A MINIATURE POWERPLANT FOR VERY SMALL, VERY LONG RANGE AUTONOMOUS AIRCRAFT

Final Report
to the
United States Department of Energy
under contract number DE-FG03-96ER82187
(Phase II SBIR)

INSITU

The Insitu Group
401 Bingen Point Way
Bingen, Washington USA 98605
www.insitugroup.com
Stephen P. Hendrickson, Principal Investigator
29 September 1999

Summary

We have developed a new piston engine offering unprecedented efficiency for a new generation of miniature robotic aircraft. Following Phase I preliminary design in 1996-97, we have gone forward in Phase II to complete detail design, and are nearing completion of a first batch of ten engines. A small-engine dynamometer facility has been built in preparation for the test program. Provisions have been included for supercharging, which will allow operation at ceilings in the 10,000 m range. Component tests and detailed analysis indicate that the engine will achieve brake-specific fuel consumption well below 300 gm/kWh at power levels of several hundred watts. This level of performance opens the door to development of tabletop-sized aircraft having transpacific range and multi-day endurance, which will offer extraordinary new capabilities for meteorology, geomagnetics, and a variety of applications in environmental monitoring and military operations.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Contents

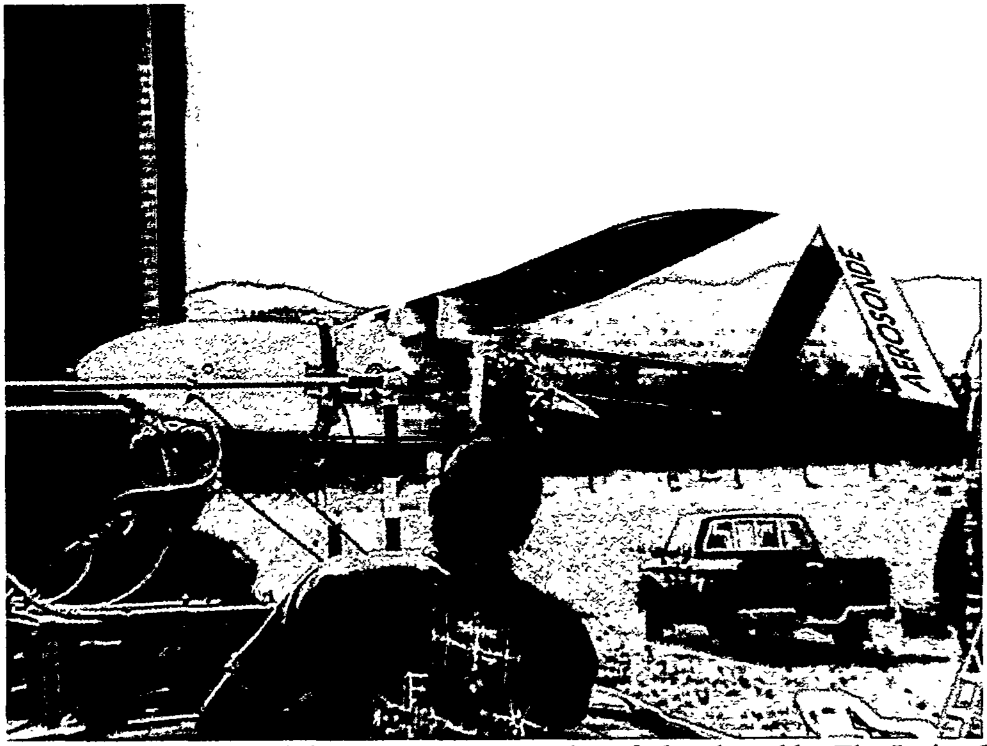


Figure 1. The Aerosonde, a miniature autonomous aircraft developed by The Insitu Group for environmental monitoring over oceans and remote areas. This "first-generation" aircraft is capable of moderately long range and endurance, as demonstrated spectacularly in August 1998 when Aerosonde *Laima* became the first unmanned aircraft to cross the Atlantic (flying 3000 km in 26 hr 45 min; see McGeer & Vagners 1999a). However many applications, for example weather reconnaissance in the Pacific (Figure 2), will require much longer range, and that in turn calls for a new powerplant offering an unprecedented combination of small scale, light weight, and high efficiency. Here we report on development of a powerplant uniquely suited to these requirements.

The need for a new small-scale engine

Workers in atmospheric science are chronically handicapped by the expense of *in situ* sampling over remote and oceanic regions of the globe. Despite the increase in volume and variety of measurements from meteorological satellites, and in observations from instrumented ships and airliners, skill in day-to-day weather forecasting continues to be limited by sparsity of *in situ* offshore soundings, of the sort that, over populated land masses, are taken economically by radiosonde balloons.[1] Research initiatives such as DoE's Atmospheric Radiation Measurement program[2] are similarly constrained by the prohibitive cost of offshore data gathering, as, to some extent, are other applications including geomagnetic survey, search-and-rescue, and interdiction.

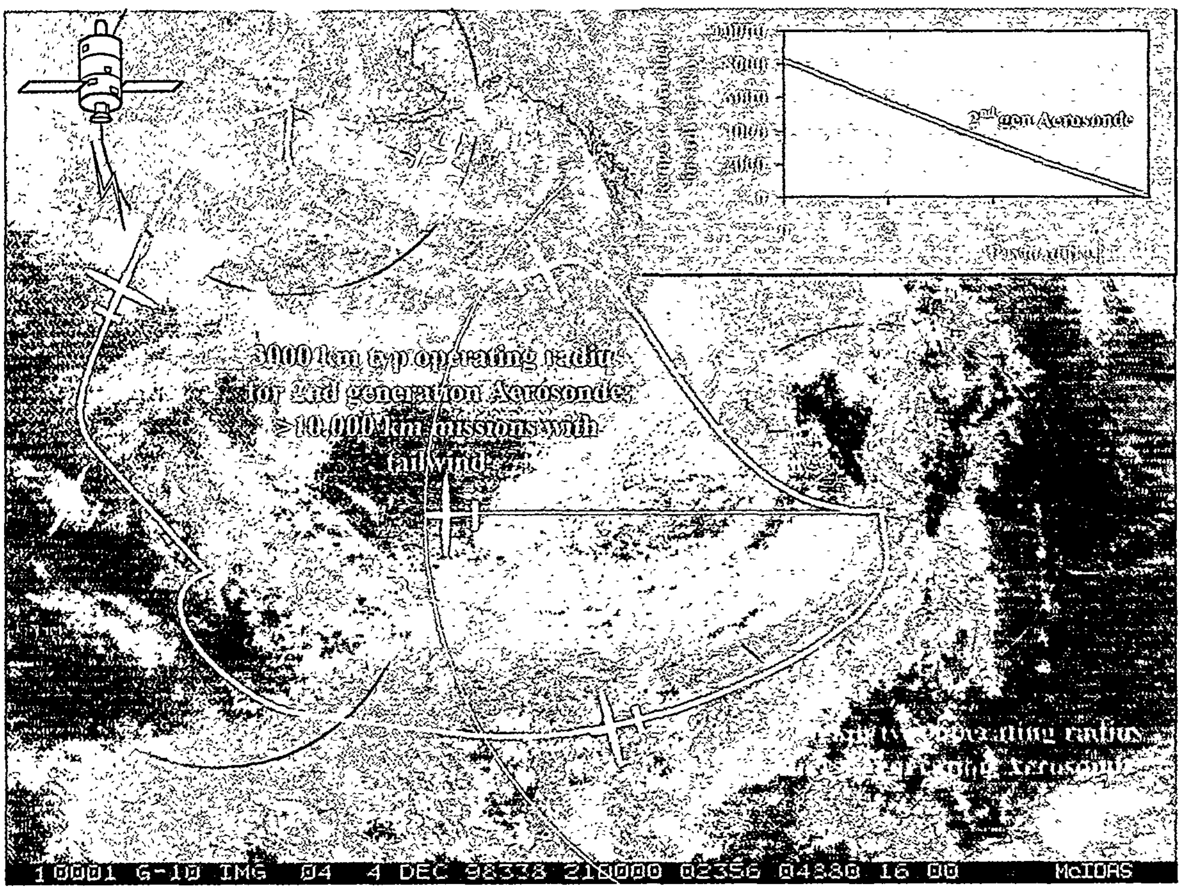
In 1991 we proposed that it would soon be possible to develop miniature robotic aircraft, small enough to fit on a tabletop, and yet capable of missions spanning thousands of kilometres and several days duration (McGeer 1991, Holland *et al.* 1992). The economies afforded by

[1] www.atmos.washington.edu/~cliff/aerosonde.html
[2] www.arm.gov

miniaturisation open the door to much improved offshore data-gathering in an expanding number of applications involving lightweight payloads, including meteorology, geomagnetics, and imaging reconnaissance. Over the last few years we have developed a first-generation miniature aircraft for meteorology, which we call an *Aerosonde* by analogy with the familiar radiosonde balloon (Figure 1). Aerosondes have been deployed for meteorological field trials at various venues around the world since 1995 (McGeer *et al.* 1999, McGeer & Vagners 1999b), and most famously for a 1998 flight from Newfoundland to Scotland. That flight made a little Aerosonde named *Laima* the first unmanned aircraft and, at only 13 kg gross weight, by far the smallest aircraft ever to make an Atlantic crossing (McGeer & Vagners 1999a).

