FROM CONCEPT TO REALITY:
A SMALL AIR QUALITY SAMPLING AIRCRAFT POWERED BY ETHANOL

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The Baylor Institute of Air Science has combined the experience gained over two decades of work in the areas of air quality investigation and development of alternative fuels for aviation into the realization of a small air pollution sampling, ethanol powered aircraft. The project comprises three phases.

The first phase has employed an ethanol powered Cessna 152 -- the first aircraft to be certified by the Federal Aviation Administration (FAA) to use ethanol as its fuel -- instrumented with a basic air-sampling package capable of providing essential information on air quality. This aircraft has been since used by the state of Texas to support an ongoing air quality monitoring program.

The second phase has involved instrumenting a Cessna 172, a popular four-seat aircraft, with an enhanced instrument package employed to obtain a more complete air quality data set. The aircraft has been successfully used in 2001 and 2002 monitoring programs in Alberta, Canada and in Texas. This aircraft is also used in an ongoing FAA research and development program of ethanol as an aviation fuel.

The third phase involves the designing of a new alcohol powered aircraft conceived to be specifically employed as a sampling aircraft. The aircraft, named “SNIFFER”, has recently been completed. Current efforts center on improving the air-monitoring package and developing the technology to be transferred to countries in need of this information.

Countries facing serious problems of air pollution and/or in the process of developing national ethanol programs are mostly interested in the educational/demonstration and technology transfer aspects of this program.

Brief History of the Project

The recently established Baylor Institute of Air Science (B.I.A.S.) at Baylor University has integrated the activities of the Renewable Aviation Fuels Development Center (RAFDC) and the Department of Aviation Sciences in order to facilitate the development and the promotion of multi-faceted and multi-disciplinary programs. The FAA has recognized the Baylor institution as a Center of Excellence and has provided funding for continued research on the use of ethanol in aviation.

RAFDC has been conducting research on the performance and emissions of alternate fuels for aviation engines, in particular ethanol, for the past two decades. Some of the past achievements and experience of the center includes:

- Supplemental Type Certificates (STCs) obtained from the FAA for the use of 100 % denatured ethanol for series of engines and aircraft -- that include a high wing type aircraft with a carbureted engine, and a low wing type aircraft with an injected engine.
- The modification of twelve aircraft to fly on ethanol -- that have accumulated thousands of hours during test flights, cross country flights, air shows performed all around the world and record flights -- the most notable being the first transatlantic flight on 100 % denatured ethanol made in 1989 from New York to Paris.
- Programs of research and comparison of performance and emissions of alternative aviation fuels, i.e. ethanol, methanol and Ethyl Tertiary Butyl Ether, and the currently used aviation gasoline.
- Programs of investigations of cleaner alternative fuels for turbine engines using blends of Biodiesel and Jet A fuel.
- Programs of air quality monitoring using instrumented aircraft.

In these last few years, the Baylor Center has been combining the experience gained in both alternative fuels research and air quality monitoring to develop the concept of a small aircraft powered by ethanol and instrumented to monitor air quality.

The pending crisis in general aviation due to the growing pressure to remove lead from aviation gasoline (Avgas) is going to be exacerbated by emerging concerns. Issues such as aircraft emissions, the contribution of fossil fuels to greenhouse gases and recognition by the scientific community of global warming, will increase the pressure to adopt alternatives to fossil fuels in aviation. According to the Argonne National Laboratory[1], for every gallon of petroleum replaced by corn ethanol, greenhouse gas emissions are reduced by 35 percent, while for every gallon of gasoline replaced by biomass ethanol, the greenhouse gas reduction potential is greater than 100 % when keeping in account the co-production of electricity.

Furthermore, the recent terrorist attacks on U.S. grounds have reaffirmed the critical need to establish a domestic fuel production industry in order to achieve energy independence and free the country from reliance on regimes that finance terrorist activities.

