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Carburetor Ice Test Methodology Evaluation Final Report

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Carburetor Ice Test Methodology Evaluation Final Report

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1. Summary and Background

Summary: The purpose of this project was to attempt to replicate the ESSO aviation piston engine carburetor ice tests from 1951 in collaboration with the FAA William J HughesTechnical Center in Atlantic City, New Jersey USA, and to document in more detail the test set up, such that these tests can be replicated by other researchers. The project delivered three major elements:

1) Set up of a Continental C-85-12 engine and carburetor air inlet conditioning systems in such a manner as to replicate/validate the 1951 study results of Grade 80 gasoline, using modern 100LL gasoline.
2) Establishment of test set up parameters, engine run conditions, and data collection methods, and development of a documented testing protocol.
3) Repeated operation of the engine the icing tests to determine the robustness of the method. While icing and commensurate drop in engine revolutions per minute (RPM), of $\geq 100$ RPM was achieved at 50° F (10° C) and relative humidity of 95% to 97% relative humidity for test runs, it was noted that:

- Repeatable formation of ice/rpm drop was more challenging than expected.
- Conditioning of intake air to meet the 95% to 97% relative humidity could be at the limit of available hardware and was constantly influenced by atmospheric pressure.
- Control of carburetor body temperature may be more critical than anticipated.

A number of recommendations have been offered to address these issues.

Background: It has recently been discovered that, in 1951, the ESSO Corporation developed a laboratory icing test using different fuels that fell within the specification of that time. A horizontally opposed, four cylinder, 85 horsepower Continental C-85 engine with no carburetor inlet air heating was the engine of choice and was used for their test development. This testing also established the baseline experience for the expectation of carburetor venturi icing using the aviation gasoline formulations commonly produced in the early 1950’s. This data was then used by engine and airframe manufacturers in the ensuing decades as they developed engine induction systems, and engine operating standards, in order to prevent or minimize carburetor ice. However, the published reports of the day did not give a test protocol or test methodology for the ESSO work. The purpose of this project is to develop those protocols and methodologies for use as a screening test for fuels development.
2. Literature Survey

A literature survey was undertaken to identify earlier studies into aviation piston engine carburetor icing. Nineteen documents were located and a brief summary of each is provided in this section.

The following literature review has direct quotes from the studies cited, and there are a number of common terms that are best defined here for ease of reference:

- CR (compression ratio)
- RPM (revolutions per minute)
- A/C (aircraft)
- RH (relative humidity)
- TO (take-off)
- EGT (exhaust gas temperature)
- F/A (fuel air ratio)
- \( Z_2 \) (Carburetor icing rate)

a. Early Carb Ice Research

|---|---|---|

Swan summarizing Clothier

- Testing used a special unleaded 73 octane fuel that was more volatile than 100/130 octane fuel
- Saturated air has moisture condense due to adiabatic cooling (fuel evaporation)
- As the relative humidity of the air increases, less temperature change is required to get to 0°F. Dry air had to drop 23°F because the energy to get the fuel to evaporate is obtained from the condensation of the water from the air (as opposed to having to heat the fuel to get it to evaporate).
- A half open throttle is the worst position with respect to icing due to increased evaporation and change of pressure of fuel through the throttle and air expansion further reduces temperature by 6°F (except at full throttle)
Bench Testing of Carburettors Some Methods in Use with Particular Reference to Mixture Characteristics

Clothier, W.C. M.
Aircraft Engineering, 1938, Vol.10(9), p.274-281

- Important variables – density of air as variations to fuel temperature and fuel density are relatively smaller
- Carburetor does not care from where the change comes – therefore you can simulate altitude by changes in air inlet pressure
- For carbs with devices responsive to pressure, the pressure applied must equal that of the altitude corresponding to the air density of the intake air, not the intake air pressure

Icing in Induction Systems

Kimball, Leo. B.

Review of induction testing

- Research group was formed – Powerplant Committee of the National Advisory Committee for Aeronautics – Subcommittee – Induction Systems Deicing
- The NACA studies used the large altitude lab at the National Bureau of Standards
- Engine G200 Cyclone and 1375 Holley carburetor
- Normal cruise, 4000 lbs/hr of air, F/A = 0.070, 20° throttle
- Conclusion: rate of ice formation goes up with F/A ratio, and increases with decreasing water droplet size
- The most dangerous point is 30°F air and fine water droplet

Investigation of Icing Characteristics of Typical Light Airplane

Coles, Willard
1949 Feb NACA Tech Note No. 1790

Most similar to Current CRC Study

- Not an engine run
- Vitiated air using -20°F refrigerated air and air heated using an electric heater to obtain the desired inlet air temperature
- Fuel temperature had no detectable impact on the experiment
- Used steam to generate the relative humidity
- Measure wet and dry bulb in plenum at the carburetor inlet
- Looked for ice on the idle fuel discharge holes – considered serious
- Throttle angle found to be critical
A tabulated summary of the work by Coles gives:

<table>
<thead>
<tr>
<th></th>
<th>Upper limit of visible ice °F</th>
<th>Upper limit serious ice °F</th>
<th>Lower limit RH %</th>
</tr>
</thead>
<tbody>
<tr>
<td>High cruise power</td>
<td>62</td>
<td>62</td>
<td>80</td>
</tr>
<tr>
<td>Low cruise power</td>
<td>70</td>
<td>63</td>
<td>60</td>
</tr>
<tr>
<td>Glide</td>
<td>93</td>
<td>93</td>
<td>30</td>
</tr>
</tbody>
</table>

|------------------------------------------------------------------------|---------------------------------------|-----------------------|