Laima's crossing left many observers surprised by the capability of miniature aircraft. However the first-generation aircraft - with a range of about 3000 km, and endurance of 30 hours - in fact falls wells short of the potential for aircraft of its size. Much improvement is not only possible,

Figure 2. Weather reconnaissance in the northeast Pacific illustrates both the need for and the capability of a second-generation Aerosonde with Insitu's new powerplant. Our first-generation aircraft can only nibble at the edges, but our planned second generation will be able to reach, loiter, and communicate via satellite throughout the basin - in this example, as suggested by Steve Lord of the US National Weather Service, by circulating through bases in Hawaii, the Aleutians, and the West Coast to take advantage of prevailing winds.. This sort of operation will satisfy an emerging requirement for economical *targeted observations* offshore (Szunyogh *et al* 1999).



but also essential for many applications (*cf.* Figure 2). These improvements will depend upon technical revisions in several areas - aerodynamics, structural design, avionics - but most importantly upon an all-new powerplant.

Table 1. Miniature long-range aircraft call for priorities in engine design quite different from those in typical small-scale engine applications. Consequently a new engine had to be developed to satisfy our requirements.

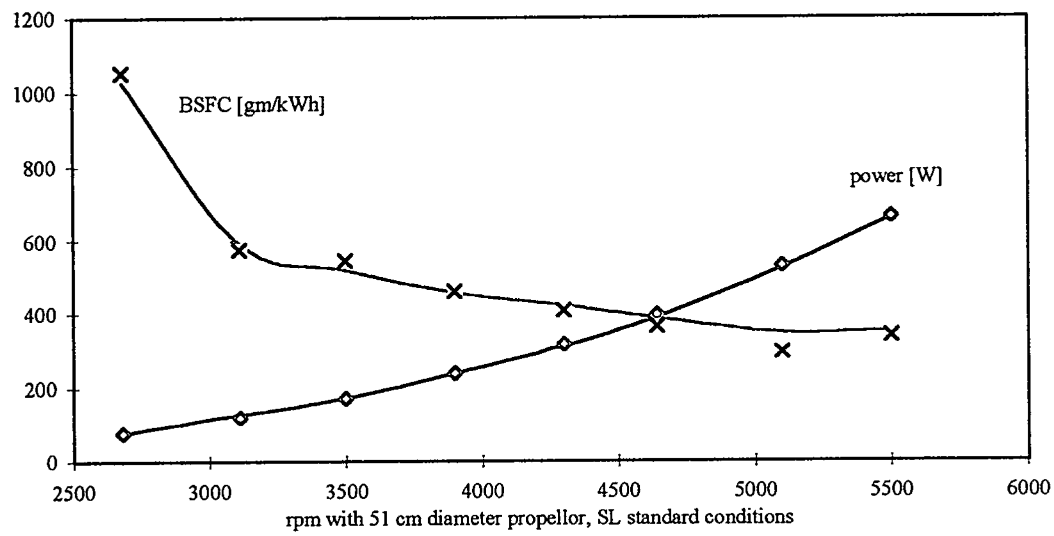
Application	Tools	Model aircraft	Aerosondes
SPECIFICATION PRIORITIES	**Cost** **Power-to-weight** Reliability Emissions Simplicity Efficiency Low-drag packaging	**Cost** **Power-to-weight** Simplicity Low-drag packaging Reliability Efficiency Emissions	**Reliability** **Efficiency** Power-to-weight Low-drag packaging Cost Simplicity Emissions
DESIGN CHOICES			
Fuel/Ignition	Gasoline/Spark	Methanol/Compression	Gasoline/Spark
Cycle	Mainly 2-stroke		Four-stroke
Induction	Carburetted		Fuel injected
Cooling	Air		Liquid
Lubrication	In fuel		Dry sump

First-generation engine

Table 1 compares the characteristics required in an Aerosonde-class aircraft engine with those of engines for garden tools and models. The Aerosonde's unusual requirements put it essentially "off-the-market". We recognised that situation when we began Aerosonde work in 1992, and, lacking the money necessary to develop a custom powerplant, our best option for a first generation was to modify a model-aircraft engine as specified in Figure 3. In its unmodified form the model engine has acceptable power-to-weight ratio, but very high fuel consumption as it runs on nitro-methanol fuel. We improve fuel consumption by fitting spark ignition and a carburettor for gasoline; an oil circuit to avoid having to run on an oil/fuel mixture; and a new piston to improve lubrication and compression. These measures make the engine acceptable for interim use, but weaknesses remain. Its gross output and specific fuel consumption are mediocre. Air cooling combined with high vibration makes it difficult to install, so the first-generation Aerosonde has no engine cowling (*cf.* Figure 1) and suffers consequent high drag. Materials-limited operating temperature (<150°C cylinder head) compromises thermodynamic-cycle efficiency, and moreover allows lead buildup which penalises longevity and reliability. The lead comes from aviation gasoline, which we use in preference to automotive fuel not only for the usual altitude-range reasons, but also because avgas evaporates rapidly and so can mix well despite low manifold temperature and short induction plumbing. Avgas, however, contains lead, and while its formulation includes lead-scavenging agents, these are ineffective at low operating temperature.

Figure 3. Characteristics of the modified model-aircraft engine in the first-generation Aerosonde. Symbols in the plot are measurements, while the curve is an estimate made by our powerplant-performance model as used in Phase I (McGeer 1997).

Model	Modified Enya R120
Type	single-cylinder, four-stroke, air-cooled, spark-ignited, carburetted, poppet-valve, direct-drive piston engine
Manufacturer	Enya Metal Products, Yokohama, Japan ES&S, Melbourne, Australia
Displacement	20 cc. (1.2 cu. in.)
Rating	0.75 kW (1 HP) at 5500 rpm
Weight	1.3 kg (excluding generator and ignition)
Fuel	Avgas 100LL



Second-generation engine history

It was clear at the beginning of the Aerosonde program that an alternative engine would be needed for the long term. We had hoped that new emissions standards for utility engines, notably in California, might promote movement from two-strokes to more efficient four-strokes, and so open new market options. Some such engines have indeed appeared, Honda's new GX series[3] being a leading example. However as yet they offer little advantage over our modified Enya with respect to efficiency or installation. Consequently we have had to develop our own engine to move forward. Design objectives include the following:

- **Fuel consumption**

A long-endurance aircraft places a very high premium on specific fuel consumption (and aerodynamic drag), for which we are willing to incur some penalties in cost, weight, and complexity.

[3] http://www.honda-engines.com/gx/index_m4se.htm

- **High-altitude operation**

Specialised meteorological and other applications may call for operation at high altitude. Hence powerplant design must allow for supercharging and appropriate thermal control, while not unduly penalising the majority of applications for which supercharging is not required.

- **Packaging**

With a high premium on aerodynamic drag, installation design requires care. This, and the thermal-control requirement, favour liquid over air cooling.

- **Reliability**

Reliability is, by small-engine standards, unusually important in Aerosonde-class applications, given the need for long-endurance unattended operation and the high cost of attrition. (Aerosondes are roughly a hundred-fold more costly than lawn mowers!)

- **Manufacturability**

Economical, repeatable manufacture is essential for service in volume.

- **Modularity**

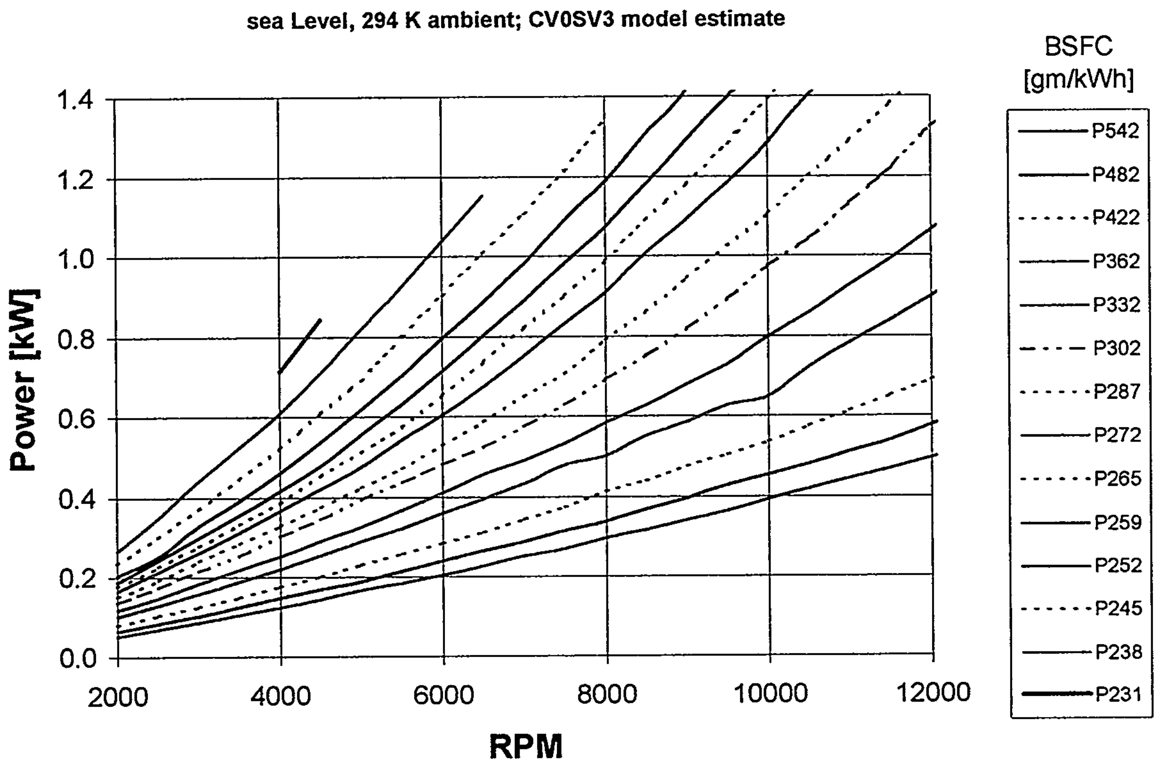
Miniature long-range aircraft will be developed over a range of sizes. Thus in addition to accommodating supercharged and normally-aspirated variants, the engine design should allow for multiplying cylinders to supply a series of power ratings.

