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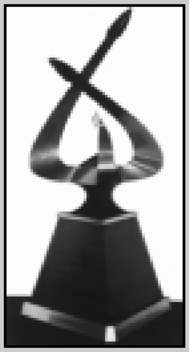
Ignition Dynamics II

BY BRIEN SEELEY AND THE CAFE BOARD



TRIAVIATHON TROPHY

CHALLENGE TROPHY

The high energy dual electronic ignition system from Electroair.

BRIEN SEELEY

This part II report on aircraft engine ignition dynamics, presents comprehensive results of flight tests comparing conventional aircraft magneto ignition to an electronic ignition system that is in popular use in homebuilt aircraft. The reader is encouraged to review Ignition Dynamics I to help interpret these discusssions. More detailed results can be found at:

www.cafefoundation.org

THE EIS-1 ELECTROAIR® IGNITION SYSTEM

The EIS-1 ignition system uses high energy, battery-powered ignition coils. It delivers a single, relatively long duration spark whose timing is programmed to vary with RPM and manifold pressure. It is not a capacitive or multiple spark discharge system. The spark plug gap determines the arc voltage and duration. A smaller gap requires lower voltage and produces a longer duration spark, while a larger gap results in a higher voltage, shorter duration spark.

For aircraft engines with two spark plugs per cylinder, the EIS-1 can be installed in two different configurations: 1) as a single electronic unit ("SE") firing the bottom spark plug in each cylinder (with a standard aircraft magneto firing the top plugs), or,

2) as dual electronic units (“DE”) that replace both aircraft magnetos. In the DE configuration, one unit fires the top spark plugs and the other fires the bottom plugs. This report compares both the SE and DE systems with that of standard dual magnetos (“DM”). The DE system, being entirely dependent on the aircraft battery, requires that a backup battery be installed.

Each EIS-1 system consists of 2 components; a timing unit and the direct ignition unit (DIU). The timing unit mounts like a magneto on the engine accessory case. It consists of an axial shaft onto which is mounted a standard Lycoming magneto drive gear. The shaft has a 60-tooth, iron gear that rotates inside the timing unit’s case past a magnetic pulse generator. This pulse generator is mounted on the perimeter of the case and delivers its triggering signal to the direct ignition unit (DIU). To set the timing to zero degrees (TDC) for starting, the timing unit is inserted into the magneto mounting pad with its shaft rotation locked with a pin after positioning the crankshaft to TDC for cylinder #1.

The EIS-1 modulates timing advance using sensors for both RPM and relative manifold pressure. For research purposes, a switch can be installed to turn on and off the manifold pressure sensor's timing advance function. As manifold pressure drops below 24" Hg., the unit begins to advance the timing by 2° for each inch Hg. of manifold pressure reduction, reaching a maximum of 42° advance at about 16.5" Hg.

The DIU sets and maintains timing at 16° BTDC as soon as the engine reaches 650 RPM after starting. As RPM increases above 1000 RPM, the unit advances the timing in a linear fashion with RPM to reach 25° BTDC timing at 2500 RPM. The typical ignition timing observed at idle is about 16-17° BTDC with the manifold pressure sensor advance turned off and about 35° BTDC with the manifold pressure sensor advance turned on. At takeoff power of 2700 RPM and 29" Hg. manifold pressure, the timing is 25° BTDC, the same as with dual magnetos. The timing settings can be customized by Electroair for different engine applications and can be ground adjusted by the aircraft owner.

A small LCD digital ignition timing indicator is mounted to the aircraft instrument panel to monitor the ignition timing.

Each DIU fires one spark plug for each cylinder and has two high voltage General Motors 'Dual Tower' coils. Each coil 'tower' attaches to its respective cylinder's spark plug wire. The Dual Tower coil actually fires two spark plugs each time it discharges, one in the cylinder that is completing its compression stroke and one in the opposite cylinder that is completing its exhaust stroke. One spark plug fires from barrel to tip electrode and the other, wired in series, fires from tip to barrel. This 'wasted spark' configuration obviates the need for a distributor and its moving parts and only slightly reduces the ignition energy delivered to the plug in the firing cylinder. According to Jeff Rose, *"We use high energy GM coils that generate 65,000 volts. The EIS-1 spark discharge is sustained over about 18° of crankshaft rotation when using a 0.030" spark plug electrode gap."*

Electroair specifications state that the average electrical current consumption of each electronic ignition unit is 0.75 amps with an instantaneous coil current that is programmed to reach 8.5 amps at the exact point at which a plug must be fired, regardless of RPM.

Each DIU with spark plug harness weighs 4.4 pounds and each timing unit weighs 1.5 pounds. This 5.9 pound total does not include the additional 7 pounds added by a spare 4 a.h. sealed lead-acid motorcycle battery, battery diode isolation device, ignition operation switch panel and attendant wiring. Each Bendix 1200 Series magneto with plug harness weighs about 6.8 pounds. A single EIS-1, if used in place of one Bendix 1200 magneto would result in no significant change in aircraft weight.

The EIS-1 uses special heavy duty automotive 'resistance type' spark plug wires in order to reduce electrical noise, produce less spark plug electrode erosion and to conduct the high voltages involved without arc leakage. Electroair's product brochure claims that the EIS-1 reduces spark plug fouling, can deliver as much as 120 mJ of spark energy and has a timing resolution of 0.5°. Jeff Rose states that there are about 1400 EIS-1 units in operation and that 150 of these are installed in the dual (DE) configuration.

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IMPORTANT NOTICE

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THE TESTBED ENGINE

The experimental IO-360A1B6X engine used in these tests has an 8.7 to one compression ratio. It is a highly modified, experimental version of the 4 cylinder, 200 hp counterweighted Lycoming engine. It has ported, polished and flow-balanced intake and

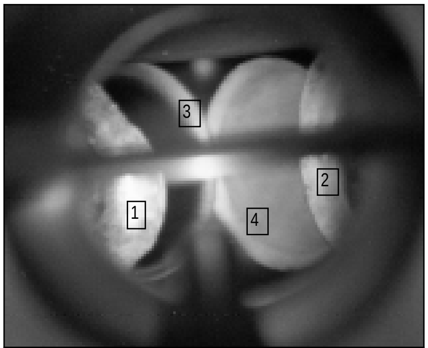


Photo A. This view looks straight into the induction plenum through the throat of the Ellison Throttle Body on the test engine, showing how the 4 induction pipes are positioned to compete for fuel mixture.

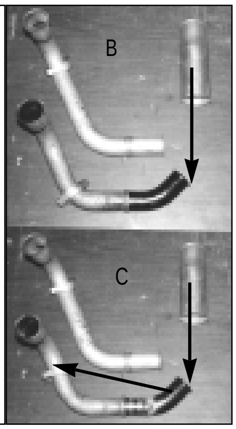


Photo B. The stock geometry of induction inlet tubes #2 and #4. Photo C. The inlet mouth of the modified #4 intake tube was moved inboard 0.25" to be more in line with the incoming fuel fog from the Ellison Throttle Body. Despite the modification, cylinder #4 remained the leanest.

exhaust ports, a 4-into-1 tuned exhaust system, as well as a low resistance air-cleaner with good ram recovery. Filtered induction air enters a custom velocity stack mounted on the inlet of the forward-facing Ellison Throttle Body.

The test engine's modified induction system has small extensions welded onto each of the four individual induction tubes to better equalize their access to the fuel fog emitted by the Ellison Throttle Body. Photos **A, B, C**. The EGT spread among the four cylinders was reduced to as little as 15-20° F by this technique, when measured at wide open throttle.

The unpressurized Bendix 1200 Series magnetos used in this study are a 'high altitude' model that uses a larger distributor and coil than the smaller Bendix S4LN magnetos. The larger coil affords a higher spark voltage that is better suited for high altitudes and lean mixtures. The larger distributor provides better resistance to internal arc/carbon tracking at these high voltages.

The test engine's tuned exhaust system provides substantial negative

FLIGHT TEST METHOD

The rate of climb and cruise fuel economy in smooth air were tested using the same density altitudes, humidity, center of gravity, power settings, cowl flap settings, and aircraft configuration. Aircraft weight was kept as similar as practicable on each flight.

The CAFE wing-mounted Barograph #3 was used for all airspeed and altitude data collection and the Vetter/CAFE Digital Acquisition Device ("DAD") was used to collect engine performance data. Calibrated KS Avionics EGT probes and Alcor CHT probes were used on all cylinders. All CHT's were corrected to a 100° F day. A PropTach digital tachometer was used to monitor RPM. Cowl flaps were left fully open at all times. Each flight was conducted with a clean but not waxed aircraft. All data were recorded once per second. A camcorder continuously recorded a view of the instrument panel and crew comments. Video recordings were synchronized to the data clock. Twenty two parameters were recorded. These included: Clock time, pressure altitude, density altitude, IAS, TAS, rate of climb, OAT, fuselage incline angle, RPM, manifold pressure, instantaneous aircraft weight, four cylinder EGTs and CHTs, oil temperature, fuel flow in gallons per hour and cowl exit temperature.

A stroboscopic ignition timing light was used to verify that the LCD timing panel indicator was accurate to within 1° at both 16° BTDC and 35° BTDC.

CAFE measurement of the EIS-1 current consumption showed the following:

0.040 amps @ 13.0V, zero RPM
0.230 amps @ 12.7V, 1020 RPM
0.260 amps @ 11.8V, 1040 RPM
0.340 amps @ 10.5V, 1055 RPM
0.560 amps @ 13.0V, 2700 RPM

ATIS information was recorded onto videotape before each flight. Dew point spreads were 18°, 17° and 15° on the flights with the DE, SE and DM ignition systems, respectively.

All ignition systems used REM37BY 'extended reach' spark plugs in these tests, with the plug gap set at 0.031" for electronic ignition and 0.018" for magneto ignition.

Each flight began with a full power, full rich mixture, and wide open throttle (w.o.t.) takeoff followed by a climb at 125 IAS mph (panel) at 2600 RPM to 8500' density altitude. This equated to 117 mph CAS. As the aircraft reached 5,000' density altitude in climb, mixture was leaned from full rich to 15.0 gph (panel). Next, level at 8500', the RPM was set to 2550 and the cruise speeds were noted at intervals of 0.5 gph fuel flow reductions from very rich to very lean settings. A climb to 12,500' density was then made, again at 117 mph CAS, w.o.t. and 2600 RPM, leaning as appropriate to remain at least 150° rich of peak EGT. Level at 12,500' density altitude, the RPM was again set to 2550 and the cruise speeds were noted at intervals of 0.5 gph fuel flow reductions from very rich to very lean settings. Finally, another climb at 117 mph CAS, w.o.t. and 2600 RPM was made to 15,000' density where the cruise settings were repeated.

Uniform inclusion criteria from stabilized level flight data were used in selecting the comparative results. The criteria were: non-turbulent air, stable OAT, stable altitude and airspeed, on-target RPM and fuel flow, stable fuselage incline angle and no ballistic effects.

Detailed tests of the SE system were conducted at 12,500' density altitude using the standard settings of w.o.t. and 2550 RPM, cowl flaps open. These included operation at 2 different ignition advance settings, 2 different spark plug gaps, and turning off each ignition unit to collect data while firing either top spark plugs only (Bendix 1200 magneto) or bottom spark plugs only (EIS-1 electronic ignition). Toggling the EIS-1 ignition from standard to advanced ignition timing allowed observation of timing effects on speed, EGT and engine smoothness. The effects of rotating the spark plug electrode gap of the leanest cylinder's (#4) bottom spark plug were evaluated on three short, consecutive flights on 2/09/02 using the SE ignition with the magneto both on and off.

The data for this report were obtained on different days and are subject to variations in lapse rate, rising or sinking airmass effects, etc.. Careful data point selection was used to minimize the influence of these variables. Performance differences that exceed 1.0 mph in TAS and 50 fpm in rate of climb are considered significant and real in this study.

