The Ohio State University Research Foundation
Columbus, Ohio

June 2008

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Columbus, Ohio

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Columbus, Ohio 43210

<u>Program Objectives and Structure</u>

The purpose of this cooperative agreement was to develop a foundation of intelligent propulsion technologies for NASA and industry that will have an impact on safety, noise, emissions and cost. These intelligent engine technologies included sensors, electronics, communications, control logic, actuators, smart materials and structures and system studies. Furthermore, this cooperative agreement helped prepare future graduates to develop the revolutionary intelligent propulsion technologies that will be needed to ensure pre-eminence of the U.S. aerospace industry.

This Propulsion 21 – Phase II program consisted of four primary research areas and associated work elements at Ohio universities: 1.0 Turbine Engine Prognostics, 2.0 Active Controls for Emissions and Noise Reduction, 3.0 Active Structural Controls and Performance, and 4.0 System Studies and Integration. Phase I, which was conducted during the period August 1, 2003, through September 30, 2004, has been reported separately.

<u>Significant Accomplishments</u>

1.0 Turbine Engine Prognostics

<u>Disk Life Meter – Cyclic Bulk Damage Understanding and Model Development, and Surface Damage – Oxidation and Corrosion (OSU)</u>

Cyclic Bulk Damage Understanding and Model Development

In this subtask, OSU conducted characterization studies of LCF samples provided by GE Aviation in order to develop a detailed understanding of the damage mechanisms operative as a function of temperature, strain range and number of cycles.

This effort was focused on characterization of LCF samples taken to failure. Features characterized include microstructure (specifically γ' size and distributions), deformation substructure and fractography of failure surfaces.

Characterization of the deformation substructure after low cycle fatigue testing at varying test parameters (test temperature and strain range) and microstructure resulted in distinctly different deformation mechanisms. Although a more detailed study of each of these mechanisms are needed in order to fully characterize the exact nature of matrix dislocations, partial dislocations, and stacking faults (SISF vs SESF) the following conclusions can be made based on this work:

1) Dislocation slip bands were found to be a prevalent deformation structure in nearly all of the specimens. The density of dislocations within the slip bands were more intense at lower temperature and high strain range while at higher temperatures the dislocations were less dense within the bands.
2) Stacking fault shear is also observed in many of the specimens which occur as a results of shear by either 1/3<112> or 1/6<112> dislocations and creates either a SISF or SESF.
3) Microtwinning was observed when fatigued at 1300 °F. This mechanism has also been identified under monotonic creep conditions in tension at the same temperature.

Oxidation and Hot Corrosion

This study determined quantitative information regarding the extent and morphology of hot corrosion damage evolved upon the surface of Ni-based superalloy Rene 104. Exposure times under an accelerated corrosion regime at 704 °C range from 0.5 to 100 hrs. Unlike oxidation, it was seen that hot corrosion proceeds at an alarmingly rapid rate. The evolution of high temperature damage can be distinguished into two regimes. The first describes damage occurring at low exposure times, corresponding to what we ascribe as a phenomenon of transient oxidation, leading to a pitted surface. Following a distinguishable incubation period, hot corrosion damage proceeds such that damage depths are typically several hundreds of microns, with a generalized attack mode dominating the corrosion observed. Characteristics of the damage evolution were quantified via optical profilometry, while microscopy and XPS were used to support mechanistic interpretations. The following conclusions were drawn:

1) Optical profilometry coupled with image analysis enabled full quantification of pit formation and hot corrosion growth kinetics. This made it possible to develop an interpolative empirical model to accurately capture the corrosion damage growth kinetics.
2) Microscopy and XPS offered complimentary insight into the corrosion mode and mechanisms at play.
3) It was seen that hot corrosion displays an incubation period prior to large-scale hot corrosion. This period was seen to be greater than 5.5 h. Corrosion damage evolution was phenomenologically represented as selective carbide oxidation causing pitting attack, followed by S-related hot corrosion leading to rapid general attack.
4) The ultimate level of hot corrosion attack sustained at 704 °C under these test conditions is seen to be severe.
5) XPS indicated a lack of Cr oxide present upon the alloy surface with continued exposure time, this was concomitant with increasing levels of S containing compounds; leading to aggressive corrosion.