We began work toward these objectives in 1996, with SBIR funding from DoE. Phase I, running through early 1997, concentrated on detailed performance modeling and preliminary design of a complete supercharged powerplant. Phase II, running from mid-1997 through mid-1999, has gone on to detailed design of the engine, fabrication of test articles, and development of a new test facility.

Figure 4. Summary specification for the "VSC-001" engine built in Phase II. See Figure 5 for more detailed performance data.

Type	single-cylinder, four-stroke, spark-ignited, geared piston engine
valving	sleeve-valve with 4 sleeve and 5 cylinder ports
cooling	pressurised liquid loop
lubrication	dry sump
fuel mixing	manifold fuel injection
rating	1.4 kW @ 10,000 rpm (sea level)
displacement	28.1 cc
bore	39.0 mm
stroke	23.5 mm
gear reduction	2.5:1
weight	1926 gm excluding generator, ignition, and injector
fuel	Avgas 100LL

Figure 5. Performance map estimated for the VSC-001 engine at sea level, plotted as contours of brake specific fuel consumption in power/rpm space. BSFC values, in gm/kWh, are listed at right; note the uneven contour spacing. (Waviness is a plotting artifact.)

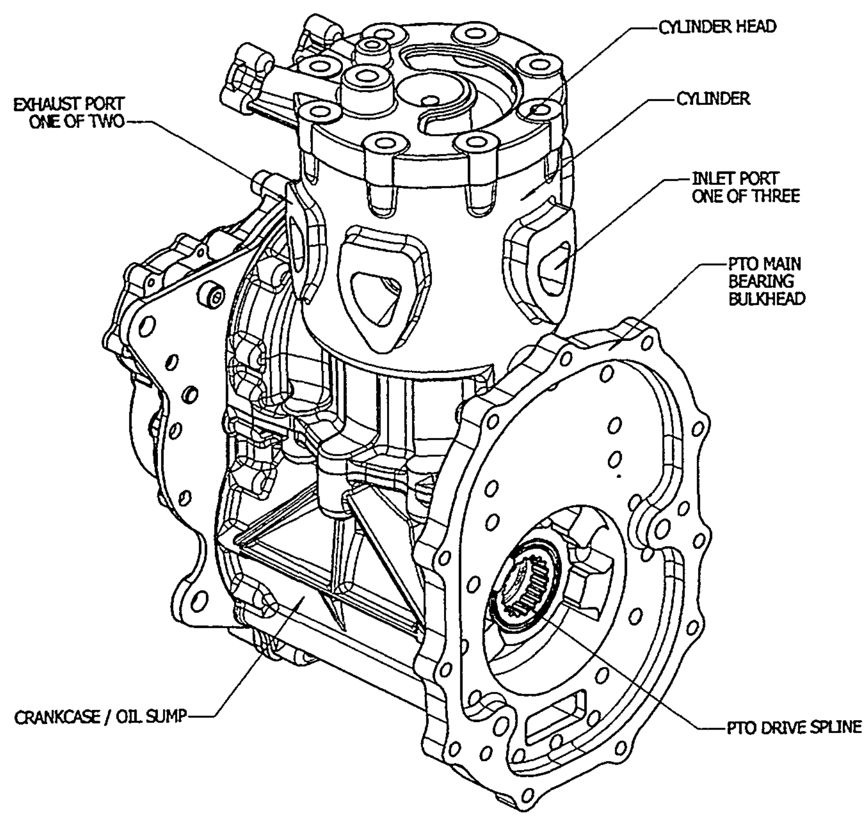


Two nontechnical constraints came into the Phase II program after it was launched in 1997. The first involves Environmental Systems & Services (Melbourne, Australia), whom we licensed to manufacture of the first-generation Aerosonde in 1995. ES&S had promised substantial matching funds for development of the second-generation powerplant, but in the event was not able to meet its commitment. The main consequence for us has been concentration on the core engine at the expense of a supercharger, for which we have done further analytical work but no hardware development. This turns out not to be a problem, at least for our initial application in weather reconnaissance, since high altitude has become less important than was thought at the outset of Phase I. For example the 1998 Northeast Pacific Experiment (Szunyogh *et al* 1998) has indicated that the main need for offshore observations is in the lower- to mid-troposphere, which can be reached with normal aspiration. Indeed it now appears that the penalties in aircraft range and cost associated with supercharging (Table 3) will be justified in only a small subset of Aerosonde-class applications.

The second constraint has been a boom in fabrication work among our specialty suppliers in Los Angeles and Taiwan. This has left us competing, often unsuccessfully, with much larger aerospace and automotive firms for shop resources. Costs and schedules have been stretched, and some parts for our first series of engines has remained in work through the end of Phase II. Firing tests of the new engine consequently will begin only in autumn 1999.

Despite these constraints, we are very pleased with the outcome of Phase II. We have an complete, innovative, fully manufacturable, robust, and high-performance design. Component tests have gone well; and we are confident of the projected performance of the complete engine. Ten engines are nearing completion, and we have a facility and program in place for bench testing as soon as assembly is complete. The engine will be in a class by itself for miniature aircraft, and should be at the heart of not only our own second-generation program (McGeer & Vagners 1999b) but also those of other manufacturers who will surely enter the "Aerosonde-class" arena over the next few years.

Figure 6. The VSC-001 engine is arranged physically as a cylinder between the main propellor gearbox, here on the right, and the accessory gearbox on the left. The cylinder is surrounded by a cooling jacket, and the spark plug is recessed. Breathing is through inlet and exhaust ports in the cylinder wall, which align with ports in a rotating/reciprocating sleeve in appropriate phases of the engine cycle. Intake and exhaust manifolds around the ports are not shown in this view.



Description of the engine

We now move to a description of the engine: concept; mechanical design; breathing; lubrication; cooling; and related matters.

In a small-displacement engine, high combustion chamber surface-to-volume makes heat loss a major design concern. One is therefore obliged to use a single-cylinder arrangement (with a counterweight scheme to control vibration) in order to keep surface-to-volume as high as possible. Beyond that, one must pay close attention to coupled design of the combustion chamber and valving. First, a domed cylinder-head cavity, with the spark plug near the top and small "squish lands" around the perimeter (Figure 7) becomes attractive, as opposed to the wedge-type heads that are popular at larger scale (Yagi *et al.* 1970). Second, since heat loss tends to reduce peak cylinder temperature, one can increase compression ratio without provoking knock. One must seize this opportunity, since the associated increase in basic Otto-cycle efficiency partially offsets thermal losses. But then one is left with a problem in valve design: a high-compression head of the preferred shape turns out to have insufficient room for properly-sized poppets.

Figure 7. A half-section isometric from the rear quarter shows the cylinder and valve-train details, with the piston at top-dead-centre. Note the location of the spark plug at the crown of a semi-spherical combustion chamber, with "squish lands" around the periphery. The rotating/reciprocating valve sleeve is shown at the top of its stroke, blocking the cylinder ports.