Figure 11a. DE System

Mooney N6057Q	Density altitude	TAS, mph	M.P.	RPM	GPH	CHT1	CHT2	CHT3	CHT4	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg. advance
DE = dual electronic																
dew point spread = 18° F	DE															
Cruise data	8552	196.6	22.8	2551	12.5	383	373	369	380	1399	1394	1446	1471	169	2506	30
Dual Electroair EIS-1	8558	198.1	22.9	2555	11.5	381	378	373	382	1483	1480	1509	1522	171	2504	30
7-13-2001	8549	197.3	22.9	2550	10.5	390	385	373	387	1552	1552	1583	1598	173	2503	30
All gph are panel (video)	8503	193.5	22.8	2550	10.0	398	396	372	383	1591	1591	1574	1567	173	2501	30
Raw TAS used	8497	191.1	22.8	2550	9.5	396	398	367	380	1565	1606	1533	1529	172	2500	30
with no cuff drag	8498	190.1	22.8	2551	9.0	398	395	357	374	1526	1557	1493	1490	173	2500	30
correction	8487	183.5	22.7	2550	8.5	379	377	336	351	1474	1495	1457	1445	169	2498	30
	8477	178.8	22.7	2553	8.0	365	370	323	338	1432	1462	1437	1410	169	2497	30
	8471	168.5	22.5	2553	7.5	331	344	300	310	1396	1446	1462	1437	165	2496	
	DE															
	Densalt.	new	M.P.	RPM	GPH	CHT#	CHT#	CHT#	CHT#	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg.
	12507	187.2	19.2	2549	11.0	379	357	382	398	1316	1261	1340	1362	177	2484	36
	12544	187.9	19.2	2544	10.5	391	378	376	389	1367	1322	1370	1408	172	2482	36
	12525	188.1	19.1	2552	10.0	401	386	382	400	1400	1367	1422	1450	172	2481	36
CF wide open	12549	189.1	19.2	2555	9.5	409	405	390	403	1458	1430	1459	1484	173	2479	36
All CHT corr. for	12569	188.4	19.2	2549	9.0	413	413	391	404	1488	1462	1491	1524	173	2479	36
100° F day	12564	188.3	19.1	2548	8.5	415	418	392	407	1526	1516	1521	1513	174	2478	36
	12555	187.6	19.2	2549	8.0	410	416	393	390	1490	1543	1476	1446	177	2477	36
	12565	183.6	19.1	2550	7.5	392	404	365	367	1436	1487	1398	1383	174	2475	36
	12563	180.1	19.1	2554	7.0	373	388	342	347	1373	1402	1362	1350	170	2474	36
	12569	173.4	18.9	2551	6.5	359	369	324	330	1337	1367	1345	1327	164	2474	36
	DE															
	Densalt.	new	M.P.	RPM	GPH	CHT#	CHT#	CHT#	CHT#	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg.
Data are W.O.T.	15008	180.0	17.1	2550	9.5	403	374	389	412	1349	1277	1342	1375	173	2463	41
Target = 2550 RPM	15007	184.2	17.1	2549	9.0	408	378	394	410	1382	1327	1372	1429	173	2462	41
TAS from careful	15004	185.8	17.3	2550	8.5	408	379	397	412	1433	1361	1425	1462	173	2462	41
review of OAT, I.A.	14994	184.2	17.1	2546	8.0	415	387	398	411	1473	1407	1460	1486	174	2461	41
stability, video, ballistics	15000	182.2	17.2	2553	7.5	415	400	401	404	1496	1462	1472	1457	178	2460	41
	14989	179.1	17.1	2546	7.0	414	410	389	386	1444	1507	1429	1380	176	2458	41
	15017	174.6	17.1	2557	6.5	390	403	374	373	1367	1462	1346	1334	174	2457	41
	14929	168.7	17.1	2541	6.0	330	350	295	303	1281	1347	1284	1265	159	2454	41
	14901	160.1	17.0	2555	5.5	315	333	275	284	1250	1291	1324	1305	158	2453	41

backpressure during the overlap stroke when measured by exhaust pressure graph.[1] Service experience with this exhaust system has shown reduced plug fouling, chamber coking, and oil contamination suggestive of effective scavenging of exhaust residuals.

Figure 11b. DM System

Mooney N6057Q	Density altitude	TAS	M.P.	RPM	GPH	CHT1	CHT2	CHT3	CHT4	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg. advance
dew point spread = 15° F	8730	194.1	23.0	2549	12.0	403	382	382	401	1486	1450	1469	1467	178	2477	25
Cruise data	8693	196.2	23.0	2544	11.0	405	392	380	397	1544	1509	1517	1529	179	2475	25
Dual Bendix 1200	8674	194.4	23.0	2553	10.0	406	394	380	398	1590	1605	1594	1602	181	2475	25
	8662	192.9	22.9	2548	9.5	405	396	381	395	1542	1608	1569	1560	172	2474	25
DM = Dual magneto	8634	189.8	23.0	2550	9.0	384	380	373	377	1501	1540	1519	1509	175	2473	25
	8627	185.0	23.0	2546	8.5	377	370	357	369	1465	1489	1484	1466	176	2472	25
All gph are panel (video)	8607	180.3	22.8	2550	8.0	356	347	339	347	1421	1460	1454	1415	172	2472	25
Raw TAS here	8617	169.1	22.8	2550	7.5	330	316	312	320	1408	1460	1452	1416	168	2471	25
i.e., no cuff drag																
has been included	DM															
	Dens. Alt.	TAS	M.P.	RPM	GPH	CHT	CHT	CHT	CHT	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	adv. °
	12599	189.6	19.4	2554	12.0	372	352	361	370	1364	1305	1344	1355	158	2459	25
	12616	189.4	19.5	2550	11.0	392	363	364	380	1407	1382	1387	1402	160	2458	25
	12626	192.0	19.5	2546	10.0	395	383	369	385	1502	1475	1461	1488	169	2457	25
8/25/01 DM	12618	192.2	19.5	2550	9.5	408	385	368	386	1529	1503	1492	1522	165	2456	25
	12592	191.9	19.5	2546	9.0	394	390	380	387	1560	1545	1524	1548	155	2455	25
	12638	187.3	19.4	2550	8.5	394	389	382	383	1547	1587	1550	1544	161	2453	25
CF wide open	12630	184.3	19.5	2547	8.0	381	380	366	368	1492	1525	1503	1491	165	2452	25
All CHT corr. for	12593	180.3	19.3	2550	7.5	364	356	350	356	1443	1464	1458	1440	164	2451	25
100° F day	12526	167.8	19.3	2550	7.0	329	312	314	315	1401	1436	1430	1399	159	2449	25
	12500	156.9	19.2	2549	6.5	318	301	303	305	1394	1467	1456	1441	157	2449	25
	DM															
Data are W.O.T.	Dens. Alt.	TAS	M.P.	RPM	GPH	CHT	CHT	CHT	CHT	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	adv. °
Target = 2550 RPM	15128	182.3	17.5	2551	10.5	400	366	370	381	1380	1314	1342	1360	174	2442	25
TAS from careful	15178	186.2	17.5	2546	10.0	383	354	356	374	1419	1344	1364	1386	172	2441	25
review of OAT, I.A.	15186	188.1	17.5	2547	9.5	380	353	356	374	1443	1373	1382	1436	171	2440	25
stability, video, ballistics	15200	187.4	17.6	2548	9.0	389	363	364	374	1474	1415	1428	1466	166	2439	25
	15154	188.0	17.6	2548	8.5	393	369	367	372	1520	1483	1466	1513	166	2437	25
	15190	184.9	17.6	2552	8.0	386	368	366	372	1516	1533	1506	1525	169	2436	25
	15172	183.2	17.5	2550	7.5	372	366	361	362	1482	1536	1510	1480	168	2434	25
	15165	179.3	17.4	2547	7.0	355	347	347	344	1429	1454	1458	1424	167	2434	25
	15139	170.3	17.4	2549	6.5	331	323	327	320	1374	1388	1420	1368	163	2433	25
	15137	155.5	17.2	2553	6.0	309	302	306	298	1371	1440	1413	1387	159	2432	25

WARNING TO ALL PILOTS:

Severe engine damage or engine failure leading to possibly fatal and destructive aircraft accidents can occur when lean mixtures or advanced ignition timing are used inappropriately. The power, ignition timing and mixture settings used by the CAFE Foundation in these experimental flight tests are not safe to be used on all engines or in all flight conditions.

Advancing ignition timing relative to that recommended by the engine manufacturer is extremely hazardous for turbocharged aircraft engines, and can be unsafe for normally aspirated engines during operation at more than 70% power. Even when operating at below 70% power, excessive ignition timing advance may, under some circumstances, pose the serious risks cited above.

FLIGHT TEST PREPARATION

Because of the engine cooling challenges of conducting full throttle climbs at best rate of climb airspeed (Vy) in summer air, several FAA climb cooling tests were conducted before taking actual cruise performance data.

With the dual electronic ignition system operating at advanced ignition timing, a significant increase in engine cooling demand was observed. Several changes to the engine cowl and induction system were made to assure adequate cooling. Cowl exit area was increased for both cylinder cooling and oil cooler. A large aft-facing air extractor bluff body was installed at the oil cooler exit, which lowered oil temperatures by 35° F. See Photo **D**. Baffle exit path openings around the bottom of the cylinder head cooling fins were selectively enlarged. Induction tube geometry was further modified to selectively enrich cylinder #4. Although these induction modifications gave the desired reduction in CHT, they somewhat widened the otherwise narrow EGT spread among cylinders. There was a noticeable loss of aircraft top speed as a result of the increased drag from these cooling system modifications.

An instability of propeller RPM required an overhauling of the propeller

Figure 11c. SE System

Mooney N6057Q	Density altitude	TAS	M.P.	RPM	GPH	CHT1	CHT2	CHT3	CHT4	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg. advance
dew point spread = 17° F	SE															
Cruise data	8500	193.3	22.7	2551	12.5	na	379	377	395	1394	1394	1445	1461	174	2509	30
One Electroair EIS-1 (Rt.)	8493	193.4	22.8	2552	11.5	na	391	379	396	1475	1475	1503	1511	174	2508	30
One magneto (Lt.)	8509	196.2	22.9	2549	11.0	na	400	380	398	1509	1501	1534	1532	177	2506	30
Magneto fires	8520	196.5	22.8	2549	10.5	na	401	380	395	1551	1553	1583	1586	177	2505	30
the top plugs	8517	191.8	22.9	2552	10.0	na	399	377	393	1583	1590	1578	1562	176	2503	30
All gph are panel (video)	8507	191.7	22.8	2552	9.5	na	398	370	378	1560	1605	1531	1532	178	2501	30
Raw TAS here	8510	189.8	22.6	2550	9.0	na	394	355	372	1517	1555	1494	1493	174	2500	30
i.e., no cuff drag	8478	181.0	22.7	2550	8.5	na	367	320	337	1470	1490	1456	1438	164	2496	30
has been included	8459	176.4	22.6	2552	8.0	na	349	310	318	1409	1460	1449	1421	164	2495	30
SE = single electronic	SE															
dew point spread = 17° F	Densalt.	new	M.P.	RPM	GPH	CHT#	CHT#	CHT#	CHT#	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg.
SE on 7/15/01	12484	188.2	19.1	2553	10.5	na	384	382	401	1380	1344	1384	1421	177	2480	36
	12490	188.1	19.2	2550	10.0	na	383	378	399	1417	1375	1430	1451	176	2476	36
	12504	190.8	19.3	2542	9.5	na	386	379	399	1455	1421	1453	1471	177	2473	36
CF wide open	12496	188.6	19.2	2551	9.0	na	390	378	394	1495	1467	1488	1511	177	2472	36
All CHT corr. for	12526	187.0	19.3	2548	8.5	na	394	377	392	1513	1508	1516	1512	178	2472	36
100° F day	12548	186.2	19.2	2546	8.0	na	393	374	380	1505	1536	1474	1456	177	2471	36
	12554	182.3	19.1	2550	7.5	na	384	355	359	1436	1488	1417	1391	175	2470	36
	12507	176.6	19.2	2555	7.0	na	355	305	321	1364	1426	1364	1355	164	2468	36
	12509	168.9	19.0	2550	6.5	na	345	291	304	1345	1370	1370	1360	164	2467	36
SE2 on 12/04/01	SE2															
dewpoint spread = 4° F	Densalt.	new	M.P.	RPM	GPH	CHT#	CHT#	CHT#	CHT#	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg.
Note: 40° v. 36° adv.	12698	178.2	17.7	2559	11.0	424	377	na	424	1221	1206	na	1314	163	2538	40
	12762	180.5	17.6	2547	10.5	400	389	na	426	1303	1273	na	1351	164	2537	40
	12685	184.7	17.7	2551	10.0	401	392	na	429	1339	1286	na	1372	165	2537	40
	12678	183.6	17.7	2548	9.5	398	394	na	429	1361	1337	na	1418	165	2537	40
this flight had	12684	183.4	17.6	2551	9.0	415	397	na	430	1424	1372	na	1448	165	2537	40
close agreement	12641	185.4	17.7	2556	8.5	421	419	na	428	1478	1429	na	1485	163	2537	40
of palt. with dalt.	12578	185.1	17.8	2547	8.0	429	425	na	421	1488	1488	na	1445	163	2537	40
Note change in	12560	181.0	17.7	2552	7.5	410	426	na	395	1428	1513	na	1384	163	2537	40
M.P. v. other flt.	12620	177.2	17.6	2555	7.0	380	394	na	368	1361	1423	na	1330	159	2536	40
at 12,500' SE	12650	171.0	17.4	2552	6.5	356	368	na	338	1328	1348	na	1315	158	2536	40
rough engine	12667	160.0	17.5	2588	6.0	315	340	na	306	1314	1330	na	1359	158	2535	40
very rough engine	12671	152.0	17.4	2556	5.8	291	329	na	289	1327	1353	na	963	154	2535	40
dew point spread = 17° F	SE															
All data are W.O.T.	Densalt.	new	M.P.	RPM	GPH	CHT#	CHT#	CHT#	CHT#	EGT1	EGT2	EGT3	EGT4	Oil T.	GVW	deg.
Target = 2550 RPM	14974	180.8	17.2	2553	10.0	na	378	392	414	1336	1240	1328	1361	178	2456	41
TAS from careful	14983	182.2	17.3	2550	9.0	na	378	397	411	1387	1342	1374	1433	178	2454	41
review of OAT, I.A.	15017	184.5	17.3	2553	8.5	na	396	401	410	1450	1372	1429	1465	177	2451	41
stability, video, ballistics	15068	185.9	17.2	2552	8.0	na	400	399	402	1485	1422	1466	1506	177	2449	41
	14996	182.4	17.4	2550	7.5	na	409	389	378	1498	1469	1470	1452	173	2444	41
	14958	179.6	17.3	2547	7.0	na	403	368	365	1422	1517	1394	1371	170	2441	41
	15021	173.6	17.2	2554	6.5	na	376	335	337	1359	1441	1348	1335	166	2440	41
	15015	168.8	17.0	2548	6.0	na	346	291	296	1316	1356	1341	1329	158	2437	41

