AFEC-AFP
A collaboration between:
*Goodrich, ZIN Technologies, CASE University,
NASA, Haric, FLX-Micro, Sienna,
and *University of Cincinnati

Managed by: Glennan Microsystems Incorporated
(Facilitated by Battelle)

Program Overview

Presentation to Honeywell

September 29, 2006

* Part of original team
Aero Turbine Engine Combustion Issues

• The US aero-propulsion industry has a target of 70% NOx and 15% CO$_2$ reduction over 1996 International Civil Aviation Org. (ICAO) standards by 2010.

• A number of the current “lean burn” schemes being developed exacerbate the conditions that lead to increased NOx and CO$_2$ emissions.

• These “lean burn” schemes have associated thermo-acoustic and “lean blow out” instabilities.

• Through active combustion control the instabilities and the conditions that lead to unwanted emissions can be mitigated without adversely affecting fuel efficiency.
AFEC Scheme

• Active control incorporates feedback sensors and modulated actuators to directly control all the parameters that determine the characteristics of combustion.

• Temperature, pressure and equivalence (air/fuel mixture) are sensed at the point of combustion. By precisely modulating these parameters in real time, combustion can be controlled more effectively.

• AFEC can optimize the combustion process, at all times and under differing load conditions, to stay within the ideal range for temperature, pressure, and fuel/air ratio that minimize the emission of NOx, CO$_2$ and particulates.
AFEC Scheme

Figure 2. Turbine Engine AFEC Concept Overview
AFEC Scheme

Synaptic Based Distributed Control

Combustor Nodes  Compressor Node  Turbine Node  Other Node

FADEC* w/AFEC

Develop control algorithms for multi-variable, MIMO systems

Sensors/Actuators

AFEC Configuration

Aug. Controller 1 15 16

* FADEC – Full Authority Digital Engine Controller
AFEC Scheme

- Smart high temperature sensors arrays incorporating digital communications – directly integrated into structural components
- Synaptically-based distributed control (w/integrated data and power bus) – local node (loop) controllers supervised by a system controller that coordinates the interaction between the nodes (spatial control)
- Smart high temperature high response actuators (>1000 Hz)
- Algorithms for both temporal and spatial control
  - Thermo-acoustic instability
  - Lean blow out
  - Continuous optimization of combustion
  - Nozzle to nozzle interaction
- Improve fuel economy by reducing stability margin (.5 to .45 equivalence)
MEMS Smart Sensor Arrays

- Develop **MEMS Smart Sensor Arrays** of SiC construction that measure the characteristic parameters of combustion (both convective temperature and pressure) and the characteristics of the incoming air (both temperature and flow) with integrated high temperature transduction electronics using an inductive link for data transfer
- Measure dynamic pressure and instantaneous equivalence
- Measure absolute temperature and pressure in FIT if funding permits
MEMS Smart Sensor Arrays

- Combustion Sensor Array
  - 600°C
  - Harvested from RF
  - Pressure sensor (capacitive)
  - Signal to frequency controller
  - Photo diode

- Air Sensor Array
  - 600°C
  - Temperature sensor (resistive)
  - Pressure sensor (capacitive)
  - Signal to frequency controller
  - ΔP for flow
  - Pressure sensor (capacitive)

300°C
- Sensor interface electronics – inductive to serial interface
Dynamic Pressure Sensor

• Single-wafer process

Silicon dioxide
Silicon nitride
Perforated membrane (polysilicon)
Contact pad (aluminium)
Hole for static pressure
Silicon substrate
Bending membrane (polysilicon)
Sensor Test Fixture

Static Pressure Input

Dynamic Pressure Input

Electrical Input/Output

UV Sensor

Pressure Sensor
UV Sensor (Instantaneous equivalence)

- Sense lean blow out
- Sense NOx production
- Sense CO2 production
- Sense Pressure
- Sense Equivalence
PROJECT OVERVIEW