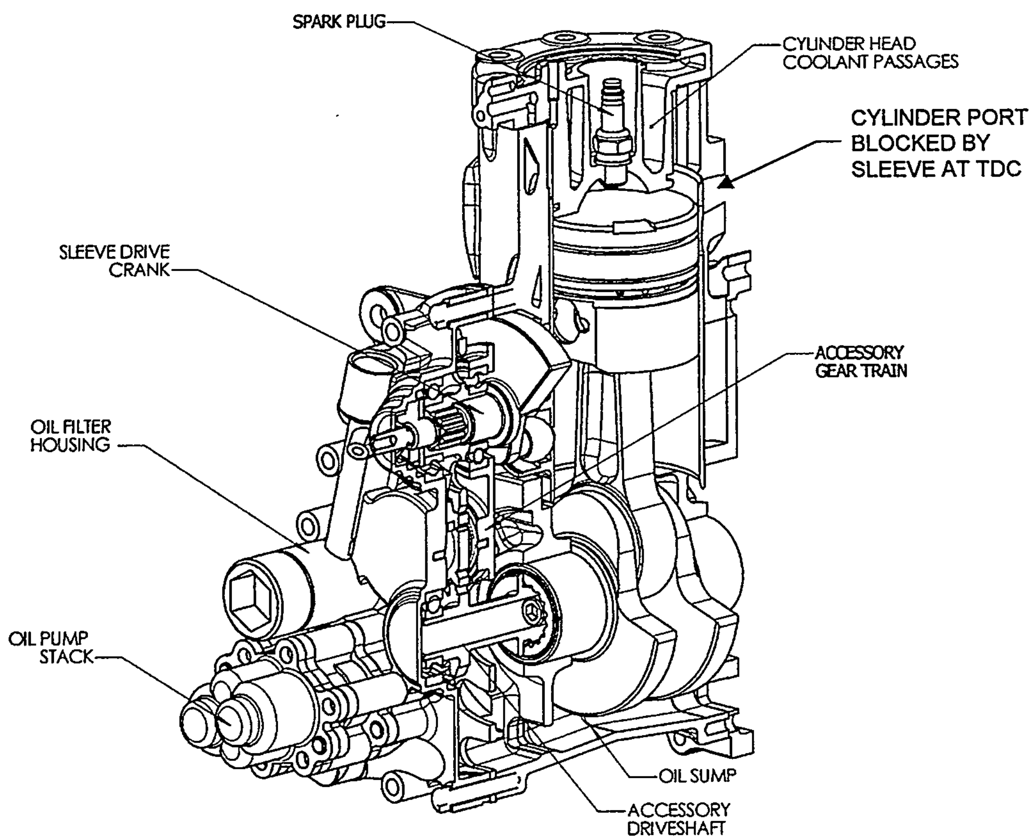
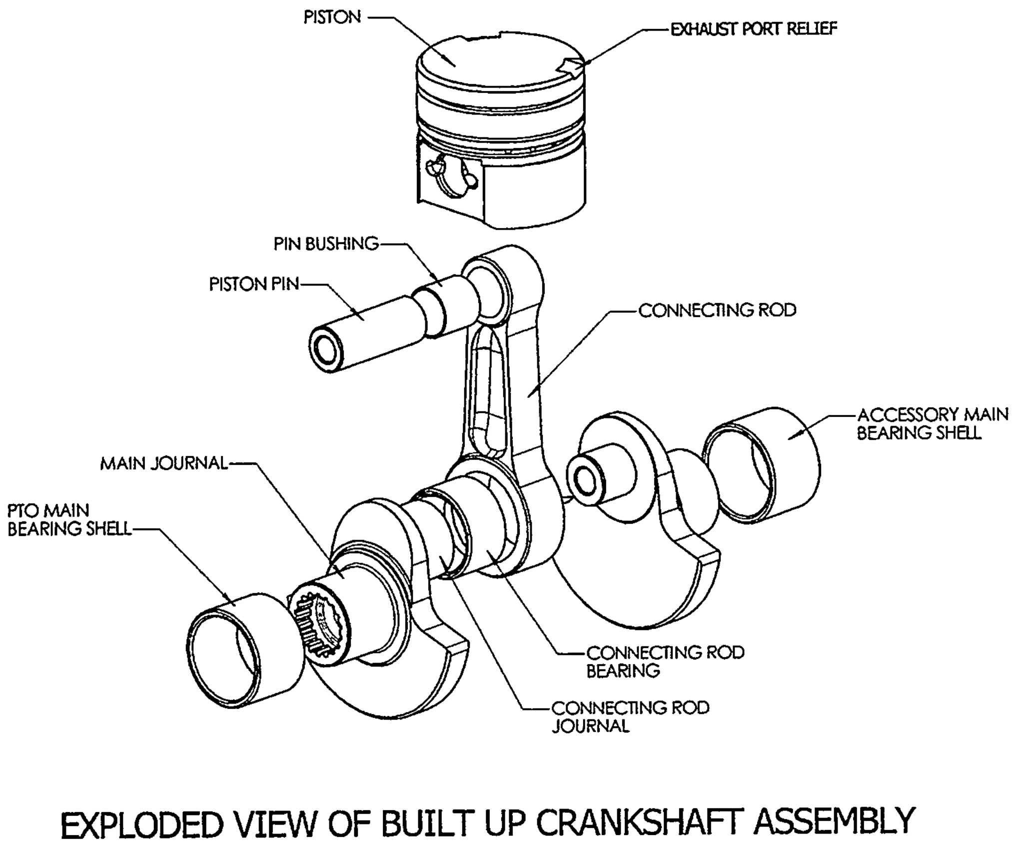


Figure 8. The power train. Note the crankshaft counterweights for balancing the piston and sleeve, and the divots in the piston crown to prevent blockage of breathing ports.



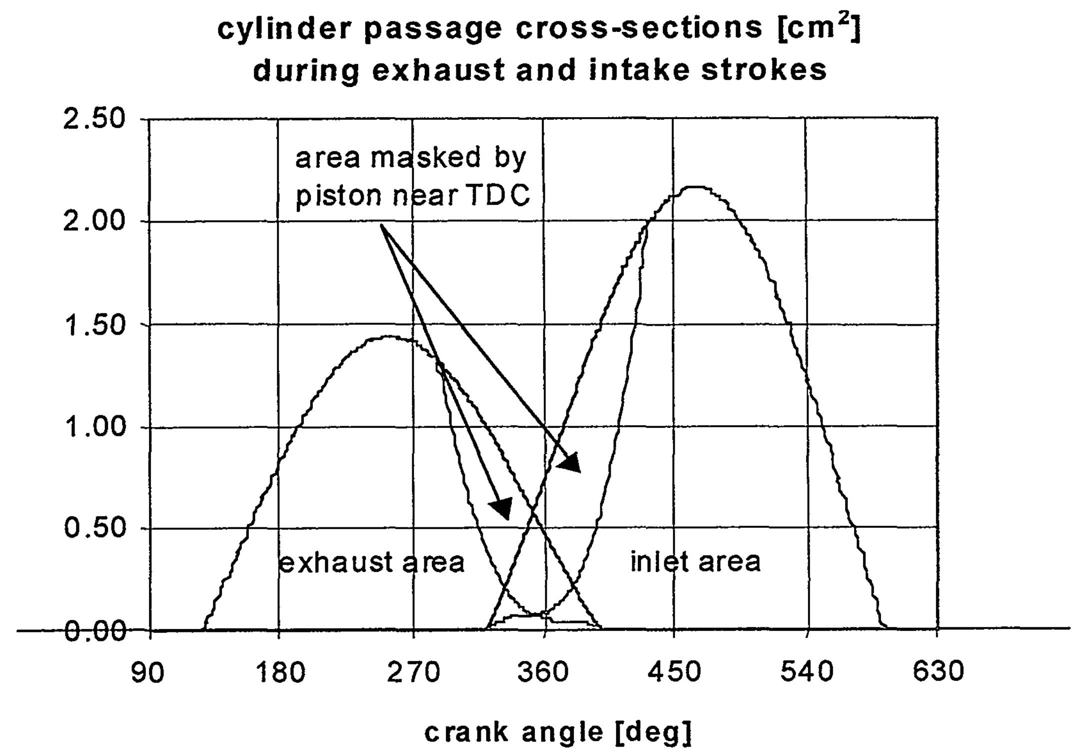
Sleeve-valving

We use sleeve-valving to accommodate the spherical combustion chamber shape. The design is similar to that used on small sleeve-valve engines by Ricardo in the 1920s (Ricardo 1960), and later, with great success, on large aircraft engines in the 1940s and 50s (Napier *Sabre*, Bristol *Centaurus*, *etc.*). A gear-driven sleeve with four pie-slice-shaped ports in its wall slides between the piston and cylinder wall, periodically aligning its ports with five matching ports in the cylinder. Combined rotation and reciprocation by the sleeve brings the ports into alignment over appropriate segments of the exhaust and intake strokes, thereby allowing flow to enter from the intake manifold and exit to the exhaust manifold (Figure 9).

The advantages of sleeve-valving - at scales large and small - lie not only in combustion chamber layout, but also in promotion of swirl and reduction of valve-train power consumption. Jet engines long ago pushed the idea from the mainstream, but for our special circumstances - and particularly for a single-cylinder engine, which eliminates some complexities in manifolding - it is the best way to maintain good combustion chamber shape and good volumetric efficiency.

One new issue arises from use of sleeve-valving with an unusually low stroke/bore ratio, namely that the top piston ring must pass over the sleeve ports near top-dead-centre. To prevent undue wear we use a two-stroke type top ring, which is pinned against rotation. (The same ring and pin arrangement is also used for the junk head ring.) The second piston ring and the oil-control ring set are of standard four-stroke type.

Figure 9. Sleeve valving (rather than poppet valving) together with low stroke/bore ratio (0.60) allows large valve areas with a semi-spherical combustion chamber. Our arrangement is similar to that used in the large sleeve-valve engines of Bristol and Napier in the 1940s, except that the stroke/bore ratio is much lower. This leaves the piston passing over the ports near top-dead-centre (*cf.* Figure 8), and calls for care in ring design.



Lubrication

The VSC engine is lubricated by a conventional dry sump circuit is shown in Figure 10. The flow is maintained by one gear-type supply pump and two scavenge pumps in the accessory cluster (*cf.* Figures 7, 12). Oil pumped from the supply tank flows under pressure through a sintered-bronze filter to the main oil gallery in the engine block. Passages from the gallery to the crankshaft supply the main bearings, and passages in the crankshaft itself supply the connecting-rod journal bearing (*cf.* Figure 8). Jets feed the valve and propellor reduction-gear trains, and a small flow lubricates the outside of the valve sleeve. The piston and piston pin are lubricated (and cooled) by oil leaking through the thrust clearance in the connecting rod big-end and the main bearings. Oil collects in sumps at either end of the crankcase and is returned by scavenge pumps to the supply tank. A ball-type relief valve is located in the main oil gallery (at maximum distance from the pressure pump.)

Figure 11. Oil pump performance, as calculated from test-rig performance. The calculated power consumption is the total for the pressure and scavenge pumps. Maximum output pressure is 584 kPa.