and governor to allow RPM to be held more constant during flight tests. The newly overhauled Hartzell prop HCE-2YR-1BF with 8467-7R blades was dynamically balanced using the ACES system just prior to the flight program.

All three ignition configurations were tested only after all of these modifications were completed.

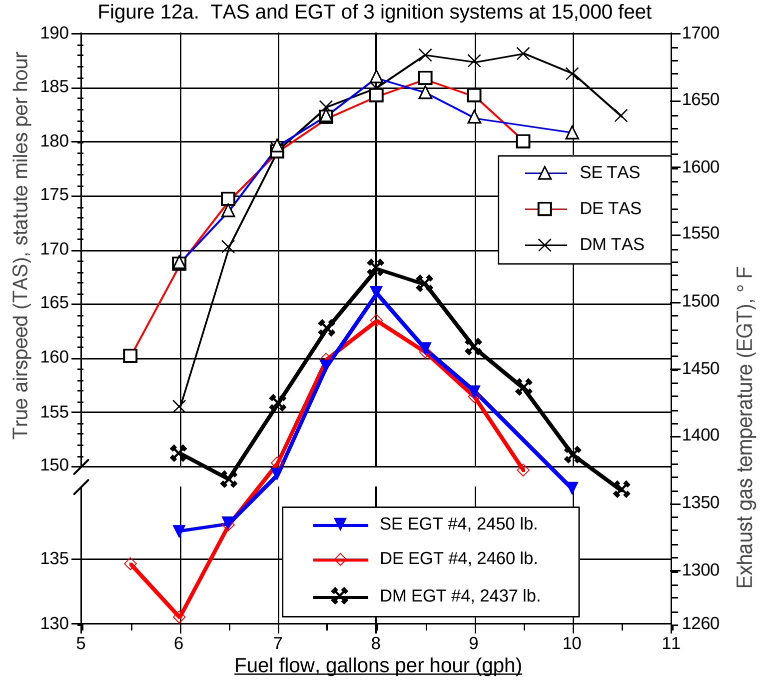
RESULTS

The results of the DE, DM and SE ignition systems tests are presented in spreadsheet form in Figures **11a,b and c**, and are graphically shown in Figures **12a and 12b.** Temperature data are included along with the true airspeeds to facilitate interpretation of the results.

Figure **12a** shows that the DE ignition, when operated at the *leanest* fuel flows with its ignition timing at 41° BTDC at 15,000' density altitude, performed better than the DM ignition whose timing was set at 25° BTDC. Their respective airspeeds at 6.0 gph are 168.7 mph DE, 168.8 mph SE and 155.5 mph with DM, a more than 13 mph advantage for the electronic ignition. This represents an 8.5% increase in airspeed with the electronic ignition. The 4 channel EGT data at these very lean mixtures (130°-200° F lean of peak) show that the DM system exhibits some lean misfiring at the 6.0 gph setting, accompanied by some engine roughness. When enriched to a fuel flow of 6.5 gph, the DM system gives 170.3 mph at 15,000' and the roughness is eliminated.

In Figure **12b**, at 12,500' density altitude, 6.5 gph yields 173.4 mph with DE ignition timing at 36° BTDC and 156.9 mph with the DM system timed at the standard 25° BTDC setting, a 16.5 mph advantage for the electronic ignition. However, the DM system at 6.5 gph again exhibits the rise in EGT that indicates lean misfiring that is not

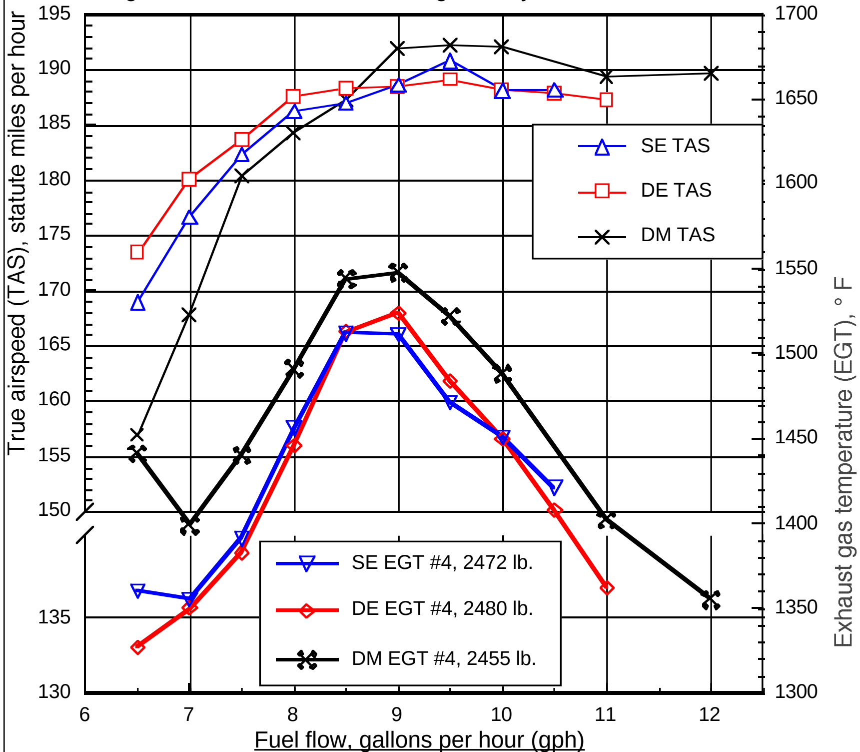
Figure 12a. TAS and EGT of 3 ignition systems at 15,000 feet



Mooney N6057Q at 15,000' density altitude, wide open throttle, 2550 RPM, wing Barograph #3. Cowl flaps fully opened. Mags @ 25° BTDC. Electroair EIS-1 electronic @ 41° BTDC. EGT from cylinder #4 (leanest).
DE = dual electronic. SE = single electronic. DM = dual magnetos.

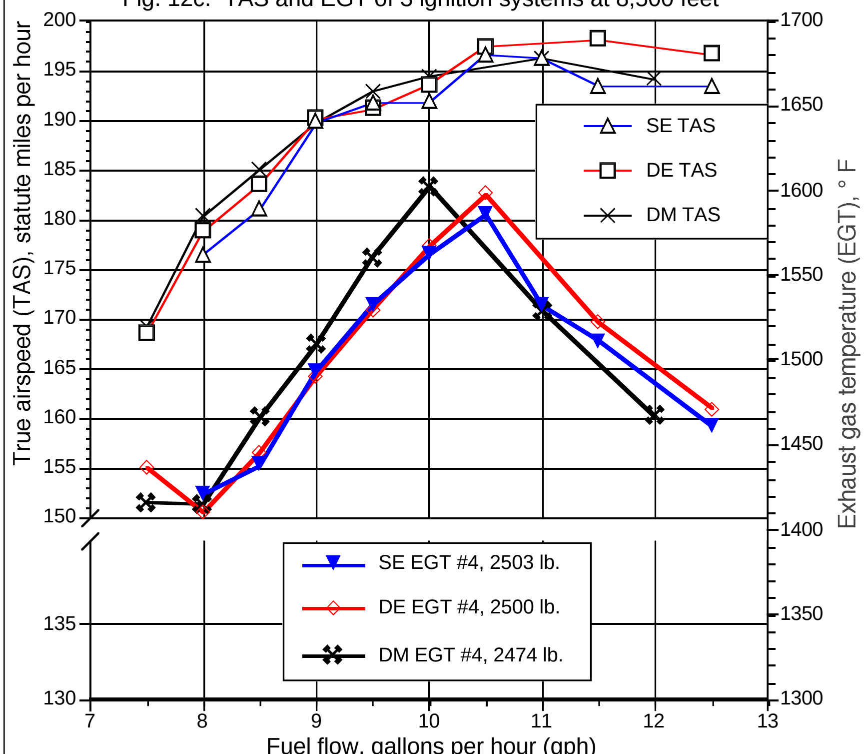
Photo **D**. Enlarged oil cooler extractor exit.

Figure 12b. TAS and EGT of 3 ignition systems at 12,500 feet



Mooney N6057Q at 12,500' density altitude, wide open throttle, 2550 RPM, wing Barograph #3 plus digital acquisition device recordings. Cowl flaps fully opened. Magnetos @ 25° BTDC. EIS-1 electronic @ 36° BTDC. DE = dual electronic. SE = single electronic. DM = dual magnetos.

Fig. 12c. TAS and EGT of 3 ignition systems at 8,500 feet



Mooney N6057Q at 8,500' density altitude, wide open throttle, 2550 RPM, wing Barograph #3. Cowl flaps fully opened. Mags @ 25° BTDC. Electronic @ 30° BTDC. EGT from cylinder #4 (leanest).
DE = dual electronic. SE = single electronic. DM = dual magnetos.

acceptable for continuous operation. At 7.0 gph, where no misfiring was evident, the DM system shows a TAS of 167.8 mph, 5.6 mph slower than DE system, while using 7.7% more fuel. These figures apply to operation at about 130-200° F lean of peak EGT, i.e., very lean.

By interpolation, at 12,500' density altitude, the dual magneto system would require about 7.2 gph to match the DE's speed of 173.4 mph on 6.5 gph-- a 10.7% fuel savings for the DE system.

The speed advantage of the electronic ignition disappears when operating at less radically lean mixtures. For example, at 15,000', when operating between 50-100° lean of peak EGT at 7.0 gph, all three ignition systems deliver about 179 mph, though the ignition timings are 41° BTDC for the DE/SE and 25° BTDC for the DM at this altitude. At rich mixtures, the DM system showed a slight speed advantage. See **12a.**

Figure **12c** shows the results of operation at 8,500' density altitude. Here, the DE and SE systems operate with 30° ignition timing while the DM remains fixed at 25° BTDC. The TAS with the DM system essentially equals or surpasses that of the DE/SE at all fuel flows leaner than peak EGT. The differences are small.

