THE TECHNOLOGY OF CAFE FLIGHT TESTING
or
Who Are Those Guys?

CAFE Challenge

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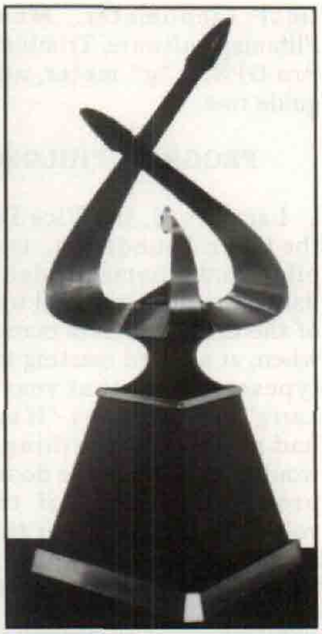


CAFE Triaviathon

Larry Ford

The members of the CAFE Foundation on the special CAFE scales: L-R, Jack Norris, Brien Seeley, Cris Hawkins, Russell Scott, Frank Braal, Otis Holt, Crandon Elmer, Larry Ford, Ed Vetter. Not pictured; C.J. Stephens, Steve Williams, Dwayne Green.

by Brien A. Seeley M.D., EAA 120126

INTRODUCTION

The EAA/CAFE Aircraft Performance Report program has called upon the members of the CAFE Foundation to develop some specialized new technical equipment. Just like in the "disaster movies" (Towering Inferno, Earthquake, etc.), it just so happens that each person in this cast of characters has abilities that prove vital to the task. Their concerted efforts to create a thorough, accurate, and convenient system for measuring multiple aspects of aircraft performance is a story of technical triumphs and determination and serves as a useful prelude to the publication of further Aircraft Performance Reports.

ACCOMPLISHMENTS

The following is a list of what this team has developed thus far:

CAFE Scales
CAFE Barograph and Pitot Probes
Wing Cuff Holsters
Digital Acquisition Device (DAD)
Sensor Amplifier Module (SAM)
Baro Input Module with Basic Output (BIMBO)
ZTG Sensors
Flight Data Software Packages
Test Flight Protocols
Prototype Torquemeter

In addition, CAFE flight testing has incorporated many commercial support items such as the Virtual Vision Sport Glasses, Flowscan transducers, a Hi-8 mini-camcorder with intercom link, cockpit display units, notebook computers, a TES 1350 sound level meter, a SmartLevel, the PropTach optical tachometer, Mentor Plus' Flitemap software, Trimble's Flitemate Pro GPS, a "g" meter, and roll rate guide tree.

PROGRAM PHILOSOPHY

Larry Ford, the Vice President of the CAFE Foundation, is a dentist, a pilot, and a homebuilder. He established the philosophical tone for most of the CAFE projects many years ago, when, at a Board meeting to review the typesetting on that year's race kit, Larry's comment was, "If my printshop had produced something like this, I wouldn't let it out the door!" His approach to the all of the CAFE's volunteer projects over the years has been to pursue high class results and "Do it right.". When the APR program was proposed, Larry spearheaded the negotiations to build a first class test facility at Sonoma County Airport. Now, when the CAFE flight test team is sleepless, tired and hungry, Larry sets up his salubrious "CAFE Cafe" and serves great coffee and Danish rolls! (We love his therapy). As chief photographer, Larry documents the CAFE projects for posterity, and many of his photos have appeared here in Sport Aviation..

CAFE SCALES

In 1981, CAFE members Bob Gutteridge, Dwayne Green, and Crandon Elmer designed and built a special purpose scale for the CAFE 400. Crandon and Dwayne worked together at NCI, a scale manufacturer, and Bob was an engineer with Hewlett-Packard. Bob performed the stress analysis, while Dwayne, an expert draftsman and former industrial arts instructor, made the drawings and oversaw the assembly of the scale. Crandon, whose training in both electronics and load cell technologies has proven vital to the program, designed the circuits and selected the proper load cells for the scale. Their reliable, portable, T-shaped steel scale became the foundation for the accuracy and success of the CAFE 400.

The same team created new, improved CAFE Scales when the Aircraft Performance Report program began. Center of gravity determination, a requirement for flight testing, demanded that the new scales separate main gear weight from nose/tailwheel weight. Thus, the new scales were built as 2 separate platforms; a 16' x 3' main gear platform capable of handling 5000 lbs. and a nose/tail gear platform 17.5' x 3' with a 1500 lbs.. capacity. Each scale deck itself weighs nearly 1000 lbs..