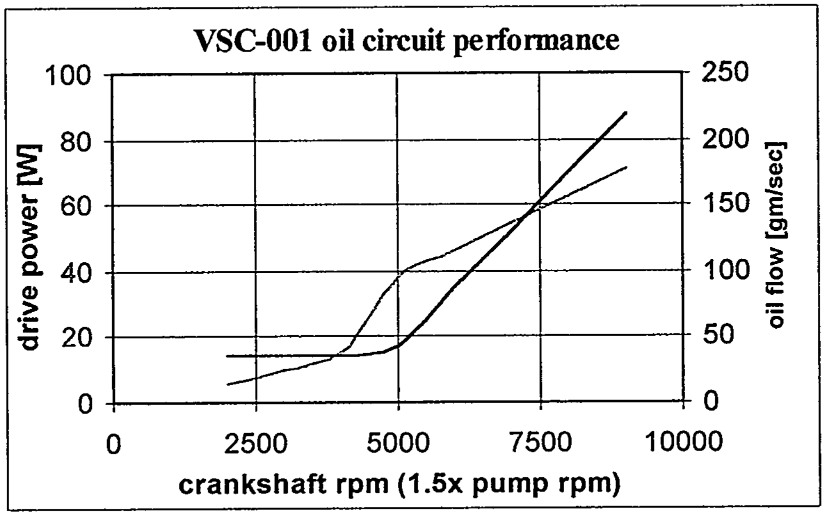


Figure 10. The VSC lubrication circuit. The supply tank is separate from the engine, while the remainder of the circuit is integral (*cf.* Figure 12).

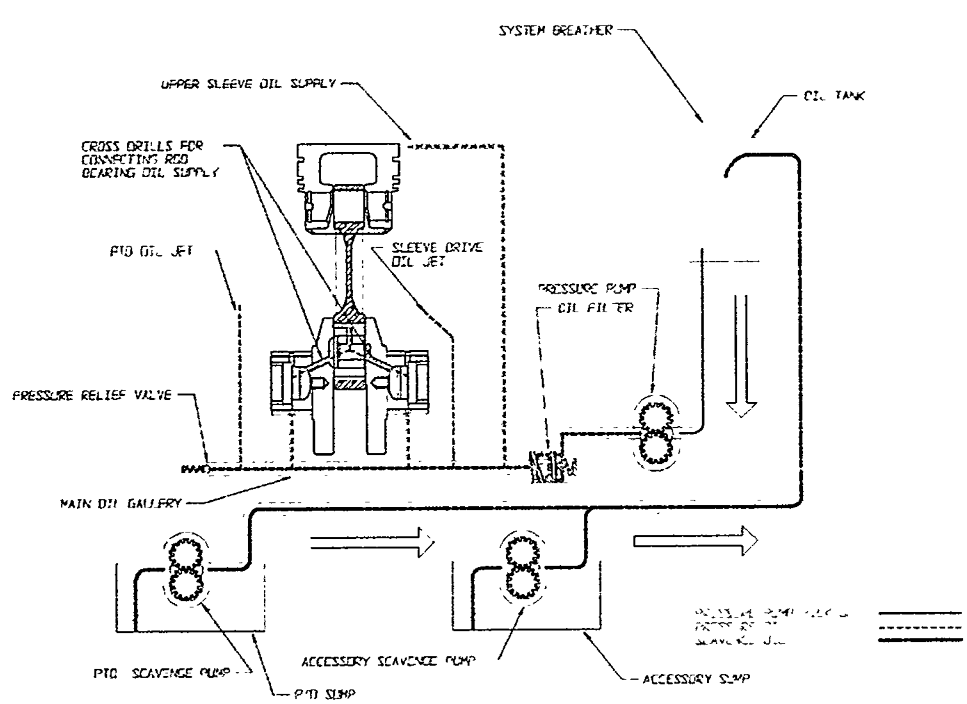
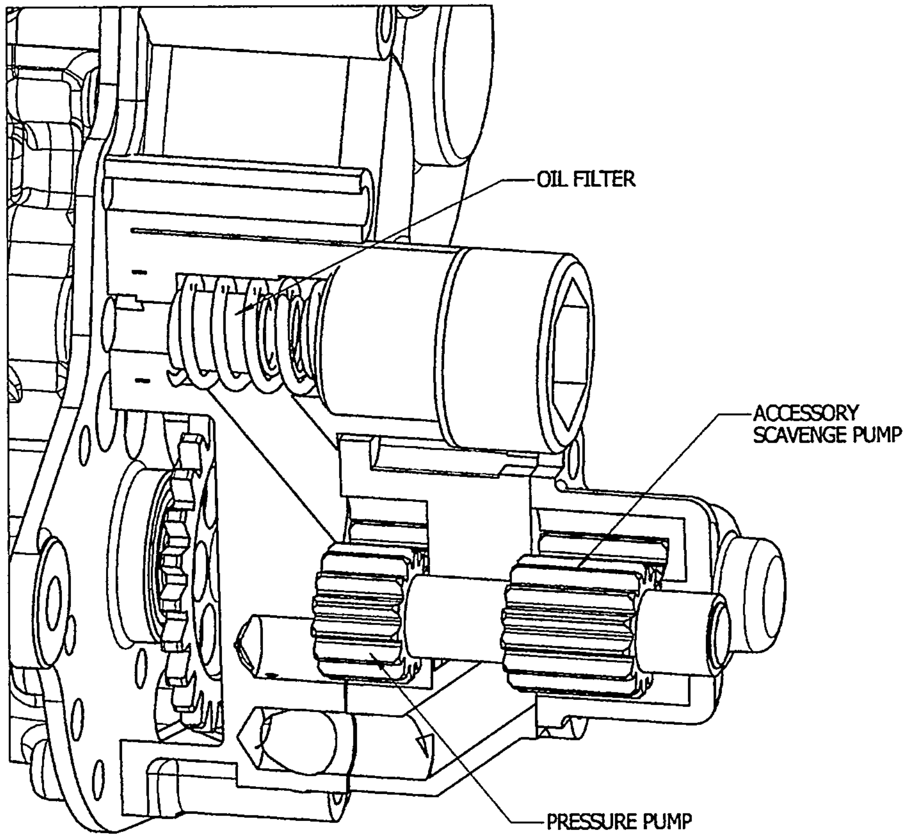


Figure 12. Detail cutaway of the oil-pump stack at the lower rear of the engine.



Cooling

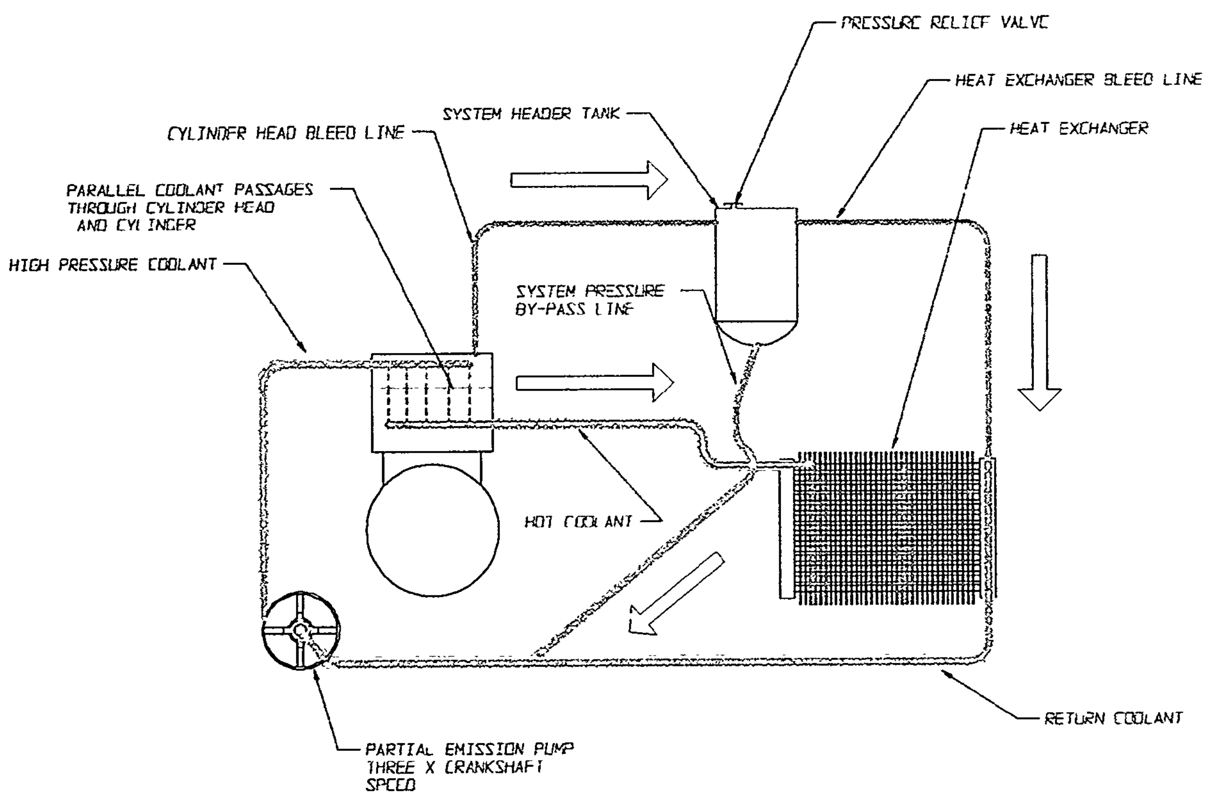
As we have noted, one of the many weaknesses of commercially-available engines in the size range of interest is air-cooling. This is problematic for low-drag installation in an aircraft, particularly in the pusher-propellor configuration which is often required for unmanned designs. Liquid cooling offers more flexibility, since it allows the engine and radiator installations to be designed separately. For example, the engine can then be installed in a tapered fuselage "boattail", and the radiator in a compact underwing duct. Liquid cooling is also attractive for handling a large altitude range, since the associated wide range of ambient temperatures would otherwise be difficult to accommodate.