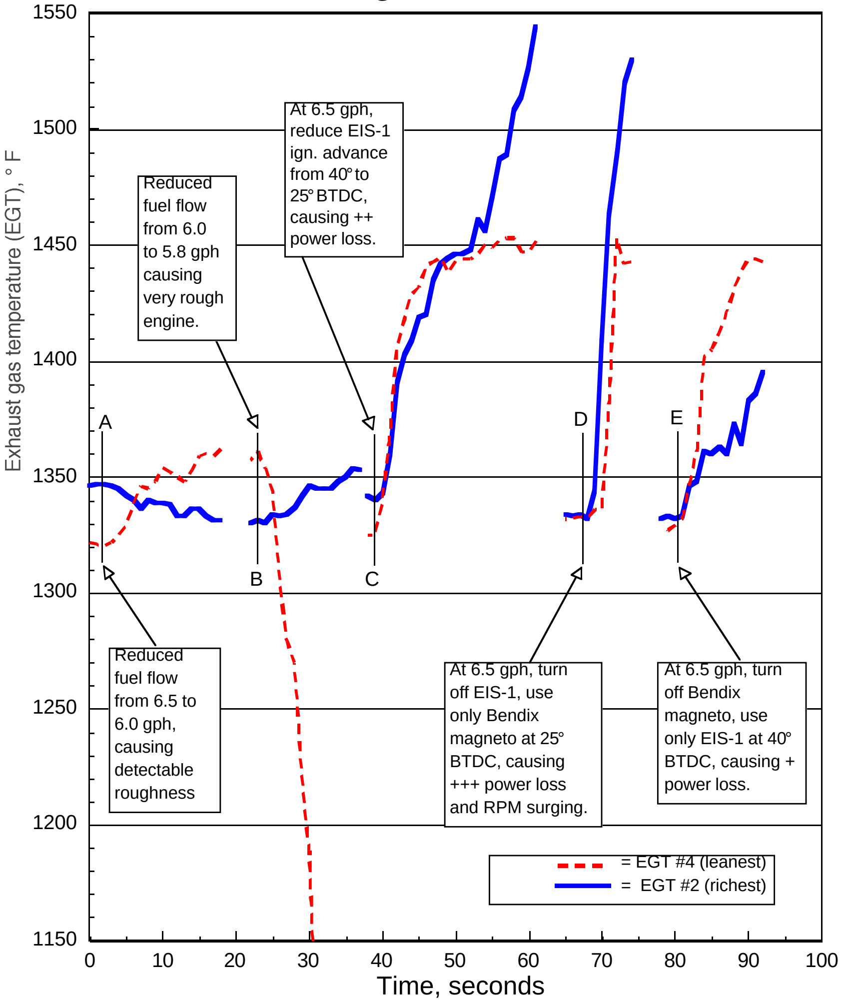
Figures **13A, B, C and D** show the changes in EGT in the SE configuration during several different modes of operation. The responses of both the leanest (#4) and richest (#2) cylinder's EGTs are plotted. Depicted are the changes that occur when the timing advance is reduced from 40° to 25° BTDC on the EIS-1 unit while the magneto remains at 25° advance. The effects of extreme leaning, turning off the EIS-1 altogether or of turning off the magneto are also shown.

Figure **14** shows a detailed comparison of the DE and DM systems at 8,500' density altitude, where the electronic ignition timing is 30° BTDC versus 25° BTDC for the magneto.

Figure **15** tabulates the rate of climb test results. At the rich mixtures used in climb tests, the DM performance surpasses that of both the SE and DE systems.

Figure **16** graphically compares the CHT's and EGT's of cylinder #4 for the DE, SE, and DM configurations at a density altitude of 15,000 feet. As

Figure 13A.



Lean misfire limits: Mooney N6057Q, 12/04/01. 12,500' density altitude. One Electroair EIS-1 at 40° ignition timing advance and one Bendix 1200 magneto at 25° timing. EGT4 (red, dotted) = leanest cylinder. EGT2 (blue, solid) = richest cylinder.

expected, the CHT is hottest and the EGT is coolest with advanced ignition timing. CHT falls dramatically with all configurations as the mixtures are made very lean. Even during the onset of lean misfire, the EGT remains much cooler than peak EGT.

The DM system reaches its lean misfire limit at significantly richer mixtures than the SE or DE system. The DE system can operate without misfire on slightly leaner mixtures than the SE system.

Four channel EGT and CHT graphs obtained with the DE system at 41° BTDC timing exaggerate the temperature spreads among the four cylinders, showing which are the leanest. In Figure **17a**, as the rich mixture is progressively leaned, #4 CHT runs hot early while #2 CHT tends to run hot later in the leaning schedule. The EGT graphs help to explain this CHT behavior. The EGT of cylinder #2, the richest cylinder, is the last to reach peak EGT while EGT #4 is the first to reach peak EGT.

Figure **17b** shows that the DM system has a smaller temperature spread among all four cylinders than is found in **17a**.

It might be expected that induction tubes #1 and #2, being the forwardmost in the induction plenum and therefore closest to the fuel fog emanating from the throat of the Ellison Throttle Body, would exhibit relatively richer mixtures and higher CHT's than the plenum's rearmost induction tubes to cylinders #3 and #4, respectively. The CHT curves in Figure **17a** tend to support this idea, as does the finding that the EGT rise of lean misfire begins at 6.0 gph for cylinders #3 and #4 but not until 5.5 gph for #1 and #2.

Figure **18** is a table that compares all 3 ignition systems at their minimum tolerable fuel flows. The cool CHTs at these low fuel flows suggest that the cooling system airflow could be reduced substantially to raise the CHT to a more thermodynamically efficient value. The table shows theoretical values for TAS and MPG that might be obtained if the cooling system were sealed up to produce a CHT of 420° F in lean cruise flight on a 100° F day or 400° F on an 80° F day. Such increases in speed require a fully closable cowl air exit that can severely restrict cooling airflow. Such tests were not possible on the testbed aircraft.

Figure **19** reveals the effect of changing the ignition timing or using a large spark plug gap. See its attached explanation.

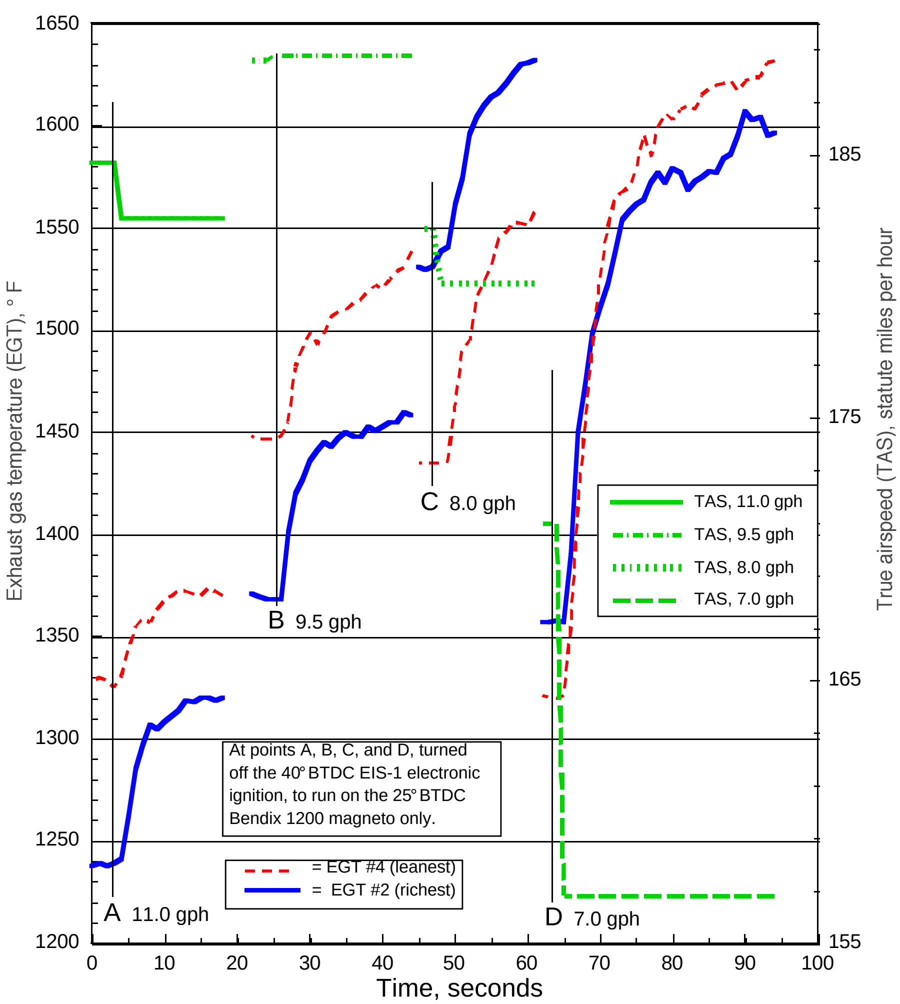
The oil temperature in all test conditions rarely rose above the Vernatherm setting of 180° F due to the excess of oil cooler airflow in the testbed aircraft.

The engine started reliably and easily with either the electronic or impulse-coupled magneto ignition. It idled smoothly at only 500 RPM with the electronic ignition, much lower than the minimum smooth idle possible with magnetos. Electroair recommends powering the DIU's with a backup battery during starting so that a large sag in main battery voltage during cranking does not upset the functioning of the DIU's circuitry.

There were no ignition malfunctions during any of these tests. The Electroair ignition units were mounted in the 'cold air' portion of the engine cowl and tolerated heat soaking of up to 175° F inside the cowl after engine shutdown on a 100° day without any subsequent malfunction.

Simultaneously switching both of the DIU's of the DE system to the backup battery source in flight using a single toggle battery selector switch caused episodes of brief but violent misfiring because of the momentary "off" condition occurring as the switch broke contact in midthrow. A better circuit method would be to power each DIU with a center off, 2 position Mil-spec. 10 amp toggle switch and select the backup battery for each DIU in succession, rather than in one throw.

Figure 13B.



Change in EGT and TAS during operation on left magneto only, 4 different fuel mixtures: Mooney N6057Q, 12/15/01. 12,500' density, w.o.t., 2550 RPM. Bottom spark plugs on Electroair EIS-1 at 40° BTDC. Top spark plugs on Bendix 1200 mag @ 25° BTDC timing.

DISCUSSION

The automotive industry has successfully developed electronically controlled, battery-dependent, high energy ignition systems for many years with excellent reliability. Today's automobile systems require very low maintenance and yet operate with complex ignition timing control inputs from sensors for manifold pressure, RPM, temperature, throttle position, exhaust oxygen level, engine knock, etc.

EAAers Jeff Rose and Klaus Savier deserve credit for having led the way in applying such technology to aircraft engines. The results of this study suggest that the EIS-1 ignition system can provide substantial gains in performance during lean mixture operation. *It must be emphasized* that the results for other electronic ignition systems or for the EIS-1 applied to any other engine may be quite different than those reported here.

Research at Ford Motor Company has shown that improvement in lean operation from multi-spark discharge ignition "is not so large as that obtainable by improving carburetion and continuing to use a standard single-spark ignition system."[2] Engine smoothness and reliability also benefit if fuel distribution/atomization deficiencies (common in many aircraft engines) are corrected prior to installing electronic ignition. The EIS-1 system was tested here on a specially modified aircraft engine that may have *already* achieved much of the performance improvements commonly attributed to adding electronic ignition to otherwise stock aircraft engines.

The DM system's Bendix 1200 magnetos are better suited to high altitude operation than are smaller, lower voltage magnetos. The testbed engine's tuned, scavenging exhaust system enhances volumetric efficiency and reduces charge contaminants that would otherwise slow flame propagation or impede the ignition process. Its fairly uniform mixture distribution, combined with the finer fuel atomization produced by the Ellison Throttle Body, allow this particular engine to operate smoothly in the DM configuration on much leaner mixtures (~150° F lean of peak EGT) than most aircraft engines.

The finding that the DM system surpassed the EIS-1 in performance at 8,500' density altitude on lean mixtures may indicate that the EIS-1 timing of 30° BTDC at this altitude is too advanced for maximum brake torque (MBT). Theoretically, the faster combustion time from a high energy spark could allow its MBT timing to be slightly later rather than earlier than that for a magneto, especially in a well-scavenged engine such as this one. Klaus Savier has found that electronic ignition delivered MBT timing for his aircraft engine operating at 29" M.P. and 1900 RPM with best power mixture at around 16° BTDC.[3] Such timing settings were not examined on the EIS-1.

The higher rates of climb shown by the DM system suggest that the EIS-1 affords no significant horsepower advantage when using an easy-to-ignite rich mixture.

The EIS-1 modulates ignition timing by RPM and *relative* manifold pressure. Due to variations in the pressure altitudes on 3 different flights at 12,500 feet, the EIS-1 delivered 3 different ignition timing settings: 36°, 40°, and 38°. An *absolute* manifold pressure sensor would correct this variability of the timing.

DETAILED EGT ANALYSIS

The EGT and TAS performance of the SE ignition system were examined in detail at 12,500' density altitude using wide open throttle and 2550 RPM, cowl flaps fully opened. Figures **13A through D** present the results.