B.I.A.S. is currently working with the FAA to conduct a program of additional testing to insure the feasibility and safety of blends of ethanol and Avgas in the field. The motivation for this research is based on the assumption that the placement of ethanol in the market place will have to allow a phase-in stage in which either fuel, Avgas or ethanol, could be the only available fuel at a given airport. This will permit ease of operation and no decrease in mobility, and it would result, even during the phase-in stage, in cost savings both at the pump and in reduced operational costs.

The ethanol industry in the United States is presented with new opportunities with potential demand for ethanol far outstripping current production capacity. The Renewable Fuels Standard would require the use of five billion gallons of renewable fuel by 2012, and an equivalent percentage of total market-share thereafter. Ethanol production capacity is growing very fast with new facilities being built and rapidly coming on line – with a predicted 2002 production reaching 2.1 billion gallons. Additionally, the potential of ethanol production from cellulosic biomass – and the consequent wider variety of feedstock available – is coming closer to reality.

The utilization of municipal waste, industrial waste, agricultural waste and dedicated energy crops, has the potential to expand domestic fuel supplies for a large percentage of countries currently importing costly fossil fuels. Many of these countries face serious problems of air pollution. There is

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[1] Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions: Argonne National Laboratory's Center for Transportation and Technology R&D Center, January 1999.

a critical need in these countries to obtain air quality data in order to determine sources and understand the dynamics of their regional air pollution. The most cost effective way to obtain this type of information necessary to develop a successful pollution abatement program is an instrumented aircraft. The use of a small air sampling aircraft using ethanol as its fuel provides a cost effective solution to the excessive cost of operation normally associated with the standard size air sampling aircraft. Additionally, the use of this aircraft would promote the technology transfer of the use of ethanol as an aviation fuel and would serve as a demonstration/educational tool to accelerate adoption of ethanol as a fuel in any country with problems of fuel availability and air pollution.

Need for air quality investigations from instrumented aircraft

Measurement of trace species in the atmosphere is important for establishing air composition and assessing air mass history and oxidative capacity of the atmosphere. A basic set of measurements that can be used to accomplish this includes both primary and secondary air pollutants. Almost all trace gas primary pollutants arise from combustion of fossil fuels, and include oxides of nitrogen, carbon, and sulfur. Measurements of individual species within these broad classes using commercial instrumentation include NO_x (nitric oxide and nitrogen dioxide), NO_y (the sum of nitrogen oxides, including NO, NO_2, HNO_3 (nitric acid), and organic nitrates (e.g. – peroxyacetyl nitrate)), CO (carbon monoxide), and SO_2 (sulfur dioxide). An important oxidative species that is both naturally occurring and is a secondary air pollutant is ozone (O_3), for which commercial instruments are available. Finally, a measurement of particulate matter mass (PM) is important for understanding a variety of PM related health and visibility issues. Taken together, this list of species (O_3, NO, NO_2, NO_y, CO, SO_2 , and PM) could be considered "state" chemistry parameters, in that they define the essential set of measurements required to define an air mass in terms of trace gas composition.

Measurement of these air quality state parameters from an aircraft platform has the obvious advantage of providing 3-dimensional spatial definition of the air composition. In addition to providing information about the vertical distribution of these trace species, use of an aircraft is an economical way to assess air composition and air quality of large geographic regions. This is particularly important when assessing the transport of pollutants from one source or region to another.

Many of the instruments that are commercially available for the state chemistry measurements are designed for use primarily at ground-based sites, where size and weight are not primary concerns. In contrast, size, weight, and power consumption must be minimized for use aboard an aircraft. In recent years, there has been a tendency towards miniaturization of many standard instruments, which facilitates the possibility of measuring all of the state chemistry parameters aboard a small sampling aircraft.

Baylor's evolution in the development of the small sampling aircraft.