Bearing System (UAk)

The objective of this program was to enhance knowledge about engine class A accidents (characterized as damage greater than $1M or loss of life) by improving the knowledge database concerning the mechanisms of spall inception and propagation and the role of material fatigue under high temperatures in rolling element bearings. The added objective to the creation of the database was the design and certification/validation of high temperature wireless sensors. The strategy involves the creation of the database using hard-wired sensors that are attached to both rotating races of a differential intershaft bearing, and then progress to implementation and validation of wireless sensors first at low temperatures (below 400 °F) and then at higher temperatures, more characteristic of temperatures in a jet engine. It should be noted that there have been cases when the time from spall initiation to catastrophic failure was less than 10 hours, a fact that is worrisome if one considers the average time of an in-flight single mission. To mitigate such a problem one needs to improve the bearing's material, design (intelligent bearings), the strategy of sensor combinations and data acquisition (pressure, temperature, acceleration, flow, debris, etc), sensor sensitivity and especially reliability (avoidance of false signals) and in-line intelligent health monitoring and data processing.

Within the WCI and Propulsion 21 programs the UAk has become a statewide partner in the Ohio Center for Advanced Power and Propulsion (OCAPP) and has been designated as the center of excellence and expertise in the domain of bearings and seals in Ohio. The University has responded by erecting a dedicated building to the OCAPP integrated technical and collaborative efforts, The Turbine Research and Testing Facility has been built in record time, less than one year, and became available for service in June 2006. The Intershaft Bearing System Test Facility was built within period of 5 months and became ready for commissioning at the end of November 2006. The facility incorporates:

(a) The test head
(b) The slave bearings lubrication loop
(c) The test bearing lubrication loop, the compressed air feed system containing two 200 HP Ingersoll-Rand compressors an accumulator tank and associated control and safety systems
(d) The air turbine driver system
(e) The slip rings lubrication circuit
(f) The glycol closed system cooling circuit with its control and safety systems
(g) The electric motor-eddy drive cooling system with its control and safety systems
(h) The pneumatic load system load with its motorized pressure regulator
(i) The local master control cabinet containing all elements for local installation control
(j) The NEFF low speed data acquisition system
(k) The National Instruments high speed data acquisition system
(l) The computer based air turbine drive control system

All these systems have been built and integrated into one functional unit that is ready for operation.

Adaptive Controls for Fault Accommodation (OSU)

Part 1 of this effort involved the estimation of immeasurable parameter such as thrust and turbine inlet temperatures in turbine engines which constitutes a significant challenge for the aircraft community. A solution to this problem is to estimate these parameters from the measured outputs using an observer. Currently existing technologies rely on Kalman and extended Kalman filters to achieve this estimation. This work involved an adaptive observer that augments the linear Kalman filter with a neural network to compensate for any nonlinearity that is not handled by the linear filter. The neural network implemented is a Ardial Basis Function Network that is trained offline using a growing and pruning algorithm. The adaptive observer was used to estimate HPT inlet temperature, thrust and stall margins.

Part 2 was concerned with fault detection, which plays a critical role in aircraft engines and the performance of their control systems. A real challenge in fault detection applications is the design of a scheme which can distinguish between model uncertainties and occurrence of faults. Therefore, a technique to accommodate uncertainties in the model, help in reducing false alarms and missed detections is essential for the enhancement of engine operations. In this effort, a dynamic/adaptive threshold algorithm was developed for aircraft engine fault detection based on both ‘unstructured’ time-varying perturbations in the model parameters as well as external disturbances. The residuals are errors between estimated and measured variables of the outputs. With this design approach, the residual crossing the dynamic/adaptive threshold indicates the occurrence of fault. By this method of ‘dynamic/adaptive threshold’, model uncertainties do not trigger a false alarm as in normal case with a constant threshold. Simulation results base on an engine Component Level Model (CML) are shown to demonstrate the effectiveness of the proposed method.

2.0 Active Controls for Emissions and Noise Reduction

Intelligent Combustor – Well Stirred Reactor (UD)

The Well Stirred Reactor (WSR) is a versatile laboratory research combustor that simulates the highly turbulent combustion process in a practical gas turbine combustor. UD studied high-turbulence level turbulence-flame chemistry interactions processes in a high pressure (20-atm) WSR. Specifically, the WSR provides bench-mark quality data on effects of pressure on lean blowout (LBO), NOx, and particulate emissions.