Figure **13A**, point "**A**", shows that the #4 cylinder EGT (red trace) rises and thus begins to show lean misfire as the mixture is leaned from 6.5 to 6.0

gph. Meanwhile, cylinder #2 shows the more typical cooling in EGT as the mixture is leaned. This contrast in EGT behavior occurs because, on the test engine, cylinder #4 is consistently the leanest while cylinder #2 is the richest.

At point "**B**", where the mixture was leaned even further to just 5.8 gph, EGT #4 plummets due to its having frequent cycles with near total absence of ignition. Here, EGT #2 finally begins to show the characteristic rising EGT of partial misfiring. Not unexpectedly, the engine was running very rough at this point "**B**".

At point "**C**", the engine was running smoothly at 6.5 gph when the manifold pressure advance was turned off, reducing the EIS-1 timing from 40° BTDC to 25° BTDC, i.e., the same setting as the magneto. This produces a very large rise in EGT on both cylinders #2 and #4 and a commensurate loss of power due to the wasteful late burning of fuel as it exits the exhaust valve.

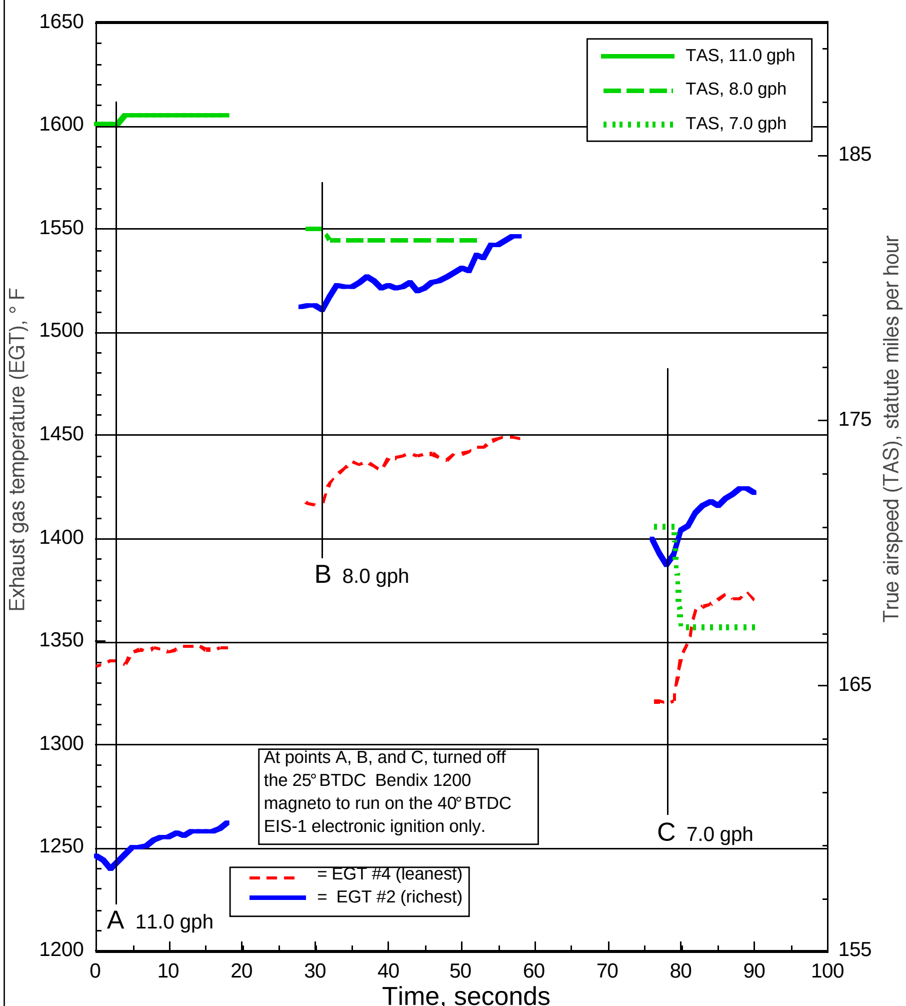
At point "**D**" in Figure **13A**, the EIS-1 unit was turned off, leaving the Bendix 1200 magneto to fire the top spark plugs only. A major power loss ensues as the EGTs both rise dramatically. Figure **13B** expands on these findings.

Point "**E**" in Figure **13A** shows that turning off the Bendix 1200 magneto causes a much more mild rise in EGT and a much less severe loss of power. In other words, even with the slow-burning mixture setting of 6.5 gph, which is the lean misfire limit, the magneto was not contributing much to the ignition process; the major share was being supplied by the advanced firings from the EIS-1's bottom spark plugs.

Figure **13B** shows the effect on EGT and TAS of turning off the EIS-1 at various mixtures. With only the top spark plugs firing at their 25° BTDC magneto timing, there is not enough time before the exhaust valve opens (EVO) to fully consume the mixture. In general, the leaner the mixture, the larger the rise in EGT upon turning off the EIS-1 because the leanest, slowest-burning mixtures need the most 'head start' at ignition. Note that the EGTs of cylinder #2 (richest) and #4 (leanest) rise different amounts.

In Figure **13B**, the TAS drops the most at the leanest setting (point "**D**"),

Figure 13C.



Change in EGT and TAS during operation on EIS-1 only, 3 different fuel mixtures: Mooney N6057Q, 12/15/01. 12,500' density, w.o.t., 2550 RPM. Bottom spark plugs on Electroair EIS-1 at 40° BTDC. Top spark plugs on Bendix 1200 mag @ 25° BTDC timing.

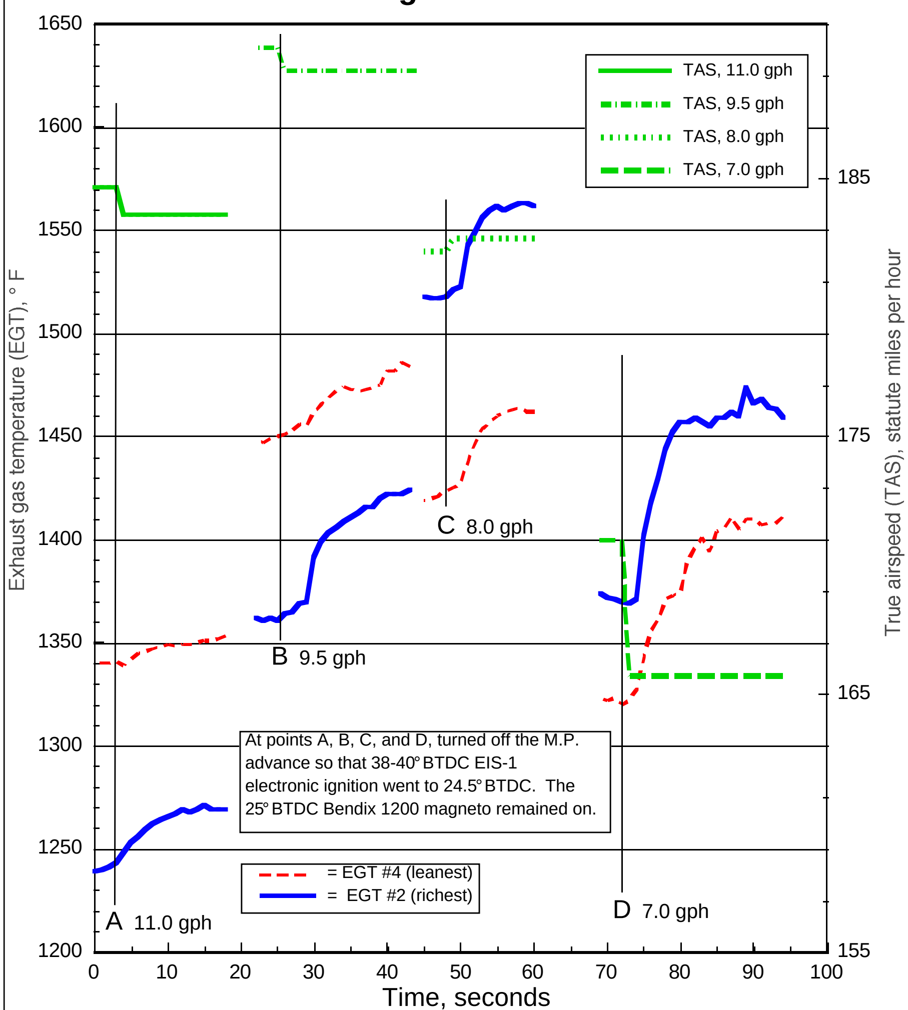
again reflecting the amount of energy wasted by fuel burning after it exits the exhaust valve. But two effects are occuring simultaneously. One is the influence of firing only the top spark plug in each cylinder. The other is the effect of retarding the timing from 40° BTDC to 25° BTDC.

Figure **13B**, point "**A**" shows a drop in TAS at 11.0 gph when the electronic ignition and its bottom spark plugs are switched off. This TAS loss is partly an indication that 'bloody rich' mixtures (200-250°F ROP EGT) do indeed burn more slowly than best power mixtures. The retarding of the timing from 40° to 25° BTDC made it too late, causing the loss of power and airspeed along with the rise in EGT. This timing retarding effect is compounded by initiating ignition at only the top spark plug (magneto) in each chamber, making combustion of the entire mixture take even longer.

At point "**B**" in Figure **13B**, the TAS increased slightly after turning off the electronic EIS-1 ignition at 9.5 gph. This is best power mixture at this RPM, M.P. and altitude. Here, a timing of 25° BTDC on single ignition appears to deliver *more* power than a setting of 40° BTDC with dual ignitions.

Best power mixtures are the fastest-burning. Running 40° BTDC timing at best power mixture appears to be too advanced--the burning occurs too early. This may impede the piston's rise near TDC and/or dissipate the peak cylinder pressure too early in the piston's descent, and thus actually reduce horsepower. The 25° BTDC timing is closer to MBT (maximum brake torque) timing at these particular conditions and the increased power occurs despite the wasted energy evident in

Figure 13D.



Change in EGT and TAS when ignition timing reduced from ~40° to 24.5° BTDC, 4 different fuel mixtures: Mooney N6057Q, 12/15/01. 12,500' density, w.o.t., 2550 RPM. Bottom spark plugs on Electroair EIS-1. Top spark plugs on Bendix 1200 mag @ 25° BTDC timing.

the higher EGT's during single magneto operation. This suggests that the Lycoming engineers who chose a fixed ignition timing of 25° BTDC for this engine made a wise choice.

In Figure **13C**, the magneto was turned off while operating at each of 3 different mixture settings.

At point “**A**”, while running 40° timing advance with the EIS-1 at 11.0 gph (~270° F rich of peak), turning off the magneto with its 25° BTDC timing shows almost no effect on EGT or TAS. This indicates that the magneto’s contribution to the ignition process is minimal. Contrast this with point “**A**” in Figure **13B**, where the absence of the EIS-1’s 40° firings has a pronounced effect on EGT and TAS.

At point “**B**” in Figure **13C**, at 8.0 gph (near peak EGT), there is a perceptible rise in EGT when turning off the magneto, but still no significant change in TAS.

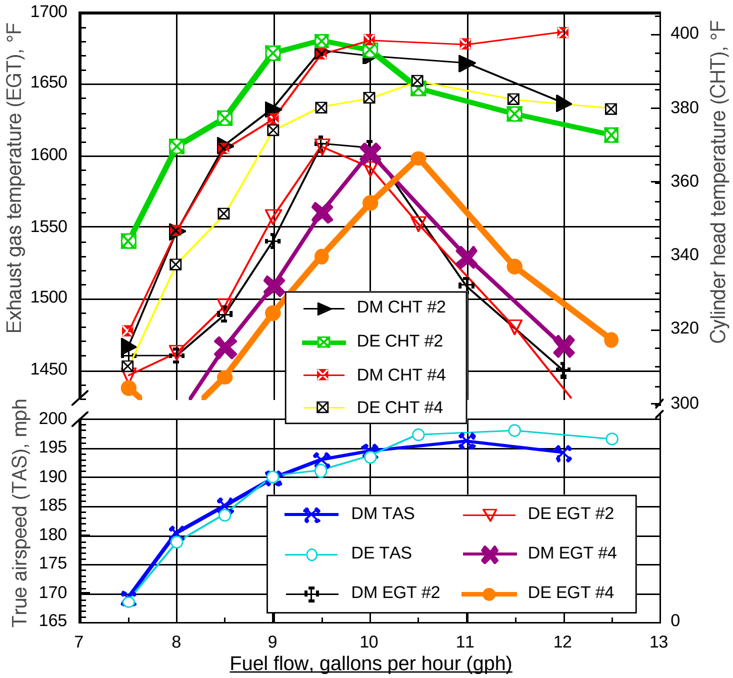
At point “**C**”, at 7.0 gph (~150° F lean of peak EGT), there is a more noticeable rise in EGT and fall in TAS when the magneto is turned off. This again indicates that, in the SE configuration with 40° electronic timing, the magneto only contributes significant ignition at the slowest-burning, leanest mixtures.