- The change in temperature can be determined if the flow is assumed to be isentropic
- Experiments with carburetors show fuel evaporation icing at inlet air temperature of 102°F meaning a local temperature reduction of up to 70°F
- Experiment determined serious throttling ice only at air temperatures <39°F and RH 100%

There was a noticeable gap in research until the 1970s and 80s

|----------------------------------------------------------------|-------------------------------------------------|------------------------------------------|

- Carburetor ice correlates to the greatest degree with distillation curve, especially at 10, 50 and 90%
- And with water density and fuel vapor pressure
- Icing rate increases with a decrease in density
- Icing rate increases with decreases in distillation
- Icing rate increases with increases in vapor pressure
- Properties also correlate with each other – 10% with vapor pressure
- Created a carburetor icing rate $Z_2$ as a function of the gasoline qualities
b. Military Research

| A Laboratory Investigation of Icing and Heated-Air De-Icing of a Chandler-Evans 1900 CPB-3 Carburetor Mounted on a Pratt & Whitney R-1830-04 Intermediate Rear Engine Section | Essex, Henry A ; Galvin, Herman B | AIRCRAFT ENGINE RESEARCH LAB CLEVELAND OH 1944 |
| Fluid De-icing Tests on a Chandler-Evans 1900 CPB-3 Carburetor Mounted on a Pratt & Whitney R-1830-04 Intermediate Rear Engine Section | Galvin, Herman B ; Essex, Henry A | 1944 |

Chandler Evans Carburetor on PW R-1830C4
- No supercharger, used constant displacement, exhausters to induce air flow
- If ice formed below impact tubes and streamlined venturi bars, F/A varied less than 2.5%. But at idling range, the variation was as much as 10% lean
- When ice formed on the tubes and bars, the metering suction was disturbed, causing F/A ratios as high as 0.130
- Second report was run at 25°F and 40°F inlet air temperature and rated power
  - 7000 lb/hr air, F/A = 0.100, and cruise 4000 lb/hr and 0.070
  - RH = 100%

Bendix Stromberg Carb on PW

| Bendix Stromberg Carburetor on PW R-1830C4 | Galvin, Herman B ; Essex, Henry A | 1944 NACA-WR-E-18; NACA-ARR-E4J18 |
- Pressure altitude 750 to 2700 feet
- Carburetor air at 20°F to 95°F
- RH from 19 to 100%
- Looking for 50lb/hr drop in air flow
- Ice formed primarily on the throttle plate
- Designs that result in cooling of the throttle plate by evaporating fuel that eddies back in its wake
- Also need to avoid fuel spray or back flow on the turning vanes of the supercharger impeller
Series of five war reports studying induction system icing – throttling, fuel evaporation and impact

- Run on electric dynamometer driving the turbocharger, no running the engine
- Limiting ice condition – specific combination of carb air heat and water content
  - Only related to heat content when the air is fully saturated
- Turbulence from the turbocharger rotation responsible for much of the refrigerator ice
- Fuels of low volatility produced less severe icing (less evaporative cooling)
  - Testing done with high volatility fuel for conservative results
- Throttle ice dependent on throttle angle as opposed to rate of air flow
  - At air flow of 4620 lb/hr of air, 27° throttle position, ice occurred at 50°F
- Fuel/air ratio varied 0.050 to 0.131 – no effect, 0.050 is already the worst case
- Fuel temperature varied 9°F to 80°F, no effect with carb air at 40°F
  - Fuel evaporation offsets increased heat content
- Example – Severe ice carb air T=35F, R/H = 100%, air flow 4670 lb/hr, F/A ratio = 0.080, saw a min air flow of 4535 lb/hr at time = 15 minutes
Ground and flight testing of “the induction system of a Twin Engine Fighter (probably an F82 Twin Mustang)

- Manifold pressure in inches of Hg absolute – 30 to 54
- 2200 (low cruise) to 3000 (take off) rpm
- Ambient air temperature 23°F to 37°F
- Ground studies from idle to T.O. power
  - A/C was not susceptible except at manifold pressures 40”Hg or higher and excessive rain
- Fuel was 100/130
- Test runs 3-6 minutes, except at low power (10 minutes)
- Testing correlated to lab testing
- Flight test did not duplicate the ground testing

|---------------------------------------------------------------|------------------|-----------------------------------------------|

Large twin engine cargo plane, likely a C47

- 32-36F experienced serious throttle ice
- Ran at maximum of 60% power due to test cell limitations
- Most interested in the supercharger
- Used 2 capsule pressure recorders for carb metering suction differential and orifice differential for air flow and air an fuel flow calculations
- F/A ratio calculated using a Wheatstone bridge measuring combustible in the “exhaust”
- Engine operation was simulated using 160°F oil

c. 1970’s/ 1980’s the FAA and Canadian Aviation Research

In the late 1970s and early 1980s the FAA and Canadian Aviation authorities authorized research on carburetor icing due to concerns rising from the use of the more volatile automotive gasoline