The new scales can quickly and accurately weigh aircraft of a wide variety of landing gear geometries. There are 4 load cells mounted on swivel joints near the 4 corners of each of the scale platforms. The platforms are very stiff in both torsion and bending, being welded ladder frames of 1/4" wall by 2" x 8" steel tubes. They are carefully set level with mortar into reinforced concrete pits in the custom foundation of the CAFE hangar.

FINISHING TOUCHES

To finish off the scales, the talents of 3 other CAFE Board member were needed. Cris Hawkins, a virtuoso machinist and mechanical designer, made the special supports for attaching the load cells to the scale. Otis Holt, a superb craftsman in wood, made a perfectly fitting wooden deck cover for the scales, such that they are perfectly flush with the floor. Otis' motto on his shop wall is, "Don't cut it until you have to". Finally, the wooden deck was finished with numerous coats of polyurethane varnish by CAFE's chief test pilot, C.J. Stephens.

When not in use, the scales become part of the hangar floor by being supported on hidden, retractable jackscrews which unload their load cells.

Crandon, highly skilled in the esoteric art of "tweaking" load cells, has tuned the new scales to resolve less than a tenth of a pound with a long term repeatability of better that 1 lb. A favorite trick of CAFE Board members is to stand on the scale with the aircraft being weighed, reach in one's pocket and discard 4 quarters while watching the digital display show the change in weight. These scales are so sensitive that the hangar door must be fully closed to take such accurate readings.

Accurately knowing an aircraft's weight before each flight makes it possible to determine its fuel consumption and drag, as will be described below.

THE CAFE BAROGRAPH

In 1985, Steve Williams, a very talented electronic engineer with Hewlett-Packard, volunteered to create a recording barograph for use by the Voyager on its World Flight. By continuously recording temperature, dynamic pressure, "q", and static pressure, and thus keeping track of airspeed and altitude, respectively, it was to provide "proof" that the aircraft flew around the world without landing. Steve's first barograph did not make the World Flight because, at the eleventh hour before Voyager's departure, a request for a redesign of its software was impossible to fulfill. However, Steve's specialized creation was destined to be discovered, and word of its capabilities reached the CAFE Board.

THE TRIAVIATHON

The CAFE Foundation was looking for an accurate and safe method of measuring flat-out speed, climb rate and stall speed on some of the high performance homebuilts attending the CAFE 400. Steve's barograph was the perfect instrument for measuring these 3 parameters, and he agreed to help use it as the basis for a new CAFE competition, the Triaviathon.

For the Triaviathon, Steve redesigned the barograph to fit into a wingtip mounted box about the size of a VHS cassette.

When the need arose for an expert in electronic circuit boards who was willing to spend hundreds of hours

Larry Ford

The Barograph Team: Steve Williams and Frank Braal building 3 new barographs, up stepped Frank Braal, one of the founders of the CAFE Foundation. He understood electronic circuits from years of working in the telephone industry, and had also designed the Braal Digital Tachometer. Frank's dedication and experience saved the day. He laid out the "bread-board" circuits and assembled all the new barographs in time for use in the first annual CAFE Triaviathon in 1986. Steve and Frank became a team.

As newer and better pressure sensing transducers became available, Steve and Frank created a third generation barograph that could be housed inside a 2" diameter aluminum tube and could be mounted on the underside of the wingtip like a rocket. For this third generation unit, Frank laidout new printed circuit boards on his computer using Steve's sketches. The pc boards were commercially made. Frank then completely assembled 3 new barographs from the component parts. These units were of lower drag and much higher accuracy than their predecessors. They were used through the 1990 Triaviathon event, and were tested to 300 mph without any demonstrable difficulty.

SUPER ACCURACY

In 1992, the proposal for EAA/CAFE Aircraft Performance Reports demanded yet another redesign of the barograph to remedy one of its shortcomings--that its transducers were temperature sensitive. In flight, the cooling due to air blast and increasing altitude would shift the output of the transducers slightly. Steve, striving for world-class accuracy, considered this shift unacceptable for aircraft performance testing.

Steve and Frank designed a microprocessor-controlled, battery-powered, insulated heater for the transducers to maintain them at a constant 100° F. The heater can be powered by 6 "D" cell flashlight batteries or by the aircraft's power bus. The redesign entailed all new printed circuit boards incorporating such changes as greater RAM capacity, a newer and more powerful microprocessor and more new software. Again Frank and Steve came through. In testing with John Durr at the NASA Ames Research Center's Calibration lab, the addition of the heater produced a major improvement in the barograph's accuracy and repeatability. The barograph was so accurate, it rivaled the lab standard to which it was being compared!