General Description

Sensor Interface Electronics
Sensor and Electronics Interface

Wireless Interface
- No interconnects (in hot zone) to fatigue-improved MTBF
- Dies can be placed in any position-improves manufacturability
- Because sensors are capacitive, don’t need to be temp. compensated and are more electromagnetic compatible (EMC compliant) than traditional sensors and no active elements to fail
- More compatible with digital communication
Integrated Combustion Cone
• Develop **Integrated Combustion Cone** of ceramic construction with embedded high temperature **smart sensor arrays** employing SiC construction (one array monitors the combustion and the other array monitors the incoming air characteristics), SiC based fuel nozzle, and that manages the air swirl and fuel mixing.
• Sensors spaced circumferentially around the face of the venturi
• Construction will be of silicon nitride and the SiC nozzle will be developed only if funding allows
Smart Injectors

- Develop **Smart Injectors** that incorporate, a highly *integrated combustion cone* with sensors, high temperature interface electronics (SOI construction), high temperature digital communications, a high temperature high response valve, and a combustion node controller (SOI construction).
Node Controller

- 300 deg C 32-bit Microcontroller
  - Leon 3 (Sparc v7) core
  - 64 KB Zener programmed PROM
  - 5 KB RAM
  - CAN 2.0 Interface
  - 16 MHz clock
  - Integrated ADC and Preamp inputs
  - Gen Purpose signal generator output
  - SOS technology
FADEC/AFEC Controller

- Develop a FADEC/Supervisory Controller with Active Fuel and Emission Control capability that directly manages the temporal and spatial combustion process in the turbine engine. The controller will rely on digital communications to coordinate all control functions with the *smart injectors*. 
The Team
- **ZIN**
  - Responsible for integrated FIT
  - Optics core competency
  - Wireless core competency
  - Pressure sensor and UV sensor core competency
- **Case**
  - High temperature sensor interface electronics core competency
  - Microfabrication core competency
- **Haric**
  - Responsible for supply of high temp. electronics
  - High temperature mixed signal electronics core competency
  - UV sensor core competency
  - Microfab processing core competency
- **NASA**
  - High temp. electronics fabrication core competency
  - High temp. packaging core competency
  - Turbine engine combustion core competency
  - Control algorithm core competency
- **Sienna**
  - High temp packaging core competency
  - Ceramics core competency
  - High temp metallization core competency
- **FLX Micro**
  - Responsible for supplying capacitive based pressure sensors
  - Pressure sensor core competency
  - SiC fabrication core competency
REQUIREMENTS PHASE

System Breakdown Structure

AFEC System 1.0

- Smart Injectors 1.1
  - Integ. F.I.T. 1.1.1
    - Sensor – Flow Temp 1.1.1.1
    - Sensor – Air Flow 1.1.1.2
    - Sensor – Dynamic Pressure 1.1.1.3
    - Sensor – Absolute Press & Temp. 1.1.1.4
    - Air Cap Assy. 1.1.1.5
    - Sensor ASIC 1.1.1.6
  - Injector Support Assy. 1.1.2
    - Support Assy. 1.1.2.1
    - Value 1.1.2.2
    - Sensor – Fuel Mass Flow 1.1.2.3
    - Drive Electronics 1.1.2.4
    - Sensor – Fuel Temp 1.1.2.5
  - Fuel Core 1.1.2.6
- Node Controller Assy. 1.1.3
  - Microcontroller Dis 1.1.3.1
  - Power Mgmt. ASIC 1.1.3.2
  - Module Assy. 1.1.3.3
  - Firmware 1.1.3.4
- Connectors 1.2.1
  - Node Controller 1.2.1.1
  - Power Mgmt. ASIC 1.2.1.2
- Conductors 1.2.2
  - Comm. Conductor 1.2.2.1
  - Power Conductor 1.2.2.2
  - Processor Board 1.3.1
    - Processor 1.3.1.1
    - Data Acquisition 1.3.2.1
    - Input/Output 1.3.3.1
    - User Interface Comm. 1.3.2.3
  - Comm. Board 1.3.2
    - Node Comm. 1.3.2.1
    - AFE Comm. 1.3.2.2
    - Node Supply 1.3.3.1
    - Controller Supply 1.3.3.2
  - Power Supply Board 1.3.3
### Statement of Work/Work Breakdown Structure – Requirements