<table>
<thead>
<tr>
<th>Aircraft Carburetor Icing Studies (Canada)</th>
<th>Gardner, L ; Moon, G.</th>
<th>1970</th>
</tr>
</thead>
</table>
- V8 automotive engine, 283 in³ coupled to 2 – 800HP dynos
- Updraft aircraft carburetor
- 90° bend and flange above the carburetor made of Plexiglas for visual ice inspections
- Throttle shaft fitted with a pointer, leading to an arbitrary scale marked in degrees to allow accurate resetting of the throttle plate
- Fuel 100/130
• Humidity and temperature control obtained with an ice tower of the type used in octane rating
• Inlet air 37-40°F
• RH = 95 – 98%
• Cooled fuel generated more durable ice so it was cooled to 37°F and equilibrated to 45°F at the carburetor.
• Optimum throttle setting to arbitrary 40° = 70% of maximum throttle opening
• Started with a constant load and measured the RPM drop, but later maintained RPM and measured the manifold pressure
• Ice formation was immediate and continuous, although it slowed with growing restriction

<table>
<thead>
<tr>
<th>Light Aircraft Piston Engine Carburetor</th>
<th>Cavage, William ; Newcomb, James ; Biehl, Keith</th>
<th>DPTFAA/CT-82/44 June 1982</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Detector/Warning Device</td>
<td></td>
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<tr>
<td>Sensitivity/Effectiveness</td>
<td></td>
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</table>

Suspected that the high vapor pressure autogas would be more prone to icing
• Continental O-200A, 201in³ displacement, CR 7.0:1
• Cessna 150 gravity feed, 0.9 psi at the carb inlet with 13 gallons
• Carburetor – Marvel Schebler MA-3SPA, dual mags, Slick 4201
• Figure 2 shows data/test equipment placement, Table 1 lists it
• Static test cell engine installation without A/C cowling and dynamic flight conditions, lower engine did not dissipate the heat as quickly as in flight, therefore warmer and more conservative
• Cooling air delta P across cylinders held at 4” water, which is higher than A/C = more heat dissipation
• Ice was noted within 30 seconds at low RPM
Flight Test Results of the Use of Ethylene Glycol Monomethyl Ether (EGME) as an Anti-Carburetor Icing Fuel Additive
Newman, Richard L 1979

Studying the Efficacy of EGME to deal with carb ice – this was a flight test
- The acceleration of the air produces a pressure drop which causes a temperature drop. Drop can be as much as 30°F in the venturi
- Fuel evaporation will drop the temperature to ~37°F
- Critical factors inlet temperature, RH and throttle angle (smaller angles more susceptible to ice)
- PA 23-150 Apache test with 2 Lycoming O-320-A38
- 80 octane fuel with 100LL where necessary
- Cruise – leaned to peak EGT
- Descent – full rich
- Carb air temperature gauges, not effective in predicting ice
  - EGT is more sensitive but it was not steady enough to be used as a measurement

<table>
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<tr>
<th>Light Aircraft Piston Engine Carburetor Ice Detector/Warning Device Sensitivity/Effectiveness</th>
<th>Cavage, William ; Newcomb, James ; Biehl, Keith</th>
<th>DPTFAA/CT-82/44 June 1982</th>
</tr>
</thead>
</table>

Studying warning devices
- Continental O-200A, 201 in3, 7.0:1, Marvel Schebler MA3SPA
- Cooled 100LL
- 2 – 1800 BTU/hr Freon type vapor cycle air conditioning units ducted together
- Humidity – water spray to RH=100%
- Carb heat – ducted heated or cooled air
- Engine was broken in then run in the same way as above
- Ice monitor was 2 boroscopes
- Under static test reliably experienced a drop to 600RPM
- Carb idle jet pressure was a good response to icing. Showed fluctuations before a performance drop was seen
- Did not have exhaust emissions analyzing equipment so could not study the F/A ratio
3. Test rig design

It should be noted that temperatures given in this report are given primarily as degrees F, since the data and charts in Esso report on which this project is tasked with replicating, are given in degrees F. This is done in order to facilitate comparison with the original Esso report. Conversions to degrees C is provided as the secondary measures.

The test rig for the carburetor ice testing consisted of a normally aspirated, horizontally opposed, Continental C-85-12 aircraft engine, Serial number 21988-6-12 (Figure 1). As per the original Esso report this C-85 engine was equipped with a Marvel Schebler, MA-3A float type carburetor, serial number CR 1 66666 (Figure 2). The engine was obtained from inventory from the Aviation Technology propulsion laboratories, where the engine was used frequently for student education, as both an operating engine and for demonstrations of cylinder removal and installation.

The engine was inspected by professional mechanics prior to the test program and found to be of suitable health. Cylinder compression tests indicated acceptable airworthy status, all well above the 60 psi minimum; carburetion checks revealed proper idle mixture flows; and magneto checks indicated proper firing of all eight spark plugs, at proper ignition timing, with single magneto operation RPM drops to be in the proper limits. The engine was installed on a portable engine run stand, where it could be operated using the proper propeller for this engine application (Figure 3).

The intent of the study was not to make a generalization to the applicability with respect to modern engines, or engines of larger size and complexity. The choice of engine was made primarily based on the fact that the unit was the one specified in the original ESSO study. However, it was also felt that replicating the study using the same model and carburetor would establish this as an affordable, available test article for future icing work. As such, fuel developers selecting the C-85-12 could do so in the assurance of a known standard allowing icing characteristics to be attributed to fuels and not differences in engines type. Using the C-85-12 as the carburetor icing test article engine, was the same in concept as the way that the United States Air Force Research (AFRL) labs had been using a Rolls-Royce (Allison) T-63 turbo shaft helicopter engine as an affordable screening engine for turbine fuel.'
It was decided to operate the engine using a propeller load instead of a dynamometer load for three reasons. First, using a suitable propeller for this engine automatically provides the proper engine load over the complete range of engine RPM. The varying power output of the engine with ice buildup would have required and extensive study on a dynamometer to determine the predictability and repeatability of the engine power output vs. RPM given unpredictable variations in carburetion as ice accumulated. Second, using propeller load makes replicating this work in the future much easier and affordable. Third, small engine dynamometers (i.e., water brake dynamometers), necessary to match the low horsepower output of the C-85 engine, are known to lack repeatability of set points.