Unfortunately, these new barographs had to be housed in 3" instead of 2" tubes to allow room for the heater's insulation and batteries. Wind tunnel tests[1] showed that the drag increment produced by this increase in wetted and frontal area was more than offset by the reduced drag of an improved design for the wing cuff/holster which attaches the barograph to the wingtip. The elaborate data from the tunnel tests characterized the drag of the barograph- wing cuff at different airspeeds and angles of attack and is now used to correct the measured airspeed of each aircraft flying with the barograph attached to its wingtip The worst case drag increment in the wind tunnel was 5 lbs.. per cuff at 233 mph IAS.

The sample printout of flight data from the barograph and engine monitors reveals the amazing resolution of this device and its utility in flight testing. The new barographs can resolve a change of altitude of only 6 inches and typically show plus or minus 1 foot stability in once per second readings in level flight. They are typically repeatable to plus or minus 2 feet of altitude on successive flights, which is far better than the usual stability of the atmosphere.

Airspeed resolution is 0.05 mph and typical error is plus or minus 0.2 mph at 50 mph and 0.06 mph at 200 mph IAS. Successive readings typically vary by 0.1 mph at a steady power setting in level flight at 200 mph IAS. These values are far less than the nearly 1% error that can occur due to pitot tube location. Needless to say, we are all very proud of Steve and Frank's achievement with these barographs.

BOOMS AND MISSILES

The fiberglass wing cuffs used to attach the barograph to the underside of the wing have proven to be wonderfully stable at all speeds tested. This is owed mostly to the 1/4" holes drilled in the upper surface of the cuffs at the 10% chord station, which, when the cuff's perimeter is thoroughly taped to the wing, deliver upper surface suction to "vacuum bag" it to the wing.

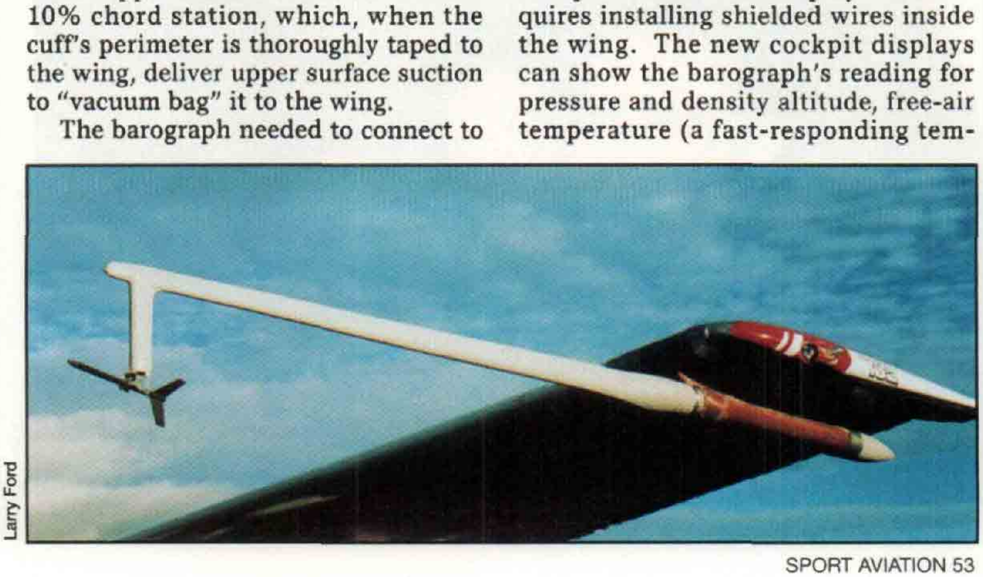
The barograph needed to connect to a calibrated pitot and static pressure sensor to deliver accurate readings in flight. Previous research[3] had shown that minimal error (1%) could be expected if a swivel-mounted pitot/static probe were placed on the end of a mast or boom on which the pitot tip was at least 1 chord length forward of the wing leading edge, and well away from the propeller disc and fuselage.

Al Strickfaden of the FAA generously provided the CAFE Foundation with approved engineering drawings[2] of such a pitot-static "missile". Cris Hawkins did a beautiful job of fabricating 3 such missiles to those specifications in 1986 and he and Frank built a gimbaled mount that provided the self-alignment into the relative wind. These missiles were tested in the NASA Ames Research Center wind tunnel and were shown to be extremely accurate.

The mast or boom onto which the pitot mounts proved to be another design challenge. At first, a round 1.25" aluminum tube was used. This was felt to be too draggy and was not stiff enough when using a long boom for long chord wings. It was replaced with a hollow graphite boom made on a long, thin male mold that was shaped like a wing of extremely high aspect ratio and symmetrical section. The graphite boom wing mounts with the leading edge down at zero degrees incidence. It had worked well at speeds up 245 mph in flight, but showed some yaw flutter in the NASA wind tunnel. After reviewing a video of the flutter, a redesign to stiffen the boom is expected to have now solved this problem.