Baylor began developing a small sampling aircraft in 1998 by designing an instrument package small enough to fit in the cabin, behind the pilots' seats, of an ethanol powered Cessna 152. The measurements included were SO_2 (sulfur dioxide; Monitor Labs® – pulsed fluorescence), O_3 (ozone; Dasibi®– UV photometry) and PM (particulate matter as b_{sp} ; Radiance Research® - nephelometry). The instruments chosen were EPA (Environmental Protection Agency) equivalent method instruments that were not modified to maximize response speed or detection limit. Despite not having these modifications, the aircraft instrument package was used to collect a data set that was important in understanding downwind photochemical transformation of primary pollutants in industrial and urban plumes. The Cessna 152 sampling aircraft was flown in Texas during the 1998-1999 air sampling seasons.

In 1999, a Cessna 172 Skyhawk was purchased and the instrument package was enhanced to achieve better response times (typically less than 5 seconds), improved detection limits, and measurement of additional trace gases and meteorological parameters. The Dasibi® ultraviolet photometry ozone instrument was replaced with a fast response modified Thermo Environment® chemiluminescence instrument. In addition, an Eco-Physics® NO (Nitric oxide) instrument was modified and installed. The instrument was modified to measure concentrations of NO and NO_y (sum of reactive nitrogen species) at intervals of 10 seconds. MetCon® j(NO_2) radiometers were also added to allow calculation of NO_2 using photostationary-state assumptions. Meteorological parameters were measured with an AIMMS-10® sensor that measures air temperature (T), relative humidity (RH), wind speed (WS) and wind direction (WD). The reconfigured platform was used during a photochemistry study conducted in Alberta, Canada.

The latest upgrade of the Cessna 172 sampling platform was to include a miniaturized photolytic NO_2 converter and the addition of another Eco-Physics® NO instrument. Both Eco-Physics® instruments were operated with time-sharing of separate inlets, allowing measurement of NO, NO_2, NO_y, and NO_y star (reactive nitrogen species less HNO_3 (Nitric acid) and aerosol nitrates). The AIMMS-10 was upgraded to an AIMMS-20 to improve wind direction and velocity accuracy. In addition, the sampling package was configured to allow collection of both filter and canister samples for later anaylsis for inorganic particulate species and non-methane hydrocarbons (NMHC), respectively. This measurement package was utilized during air quality studies in Alberta, Canada, and Texas during the summer of 2002. A sketch of this instrument package is shown in **Figure 1**.

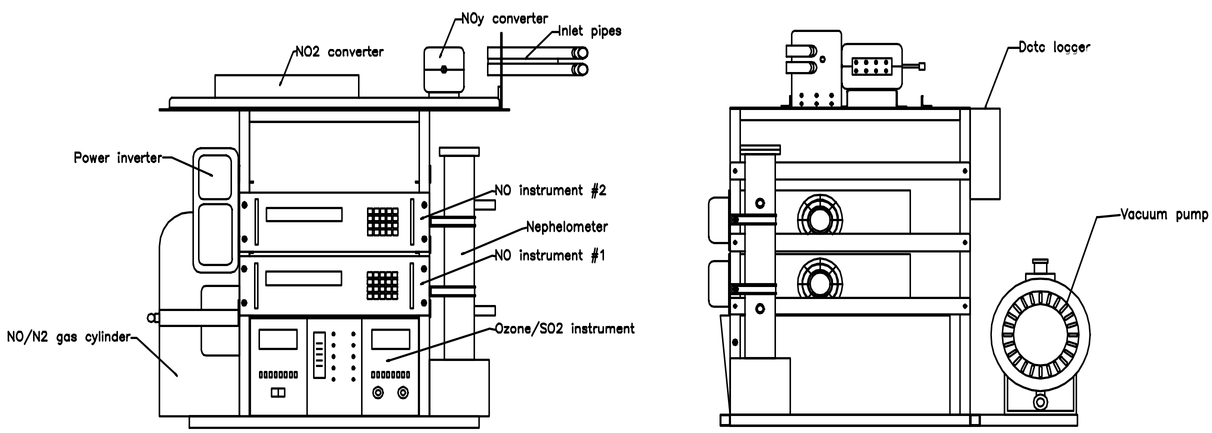

Figure 1. *A sketch of the instrument package installed on the Cessna 172 for the 2002 sampling season*