A carburetor air inlet plenum was constructed to adapt an eight-inch round, diameter air delivery duct to the engine (Figure 4). The square plenum box was constructed in such a way as to support the weight of the air delivery duct without imposing any mechanical loads on the carburetor inlet air box. In order to provide a large plenum in advance of the carburetor air box inlet, the carburetor air box was removed from the engine, rotated 90 degrees to the left and installed on the carburetor. This was done in order to be able to create a large plenum adapter. If the carburetor air inlet were to face forward, as installed on an aircraft, a large plenum chamber would have been precluded by interference with the plane of rotation of the engine propeller.
Originally, the concept was to create a large plenum adapter below the carburetor and to channel the air to the carburetor inlet box through a small square duct, however this original design was abandoned due to concerns about restricted air flows needing to make sharp bends prior to the carburetor inlet, and the affect that it might have on maintaining proper water suspension in the air.

A decision was also made to only condition the inlet air going into the carburetor, and not to immerse the entire carburetor in a cold flow duct. This decision was made for two reasons. First, there was an unknown as to how much air leakage could be allowed from a fully immersive plenum chamber and still be able to provide the proper airflow volume to the carburetor inlet. Second, there were concerns that if a large, fully immersive plenum were built around the carburetor, control of the humidity going in the inlet would be unpredictable. There were concerns that humidity might fall out of the air in such a plenum chamber. It was felt that a more conservative approach to humidity control would be to provide ducting directly to the carburetor inlet.

The graphs in the Esso report (Appendix I), shows that ambient air surrounding the carburetor was approximately the same as the temperature of the air going into the carburetor inlet. A fully immersive plenum chamber design would have facilitated this temperature control, however it was felt that the matching of the external carburetor area temperature could be done sufficiently by matching the carburetor inlet flows to the ambient temperatures of the day when the test was run. Since the tests were scheduled to be run in the fall of 2014 in central Indiana, matching these temperatures was deemed to be a simple task.
Once experience was gained in the control and measurement test parameters, it was felt that a
determination should be made if additional processed air could be used to regulate the carburetor
temperature. This would then alleviate the need to wait for appropriate ambient temperature conditions
for test runs.

The engine inlet plenum was connected to an Environmental Tectonics Corporation, CAS-700 system,
via 8-inch round duct work (Figure 5). The engine was located 25 feet from the outlet of the CAS-700,
which was well within the thirty (30) feet maximum distance allowed for conditioned air, as specified by
Environmental Tectonics for the CAS-700. The 40° F (4.4°C) and 50° F (10.0°C) and 95% humidity,
respectively, as shown on the curves in the Esso report, were known to be at the extreme limits of the
specifications for the CAS-700. Conversations with representatives from Environmental Tectonics
Corporation indicated that the 40° F (4.4°C) point called out in the Esso report was likely beyond the
capability of the CAS-700, the 45° F (7.2°C) point was possible. For the points between 50° F (10.0°C)
and 60° F (15.6°C), the CAS-700 was able to meet these temperature, humidity, and dew point
parameters.

Figure 5 The combustion air processing unit
Insulated ducting was fabricated to run between the CAS-700 and the outdoor engine run stand. Insulation was added to ensure minimal heat rise in the conditioned air. A temperature rise of 2° F (1.11° C) was seen between the output of the CAS-700 and the engine inlet plenum. This temperature rise was corrected at the CAS-700 source to allow for the temperature increase, and still provide the target temperature at the engine inlet plenum.

To confirm target the humidity of the air at the engine plenum, an Omega Engineering, Inc., RH-USB temperature and humidity probe was installed at the carburetor inlet plenum (Figure 6 external view of probe) (Figure 7 internal duct view of probe looking in the duct at the carburetor air filter). This probe connected directly to a standard PC computer to provide a direct readout of the temperature and humidity of the air at the plenum (Figure 8). The specifications for the RH-USB probe are given below. All temperature and humidity readings in this report were recorded via this probe.

**SPECIFICATIONS**

**Temperature:**
- **Range:** -17 to 49ºC (1 to 120ºF)
- **Accuracy:** ±1ºC (±1.8°F)

**Relative Humidity:**
- **Range:** 2 to 98% RH
- **Accuracy:** ±3% RH (@ 15 to 90% RH)
- **Repeatability:** ±1% RH

**PC Interface:** USB

**USB Cable:** Integral to sensor, 2 m (6') (shielded) Type A plug

**Software (Included):** Requires Windows® 2000, XP, or Vista operating system

**Housing:** 316 stainless steel

**Dimensions:** 138 L x 16 mm D (5.5 x 0.625")

**Weight:** 67 g (0.18 lbs)

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Figure 6  Exterior view of humidity probe in plenum
Preparatory engine runs were made with this probe in place, to verify that the insulating material between the engine exhaust and the plenum chamber was sufficient to ensure that there would be no measurable radiant heating of the inlet air from the engine exhaust. Repeated test runs confirmed that the temperature in the plenum remained unaffected by the heat from the engine exhaust.