TEST PILOT FRIENDLY

The final chapter in the saga of the CAFE Barograph is the breakthrough of being able to deliver the formatted and calibrated barograph data to the cockpit for real time display. This requires installing shielded wires inside the wing. The new cockpit displays can show the barograph's reading for pressure and density altitude, free-air temperature (a fast-responding tem-


Larry Ford

Flight Data 3-6-94

Barograph #2	Clock	Marker	Press/Alt	Dens/Alt	IAS	TAS	Climb/Sink	M.P.	RPM	Rev/mile	GPS	A/C Wt.
	17:05:01	—	210.5	944.6	118.55	120.13	1036	28.9	2497	1247	15.9	1390.7
	17:05:02	—	231.3	970.1	120.13	121.78	1271	28.8	2502	1233	15.8	1390.7
	17:05:03	—	248.7	988.2	121.62	123.32	1071	28.8	2496	1214	15.8	1390.6
	17:05:04	—	268.4	1011.2	122.96	124.73	1206	28.8	2501	1203	15.8	1390.6
	17:05:05	—	288.1	1034.3	122.55	124.35	1207	28.8	2501	1207	15.7	1390.6

perature sensor is on the end of the boom), IAS, TAS, and rate of climb or sink. The angle of attack, yaw angle and relative humidity will also be recordable and available for cockpit display in the near future. By combining the TAS and propeller RPM readings, a revolutions per mile display has been created, and serves as a great aid to the test pilot in zero thrust glide testing. The temperature lapse rate can also be displayed in real time, and this has been shown to be an important predictor of the quality of the atmosphere for flight testing on a given day.[4]

ENGINE MONITORING

The need to record and display engine data alongside all of the nifty flight data from the barograph has been elegantly fulfilled by CAFE member Ed Vetter, an electronic engineer with MCI. Ed's ability to design circuits, build them, and write custom software to make the circuits perfom multiple tasks has become a valued part of the APR program. He is tireless, prolific, imaginative and loves airplanes.

Ed created the "DAD", or Digital Acquisition Device. This miniature multichannel micro-chip device has the amazing ability to simultaneously record RPM, manifold pressure, CHT, oil temperature, fuselage incline angle, noise level, induction air temperature, crankshaft position (for detecting zero thrust), fuel flow, fuel used, instantaneous aircraft weight along with a pilot's "push-to-mark data" switch. It records and can display these items once per second and has many other channels available for things such as cooling system ram recovery, EGT, torque from a torquemeter, exhaust system back pressure, etc. It can be easily mounted with nylon strap ties in the engine compartment and communicates with the cockpit through the firewall using a bulkhead BNC connector and coaxial cable. Modular in design, several DAD's can be linked to increase the number of recording channels. The various sensors connect to the DAD via the SAM, or Sensor Amplifier Module. In the cockpit, the barograph's output leads first connect to the BIMBO, or Barograph Input Module for Basic Output, and thence to the DAD.

The resolution of the DAD is basically 1 part in 4096. The sensors used to send information to the DAD are of a variety of different types, and their accuracy has been enhanced by Ed's custom calibration of each one. Flowscan's in-line "turbine-wheel" flow sensor is used for gph with repeatability of .25%. A TES 1350 high quality noise level meter is used and is accurate to 1 dBA (slow). Alcor's high quality CHT probes are accurate to 3° F and oil temperature has 1% accuracy. RPM accuracy is .25 RPM. Manifold pressure sensing is accurate to .5%. Ed has designed and built his own digital recording inclinometer which can resolve .1°. He also wrote software to use a known CAFE Scale reading before each takeoff along with continuous fuel flow to continuously update and display aircraft total weight in flight.

Like the barograph, Ed's DAD has undergone several redesigns to make it smaller, more versatile and more convenient to use. It now uses the hard disk of a 486 laptop computer as its memory and can thus record 32 channels of once per second data for about 10 continuous hours of continuous flight. As the photographs reveal, it is now a very tidy little package.

Ed and his son Daniel regularly fly Ed's Mooney from his home base in San Jose to the CAFE test center in Santa Rosa to participate in flight testing.


Larry Ford

Otis Holt, C.J. Stephens, and Ed Vetter. Note camcorder in rear.

ZERO THRUST SENSING

A new aspect of the CAFE flight test is the crankshaft position sensor used in zero thrust glide testing. This idea originated with Jack Norris and consists of a stiff music wire mounted to the crankcase just aft of the crankshaft flange. The wire detects the movement of the crankshaft aftward during windmilling flight by being positioned so as to detect the mid-point of the crankshaft's end play. When the condition of zero thrust is achieved, two LED's illuminate, one for the test pilot and another taped to the edge of a camcorder lens which is aimed at the instrument panel.