An important feature of 2002 Cessna 172 instrument package is that an attempt was made to utilize common resources to save on weight and power consumption. For example, the system included one vacuum pump to service both of the NO instruments as well as the ozone and SO_2 instruments. Also, the ozone and SO_2 instruments were installed in the same instrument enclosure and shared one power supply. As discussed in the next section, further consolidation of instrument resources planned for the SNIFFER aircraft (e.g. - power, vacuum, data acquisition) promises further reduction in overall package size, weight and power consumption. In addition, consolidation of these resources offers the opportunity to install the system in a distributed way, taking advantage of the several equipment bays available on the SNIFFER aircraft.

The SNIFFER: Integrated Air Quality Measurement Package

The design of the integrated air quality measurement package evolved from the experience gained using the measurement packages on the two Cessna aircraft described above. The overall design concept was to provide a largely autonomous sampling system, including self calibration and conditional control (e.g. – the instruments automatically sample zero air until the aircraft is airborne), with data display and instrument controls that would allow one pilot/scientist to perform the air quality sampling. While many aspects of the system are still under development, the essential features of the equipment in the first development phase are described below.

Overall design. The overall design concept for the air quality instrumentation package installed on the SNIFFER aircraft is to utilize commercially available and state-of-the-art miniaturized versions of the standard instruments required to measure the state chemistry and air quality parameters described earlier. The SNIFFER aircraft was designed with four equipment bays (fore and aft of the pilot and observer and in both wings). Extensive use of shared resources allows installation of the detector components for the various instruments in the optimally located wing bays, while the power, vacuum, data acquisition, and reagent gas shared resources are located in the fuselage bays. Four similar inlet probes, each customized internally for the different measurement systems, are mounted in the clear air beneath the wings. The embedded-computer data acquisition and control system is connected to a small touch screen LCD display console that can either be held by the observer or mounted on the dashboard of the aircraft. All of the equipment on-board can be controlled from the display console or a centralized power distribution/ valve control box. The instrument systems are designed in a modular way to allow re-configuration of the measurement package for different instruments depending on the particular air quality application. The first phase of the development project is focusing on the state air quality parameters described above with the exception of SO_2. Future work will include installation of a miniaturized SO_2 instrument.

Air quality instrumentation. As mentioned above, the first phase of development of the integrated air quality measurement package includes sensors for ozone, NO/NO2/NOy, CO, PM (via nephelometry), and meteorological parameters (WS, WD, T, RH). The instrumentation installed is listed in **Table 1**.

Module	Measurement principal	Detector manufacturer	Performance enhancements required for aircraft deployment
Ozone	UV absorption	2B Technologies	None.
NO	NO+O3 Chemiluminescence	Sonoma Technology	None.
NO_2	Chemiluminescence / photolytic conversion	Sonoma Technology	None.
NO_y	Chemiluminescence / Heated Mo conversion	Sonoma Technology	None.
CO	HgO reaction bed/UV adsorption	2B Technologies	Flow control and catalytic zero.
PM mass (as b_{sp})	Nephelometry	Radiance Research	None.
Meteorology	Winds: pressure sensor array and differential GPS Temperature: Pt resistance thermometer RH: solid-state sensor	Aventech Research (AIMMS 20)	None.

Table 1. *Instrument modules to be included in the first phase integrated air quality sampling system.*

The detector elements of these instruments are all located in the wing bays of the SNIFFER aircraft. Separate inlet/sensor probes are provided for the meteorology system, the CO and ozone instruments, the nephelometer, and the NOx,y system. The inlets are located very close to the actual detector elements, enhancing the response speed of the measurement package.

Shared resources. The shared resources for the measurement package include a high performance vacuum pump and lightweight calibration and reagent gas cylinders installed in the aft fuselage equipment bay, and a DC power inverter, DC/DC power supply, and PC-104 based data acquisition and control system installed in the forward fuselage equipment bay. Provision was made in the aircraft design to allow for routing of cables and piping between all of the equipment bays. A sketch of the aircraft showing the location of the equipment bays is shown in **Figure 2**.