During this phase of the program, the University of Dayton performed the following tasks:

(1) Assemble and check out the high pressure WSR
(2) Baseline WSR tests at room temperature and pressure using various fuels
(3) WSR Data interpretation and reporting

UD designed, fabricated, and assembled a WSR with the following specifications:

- Operating pressure = 1-20 atm.
- Air flow rates: 2.0 lbm/sec
- Fuel flow rate: 0.2 lbm/sec
- Residence Time = 2-8 ms
- Equivalence ratio = 0.3-2.5
- Fuels: Jet A, JP-8, heptane and decane.

High-pressure WSR experiments and test results have direct practical applications in gas turbine combustor design in terms of improving combustion efficiency, combustion stability, fuel economy and decreasing pollutant emissions. Results and conclusions of these studies are of direct practical benefits to NASA Glenn, GEAE, and Parker-Hannifin and also the Air Force Research Laboratory (AFRL)

Intelligent Combustor Control – TAPS/LBO/Lean Flammability Limits (UC)

Manifestations of combustion instability in a multiple swirl low emission gas turbine combustor were studied. Unstable combustion was investigated in different combustor setups, including with or without a premixing section, and with gaseous and liquid fuel via measurement of dynamics of pressure, flame and radical emissions. A set of four optical fibers integrated inside the multiple swirler fuel injector assembly monitored the local active radical emissions to provide phase information on unsteady dynamics. The acoustic pressure signal from a microphone was conditioned as the trigger signal for phase-locked OH* chemiluminescene imaging of the global flame. The flame dynamics are shown to be in different format for different geometries and types of fuel. The motions of the flame front are shown to be closely related to the combustion instability driving mechanism, either periodic large flow structures or pulsation in the fuel line. Analysis of the transition from unstable to stable combustion revealed that the advantage of better mixing with gaseous fuel was offset by the faster growth rate of pressure oscillations. It was also found that the oscillations of pressure lead flame in both gaseous fuel and spray combustion when unstable combustion takes place.

Combustion dynamics pose serious challenge for modern low NOx emission gas turbine combustors. Accurate detection of pressure oscillation signals associated with combustion dynamics is crucial for control of combustion dynamics and assurance of reliable operation and extended life time of the engines. However, the installation of the pressure transducer is often limited by the temperature the sensor can withstand. This effort addressed the possible signal distortion due to commonly used pressure sensor installation on a stand-off tube. The effects of the tube and extension “tails” lengths on the measured pressure signals using different types of piezoelectric pressure transducer are described. A two-dimensional wave tube is used to generate clean planar waves for this study. The stand-off tube was found to be responsible for pseudo peaks in the spectrum whose frequency depends on the tube length. The extension “tail” also modifies the spectrum of the detected signal by introducing low frequency modulation of the spectrum. For proper signal detection, the length of the tube has to be carefully selected to avoid artificial distortion of signals at the frequency range of interest.

Intelligent Combustor – Active Combustion Control/MEMS (CWRU)

Prototypes for a ‘smart’ microvalve have been developed. The developed MEMS technology supports the development of necessary fuel modulation techniques for the Active Combustion Control work element of this research program.

The ‘smart’ valve is comprised of the microvalve itself as well as a micromachined flow sensor with the necessary read-out electronics to enable a fully closed-loop control scheme. The microvalve utilizes a piezoelectric actuator with novel pressure balancing and mechanical amplification schemes. Tests with de-ionized water show 7% modulation at a flow of 100mL/min. at a pressure of ~20 psi when the applied drive voltage set to 50 Hz is varied from 84-120 V. The cantilever type volumetric flow sensor utilizes piezo resistive techniques for read-out. Tests of the flow sensor in de-ionized water showed flow measurement capability at room temperature for flows up to 660 mL/min. Separate high temperature tests of the flow sensor interface IC implemented in an inexpensive bulk CMOS process showed stable performance beyond the targeted operating temperature requirement of 250 °C.

Active Noise Reduction – Fluidic Injection, Shape Memory Alloys & Acoustic Liners (UC)

This effort investigated the potential for using fluidic injection on both fan and core streams to reduce subsonic turbofan jet noise. Fluidic injection consists of small jets of air injected directly into the shear layer between two jet streams. This injection induces stream-wise vorticity in the flow which entrains air between the streams and yields greater mixing relative to conventional configurations without fluidic injection. Enhanced mixing has been shown to reduce the mean jet velocity and temperature, therefore, reducing jet noise. Fluidic injection experimental testing was performed in three-stream flow at the GE Aviation Anechoic Free-Jet Test Cell 41 Facility. Test results demonstrate jet noise peak sound pressure level reductions of 1 to 2 dB, resulting in a maximum overall sound pressure level reduction of 1.6 dB. The greatest jet noise reduction occurs after optimizing the balance between low frequency noise reduction and high frequency noise generation.