Thanks to the careful observations of Otis Holt, the exact positioning of the music wire was found to be critical to detecting the "true" point of zero thrust. Otis investigated this by flying dozens of trial runs with the wire positioned at various stations. Using the CAFE Flying Club's Cessna 152 "mule", he proved that the heat expansion of the crankcase and the resistance of the oil film on the thrust bearings make the mid-travel of the crankshaft's end play act like a moving target in flight. The CAFE braintrust

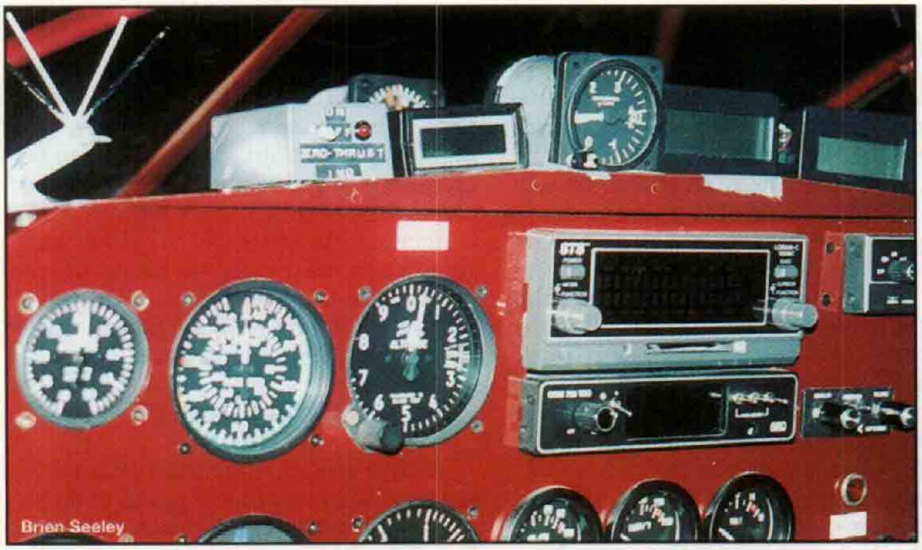
Flight Data 3-6-94 (Cont.)

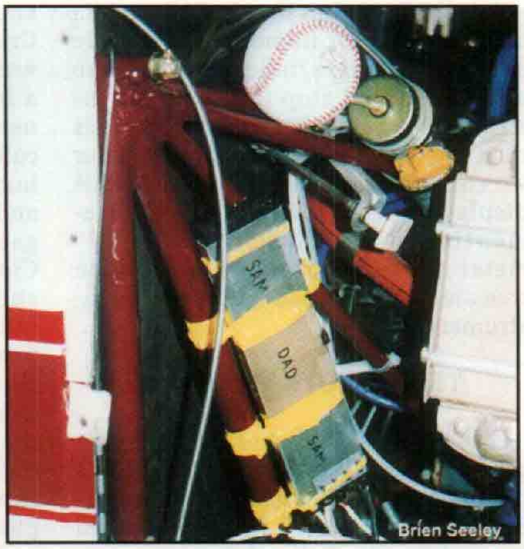
3-6-94 (Cont.)	Clock	CHT	Oil T.	Carb Air	OAT	Incline	Crank P.S.	dBa	Cuff Drag	Lapse
	17:05:01	282	119	77.4	69.1	9.5	—	109.5	3.8	0.41
	17:05:02	286	121	77.1	69.1	9.3	—	109.3	3.8	0.42
	17:05:03	289	122	76.9	69.1	9.1	—	109.1	3.8	0.42
	17:05:04	290	125	76.9	68.9	9.1	—	109.2	3.8	0.43
	17:05:05	295	127	76.8	68.9	8.9	—	109.1	3.8	0.43