Additionally, the Omega probe was placed in the duct at the exact location of the temperature/humidity sensor for the CAS-700 conditioned air system, and the readouts from the Omega probe matched to those of the sensors in the CAS-700. This verified that the temperature and humidity being monitored at the engine, indeed corresponded to the temperature and humidity being produced at the outlet of the CAS-700.
Engine RPM was monitored for gross RPM movements using the standard engine tachometer. However, for precise RPM monitoring and for verification of the tachometer accuracy, a Honeywell Vibrex 2000 propeller balancer and vibration analyzer was connected to the engine (Figure 9). The Vibrex 2000 was widely used in the aviation industry for helicopter rotor and propeller blade balancing, where repeatability and precision were required.

The Vibrex 2000 was capable of detecting RPM changes to within one RPM. The unit used a photocell (Figure 10) to sense the passing of a reflective target stuck to the aft side of the engine propeller.
A photocell (Part Number 902-12900, SN 04565) was procured from Diagnostic Solutions International, LLC, Ontario, California (an authorized distributor and service center for the Honeywell/Chadwick Helmith Vibrex 2000.)

The fuel system consisted of a 25 gallon stainless steel fuel tank, located on the top of the test stand. The fuel was gravity fed to the engine via a fuel strainer/filter. The strainer filter had a glass bowl, which allowed for a visual check for any water in the fuel. (See Figure 11) When not in use the engine was stored in an indoor, dry, heated space. (See Figure 12). Two different batches of fuel were used in this experiment. The first batch sat in the engine fuel tank for approximately 6 months before the test and the second batch was fresh 100LL aviation gasoline, procured locally from Lafayette Aviation, Inc., West Lafayette, Indiana. Inspection data is provided in Appendix III. Some ‘weathering’ of the test fuel is apparent where the vapor pressure has reduced to 33.9 kPa and the T10% increased above 167° F (75 °C). This is a result of the time necessary to build/commission the test equipment, storage conditions and mixing of batches. Some discussion of how this might have impacted measurements is provided in the Results of Testing, Conclusions and Recommendations sections of this report. As a general note the 100LL fuel from the chosen supply source has always been found to be of a consistently high quality, with this anomaly is due to the circumstances mentioned.
4. Test Methodology

Assumptions and delimitations

Consultation with Dave Atwood, the FAA William J. Hughes Technical Center, Atlantic City, NJ, was required to define several of the delimitations and assumptions for this testing. First, original Esso report specified that the engine was run on “Aviation Grade 80” gasoline. For this test, octane aviation gasoline was highly impractical to obtain, so the decision was made to attempt to replicate the Esso tests using a contemporary 100LL aviation gasoline. At the time of testing the gasoline was sampled, for later be evaluation of moisture content, or other tests deemed suitable at a later date.

After the initial engine set up runs, the decision was made to conduct the tests without the engine air filter installed. Set up testing with the filter installed, revealed that the engine inlet filter seemed to be providing a condensation point for the humid air entering the engine intake. Runs with and without the engine inlet filter, under same day conditions, revealed that with the filter installed there was less carburetor icing. In addition, the type of inlet filter used, pleated paper media vs. open cell foam type, could cause further variations. Post run inspections of the filter media, on runs with the filter installed indicated a saturated wet filter media and indications that water had been condensed on the filter media and not passing through to the carburetor. There were also visual indications that the humidity in the air had condensed on the filter media and had exited the rear of the filter as water droplets. Given the knowledge that the type of icing being evaluated was related to fuel evaporation ice and venturi ice, the presence of water as droplets would not provide the data desired. Water droplets would form impact ice on the front side of the throttle plate, but this typically would only happen at temperatures closer to 32°F (0°C). Based on these assessments, the decision was made to conduct the tests without the carburetor inlet filter. The CAS 700 provided air filtration at the inlet to the combustion air processing prior to the chilling and humidification of the air being delivered to the engine, so the engine was still receiving clean filtered air.
The point of the test was to attempt to repeat the Esso work, evaluate any differences in the graphs between the contemporary 100LL aviation gasoline and the original grade 80 fuel, determine if icing could be reproduced, and to document the test set up and procedures for successfully conducting an icing test. Therefore, while the omission of the air filter would not be representative of the operational fleet, it was acceptable for the present study.
Test procedures

1. Perform pre-run inspection, including inspection of the system fuel sump for any visible water in the sight glass.
2. Acquire the current ambient temperature, relative humidity, dew point, and barometric pressures.
3. Verify the ambient temperature and relative humidity using the Omega probe.
4. Start and stabilize the CAS-700 for 30 minutes prior to programming the set points. This was done with the air supply duct disconnected from the carburetor inlet plenum. See Figure 3 above.
5. Connect the CAS-700 to the engine inlet and cool the carburetor to the temperature set point of the test, but at ambient or low humidity.
6. Engage the temperature and humidity set points on the CAS-700.
7. Verify the ambient temperature and relative humidity using the Omega probe.
8. After approximately 30 minutes of stabilization time, operate the engine for 3 minutes to warm the engine at 1000 RPM.
9. Shut down the engine, and connect the conditioned air duct to the carburetor plenum.
10. Restart the engine, and idle at 1000 RPM for 30 seconds.
11. Verify the temperature and humidity of the air in the plenum using the Omega probe.
12. Increase engine speed to 1750 RPM as specified in the Esso report, and start the clock, and initiate data recording with the Omega software.
13. Manual recordings of RPM, temperatures, and humidity were made at one minute intervals.
14. If RPM degraded, note the time and amount of RPM loss.
15. Continue the test for twenty (20) minutes.
16. At the twenty (20) minute mark, reduce the engine speed to idle and stabilize idle if possible. At the same time, reduce the conditioned air supply to reflect ambient temperatures and humidity. Note: Longer duration tests of 30 minutes were conducted to determine the extent of rpm drop on some runs.
17. Idle the engine for two (2) minutes and shut down.
18. Collect 10 ml sample of gasoline used for later analysis. Sample should be collected using acceptable scientific fluid collections procedures to prevent contamination of the fuel during the collection process. For these tests, the samples were taken using a pipettes, and standard sample jars directly from the fuel tank.
19. The engine should be allowed to rest for two hours in an environment of 60° F (15.6° C) to 70° F (21.1° C), before a repeated test is made in order to ensure that the carburetor is clear of ice from any previous runs.
5. Results of Testing