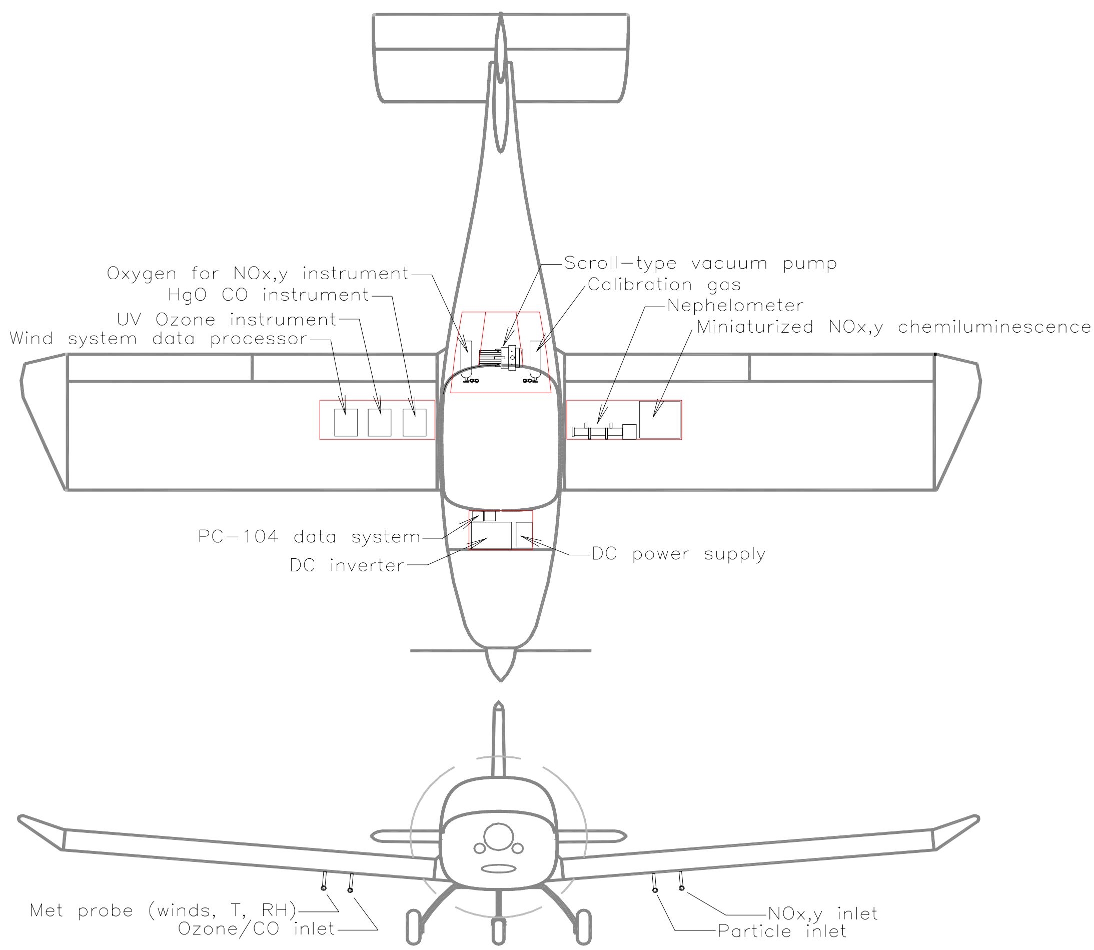

Figure 2. *Sketch of the SNIFFER aircraft outline showing the locations of the 4 equipment bays and the instruments to be installed on the aircraft during the first phase of the project.*

Data acquisition, display, and processing. The data acquisition system used for the integrated air quality measurement system is a PC-104 format embedded computer/data acquisition system. The software used (DaqLab®) allows data acquisition and conditional control of the integrated instrument package from the cockpit-mounted touch screen display. Programming of the on-board computer is accomplished by connection to a remote computer via Ethernet.