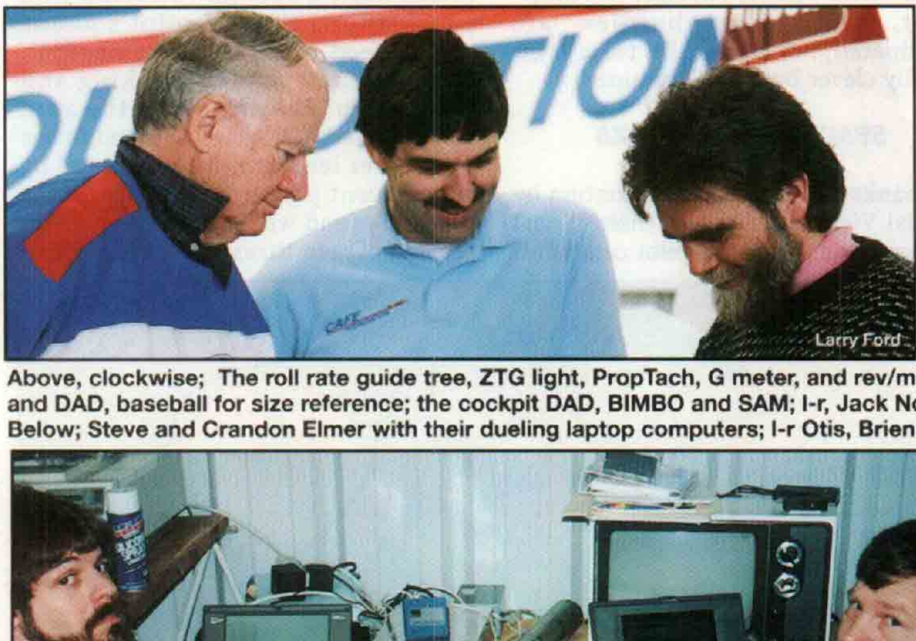
attacked this problem and decided that an analog sensor of crankshaft position was needed. Ed Vetter designed and built such a device in which a pair of optical sensors detect and graphically display the position of the crank anywhere from full forward tractor mode to full aft windmilling mode. This display allows the pilot to find the "sweet spot" half way between the two extremes. Ed's graphic display is an ideal solution to this situation.

WHY ZERO THRUST?

Jack Norris has determined that if an aircraft whose propeller is made "invisible" by turning at zero thrust, can be glided at different airspeeds at a known







Above, clockwise; The roll rate guide tree, ZTG light, PropTach, G meter, and rev/mile displays atop the panel; the engine bay SAM's and DAD, baseball for size reference; the cockpit DAD, BIMBO and SAM; l-r, Jack Norris, Cris Hawkins, and Otis Holt compare notes. Below; Steve and Crandon Elmer with their dueling laptop computers; l-r Otis, Brien Seeley, and Larry Ford build a new test cowling.

total aircraft weight, its drag can be computed merely by knowing its sink rate and airspeed. A graphical plot of drag versus IAS is called the drag polar of the aircraft, and from it can be calculated nearly all of the aerodynamic parameters for that aircraft. This is why the DAD delivers continuous aircraft weight and the barograph delivers airspeeds and sink rates, all monitored while the pilot glides with the crankshaft sensor showing zero thrust. Jack will soon present a complete discussion of zero thrust glide testing in an upcoming issue of Sport Aviation.

Jack's work has shown him that each aircraft-propeller combination has a characteristic ratio of revolutions per mile while at zero thrust. To further help the test pilots find the zero thrust point, Ed Vetter has now built 2 custom LCD displays for numerical revs/mile and graphical revs/mile, and these are easily mounted atop the aircraft's instrument panel. Also mounted there is the PropTach optical digital tachometer which sends its signal to the DAD while displaying it for the pilot. The aforementioned zero thrust light, a "G" meter and a miniature roll rate guide tree are also mounted on top of the instrument panel.

TEST PILOTS WHO CAN

From the beginning of the APR program, the CAFE team has enjoyed the patient and flexible natures of two excellent test pilots, C.J. Stephens and Russell Scott. Both of them possess ideal combinations of coolheadedness, experience, instinct, and intelligence. C.J. flew F4's in Vietnam and races unlimiteds at Reno. Russell has 1000 hours in the SR-71, among his many other credits. They both have very impressive curriculum vitae's, too lengthy to list here.

It is a delight to review the videos of their flights and see how smoothly and accurately they operate all the controls in aircraft that are, initially, foreign to them. Their careful and conservative manners have quickly dispelled the qualms of the aircraft owners presenting their aircraft for testing.

C.J. and Russell teamed up to write a practical, safe and meaningful protocol for flight testing of homebuilts. After they consulted numerous references[5,6,7], they included all of the relevant characteristics that prospective kit buyers might need to know.

TORQUEMETER

Measurement of engine horsepower is another ticklish requirement for good flight testing. Power charts are notoriously inaccurate and often optimistic. Extrapolation from an accurate gph meter using bsfc values can estimate horsepower. However, the CAFE team wanted a way to directly measure horsepower, especially when dealing with "hot-rodded" engines.