Active Noise Reduction – Plasma Injection (OSU)

Localized arc filament plasma actuators were used to control an axisymmetric Mach 0.9 jet with a Reynolds number based on the nozzle exit diameter of about 7.6×10^5. Eight actuators, distributed azimuthally inside the nozzle, near the nozzle exit, were used to excite various azimuthal modes of the jet over a large frequency range (St_{DF} of 0.1 to 5.0). Time-resolved pressure measurements were used to investigate the development of actuation perturbations and instability waves in the jet, PIV measurements were used to evaluate the effects of control on the mean velocity and turbulence field, and far-field sound was measured to evaluate the control effect on the radiated acoustic field. The jet responded to the forcing over a large range of excitation frequencies with varying degrees. When exciting at low frequencies, the instability waves grew slowly, saturated farther downstream, and stayed saturated for a longer time before decaying gradually. The saturation and decay of instability waves moved farther upstream as the excitation frequency increased. Instability waves with higher azimuthal modes exhibited faster decay. PIV results showed that when exciting the jet preferred mode instability at lower azimuthal modes, the jet's potential core shortened and the turbulent kinetic energy significantly increased. For higher frequencies and higher azimuthal modes, forcing had less of an impact on the mean velocity and turbulent kinetic energy. Far-field acoustic results showed a significant noise increase (2 to 4 dB), more at 90° than 30°, when the jet is excited around the jet preferred mode instability frequency (St_{DF} = 0.2-0.5), in agreement with the results in the literature. Noise reduction of 0.5 to over 1.0 dB is observed over a large excitation frequency range - this reduction seems to peak around St_{DF} = 1.5 to 2.0 at 30° angle, but around St_{DF} = 3.0 to 3.5 at 90° angle. While forcing the jet with higher azimuthal modes is advantageous for noise mitigation at 30° angle and lower frequencies, the effect is not as clear in higher forcing frequencies and at 90° angle.

3.0 Active Structural Controls and Performance

Thermal Management & Advanced Cooling (OSU)

Turbine Cooling Control – Combustor Simulator

This portion of the program was designed to significantly improve the capability to obtain film effectiveness measurements and the analysis of those resulting measurements for a fully cooled high-pressure turbine stage operating under design corrected conditions. After many years of successful development, the experimental state-of-the-art has now advanced to the point where these measurements are currently being obtained under as realistic of conditions as can be produced under laboratory-controlled conditions. This includes the ability to generate combustor-like flow path temperature profiles at the entrance to the high-pressure turbine vane (HPTV), representative turbulence intensity at the inlet to the HPTV, and duplication of the coolant flow parameters consistent with actual engine operation. All of the technology developed as part of this program is being utilized within the ongoing NASA/DoD URETI measurement program.

Trailing Edge Cooling of Turbine Blades

This study was divided into two parts, the first directed towards developing an analytical model for rather simple geometries to study the effects of rotation and bleed. The second approach centers around the numerical computation of the flow in a trailing edge cavity using a realistic model for the trailing edge geometry which was provided by the General Electric Company.

In an attempt to understand the complicated problem of trailing-edge cooling on a turbine blade, a study has been initiated with the long term goal of simulating steady, rotational internal flow in a trailing edge cavity with pressure side bleed ports. An additional goal of the study was to develop some insight as to how trailing edge cooling can be optimized.

The results were representative of a number of calculations performed for a variety of cases. Parametric studies for various values of wall temperature, pressure, and most importantly, different distributions of the mass flux outwards from the eighteen pressure bleed slots were considered. as part of this study. It was hoped that the numerical results would allow us to ascertain if there were an optimum distribution of mass transfer, or other parameters that would be beneficial in optimizing the thermal management for such configurations. Unfortunately, for the cases considered no optimum situation could be deduced, at least for the cases studied in this effort during the time allotted for the project.

An attempt was made at trying to modify the shape of the turbine blade geometry used in this study. However, the complexity of the shape made it impossible to successfully redesign the part.