The data display includes a GPS (Global Positioning System) referenced track plot that includes the ability to change the color of the track in proportion to the concentration measured with any of the on-board instruments. This feature allows a single pilot/scientist to most efficiently fly a pattern to characterize a particular air mass or plume. Other screens available to the observer include status of the various instruments, time series plots, vertical profile plots, and control of event-triggered sampling such as NMHC canister sampling.

Processing of the data collected is performed on the fly using the results of automatic calibrations and zeros. Thus, at the end of a flight, preliminary data and data plots can be directly downloaded from the aircraft. Subsequent data processing to allow editing of spurious data is performed using Igor Pro® software.

The SNIFFER: Airframe and Power plant

The SNIFFER is made of a composite eggshell structure. The aircraft is a two-place, side by side seating, enclosed by a molded Plexiglas canopy that slides forward to open. The engine mount is steel tubing with the engine space enclosed by two cowlings removable from both bottom and top with cowl fasteners. It is a low wing aircraft with chromium molybdenum wing attach points that slide in the main fuselage. This system allows for rapid removal and installation of the wings. The undercarriage is a standard fix tricycle landing gear with a full swiveling nose wheel.

Picture 1: *The SNIFFER*

The power-plant is a Rotax 912 UL 80 horsepower engine. A similar engine previously has been modified to run on ethanol for use in an ultralight aircraft. The ultralight was successfully flown many hours on ethanol. Ethanol's high octane, high oxygen content, cooler and cleaner burning, detonation resistance, higher thermal efficiency and power, and its chemical simplicity are the characteristics that make it an ideal fuel for this type of engine.

The SNIFFER is constructed with a revolutionary design that produces an extremely lightweight aircraft combined with very low drag profile. This results in the ability to carry two persons, in this case the pilot and an instrument operator, full fuel and up to a 300-pound instrument package. The fuel consumption is approximately 4.3 gallons per hour of ethanol at normal cruise airspeed of 124 miles per hour. This enables the aircraft to fly for 3.90 hours with a fuel reserve of 45 minutes, the standard requirement for VFR (Visual Flight Rules) flight. Under these circumstances, the aircraft would have a no-wind range of slightly over 480 statute miles. In some circumstances, it is desirable to remain aloft for as long as possible, and since the aircraft can fly at air speeds as low as 42 miles per hour, it is possible to remain in flight for as long as 5.6 hours with a 45 minute reserve.

The figure of 80 horsepower assumes the use of gasoline as fuel. However, due to the higher latent heat of vaporization of ethanol when compared to gasoline, ethanol produces from 5% to 20% more power when operating at full throttle at sea level. This occurs because the heat required to vaporize the fuel is greater, hence effectively decreasing the density altitude of the aircraft as far as the engine is concerned. The power increase due to the use of ethanol has not yet been determined for this particular type of Rotax engine. Hence at this time, the increased safety margin during takeoff, as a result of the additional power available, can not be quantified.

Economics

The fuel: The current bulk cost of ethanol in the U. S. is approximately $1.00 per gallon while the bulk cost of Avgas is approximately $1.80 per gallon. While these figures vary widely throughout the country, ethanol is substantially less expensive than Avgas. Even factoring in the lower energy density of ethanol when compared with Avgas, the economics are still in favor of ethanol. Extensive testing has shown that in the worst-case scenario of range loss, occurring in low compression engines, 20% more ethanol is required when compared with Avgas. Thus with a 42% decrease in the cost of fuel, combined with a 20% loss of range there is still approximately a 20% decrease in the cost per mile when using ethanol rather than Avgas. Engineers involved in the certification testing of ethanol have estimated conservatively that the time between overhaul could easily double, providing another substantial decrease in operating costs for ethanol powered aircraft. Additional savings in the cost of operation of ethanol powered aircraft will be realized when the use of technologies to produce ethanol from cellulose results in a further decrease in the cost of ethanol. In the U.S. the current production of ethanol is approximately 6 times the consumption of Avgas. Thus, there is no concern about adequate supply for aviation. On the other hand, this is a high visibility market that represents a substantial percentage of the entire ethanol production and, as such, should be very attractive to the ethanol industry.