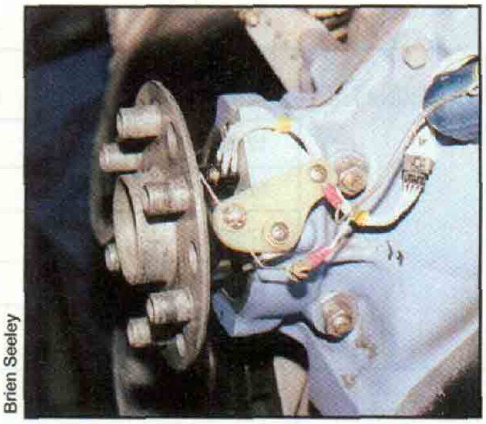
The idea of using strain gauges mounted on a prop extension to detect torque is not a new one. However all of the existing aircraft torquemeters are now stamped "for ground running only" due to the product liability environment. The only torquemeters that are deemed airworthy, are known to be fraught with problems of accuracy and calibration.

When the CAFE teamed learned of this, they took their typical approach-- "Let's build our own!!" For this Herculean task, all of the CAFE resources were tapped. Dwayne and Cris' AutoCad drawing of a prototype was passed on to Jack Norris, who, as a formally trained mechanical engineer, performed a stress analysis and called out the wall thicknesses for the hub. Cris machined the prototype hub and Crandon made sure that the strain gauges were correctly bonded to it. Crandon built a prototype sensing circuit and its initial testing shows the hub capable of resolving only 2 inch-pounds of torque and just 1 lb. of thrust!! Steve, Ed and Frank joined Crandon to brainstorm ways to power the hub circuits and get the data out of the hub and into the cockpit. A breakthrough idea surfaced and looks very promising.

The hub awaits further development, and many hurdles are anticipated, but this CAFE team is an awfully clever bunch. Stay tuned.

SPACE AGE GOGGLES

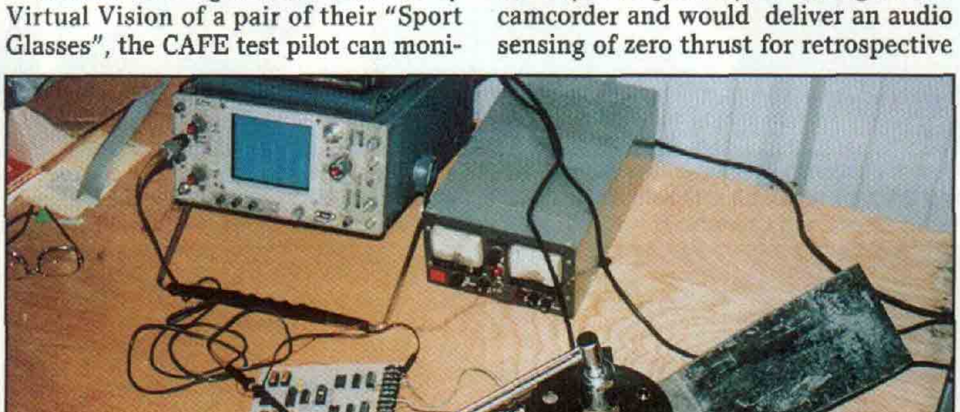
Thanks to the generous donation by Virtual Vision of a pair of their "Sport Glasses", the CAFE test pilot can monitor a full TV display of any of the channels of barograph or DAD flight data selected for display. These amazing goggles have a tiny but readable TV display placed in the part of the glasses normally devoted to a bifocal segment. The pilot, by merely looking slightly downward, can monitor this TV with his dominant eye. This can allow the pilot to be a "one man band" when flying a single seat aircraft. It can also be programmed for showing moving map displays from GPS or even 49er games!. It accepts standard NTSC video and should become a welcome means of enjoying moving map technology in different aircraft without major alterations to the instrument panel.



Brien Seeley

OTHER GOODIES

A Hi-8 Nikon camcorder is used to monitor the instrument panel and the accessory displays mentioned above. Frank built a special intercom link which allows the test pilot's phone jack to feed audio to the camcorder. He suggested that the making and breaking of the circuit to the zero thrust glide LED, which is taped to the camcorder lens, could be detected by the adjacent phone jack wiring on the camcorder and would deliver an audio sensing of zero thrust for retrospective



Larry Ford

The CAFE Torquemeter hub under test with prototype circuit and display.

analysis. Indeed it is, and this is useful. The camcorder makes a very valuable backup data log and allows recording of all of the test pilot's and co-pilot's comments.

NO MORE SA!

The potential uses of GPS and moving map technology for flight testing are many. Trimble Navigation and Mentor Plus Software are ready and willing to assist the CAFE Foundation in using their donated equipment and software to track the test aircraft's takeoff and landing distances, geometric climb, etc. The use of differential GPS has been considered, but what is really needed is for our Pentagon to turn off the selective availability of the satellite information. The march of technology will someday make this possible, and the benefits will be great.