Finally, the case wherein the part was also allowed to rotate, like those cases considered in the analytical models analyzed above, was evaluated. Efforts were not successful. The CFX software, while having an option for a rotating frame of reference, did not converge to a >good= solution, at least not for the cases considered in this study. It was not clear what the difficulties were. Certainly, additional studies which concentrate on the rotational aspects of the flow are warranted.

Cooling Flow Injection Bench Tests

This work describes the configuration of the AARL/OSU 3 inch by 6 inch transonic heat transfer wind tunnel and summarizes the results of a basic preliminary test program incorporating four coolant injection configurations. The primary flow was impulsively heated to approximately 350 °F at a Mach number of 0.6 to 0.8. Data were acquired from a thin-skin data module, a segment of the wind tunnel wall, with and without cooling flow injected upstream from the data module. Reduced and normalized heat transfer coefficients are reported over a wide range of cooling flow rates. Reductions of as much as 40% are reported for a tangent-slot injection configuration.

Turbine Cooling Control – Unstable Profile Prediction, Enhanced HT, Tech Demo (UC)

Effort 1

Steady and unsteady pretest predictions have been performed of the OSU test rig. This case includes purge cavities that were simulated. The steady multi-stage solutions were performed using a multi-stage “mixing-plane” approach in which the unsteady connection between upstream and downstream blade rows is replaced by a steady axially symmetric inflow condition. Unsteady results were performed with a forced unsteady profile formed from the upstream exit flow.

The purpose of the effort was to understand how purge cavity flows affect the temperature profiles at the exit. Steady results indicate that the purge flow exits the cavity in a circumferentially even manner, whereas the unsteady solutions demonstrate a defined coalescence of the purge flow in two areas, one along the hub on the pressure side and the other somewhere between 20 and 30% span on the suction side. The latter propagates essentially mid passage and provides no associated cooling, although it does significantly affect the averaged exit temperature profiles. Instantaneous solutions show that there is a range of locations where this purge flow travels but the time averaged effect is still a relatively distinct feature. The results suggest inclusion of purge geometry effects is necessary for accurate prediction of this flow field.

Effort 2

The complete UC Combustion Research Facility was computed as part of this effort. Grid generation was a major aspect of this exercise and was the bulk of the work performed. The UC CRF consists of a cylindrical combustor made of perforated steel for enhanced mixing. This can resides in a circular pipe and is fed by an external fuel line. The circular pipe is then connected to an unloaded cooled stage-one turbine vane which resides in a rectangular duct. The transition from the circular to the rectangular flow path takes place in a transition region. The stage-one turbine vane is cooled with 64 holes including 4 rows of showerhead cooling and 2 rows on the flat portion of the geometry. These cooling holes are inclined to the main flow and are representative of typical cooling strategies. The simulation of the vane utilized symmetry and consisted of half the main flow, the associated cooling holes and the coolant feed plenum. The vane geometry was computed previously in isolation and resulted in an approximately 14 million cell grid. The complete combustor, transition duct, stage-one vane grid resulted in upwards of 50 million grid cells. The objective of the gridding for all main flow surfaces was to obtain surfaces on which $y+<1$. This was achieved over most of the domain.

The grid generation process was then followed by several initial solutions, the first of which were performed to obtain reasonably accurate initial $y+$ values to further guide the gridding process. Cold flow cases without fuel were computed with these good grids and form the basis for further studies.

Effort 3

The third effort in some senses straddled both main tasks. It was initially proposed that a cooled version of the OSU test rig be simulated and coolant unsteadiness studied both from the perspective of the rotor/stator interaction and from possible pulsed coolant approaches designed to offset detrimental effects of the former. Unfortunately, this geometry was not provided to the investigators forcing the use of the available cooled unloaded vane from the UC CRF [1]. Previous studies of this geometry had been performed and it offered both a platform for continued grid generation development and a convenient geometry for pulsed cooling.

The initial effort was directed at understanding available experimental data. Previous heat transfer experiments were performed by Ou et al. on a similar geometry but with “coolant” warmer than the main flow. The idea being that a heat transfer analogy could be constructed. The current work then explored whether this idea is a workable strategy for a full turbine blade. The results suggest that while it may be possible to match conditions over a spanwise averaged portion of the vane it is not possible to match local details of the flow. The situation is improved if only a single row of holes is employed and indeed better data matches to cool coolant are possible over a select range of the spanwise averaged analysis. But the use of multiple holes removes the possibility of a reasonable match over the entire vane surface. In addition, local variations cannot be correctly correlated. The effort explored the ideas of matching velocity ratios, mass flow ratios and momentum ratios, but none were reasonable approaches without *a priori* knowledge of the solution.