In our Phase I design study we considered an unconventional two-phase coolant circuit, but as we moved into detail design we opted for a more familiar pressurised-liquid system as drawn in Figure 13.

Ignition and fuel supply

Most small-scale engines, including the modified Enya in the first-generation Aerosonde, use pump-type carburettors. Our experience is that the ready availability and low cost of these

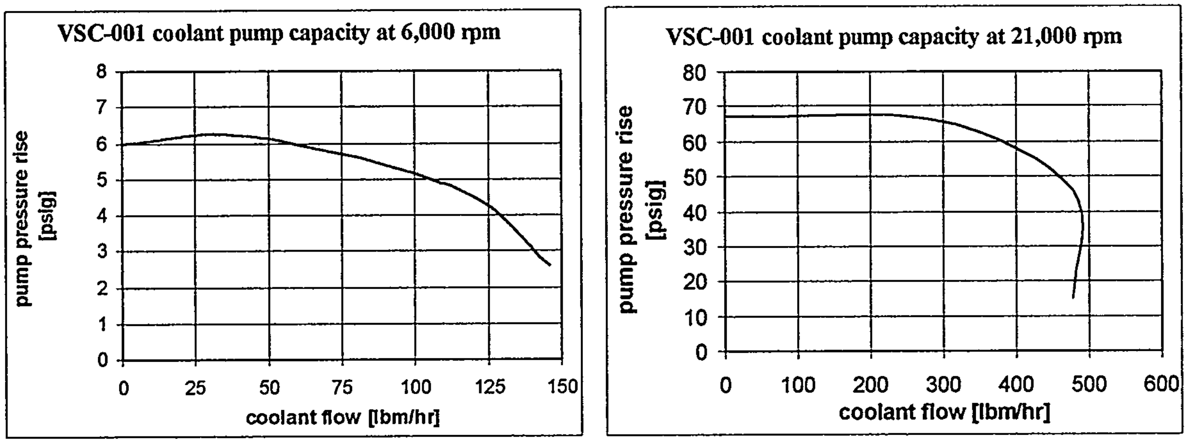
Figure 13. The cooling circuit follows contemporary auto-racing practice in that it utilises high flow rates in the areas of maximum heat rejection. Water/antifreeze coolant pressurised to 100 kPa enters the cylinder head around the spark plug boss at about 102°C, flows in an annulus down the upper cylinder head and thence at high velocity through parallel passages past the exhaust and inlet ports to the cylinder jacket. The coolant collects in the cylinder jacket at about 110°C, and exits to a heat exchanger separate from the engine. A non-integral header tank is at the highest point in the circuit, with bleed lines for filling and vapour separation. The bypass line from the header tank supplies fluid to the pump as an anti-cavitation measure at high flow rates. The heat exchanger would be sized for the flight application. As an example, our sizing of a tube/fin exchanger for a supercharged second-generation Aerosonde, with ceiling around 10 km, calls for about 40 cm^2 frontal area, about 4 cm streamwise length, and a filled weight around 300 gm.



carburettors does not compensate for their part-to-part variability and indifferent mixture control. Thus with the Aerosonde's current powerplant, every carburettor/engine combination must be laboriously tuned and mapped on a test stand, and the resulting data stored by the receiving aircraft for use in its internal performance model. This process must be repeated at each overhaul (which, because of the lead-deposit problem mentioned earlier, is done at intervals of about fifty hours), and despite all this effort, variation in fuel flow of 20% from one powerplant to the next is not unheard-of.

These problems can be sharply reduced by fuel injection, which offers precision and easy repeatability. In 1998 ES&S began developing fuel injection for the Enya, using modified

Figure 14. The coolant pump is a partial emission (Barske) impeller within the accessory case at the rear of the engine. It is geared-up by a factor of 2.94 relative to crankshaft speed. The plots show example capacity measurements.



automotive hardware. ES&S has been bench-running this equipment throughout 1999, and we have arranged to use the same injector for initial development of the VSC engine. Both injection and spark timing will be controlled by a speed/density algorithm. Autronics Pty Ltd (Melbourne) supplied the digital/programmable engine controller for our test cell, which is a standard system used in auto racing. We see a clear path to take that system forward to a flightweight system for the second-generation Aerosonde.

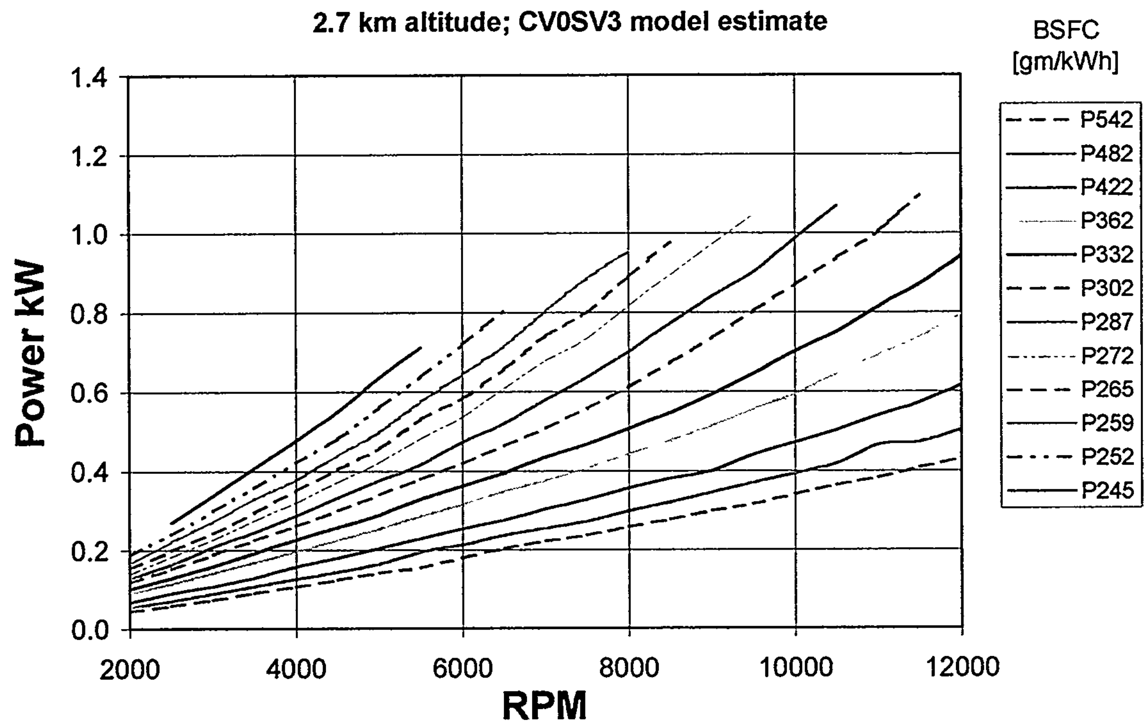
Performance

The VSC engine has been designed for efficiency, and its brake-specific fuel consumption is indeed expected to be exceptional for such a small engine. As shown in Figure 5, the minimum SFC at sea level is expected to be about 230 gm/kWh, and a value around 300 gm/kWh would be reasonable in cruise (where power is typically turned down to a fraction of maximum output). By comparison the cruise SFC of the first-generation Aerosonde is typically 400-500 gm/kWh.

Figure 16 shows performance maps for altitudes of 2.7 and 5.5 km with the engine running normally-aspirated. An Aerosonde would actually become marginally more efficient with increasing altitude, and so have longer range: the cruise power requirement goes up, while the available engine power goes down, so the "turn-down" penalty diminishes. Thus at 5.5 km a second-generation Aerosonde would typically cruise in the area of power/rpm space below 300 gm/kWh in Figure 16.

Our calculated SFCs are remarkably low - perhaps suspiciously so, remembering that performance has yet to be measured on the bench. However the components of our performance model (McGeer 1997) have been calibrated with some care: against the Enya (Figure 3); against historical data on sleeve-valve engines; against data on various other engines and pumps; and against our own component tests (Figures 10, 14). So we look forward with confidence, but also impatience and expectation, to measuring our test engines in autumn 1999.

Figure 15. Performance maps estimated for the VSC-001 engine at altitudes of 2.7 and 5.5 km, standard atmosphere. (*cf.* Figure 5).