See Figure **13C**, and point “**E**” in Figure **13A**. Calculation shows that, at 2550 RPM, the advertised spark duration of 1.8 milliseconds for the EIS-1 using 0.030" spark plug gap would provide a continuous spark from 41° BTDC to 13.5° BTDC. With the SE system, this would overlap the 25° BTDC spark delivered by the magneto. Especially with rich mixtures, the flame front that originates at 40° BTDC from the SE bottom spark plug might be expected to partially engulf the magneto's top spark plug electrodes before they fire their spark. Such circumstances may burden the magneto coil with having to fire its spark into a somewhat increased pressure environment, increasing the possibility of stray arcing in its distributor or coil. Although we saw no evidence of arcing and know of no reports of it thusfar in users of the SE system, it is suggested that the magneto-fired spark plug gaps be kept properly small when using the SE system.

Figure **13D** depicts the effects of turning off the manifold pressure-modulated timing advance of the EIS-1. This changes the timing of the bottom spark plugs to 25° BTDC from their advanced setting of 40° BTDC and retains dual ignition operation. The results show a consistent but mild rise in EGT at every fuel flow setting examined, indicating the delay in the burning of the fuel. This is accompanied by the familiar drop in TAS at all except the 8.0 gph (stoichiometric) setting (point “**C**”, Figure **13D**), where the airspeed actually rose by almost 1.0 mph. This rise of TAS demonstrates better power with dual ignition at 25° BTDC at these particular settings than when the bottom plugs were firing at 40° BTDC, i.e., it is closer to the MBT timing. As was shown in Figure **13B**, point “**B**”, the increased power from an optimized timing setting (closer to MBT) more than compensates for the wasted energy of higher EGTs that accompany such retarded timing.

The ‘burn speed’ of the 8.0 gph stoichiometric mixture is slower than the 9.5 gph best power mixture. The loss of TAS at 9.5 gph (Figure **13D**, point “**B**”), differs from the *rise* in TAS found at 9.5 gph in Figure **13B**, point “**B**”, where only the top spark plugs were firing. To explain why this situation reverses at 9.5 gph, recognize that flame spread is faster when originated at two spark plugs than when originated at only one. Thus, with *both* spark plugs firing, 25° BTDC advance is slightly too early for MBT at 9.5 gph (Figure **13D**, point “**B**”) whereas with only the top spark plugs firing, the slower flame spread places 25° timing close to MBT. The MBT setting at 9.5 gph with all spark plugs firing thus would likely be about 20° BTDC. This is true even though the EGT is shown

Figure 14. Fuel flow versus EGT, CHT and TAS: DM v. DE ignition.



Mooney N6057Q at 8,500' density altitude, wide open throttle, 2550 RPM, richest cylinder #2, leanest cylinder #4. Wing Barograph #3 and Vetter DAD records. DE = dual electronic EIS-1 ignition @ 30° BTDC. DM = dual Bendix 1200 magnetos @ 25° BTDC.

At 23" Hg. of manifold pressure, the EGTs of the richest cylinder (#2) are not affected by the 4° timing difference from DM to DE while the EGTs of the leanest cylinder (#4) differ significantly. The DE CHT #4 is lower than the DM CHT #4 at all fuel flows. The DE CHT #2 is hotter when LOP and cooler when ROP compared to DM CHT #2. TAS differences are small but indicate that the DE system is fastest using rich mixtures and the DM system is fastest using lean mixtures.

to rise as the 40° BTDC timing is cut to 25°.

Simply modulating ignition timing according to manifold pressure and RPM ignores the direct and profound dependency of MBT timing on the fuel/air mixture. Figure **13** clearly depicts this dependency and suggests the need for a sensor such as an exhaust oxygen sensor to modulate ignition timing with mixture. Although such sensors are purported to be problematic in engines that use leaded fuels, hopefully this technical problem will soon be solved for aircraft engines.

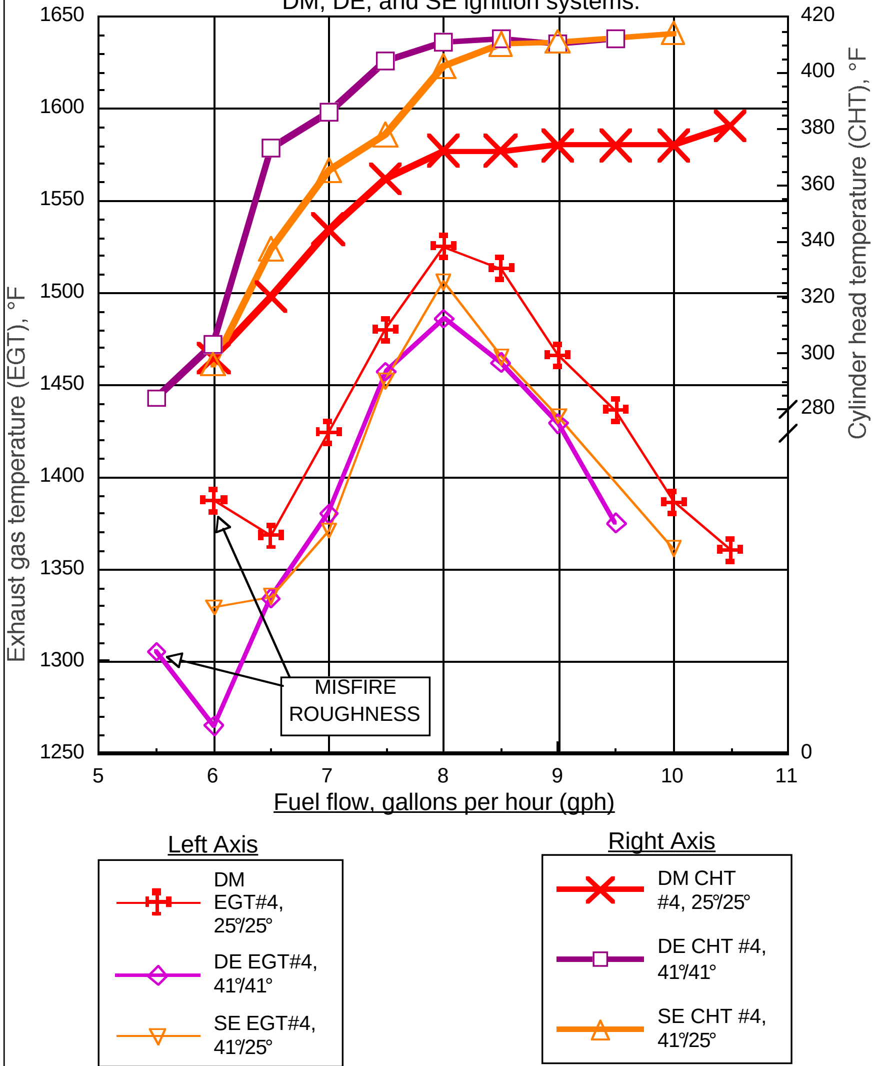
The EGT spread shown in Figure **17a** suggests that the mixture distribution of this engine could be further improved. Cylinder #2 is too rich and cylinder #4 is too lean. Because the intake mouth of induction tubes #2 and #4 share the incoming fuel fog on the left side of the Ellison Throttle Body, with #2's mouth placed directly in front of #4's, a further reduction in EGT and CHT spread can likely be achieved by moving #2's mouth slightly aside to send more fog to #4's.

Figure **17b** shows that the lean misfire of all cylinders in the DM configuration begins at 6.5 gph, a richer setting than the 6.0 gph misfire limit for the DE system shown in **17a**.

Figure 15. Electroair EIS-1 ignition versus Bendix 1200 magneto in rate of climb performance.

Mooney N6057Q	Ign.	Density alt.	gph	Weight, lb.	pEGT, °F	EGT, °F	ROP, °F	CHT, °F	OAT, °F	Timing, °BTDC	ROC, fpm
ROC = Rate of climb	DE	2500-3500	18.7	2525	1620	1409	211	399	81	25	1511
pEGT = peak EGT, est.											
ROP = rich of peak	DE	3500-4500	17.7	2523	1610	1398	212	407	81	25	998
fpm = feet per minute	SE	3500-4500	17.1	2525	1610	1387	223	408	71	25	970
CHT = cyl. head temp.	DM	3500-4500	17.8	2485	1620	1353	267	402	77	25	1138
EGT = exh. gas temp.	DM	3500-4500	17.8	2536	1620	1358	262	422	55	25	1029
DE=dual electronic											
SE=single electronic	DE	7500-8500	15.0	2514	1600	1408	192	421	64	30	704
DM=dual magneto	SE	7500-8500	15.0	2516	1590	1413	177	436	62	30	701
	DM	7500-8500	15.0	2480	1605	1388	217	420	70	25	787
w.o.t., 2600 RPM	DM	7500-8500	15.0	2530	1605	1394	211	424	55	25	721
125 IAS mph, panel											
cowl flap full open	DE	10500-11500	13.3	2490	1560	1375	185	430	49	34	557
	SE	10500-11500	12.8	2488	1550	1381	169	429	52	34	531
gph = panel FlowScan	DM	10500-11500	13.5	2466	1570	1353	217	402	62	25	579
CHT= hottest (cyl #4)											
EGT = leanest (cyl #4)	DE	11500-12500	13.1	2487	1525	1315	210	430	46	35	452
CHT for 100°F day	SE	11500-12500	12.7	2485	1515	1360	155	428	47	35	459
	DM	11500-12500	13.3	2464	1550	1341	209	402	57	25	508
Dew point spreads:											
DE = 18°F	DE	14000-15000	10.6	2447	1490	1364	126	425	35	40	349
SE = 17°F	SE	14000-15000	10.6	2461	1510	1386	124	439	40	40	345
DM = 15°F	DM	14000-15000	11.0	2444	1530	1380	150	402	48	25	415

Figure 16. Fuel flow versus EGT, CHT at 15,000'.
DM, DE, and SE ignition systems.



Mooney N6057Q at 15,000' density altitude, wide open throttle, 2550 RPM, hottest cylinder #4, Vetter DAD recordings. DM = dual Bendix 1200 magnetos (25° BTDC) DE = dual electronic EIS-1 (41° BTDC) SE = single electronic EIS-1 (41° BTDC) with single Bendix magneto (25° BTDC)

Though firing at the same 41° timing at 15,000' as the DE system, the SE system probably operates as if its ignition were timed later due to the slower burning that results when early firing is initiated only at the SE bottom spark plug. Thus, a slight increase in timing advance relative to the DE system might be expected to help extend the lean misfire limit of the SE system and improve its power output. Figure **19** appears to confirm this idea by showing SE data for both 36° and 40° BTDC timing at 12,500' altitude. Note here that the airspeed developed with mixtures near the lean limit is slightly better at 40° timing than at 36° timing and that the converse is true at rich mixtures. Also note the expected increase in CHT and decrease in EGT with the 40° timing.

In Figure **19**, the 36° timing was too rough running at 6.0 gph to obtain a stable TAS. We estimate that this would have yielded about 15 mph slower than the TAS of the 40° timing at 6.0 gph. The use of a 0.060" electrode gap on the bottom spark plug of cylinder #4 (the leanest cylinder) caused it to prematurely misfire relative to the lean limit found using the standard 0.031" gap. Presumably, the diminished spark duration of the larger gap did not last long enough to reliably ignite the very scarce fuel molecules at the leanest mixtures.

Figures **20a,b and 21** show the results of "clocking" the electrode gap axis of the bottom spark plug in cylinder #4. The results are explained in the accompanying sidebar.

Figure **22** clearly shows the large effect on EGT from advancing the ignition timing. The peak EGT at 15,000' and 41° BTDC timing is lower and occurs at a leaner mixture than with 25° magneto timing. The fact that the DE and DM EGT's nearly match at 8,500' suggests that it is the *timing* and not the high energy that causes the EGTs of these two systems to differ at 15,000'.

Textron Lycoming's Flyer newsletter states that they allow *"leaning to peak EGT at 75% power and below on our direct drive normally aspirated engines."*[4] They also state that *"leaning past the peak (EGT) is not recommended"*.