The effort was then shifted to study pulsed cooling. The idea was to explore the effect of pulsing the feed plenum flow and understanding the relationships between coolant forcing, film response and local cooling effectiveness. This work is ongoing.

Smart Containment System (UAk)

The general objective of this research was to investigate possible scenarios of crack propagation in a composite softwall containment system due to forces produced by the unbalanced fan after the blade out event in the engine. The particular objective of this study was to apply a force-moment system to the front flange of the containment in a dynamic and static way in order to propagate the crack from the initial hole.

In the first step of the investigation, the blade-out was simulated to produce a realistic hole in the containment. Results of the simulation were also used to assess the loading produced by the interaction of the unbalanced fan with the undamaged section of the containment system. It was found that the containment can be subjected to twisting, shearing and bending forces and moments.

The post impact loading conditions were studied parametrically using LsDyna3D for a dynamic case and ABAQUS implicit code for a static load application. In each case, the energy stored in the inner housing and stresses in elements of highest stress concentration were measured. LsDyna3D simulations demonstrated crack initiation and propagation for the applied moments. It was observed that the crack path depended on the type of elements used and the density of the mesh used in the simulation.

4.0 System Studies and Integration

System/Optimization Studies (OSU)

The overall purpose of this study was to determine the effect of engine component degradation on performance and the progression of component degradation as a function of engine cycles or service time. The effect of degradation was approached using a fairly detailed simulation of two specific engine tpes, based on actual engine models, for two classes of commercial aircraft: A 150 passenger (150PAX) plane and a 300 passenger (300PAX) plane. The engines that served as the models for these two classes of aircraft are the CFM56-7 and the GE90. The engines were simulated and the analysis done with the Numerical Propulsion Simulation System (NPSS) computer code obtained from NASA Glenn Research Center. NPSS incorporates the operating maps for the rotating components. To perform the analysis, the maps were decremented in efficiency to simulate component degradation. In this manner, specific relations for the effect of particular component degradation on overall engine performance was determined and compiled.

The problem of determining component degradation as a function of engine cycles was not completed. Though numerous models and experimental data are available in the open literature for component degradation as a function of the particular parameters that affect efficiency, actual data to correlate component degradation a function of engine operating cycles was not found. A proprietary database was obtained of in-flight engine data that did provide overall changes in certain engine operating parameters, most notably inter-stage temperature of the low-pressure turbine (T4.9)., but specific mechanisms causing component degradation could not be identified from this information. The database was, however, used to verify the 150PAX engine model by direct comparison of measured engine performance with the NPSS simulation.

Integration of the OCAPP Universities (OSU)

Propulsion 21 –Phase II represents a unique cooperation between NASA, GE Aviation, a number of industries working with GE and five universities in the state of Ohio. GE coordinated the work of its industry partners. The Ohio State University, representing OCAPP, the Ohio Center for Advanced Propulsion and Power, led the research activities at 5 key universities, i.e., The Ohio State University, the University of Cincinnati, the University of Dayton, the University of Akron and Case Western Reserve University.

The activities focused on the identification, integration and development of key propulsion technologies required to meet the objectives of future subsonic commercial power plants:

- Reduced Community Noise
- Reduced Fuel Consumption
- Improved Thrust/Weight ratio
- Lower Emissions

Each technology described above was developed as a collaborative effort between one or more universities, NASA and the industry. The integration effort concentrated on 1) the development of analytical tools to optimize propulsion systems and perform the tradeoffs necessary between the different requirements, and 2) the work necessary to assure good collaboration and integration between the universities on individual technology developments.

The analytical tools used for the trade-off assessments were primarily NPSS (Numerical Propulsion System Simulation), WATE (Weight Analysis of Gas Turbine Engines) and FLOPS (Flight Optimization Systems).

The result of the studies indicates without any doubt the benefits of Intelligent Engines and eventually Variable Cycle Engines. They indicate that high bypass turbofans are asked to operate at severe off-design conditions. For example, a propulsion system designed to maximize thrust, minimize temperature, noise and emissions at takeoff is being asked also to minimize fuel consumption at altitude. Variable Cycles permit this in a more efficient manner.