Most of the early work on this project in the spring and early summer of 2014 was in the background research, setup of the CAS-700, fabrication of the plenums and ducts, and the preparation of the engine. Fortunately, this background work coincided with unusually severe winter weather in the spring of 2014 that precluded any runs in the cooler spring weather.

Engine runs were made during the CAS-700 calibration set up by Environmental Tectonics Corporation in September of 2014. Measurements done during the runs in this configuration revealed estimates of heat gains of around 2°F (1.11°C) between the CAS and the engine. These heat gains were anticipated. The CAS-700 output was adjusted to meet the temperature and humidity readings from the Omega probe.

This was relevant because during the calibration runs of the CAS-700, the factory technician set the combustion air processing unit to the 50°F (10.0°C) and 95% humidity setting. Cold fog was observed coming out of the end of the 8-inch duct at the engine. An engine run made in this configuration produced a drop in RPM. This event was reported in the September monthly report to CRC.

“ETC completed the system repairs and calibration over the weekend of October 4 and 5. During the calibration runs for the combustion air unit, the engine was installed on test and operated successfully. Of note, during the calibration runs for the combustion air unit, the parameters were set to 50°F (10°C) and 95 percent humidity. The engine was run at that setting for eleven minutes. At 7 minutes a 100 RPM drop was noted, and after 11 minutes a 160 RPM drop was noted. This provided at least some evidence that the system was going to be able to generate induction system ice.”

When the gains in heat in the uninsulated duct were factored in later, the 50°F (10.0°C) setting at the CAS output was estimated to actually be around 52°F (11.1°C) at the carburetor plenum, with a corresponding slight lowering of humidity. This data then plotted very closely with the 55°F (12.8°C) test point on the graph in Figure 5 of the Esso report in Appendix I of this report.

With this very encouraging data point, completion of the duct insulation was done, and the Omega sensors were correlated with the CAS outputs. Unfortunately during the final calibration by the Environmental Tectonics Corporation technician, the boiler system used for generating the system humidity developed a number of substantial water leaks at soldered fittings, of a magnitude severe enough to preclude further runs until repairs could be made. As of the first of November of 2014, most of the leaks were stopped to the point where further testing could commence.

Testing resumed in late November of 2014 and continued through mid-December of 2014. Various temperature and humidity settings were attempted, and correlations runs were made to match the humidity sensor output on the CAS-700 with the readings on the Omega humidity probe. The ambient air temperatures were between 40°F (4.5°C) and 50°F (10.0°C). These ambient air temperatures provided an external carburetor air temperature in the ranges indicated in the Esso report. Runs were made to evaluate the connection protocols between the CAS-700 and the engine. It was noted that on some runs, the RPM would fall off between 150 and 250 RPM, given the expected carburetor ice indications. There was, however, a problem with consistency of the icing of the carburetor, since this
RPM loss was not evidenced on every run. Runs to correlate plenum temperature, CAS-700 output temperatures, CAS-700 output humidity, and open vs. closed plenum connections were evaluated. However, under seemingly identical conditions there might or might not be carburetor ice formation. After repeated runs, a correlation was noticed with ambient atmospheric conditions related to high vs. low barometric pressure readings. The CAS-700 did not control atmospheric pressure, and as such the ambient air pressure in the engine plenum duct could vary given different ambient barometric pressures.

It was noted that on days with all other conditions identical, that a barometric pressure above 30 in-hg would preclude ice formation. Further refinements of this finding indicated that barometric readings as low as 29 in-hg might inhibit the ice formation. Runs of the CAS-700 were conducted to experiment with this finding running open ductwork at the engine, but without the engine connected to the air supply duct. On days of low barometric pressures, the Omega probe would read 97 to 98 percent relative humidity at the air supply duct, and large amounts of visible fog could be seen coming out of the air supply duct. At that point, the air supply duct was checked prior to each engine run to see if visible fog, and a 97 to 98 percent relative humidity reading were present prior to the engine runs. Where visible fog was present, engine icing occurred as anticipated. Where no visible fog occurred engine icing did not occur.

With this correlation noted, further runs were made on days with low ambient barometric pressures. Under these conditions the engine displayed the desired icing tendencies.

Figure 5 of Esso study reported a bell curve where at 40° F (4.4 C) produced a 100 RPM drop, 50° F (10.0° C) produced a 400 RPM drop, and 60° F (15.6° C) produced a 75 RPM drop. Given that the purpose of the test was to demonstrate the repeatability of the 1953 Esso report and to establish a procedure and process for replicating the ice formation described in that report, it was decided to make the testing runs at the 95% humidity and 50° F (10.0° C) levels, in order to demonstrate the worst case icing conditions in the Esso report. It was decided that it was most important to see if a 400 RPM drop could be repeatedly produced.