The aircraft: The basic motivation in the development of the small sampling aircraft is to provide a low cost air pollution sampling aircraft. The operating cost of Baylor's twin-turbo prop DeHavilland DHC-6 is approximately 20 times the projected operating cost of the SNIFFER. A used Twin Otter with mid-time engines and in reasonable condition can be purchased for approximately $1,000,000. The SNIFFER is projected to cost $50,000 new. Thus, 20 of this type of small sampling aircraft can be purchased new for the cost of one high time, used, medium-sized sampling aircraft as represented by the DHC-6. Additional savings are planned eventually by improving the data display in the cockpit in order that the air sampling flight can be conducted with the pilot also functioning as the instrument operator. This requires a highly trained individual with superior pilot skills, thorough understanding of air pollution instrumentation and air pollution chemistry in addition to an understanding of the effective use of an aircraft as an air-sampling platform. The education and training of this type of scientist-pilot is the goal of the program currently in place at B.I.A.S.

Implementation

The small sampling aircraft powered by a renewable fuel has become a reality thanks to the combination of technical developments, research opportunities, field experiences and determined efforts employed over the past three decades.

These concerted efforts have led to a cost effective air quality monitoring system to determine level of air pollutants, their location in three dimensions, critical factors in their make up, sources and evolution of the principal pollutants.

Moving to the international dimension of this opportunity, a Memorandum of Understanding with Thailand is in place to establish a comprehensive program involving this concept. Other countries have expressed varying degrees of interest in the concept.

There are three primary reasons for implementation of this program in these and other countries: 1) a determination to establish a domestic ethanol industry; 2) decisions to determine the least costly and most effective way to establish pollution levels, their nature, and the best method to deal with these pollutants in major cities; and 3) a need to establish a market for ethanol with minimum government-provided incentives. The high cost of aviation gasoline makes ethanol very attractive as a replacement fuel for the aviation market.

The convergence of all of these factors coincides with a decision by Baylor University to promote the Department of Aviation Science into the Baylor Institute for Air Sciences. The program has about 100 students enrolled in an academic curriculum called the "Scientist/Pilot Program". This in-place program provides graduates with a commercial pilot license and instrument rating with a Bachelor of Science degree. All of these activities set the stage for the next major advance: 1) a flight-training program using ethanol powered aircrafts directly under the auspices of the Institute; 2) an academic course that trains its graduates to install, operate miniaturized air pollution monitoring equipment in an aircraft and fly it; 3) transfer of the technology and the scientist/pilot curriculum to other countries by: (i) training pilots and ground personnel to fly the aircraft, operate the pollution monitoring equipment, analyze the results and portray the results in a manner and format meeting the needs of local air quality control authorities; and (ii) conducting flight operations until the local comprehensive program becomes self-sustainable with electronic and distant learning support from the Institute. The Institute will provide continuous technical and scientific support to upgrade the program.

The institute is working toward jump-starting this program by providing the opportunity for pilot-projects to be implemented in selected countries through cooperative programs. The cooperation can involve all of the aspects of the program, or it can be limited to just the field operations and/or the demonstration/educational part of the program.

The SNIFFER will be certified initially in the U.S. Once this is accomplished, certification in other countries interested in using the aircraft will be obtained through a well-established and significantly shorter process than the initial certification.

Conclusion

Renewable resources are inexhaustible when used in a sustainable manner. They create energy decentralization and independence from global fossil fuel control while at the same time reviving local and rural economies. Domestic production of ethanol can also eliminate supply interruptions while helping to bring an end to international conflicts caused by limited fossil resources.

The low cost ethanol powered aircraft, specifically designed to monitor air quality, provides great potential for wide implementation in countries around the world not able to afford these type of investigations while helping to promote programs involving both air quality and the advancement of alcohols as alternative fuels.

The small sampling aircraft will be invaluable in promoting programs with potential of achieving national energy security, strong rural economies and ultimately clean air for all people.

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