Wide experience has shown that, when a reasonably even mixture distribution exists, conventional aircraft engines can safely operate continuously lean of peak EGT with the following <u>important</u> stipulations:

1) It must be at less than 70% power. For normally aspirated engines, it is generally at altitudes above 10,000 feet where w.o.t. settings, which are best able to give even mixture distribution, deliver no more than 70% power.

2) It is verified by EGT measurements that all cylinders are at least 25° lean of peak EGT. Ideally, the multi-cylinder EGT/CHT gauge should have an alarm capability such as those built by JPI and KS Avionics.

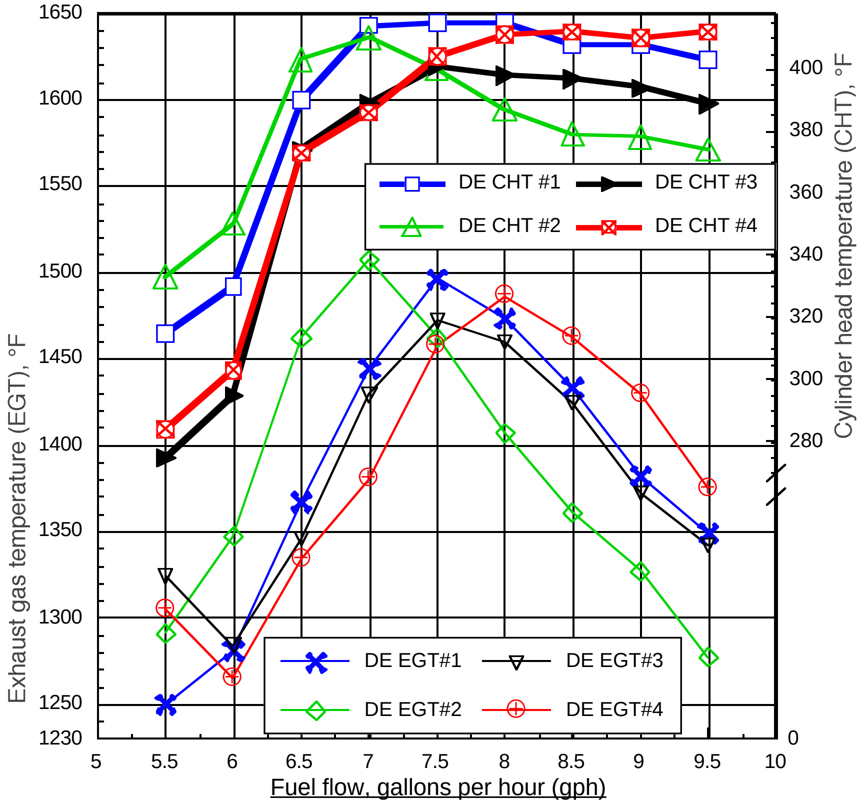
3) All cylinder's CHTs' must be within acceptable limits for continuous operation (generally below 420° F) when measured by an accurate multi-cylinder CHT gauge.

4) There must be no evidence of noticeable roughness.

CONCLUSIONS

1) Advanced ignition timing with the EIS-1 high energy electronic ignition system significantly improved aircraft speed and fuel economy in cruise flight at high altitude during operation with very lean mixtures.

Figure 17a. DE system: EGT and CHT spreads for all four cylinders.



Mooney N6057Q; 15,000' density alt., wide open throttle, 2550 RPM, Vetter DAD records. CHT corrected to 100 °F day. DE = dual electronic EIS-1 ignitions @ 41° BTDC timing. Note cylinder #2 clearly has the richest mixture at any fuel flow.

2) These advantages will most benefit aircraft of relatively low span loading that are designed to cruise above 10,000 feet with normally aspirated engines .

3) Before installing electronic ignition on an aircraft:

a) Its engine induction and mixture distribution should be optimized using high quality, multi-cylinder EGT/CHT gauges to balance the flow to all cylinders.

b) The adequacy of the engine cooling system should be tested and confirmed as more than adequate.

c) The engine operator should acquire a thorough understanding of the maintenance and operation of electronic ignition and recognize and accept the risks in its use.

4) The SE system ignition timing appears to optimize at a slightly more advanced setting than the DE system.

5) As the fuel mixture is leaned, the progressive reduction in flame speed can be as much as 50-60%. Programming the ignition to MBT timing during such lean operation requires a closed loop fuel mixture sensor in addition to inputs from absolute manifold pressure and RPM.

6. Lean operation can best be optimized by a properly timed, high energy, long duration spark applied across a large electrode gap that is ideally oriented with respect to local combustion chamber swirl.

Other electronic ignition systems may perform differently than the EIS-1 system tested here and may be the subject of future study by the CAFE Foundation.

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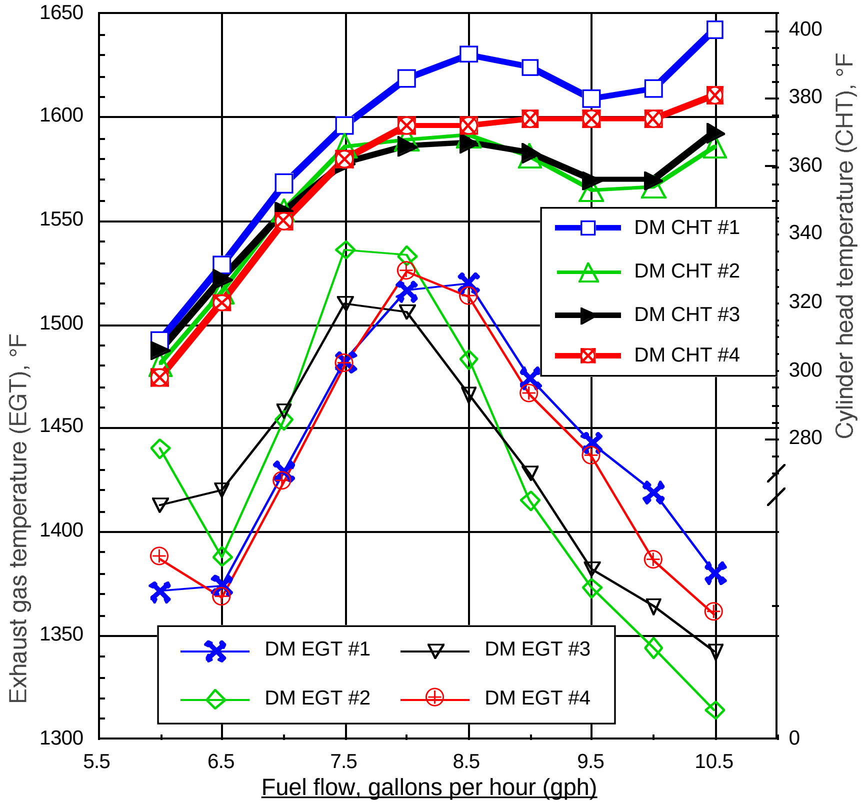
Internet links:
cafefoundation.org
electroair@juno.com (Electroair®)
LightSpeedEngineering.com

Figure 17b. DM system: EGT and CHT spreads for all four cylinders.



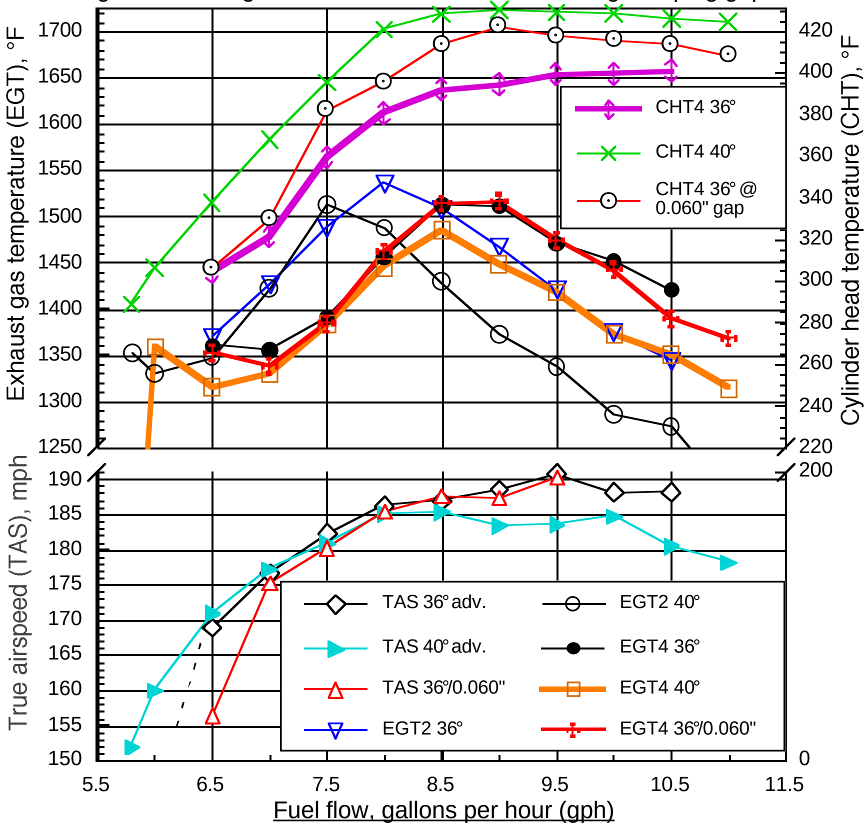
Mooney N6057Q; 15,000' density alt., wide open throttle, 2550 RPM, Vetter DAD records. CHT for 100 °F day. DM = dual Bendix magnetos @ 25° BTDC timing. At 6.0 gph, the rise in EGT due to misfire is greatest for cyl. #2

Figure 18. Cooling drag at lean limit operation--calculated potential TAS and MPG gains with cowl flap fully closed.

Mooney N6057Q	Ign.	Dens. alt.	gph	TAS	MPG	LOP EGT, °F	EGT spread, °F	CHT, °F	CHT margin, °F	Cooling excess, %	Drag savings, %	Mph gain	New TAS	New MPG
Lean limit operation	DE	8500	8.0	178.8	22.4	159/144/146/188	44	370	50	38%	3.8%	3.4	182.2	22.8
EIS-1 v. Bendix magneto	SE	8500	8.0	176.4	22.1	174/145/134/165	40	349	71	53%	5.3%	4.9	181.3	22.7
LOP = lean of peak	DM	8500	8.0	180.3	22.5	169/148/140/187	47	356	64	48%	4.8%	4.5	184.8	23.1
All CHTs = 100 °F day														
	DE	12500	6.5	173.4	26.7	189/176/176/197	21	368	52	39%	3.9%	3.5	176.9	27.2
Potential gains in TAS, MPG	SE	12500	7.0	176.6	25.2	149/110/152/157	47	355	65	49%	4.9%	4.5	181.1	25.9
If target CHT=420 °F	DM	12500	7.0	167.8	24.0	159/151/120/149	39	329	91	68%	6.8%	6.0	173.8	24.8
TAS with wing cuffs on														
DE (dual electronic)	DE	15000	6.0	168.7	28.1	215/160/188/221	55	350	70	53%	5.3%	4.6	173.3	28.9
SE (single electronic)	SE	15000	6.0	168.8	28.1	182/161/129/177	53	346	74	56%	5.6%	4.9	173.7	28.9
DM (dual magneto)	DM	15000	6.5	170.3	26.2	146/148/90/149	59	331	89	67%	6.7%	6.0	176.3	27.1

Cooling drag excess at lean mixture operation with cowl flaps fully open: A cowl exit that can be almost completely closed would be necessary to achieve these calculated gains in TAS and MPG. All TAS are uncorrected for wing cuff drag and thus are low by 3-5 mph. Assume 0.75% cooling drag reduction per °F rise in CHT, assume cooling drag = 10% of total drag and that induced drag fraction = zero. Source: Lycoming cooling data showing 30% less cooling drag for CHT of 435° F than for CHT of 400° F.

Figure 19. SE ignition: EGT, CHT and TAS, timing and plug gap effects.



Mooney N6057Q: IO-360A1B6X engine. 12,500' density altitude. Electroair EIS-1 firing bottom plugs using 0.031" gap, Bendix 1200 magneto @ 25° BTDC firing top plugs using 0.018" gap. Wide open throttle, 2550 RPM, All CHT's corr. to 100° F day. Cyl # 4 (leanest) bottom plug gap = 0.060" on 1/10/02 flight only. Aircraft weights: 2472 lb. @ 36°, 2537 lb. @ 40°, 2490 lb. @ 0.060" gap.