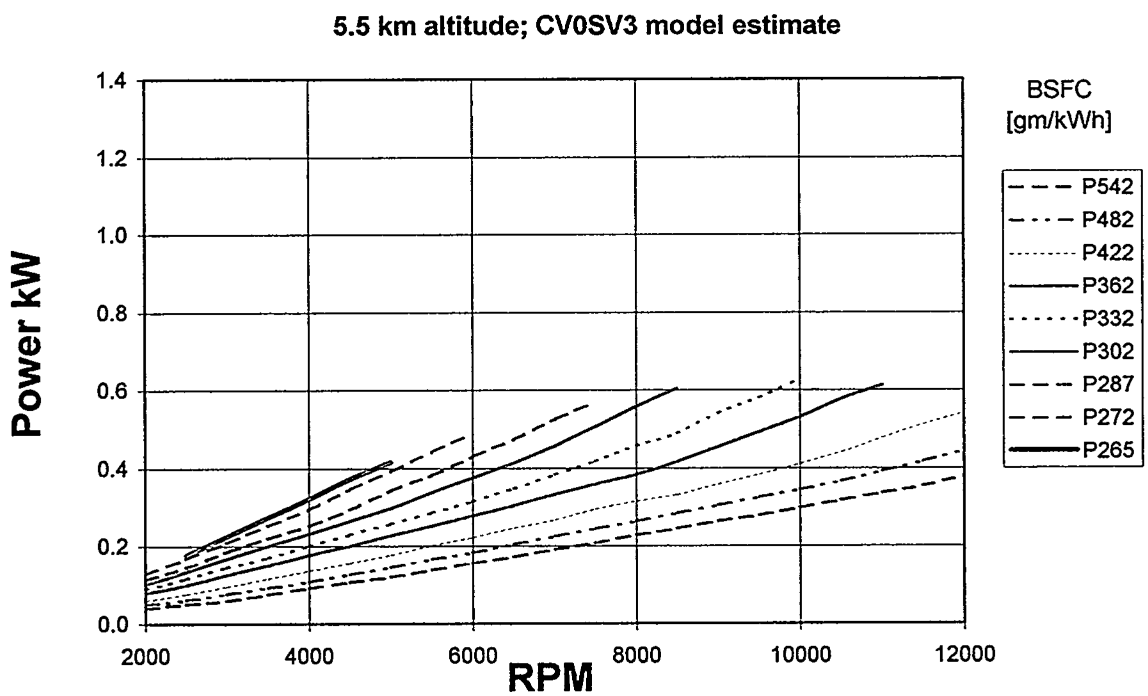
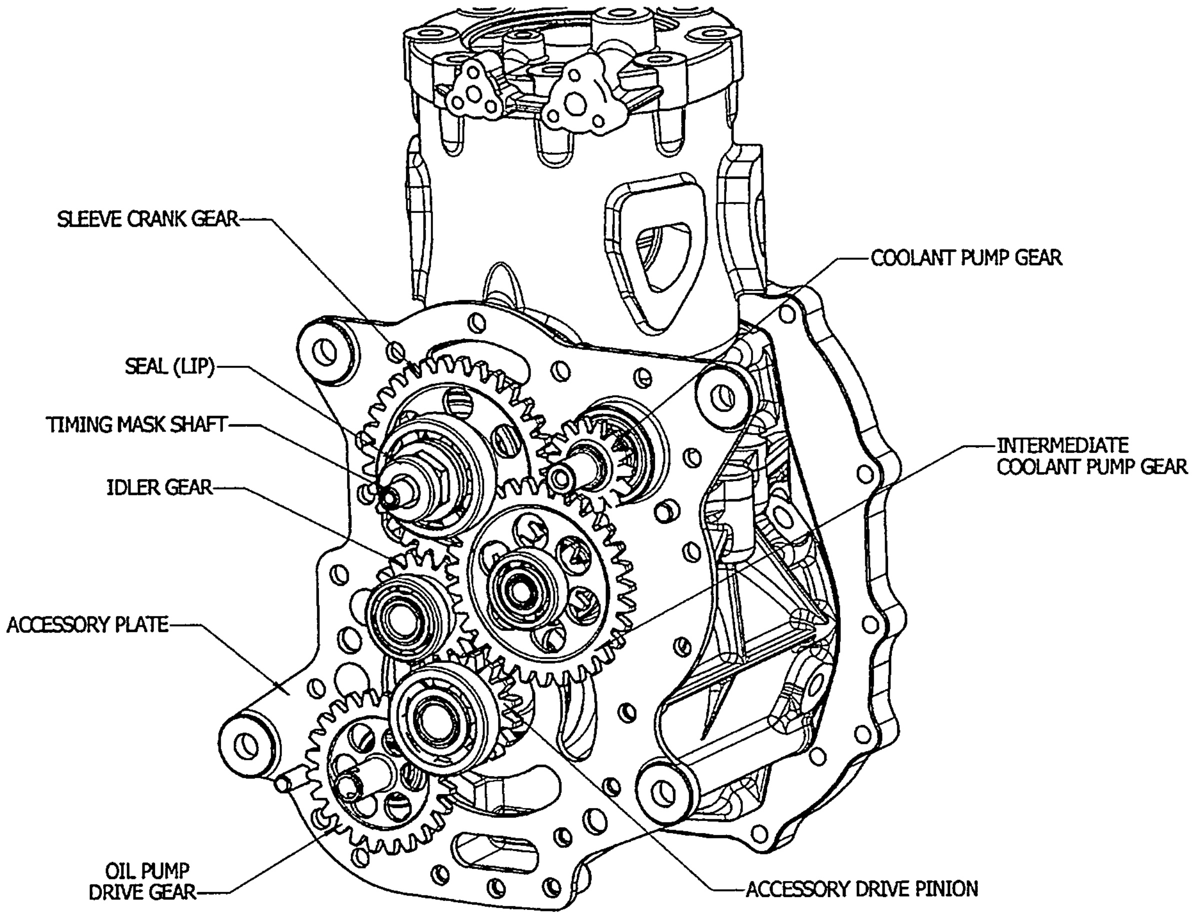


Figure 16. Isometric view of the rear of the engine, with the accessory case removed to expose the drives for oil pumps, coolant pump, and sleeve. The case also allows for a generator drive.



Supercharging

As discussed in our Phase I report (McGeer 1997), supercharging a small-displacement engine calls for a different approach than is used for engines of larger capacity. For engine rated at tens of kilowatts and upward, supercharging is most practically done with turbomachinery (usually, for reciprocating engines, a centrifugal-flow compressor driven by a centrifugal-flow exhaust turbine, the pair running independently of the engine, and controlling flow to the engine by metering exhaust gas around the turbine via a wastegate). At small scale, however, turbomachinery becomes impractical: components would be too tiny, rotational speeds too high, and Reynolds numbers too low for practical manufacture and service. Instead one must use a positive-displacement pump.

In the course of Phases I and II we have analysed several types of pump, including piston, epitrochoid rotary (McGeer 1997), Lysholm screw, and rotary vane. Analysis in collaboration with Alvin Lowi and Associates (Rancho Palos Verdes, California) indicates that a positive-displacement analog of a turbocharger, including both compressor and expander pumps, offers a marginal or negative efficiency advantage relative to a engine-driven compressor pump. Of the candidate engine-driven pumps, we consider that the best option is a rotary-vane pump driven through a differential gear. The advantage of this arrangement lies particularly in simple adaptation to a wide altitude range, with the differential drive used to limit manifold pressure at lower altitudes (following Dawson *et al.* 1964).

Table 2 lists characteristics of a candidate single-stage vane pump. We see adding a pump of this type as a practical first step in supercharging the core engine, with possibilities for higher boost to be considered at a later stage. Associated aircraft performance is discussed below.

Table 2. Candidate engine-driven supercharger for operation at altitudes around 10 km

type	crankshaft-driven, oil-less, vane-type rotary pump
vanes	6
displacement	53.7 cc per pump rev
pump/crankshaft rpm	1:1
design pressure ratio	3.5
design rpm	8000
design oil-free capacity	5200 cc/sec
overall efficiency	0.63 relative to adiabatic
rotor diameter	5.7 cm
rotor length	5.7 cm
overall diameter	8.6 cm
overall length	7.3 cm
weight	948 gm

Test facility

In parallel with our engine-design program, the Phase II work has included construction of a small-engine test facility as shown diagrammatically in Figure 17. It is run by two PCs: one, running *Labview*, for data acquisition, and a second for control of fuel and ignition through an Autronics automotive computer. The facility is instrumented for fuel and air flow; torque; speed; and ambient and powerplant temperatures and pressures. Fuel injection and spark timing are programmable through the PC as functions of throttle position, engine speed, manifold pressure, and ambient pressure.

The test facility was put into service early in 1999, and has been developed in testing Enya and two-stroke engines in preparation for running the VSC engine. For this work we have used propellors to load the engine, which is clumsy inasmuch as a series of propellors must be used to map speed/power space (as in Figure 5). We plan soon to switch to a water-brake load, for which most of the necessary hardware is in place, and final components are currently in fabrication.