The engine was run using the 50° F (10.0° C) and 95% relative humidity points. Four separate tests were conducted following the procedures specified. The carburetor inlet temperature and relative humidity were kept constant during the engine runs. Throttle position was held constant. Engine RPM was recorded every 60 seconds. The engine began to show signs of ice with a drop of engine RPM. Many runs were made at this set point, however, only the four “official” test runs were included in this report.

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>Ambient Temperature C</th>
<th>Ambient Humidity %</th>
<th>Ambient Pressure in Hg</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>10-Nov-14</td>
<td>14</td>
<td>58</td>
<td>29.74</td>
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<tr>
<td>2</td>
<td>10-Nov-14</td>
<td>16</td>
<td>47</td>
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<td>17</td>
<td>41</td>
<td>29.64</td>
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<tr>
<td>4</td>
<td>11-Nov-14</td>
<td>13</td>
<td>66</td>
<td>29.71</td>
</tr>
</tbody>
</table>
Figure 5 of the Esso report attached in Appendix I, shows that at 97 percent humidity, 50° F (10.0° C), barometric pressure unspecified, that a 400 RPM drop could be seen in approximately 5 minutes. In Figure 13 of this report, it can be seen that the RPM drop did happen, but over a longer period of time. As noted in Section 3 and Appendix III, the possible variation in fuel volatility between the current and earlier Esso work may be a contributory factor to this observation. This time window for ice accumulation, however has proven consistent with this engine and this CAS 700 unit regardless of the 100LL fuel operated in the engine. Runs 1 and 2 were terminated at 20 and 25 minutes respectively, since there were no further indications of continued RPM loss, and the engine had displayed indications of self-clearing of the ice. Runs 3 and 4 were allowed to run longer since the icing showed indications of increasing as time went on. Run 4, produced a drop in the shortest duration, however it also did not begin displaying substantial RPM losses for about 11 to 12 minutes. It should be noted that on many of the set up runs, there would be an initial 150 RPM loss after 5 to 10 minutes, and then the engine would continue to function at that level for another 20 or 30 minutes. In some cases the engine would demonstrate a 150 RPM drop, and then the ice would self-clear and the engine would return to full RPM. See Figure 14. After the ice self-cleared, the test run was aborted and the engine allowed to warm before additional testing. The engine was resistant to ice formation, regardless of the amount of cold, humid air delivered to the engine inlet. It is interesting to note that the initial formation of ice produced a slightly audible difference in engine sound, slightly lower frequency and smoother. This slight audible difference preceded any observed RPM or manifold pressure drop.

**Figure 13 Plots of RPM vs. Time for the four “official” ice runs**
While there were over twenty engine runs made to test the set up and manipulate parameters, there were four “official” runs made where the intention was to predictably get ice formation. That data is recorded for this report. After the issues with barometric pressure were accounted for, and the carburetor icing was induced. 10ml samples of fuel were taken post run on all four official runs, and were stored for moisture content analysis.

Figure 14 Example of ice formation where ice self-cleared
A longer duration test of 50 minutes was performed to determine the extent engine rpm loss and if the drop in rpm would stabilize. Figure 15 in this report shows an extended ice run to determine how much RPM degradation was possible. During the test, engine rpm continuously dropped until the engine RPM had degraded to 600 rpm. The engine had to be shut-down using the magneto switches and fuel shut off valve, after loss of control of the throttle and mixture due to ice in the carburetor was discovered. When the engine was shutdown, fuel was observed leaking from the carburetor until the carburetor was again warmed. No further engine testing was then conducted past the 30 minute mark for safety reasons.

**Figure 15 Operation of engine with ice until loss of carb control**
6. Conclusions

Introducing air at 95 to 97 percent relative humidity into the inlet of a Continental C-85 engine can produce a carburetor icing effect in a manner consistent with the Esso report.

Given that the exact test setup and methodology of the Esso report was not available, it was difficult to exactly duplicate the curves within the document. All that could be done was evaluate the curves and then “reverse engineer” a process in an attempt to replicate the data. There were some variables noted.

1. The presence of a carburetor air inlet filter screen,
2. Ambient air temperature/humidity on the exterior of the carburetor,

The presence of a carburetor air inlet filter screen seems to allow the suspended water in the humid air to precipitate out of the air prior to entering the carburetor. Therefore, no air inlet filter or screen is recommended for comparative fuel testing.

If the air temperature on the exterior of the carburetor is warmer than the air entering the carburetor, this may delay the attachment of the ice, due to the slightly warmer aluminum casting walls of the carburetor. This may also facilitate the dislodging, (self-clearing) of the ice during the runs. Therefore, extending the plenum to include the external side of the carburetor is recommended. While total emersion of the carburetor in cold flow was decided against at the onset of this project, experience gained with airflow control to the carburetor indicated that a total emersion of the carburetor was indeed preferred. Experience gained here revealed that proper airflow control to the carburetor was possible with the equipment selected for this project, and that there would be no adverse interactions between the combustion air supply and the running engine.