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
| 1 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 2 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 3 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 4 | Task 123456789 1 0 1 1 1 2 1 3 1 4 1 5 1 6 | Performers 20 |
| 5 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 6 | Program Management | GM Inc. |
| 7 | 1.0 Requirements Development | Goodrich |
| 8 | 1.1 Baseline and Characterization Testing | Goodrich |
| 9 | 1.2 Control System | GE, NASA, Goodrich, GM Inc. |
| 10 | 1.3 Smart Sensor Array | Goodrich, GM Inc., Team |
| 11 | 1.4 Integrated Combustion Cone | Goodrich, GM Inc., Team |
| 12 | 1.5 Smart Injector | Goodrich, GM Inc., Team |
### Statement of Work/Work Breakdown Structure – Sensor Arrays

|   | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S                  |
| 13| 2.0 Smart Sensor Array |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | ZIN                 |
| 15| 2.2 Combustion Die (SiC Photo Diode and Cap. Pressure Sensor) Fabrication |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | FLX Micro, NASA, CASE, Pentalim          |
| 16| 2.3 Combustion Die (SiC Photo Diode and Cap. Pressure Sensor) Test |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | FLX                                    |
| 18| 2.5 Air Flow Die (Temp. and SiC 2 Cap. Pressure Sensors) Fabrication |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | FLX Micro, CASE, Pentalim                |
| 19| 2.6 Air Flow Die (Temp. and SiC 2 Cap. Pressure Sensors) Test |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | FLX                                    |
| 20| 2.10 Encapsulation/Packaging |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Sienna & ZIN                |
| 21|  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |                                      |
# Statement of Work/Work Breakdown Structure – Int. Comb. Cone

|   | A       | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S                      |
|---|---------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|------------------------|
| 22| 3.0     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | ZIN                    |
| 23| 3.1     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, Sienna, ZIN, GM Inc.    |
| 24| 3.2     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Sienna                  |
| 25| 3.3     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, CASE, Pentalim, FLX Micro, GM Inc. |
| 26| 3.4     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Pentalim, FLX Micro      |
| 27| 3.5     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | FLX Micro                |
| 28| 3.6     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | CASE, ZIN, Goodrich     |
| 29| 3.7     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | CASE, ZIN, NASA          |
| 30| 3.8     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Sienna, ZIN              |
| 31| 3.8     |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | ZIN                     |

**General Description**

- **3.0 Integrated Combustion Cone**
  - 3.1 Ceramic Housing Design
  - 3.2 Ceramic Housing Fab
  - 3.3 Sensor Interface Electronics Design
  - 3.4 Sensor Interface Electronics Fabrication
  - 3.5 Sensor Interface Electronics Test
  - 3.6 SiC Nozzle design
  - 3.7 SiC Nozzle Fabrication
  - 3.8 Integration of Sensor Arrays and Nozzle into Ceramic Housing
  - 3.8 Environmental testing (temp., sensor, nozzle, mixing, vibration, EMI/RFI, durability)
**General Description**

**Statement of Work/Work Breakdown Structure – Smart Injector**

|   | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
| 33 | 4.0 Smart Injector |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 34 | 4.1 Injector Housing Design |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 35 | 4.2 Injector Housing Fabrication |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 36 | 4.3 Actuator Development |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 37 | 4.4 Fuel Valve Design |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, GM Inc. |
| 38 | 4.5 Fuel Valve Fabrication |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 39 | 4.6 Design Cone Interface Electronics (SOI) |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Pentalim, CASE |
| 40 | 4.7 Fabricate Cone Interface Electronics |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Pentalim, CASE |
| 41 | 4.8 Design Node Controller |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Pentalim, CASE, GM Inc. |
| 42 | 4.9 Fabricate Node Controller |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Pentalim, CASE |
| 43 | 4.10 Integrate all Sub-assemblies (valve/actuator, integrated cone, sensor array interface electronics, injector housing, and node controller) |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich |
| 44 | 4.11 Flame Tube Test (close loop combustion control, thermo-acoustic instability control, durability) |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | NASA, Goodrich |