CONCLUSION

It should be apparent that the CAFE Foundation has made major strides in refining and automating the science of flight testing. This has all been made possible by funding from EAA, by Tom Poberezny's leadership, and by an enormous amount of work by this talented CAFE team.

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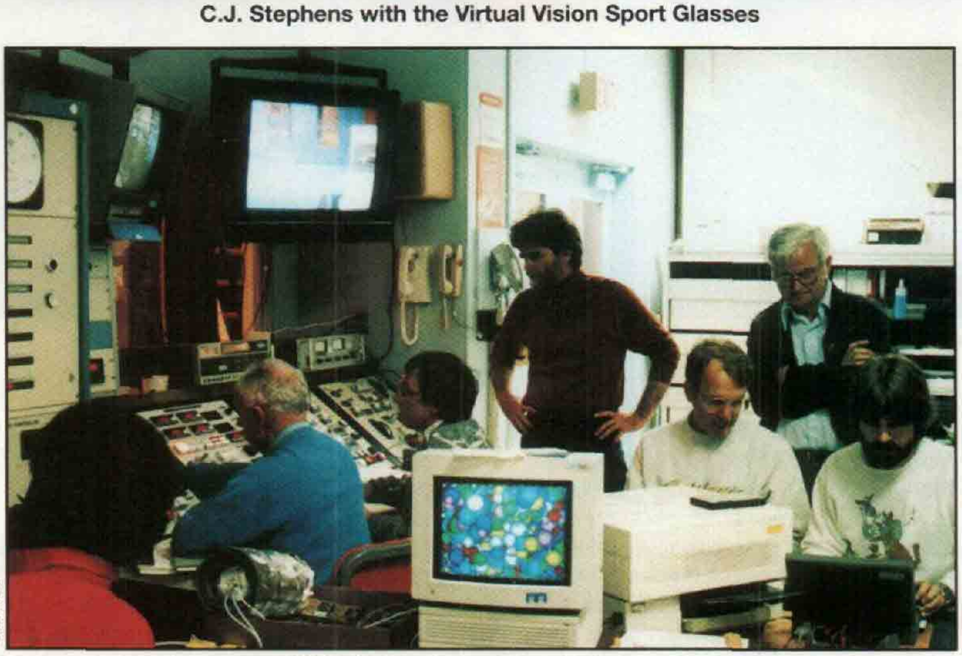
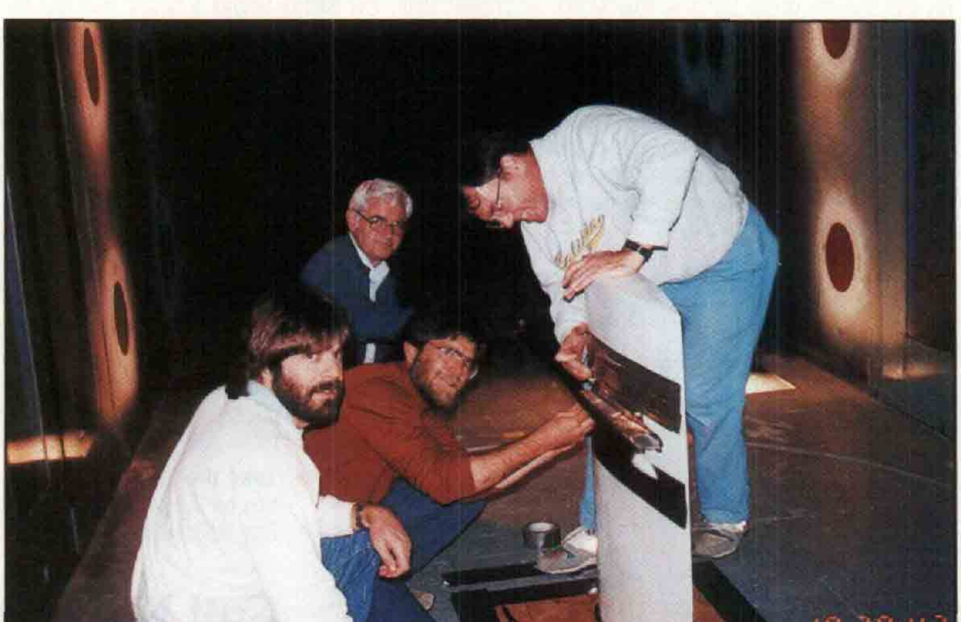
Larry Ford

C.J. Stephens with the Virtual Vision Sport Glasses


Otis Holt

NASA's wind tunnel control room.



Leo Hall

l-r; Steve, Frank, Otis and Brien inside the NASA wind tunnel.