Figure 19 Explanation:

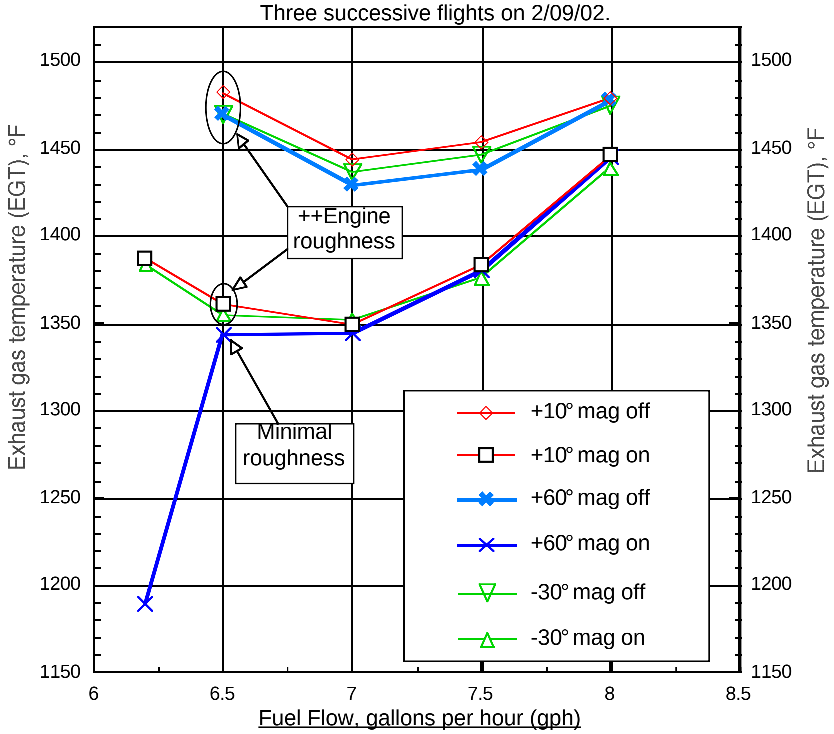
The 40° timing produces a hotter CHT than 36° timing. This is a finding consistent with most of the data from other flights in which advancing the timing increases CHT. Likewise, the 40° timed EGTs are generally cooler than when at 36° timing. More of the heat of combustion goes into the cylinder head and less remains in the exhaust gas when using 40° timing than with 36° timing.

The TAS with the 40° timing is faster than with 36° timing at their lean misfire limit of 6.5 gph. The TAS with 40° spark advance was slower than with 36° advance when using ROP mixtures. This is presumably because rich mixtures burn faster, calling for less timing advance to optimize power.

When the #4 bottom spark plug gap was set to 0.060", the engine reached its lean misfire limit sooner, with perceptible roughness beginning at 7.0 gph rather than the 6.5 gph limit found on the other flights that used the standard gap of 0.031". The large gap misfired badly at 6.5 gph with a large loss of TAS and major engine roughness.

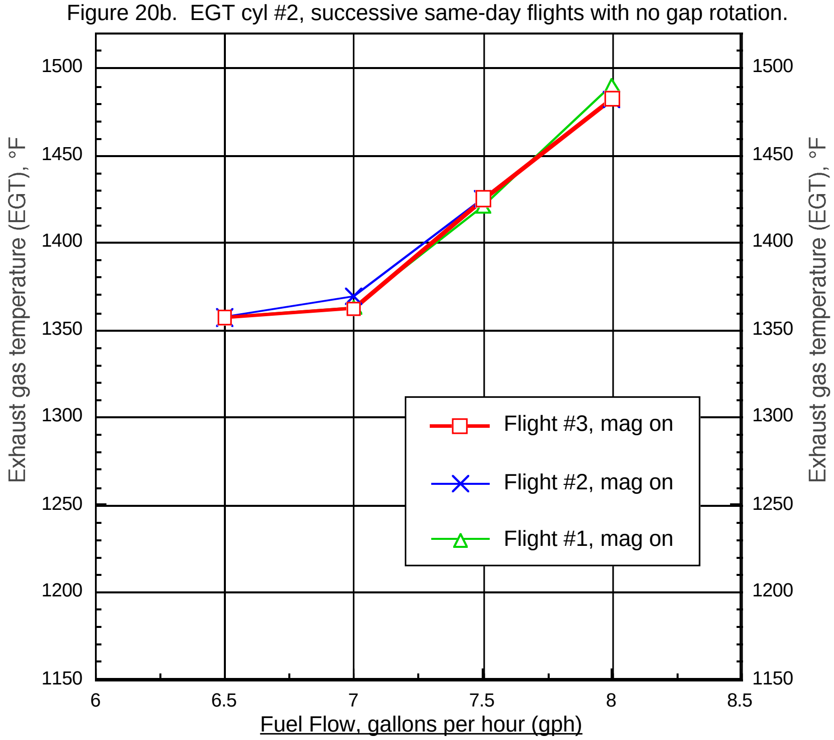
The 40° timing allowed the engine to continue running without severe roughness at just 6.0 gph. However, at 5.8 gph, the roughness became prominent and uncomfortable as EGT #4 40° plummeted due to frequent cycles of severe misfire.

Figure 20a. EGT cyl #4 at 3 different electrode gap rotations. Three successive flights on 2/09/02.



Mooney N6057Q; SE ignition at 12,500' wide open throttle, 2550 RPM, Vetter DAD recordings. EIS-1 fires bottom plugs at 36° BTDC with 0.031" gap. Bendix Magneto @ 25° BTDC fires top plugs with 0.018" gap. Cylinder #4 (leanest) bottom spark plug electrode gap axis tested at 3 different rotations: Flt. #1 = stock = -30° Flt. #2 = +60° Flt. #3 = +10° See Figures **20b, 21.**

Figure 20b. EGT cyl #2, successive same-day flights with no gap rotation.



Mooney N6057Q at 12,500' density altlitude. SE config., wide open throttle, 2550 RPM, Vetter DAD recordings. EIS-1 fires bottom plugs at 36° BTDC with 0.031" gap. Bendix Magneto @ 25° BTDC fires top plugs with 0.018" gap. Cylinder #2 (richest) has its plug electrode axes remaining at stock rotation on all 3 flights while cylinder #4 has its bottom plug gap rotations set to #1 = -30°, #2 = +60°, #3 = +10°. Figure **20a** shows gap rotation effects on EGT.

Figures 20a and 20b Explanation:

In Figure 20a, the lowest EGT at each gph setting indicates the most complete combustion before EVO (exhaust valve opening). The blue lines suggest that the +60° spark plug electrode axis gives the most complete combustion at the leanest mixtures short of the misfire limit. The +10° axis (red lines) show higher EGT's in both the dual and single ignition modes, which implies a slower initiation of the combustion process, causing it to take longer.

Some research suggests that, if the electrode gap is oriented perpendicular to the 'wind' or direction of gas swirl in the combustion chamber at the moment of ignition, a high energy spark can be stretched into a loop shape that better ignites extremely lean mixtures because of the greater surface area of such a looped spark.[5] The blue line in Figure 20a suggests that the +60° gap axis is so oriented. That the +60° axis also demonstrated what both cockpit observers noted as smoother engine operation at 6.5 gph than the other two gap axes tested also implies that, for this particular engine, cylinder, throttle setting and RPM, the +60° axis provides more complete ignition than the others tested.

Figure 20b shows the control values for cylinder #2's EGT at the exact same second at which the data in Figure 20a was obtained for cylinder #4. There is close agreement in cylinder #2's EGTs on all three flights. If any difference in fuel flow *is* apparent between the second flight with +60° gap (blue line on graph) versus the first or third flights, it was that the second flight used a slightly richer mixture at the nominal 7.0 gph setting. For example, if the second flight used 7.05 gph where the other flights used 6.95 gph, the slightly higher (blue) EGT in Figure 20b would be the expected result at the 7.0 gph point.

If indeed the second flight had such a richer mixture, this would be expected to cause *higher* EGTs for the blue line trace at the 7.0 gph point in Figure 20a. Instead, Figure 20a shows the blue line trace to be *lower* at the 7.0 gph point. This implies that the observed differences are real and not artifact or noise.

The fact that the dark blue line plummets at the 6.2 gph setting is likely due to the spark being blown out by a 'wind' in the combustion chamber that likely blows perpendicularly across the +60° gap axis. This 'wind' may be somewhat blocked by the 'upwind' electrode with both the -30° and +10° axes, thus their sheltered gap can escape having its spark stretched out to a larger arc length. A stretched spark blows out when the spark energy is no longer sufficient to ionize the scarce (lean) molecules across its longer arc loop length.

Note that at 8.0 gph, with its easy-to-ignite, faster burning mixture, the gap axis appears to have little or no effect on EGT.

Figure 21. Spark plug electrode axis color corresponds to those in Figure 20a.

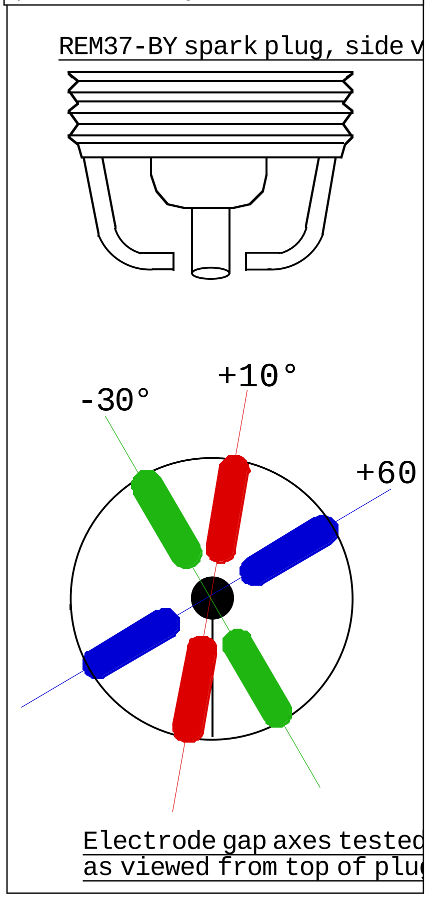
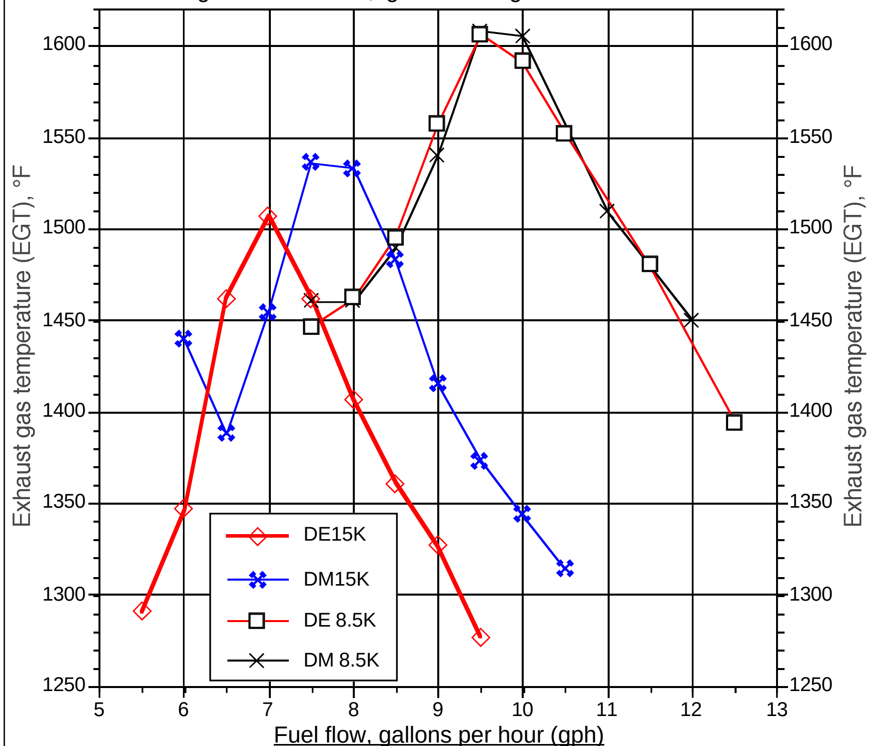


Figure 22. EGT#2, ignition timing advance effects.



Mooney N6057Q. EGT of cylinder #2 (richest) at 8,500' and 15,000' density altltudes. Wide open throttle, 2550 RPM, wing Barograph #3. Cowl flaps fully opened. DM at 25° BTDC. DE at 30° BTDC @ 8,500' and at 41° BTDC @ 15,000'. Vetter DAD records. DM = dual Bendix 1200 magnetos. DE = dual electronic ignition, Electroair EIS-1.