**PROJECT OVERVIEW**
## Statement of Work/Work Breakdown Structure – AFEC Controller

|   | A                | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S                      |
| 46| 5.0 Control System |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich                |
| 47| 5.1 Design Hardware |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, Pentalim, GM Inc. |
| 48| 5.2 Fabricate Hardware |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, Pentalim       |
| 49| 5.3 Design Digital Communications Chip Set (SOI) |   |   |   |   |   |   |   | M35 |   |   |   |   |   |   |   |   |   | Goodrich, Pentalim, CASE |
| 50| 5.4 Develop Combustion Loop Algorithm |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, NASA           |
| 51| 5.5 Develop Spatial/Patern Factor Control Algorithm |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, NASA           |
| 52| 5.8 Base Line State-of-the-art Annular Rig Test |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, NASA           |
| 53| 5.9 AFEC Annular Rig Test |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | Goodrich, NASA           |
| 54|                  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
## PROJECT OVERVIEW

### General Description

### Technical Outcomes and Key Milestones for 1st Year

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Timing</th>
<th>Metric</th>
<th>Minimum Value for Successful Result</th>
<th>Test Method</th>
<th>Decision Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline and Characterization Testing</td>
<td>Beginning of year 1</td>
<td>Measure instabilities, mixing properties with pulsed fuel, atomization with pulsed fuel, and ident. failure modes</td>
<td>Not applicable</td>
<td>High pressure test rig</td>
<td>Establish baseline for project</td>
</tr>
<tr>
<td>Detailed requirements for the total AFEC system</td>
<td>Middle of year 1</td>
<td>Percent complete</td>
<td>100%</td>
<td>Accepted according to Goodrich's own product development criteria</td>
<td>Do not proceed with the project unless complete.</td>
</tr>
<tr>
<td>The designs for the combustion sensor array, air flow sensor array and fuel flow sensor die are complete</td>
<td>End of year 1</td>
<td>Layout and mask designs are complete</td>
<td>Layout and masks are 80% complete</td>
<td>Mask steps completed</td>
<td>Continue with project or proceed with reduced set of sensors</td>
</tr>
<tr>
<td>The designs for the sensor interface electronics are complete</td>
<td>End of year 1</td>
<td>Layout and mask designs are complete</td>
<td>Layout and masks are 80% complete</td>
<td>Mask steps completed</td>
<td>Continue with project or proceed with direct interface scheme</td>
</tr>
<tr>
<td>SIC Nozzle design complete</td>
<td>End of year 1</td>
<td>Detailed drawings and process sheet are complete</td>
<td>Drawings and process sheets are 80% complete</td>
<td>Goodrich's earned value system</td>
<td>Continue with project or use conventional nozzle</td>
</tr>
<tr>
<td>High temperature digital communication chip design complete</td>
<td>End of year 1</td>
<td>Layout and mask designs are complete</td>
<td>Layout and masks are 80% complete</td>
<td>Mask steps completed</td>
<td>Continue with project or proceed with centralized control scheme</td>
</tr>
</tbody>
</table>
PROJECT OVERVIEW

General Description

Figure 1. Pathways to economic and environmental benefits enabled by AFEC. (Sources: Numerous Government and industry publications)
• We are developing products for a broad base of applications – not just for turbine engines
• We are operating as a business group and establishing the basis for a supply chain
• We are providing the stimulus for the improved business of our team members – we will lay the foundation for volume business
• As a team, we are an extension of Honeywell’s development group