The advent of VCE's permit the addition of a 3^{rd} stream. For example, the flow in the outer duct can be maximized at take-off for thrust and low noise while reduced at altitude for improved propulsion efficiency and good fuel consumption. These systems, which have been discussed in the military in the supersonic field, are worth examining for subsonic transports as the cost of fuel is becoming a more important factor in the cost of operation.

Active systems are of primary importance to optimize cycles as well as noise to minimize performance losses and emissions with equivalent operability protection.

The integration between the different OCAPP universities has been rewarding, as it demonstrated the benefits of cooperation and the use of multiple facilities to produce a first class research consortium.

<u>Publications & Presentations</u>

C.A. Yablinsky, R.R. Unocic, M.J. Mills, K.M.Flores, J.C.Williams, "Characterization of Low Cycle Fatigue in a Ni-Base Turbine Disk Alloy", **MS&T 2006 – Cincinnati, OH**

C.A. Yablinsky, R.R. Unocic, M.J. Mills, K.M. Flores, J.C. Williams, D. Mourer, D. Wei, D. Whitis, T. Gabb, "Characterization of Fatigue Mechanisms in Ni-base Superalloys using Selectively Extracted TEM Foils", **MRS 2006 – Boston, MA**

D. Bhattacharyya, L. Kovarik, R. Unocic, D. Mourer and M.Mills, "Studies of Dislocation and Stacking Fault Structures and Contrast in Ni based Superalloys During Low-Cycle Fatigue", to be presented at **TMS Annual Meeting, 2007**

S. Karthikeyan, R.R. Unocic, P.M.Sarosi, G.B. Viswanathan, D.D. Whitis and M.J. Mills, "Modeling Microtwinning During Creep in Ni-based Superalloys", tbd

P.Shankar and R.Yedavalli, "A Neural Network Based Adaptive Observer for Turbine Engine Parameter Estimation", **Proceedings of GT2006 ASME Turbo Expo: Power for Land, Sea and Air", May 8-11, 2006, Barcelona, Spain**

R. Yedavalli and W. Li, "Aircraft Engine Fault Detection Using Dynamic/Adaptive Threshold Approach", to be presented at **Proceedings of GT2007 ASME Turbo Expo 2007**: Power for Land, Sea and Air, May 14-17, 2007, Montreal, Canada

S.Stoffer, R.Pawlik, J.Zelina and D.Ballal, "Combustion Performance and Emission Characteristics for a WSR for Low-Volatility Hydrocarbon Fuel", to be presented at **43^{rd} AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, OH, 8-11 July 2007**

G.LI and E.Gutmark, “Manifestations of Combustion Instability In a Multi-swirl Stabilized Gas Turbine Combustor”, **AIAA,** tbd

X.Yu and S.Garverick, “Mixed-Signal, 275 C Instrumentation Amplifier in Bulk CMOS”, **IEEE 2005 Custom Integrated Circuits Conference, 0-7803-9023-7/05**
X.Yu and S.Garverick, “A 300 C, 110-dB Sigma-Delta Modulator with Programmable Gain in Bulk CMOS”, tbd

S.Harrison and E.Gutmark, “Jet Noise Reduction by Fluidic Injection On a Separate Flow Exhaust System”, **AIAA**, tbd

M.Samimy, J-H.Kim, I.Adamovish, Y.Utkin, and J.Kastner, “Toward Noise Mitigation in High Speed and High Reynolds Number Jets Using Plasma Actuators”, **AIAA**, tbd

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<u>Inventions</u>

None

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14. ABSTRACT
The purpose of this cooperative agreement was to develop a foundation of intelligent propulsion technologies for NASA and industry that will have an impact on safety, noise, emissions, and cost. These intelligent engine technologies included sensors, electronics, communications, control logic, actuators, smart materials and structures, and system studies. Furthermore, this cooperative agreement helped prepare future graduates to develop the revolutionary intelligent propulsion technologies that will be needed to ensure pre-eminence of the U.S. aerospace industry. This Propulsion 21 - Phase ll program consisted of four primary research areas and associated work elements at Ohio universities: 1.0 Turbine Engine Prognostics, 2.0 Active Controls for Emissions and Noise Reduction, 3.0 Active Structural Controls and Performance, and 4.0 System Studies and Integration. Phase l, which was conducted during the period August 1, 2003, through September 30, 2004, has been reported separately.

15. SUBJECT TERMS
Turbine engine prognostics; Active controls; Noise reductions; Active structural controls; System studies; Integration

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