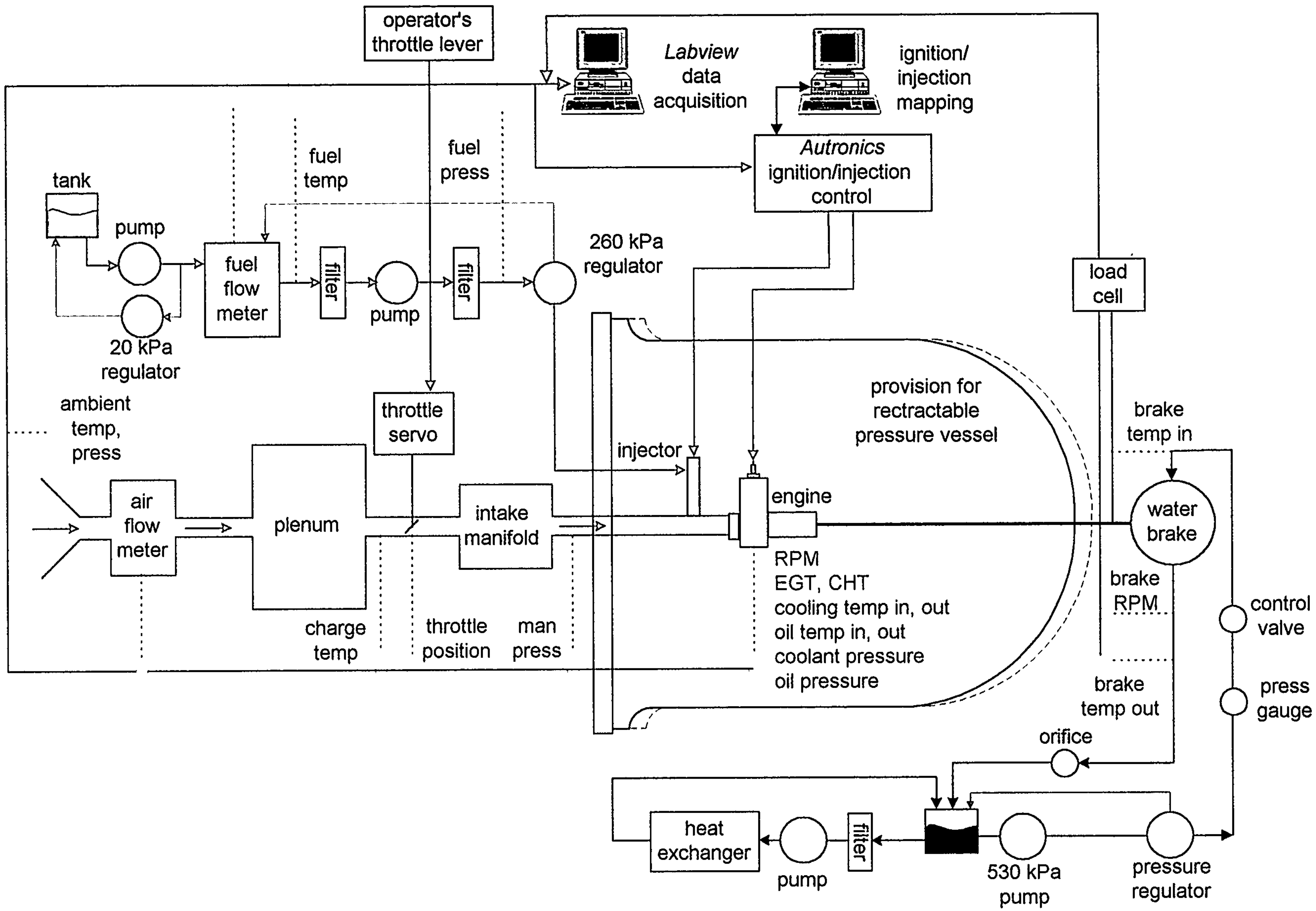


Figure 17. Insitu's small-engine test facility.

Table 3. Summary specifications for the current first-generation Aerosonde, and for second-generation Aerosondes with normally-aspirated and supercharged versions of the VSC engine.

AIRCRAFT	*First-Generation Aerosonde*	*Normally-aspirated Second-Generation Aerosonde*	*Supercharged Second-Generation Aerosonde*
	Dimensions		
Wing span	2.90 m	3.00 m	3.50 m
Wing area	0.57 sq m	0.60 sq m	0.65 sq m
Overall length	1.7 m	1.2 m	1.2 m
	Weights		
Airframe	2.9 kg	3.7 kg	3.9 kg
Avionics/Payload	2.1 kg	3.0 kg	3.0 kg
Powerplant	2.2 kg	3.8 kg	4.8 kg
Typical empty weight	8.2 kg	11.8 kg	12.9 kg
Maximum fuel weight	5.0 kg	6.6 kg	6.6 kg
Maximum launch weight	13.4 kg	18.5 kg	19.5 kg
	Performance		
Max level speed	54 knots	87 knots	87 knots
Cruise speed at ceiling	40 knots	58 knots	74 knots
Minimum speed at SL	40 knots	43 knots	43 knots
Max SL climb @ max weigh	2 m/s	4.4 m/s	4 m/s
Service ceiling	4,500 m/14,500 ft	6,500 m/21,000 ft	11,000 m/36,000 ft
Still-air range, no reserves	3000 km	9000 km	4400 km
Endurance, no reserves	32 hr at SL	87 hr at SL	31 hr at 11,000 m

Second-generation Aerosondes with the VSC powerplant

Our objective in developing the VSC engine is to power a new generation of Aerosonde-class aircraft, which can be much improved over our current model (*cf.* Table 3). With the VSC, offering nearly double the power of the current Enya, a second-generation Aerosonde will be able to carry more fuel, use its fuel more efficiently, and generate less drag by virtue of a tidier engine installation. The result will be a roughly *threefold* increment in range and endurance, to about 9,000 km and nearly four days: quite comfortable to do, for example, Tokyo-Vancouver, even in still air. Without supercharging, service ceiling will go up to 6.5 km (and higher as fuel is burned), which is quite sufficient for most meteorological applications. With supercharging, an aircraft designed for high altitude will be able to operate at 11 km, and still have transatlantic range.

It is grand, but not out of line, to suggest that this level of performance will be revolutionary - at least if it can be had for modest cost. Our estimate is that second-generation Aerosondes will have a unit cost around $20K if produced in volume of around 1,000 units per year. The engine (in normally-aspirated form) will account for a few thousand dollars of the total: expensive compared with most utility engines, but cheaper than the current labour-intensive Enya.

So will wide-scale service actually follow? Certainly the trials program to date, and particularly the transatlantic demonstration in 1998, have established the Aerosonde concept as practical. Long range, endurance, and autonomy have been proven. High-quality observations have consistently been made of pressure, temperature, humidity, and wind (Becker *et al.* 1999) and measurements of icing and precipitation have been demonstrated (McGeer 1998a, McGeer *et al.* 1999). Regulatory and air-traffic authorities have been quick to appreciate the potential of Aerosonde operations, and helpful in finding ways to accommodate them. Aerosonde experience is helping toward establishment of new regulatory standards for unmanned-aircraft operations (Vagners *et. al.* 1999, McGeer & Vagners 1999b). Severe-weather encounters, together with analysis of navigation in hurricane-force winds (McGeer 1996b, Tyrrell *et al.* 1999) have pointed the way toward cyclone reconnaissance. Weather services - particularly those of Australia, Canada, Taiwan, and the United States, which have been directly involved in field trials - are weighing Aerosondes as prospective components of their observing networks.

In short, whether or not wide-scale offshore service develops is now widely recognised to be neither a technical nor a regulatory question, but rather a matter of money: of finding about $4M to complete engineering development of a second-generation Aerosonde, and a few tens of millions of dollars per year to maintain a comprehensive program of offshore monitoring worldwide. The sums at issue are comparable with current expenditures on the global radiosonde-balloon network, and much less than expenditures on satellite observations. Many meteorologists feel that the value received in forecast benefit would be extraordinary. We have, then, a strong case. With continued effort, and unwavering vision, we can see it through to realisation.

References

1. Association for Unmanned Vehicle Systems International Web site: www.auvsi.org/auvsicc/
2. J. Becker *et al.* The basic Aerosonde observations suite. *Proc. Third Symposium on Integrated Observing Systems*: 57-59. American Meteorological Society, Dallas, January 1999.
3. J.G. Dawson, W.J. Hayward and P.W.Glamann. Some experiences with a differentially supercharged diesel engine. *Proc. Instn. Mech. Engrs.* 178 pt. 2A, 157-182, 1963-64.
4. G.J. Holland, T. McGeer and H.H. Youngren. Autonomous aerosondes for economical atmospheric soundings anywhere on the globe. *Bulletin of the American Meteorological Society* 73(12):1987-1999, December 1992.
5. Insitu Group Web site: www.insitugroup.com
6. T. McGeer. *Autonomous Aerosondes for meteorological measurements in remote areas.* Aurora Flight Sciences technical report, Alexandria, Virginia, June 1991. (29 pages)
7. T. McGeer. Aerosonde field experience and the prize on the eye. *ONR Symposium on Tropical Cyclones*, Melbourne, Australia. December 1996.
8. T. McGeer. *A miniature powerplant for very small, very long range autonomous aircraft.* Final report under DoE Phase I SBIR DE-FG03-96ER82187. The Insitu Group, Bingen, Washington USA, April 1997. (27 pages)
9. T. McGeer *et al.* Aerosonde operations in 1998. *Proc. Third Symposium on Integrated Observing Systems*: 60-63. American Meteorological Society, Dallas, January 1999.

10. T. McGeer and J. Vagners. Historic crossing: an unmanned aircraft's Atlantic flight. *GPS World* 10(2): 24-30, February 1999.
11. T. McGeer. *Field testing of aerosondes in offshore meteorological reconnaissance.* Final report under NOAA 50-DKNA-7-90154. The Insitu Group, Bingen, Washington USA, July 1999. (41 pages)
12. T. McGeer and J. Vagners. Wide-scale use of long-range miniature Aerosondes over the world's oceans. *Proc. AUVSI 26th annual symposium.* Association for Unmanned Vehicle Systems International, Baltimore, July 1999.
13. Sir Harry Ricardo. *The High Speed Internal Combustion Engine. 4th ed.* Blackie & Son, London. 1960.
14. I. Szunyogh *et al.* Ensemble-based targeted observations during NORPEX. *Proc. Third Symposium on Integrated Observing Systems:* 74-77. American Meteorological Society, Dallas, January 1999.
15. G. Tyrrell, L. Leslie, and G. Holland. Aerosonde deployment strategies to improve tropical cyclone forecasting. *Proc. Third Symposium on Integrated Observing Systems:* 67-69. American Meteorological Society, Dallas, January 1999.
16. J. Vagners, L. Newcome, and T. McGeer. Quantitive risk management as a regulatory approach for civil UAVs. Presented at the *Second Annual European Unmanned Vehicle Systems Association conference on UAV Certification*, June 1999.
17. S.Yagi, A. Ishizuya and I. Fujii. Research and development of high-speed, high-performance, small-displacement Honda engines. SAE Paper 700122, 1970.