Barometric pressure was seen to correlate strongly to ice formation, in that it seemed to have a substantial effect on the ability to meet the 95% to 97% relative humidity value. Atmospheric air pressures above 30 in-hg would not produce the humidity values required and noticeable “fog” from the conditioned air supply was not observed. At atmospheric pressures below 29.7 in-hg “fog” could always be observed from the conditioned air source and carburetor icing was predictable at those points. Much time was spent on understanding the effect of atmospheric pressure on the humidity output of the conditioned air, and this was the biggest obstacle in the test set up. The barometric pressure in the supply duct should either be controlled or monitored. If control is not possible, then an evaluation of the test apparatus should be done to determine the maximum allowable barometric pressure that the test can tolerate. It was determined that the combustion air supply should have been better able to compensate for the changes in barometric pressure in setting and holding the dew point. The barometric pressure changes seemed to affect more of the ability of the combustion air source to set and hold the 97% humidity level, than of the engine to create ice at the 97% humidity level. Post-test investigations revealed that the particular style of humidity sensor used by the CAS 700 combustion air source, was particularly prone to saturation at the higher humidifies. It is believed that this saturation of the humidity sensor in the combustion air source precluded consistent dew point set points. On the days however when the independent relative humidity sensors indicated 97% humidity, which happened on the low barometric pressure days, ice did form to some degree in the carburetor. Thus the conclusion is that changes in barometric pressure were affecting the ability of the CAS 700 to set and hold the 97%
relative humidity point, and not on whether the barometric pressure was directly influencing the formation of ice in the carburetor. A replacement probe was ordered, but given a six month back order lead time, was unavailable for inclusion in this project test. Subsequent runs of the system following the conclusion of this test program, revealed that while the newer humidity tolerant probe did help some, the real drive in creating the 95% to 97% humidity was atmospheric pressure. For this combination of engine and inlet air processing, a barometric pressure of less than 29.7 in-hg has proven to be a consistent required variable.

Because the decision was made to use a contemporary 100LL aviation gasoline instead of the 80 octane fuel called out in the Esso report, there is the potential for the data between the current study and the Esso report to be different. The rate at which the engine loses RPM, or the degree of RPM loss, could vary with volatility as noted. Input from representatives of the FAA at the William J. Hughes Technical Center, indicated a belief that any differences were insignificant, and that the tests could be run on 100LL. However, there is no way to know for sure whether there would be any differences or not without details of the product used by Esso. Even an 80 octane fuel blended in 2014 is possibly not of an identical composition as an 80 octane blended in 1951. Therefore there is the possibility that any modern fuel 100LL, or a recent 80 octane blend, would still not address this issue. While everyone, including the researchers in this report, agree there is little likelihood that a modern fuel vs. a 1951 blended fuel is different enough to have an impact on this test, the researchers, would be remiss for not noting this variable.

Of note for this test is the variance in fuel vapor pressure and T10% as detailed in Appendix III. The historical reports provide vapor pressure as Reid Vapor Pressure (RVP) in “lb.”, and the 2015 analysis for the test fuel provides Dry Vapor Pressure Equivalent (DVPE) in kPa. RVP’s ranged from 6.2 lb. to 6.5 lb. for the historical data which is greater than the 33.9 kPa recorded in the current work. DVPE is given in ASTM D5591 as the total vapor pressure in a vacuum and RVP is given in ASTM D323 as the absolute vapor pressure at 100°F, and can include dissolved water. 40 CFR 4065.710 states that the intent is that DVPE to be equivalent to RVP for gasoline. That said, a direct numerical conversion of 33.9 kPa to pounds (psi) would equal 4.9 pounds, significantly lower than the historical data. In addition, T10% was some 20 °F higher for the current test fuel versus the 1947 to 1954 survey. Based on this conversion there would appear to be some potential difference between the historical gasoline and the current test fuel which might account for greater resistance to icing.

With regard to the replication of the curves in the Esso report, the formation of ice in a carburetor under the conditions of the present test, did not happen with the repeatability and predictability that the report curves would imply. Quite the contrary, the engines seemed to be ice tolerant (with regard to venturi ice and fuel evaporation ice) to some degree. In the many set up and test runs performed, it was evident that after initial minor ice formation, resulting in a 50 to 200 RPM drop, the engine continued to operate in spite of the ice, and in several cases self-cleared the ice and returned to full power. The close proximity of the engine control cab to the engine, allowed the researchers to hear and feel the engine as well during the icing process. There was audible evidence of the initial ice formation, and of repeated ice clearing events. As mentioned earlier, if there had been sufficient time the temperature conditioning of the carburetor body was to be investigated using the controlled air supply. Unfortunately this was not possible within the current test program. This may be an important parameter as the ESSO report states ‘Icing occurs when the vaporization of fuel in the intake air stream at the carburetor extracts sufficient heat from the air and surrounding metal surfaces to reduce the temperatures below freezing.’
Maintaining the air surrounding the carburetor at 50 °F is also cited as one of the key parameters. The current test sought to achieve this by identifying ambient conditions to match test temperature. The most severe icing event in Figure 13 was for the lowest ambient air temperature day of 55.4° F (13° C) with highest humidity, 66%, but not quite matching the intake air conditions of 50° F (10.0°C), 95%. This suggests further work could usefully investigate external carburetor environment to improve test effectiveness and repeatability.

The 50° F (10.0° C) with 95% relative humidity point does seem to produce the most dramatic RPM loss. Test runs at higher temperatures, 55° F (12.7°C) and 60° F (15.6° C), produced a slight or negligible RPM loss.

It was discovered over the course of the test runs that the specific type of humidity probe in the CAS-700 would become saturated at high relative humidity at low temperatures. This precluded any meaningful data collection at the low temperature side of the curve, 45°F (7.2° C). A different humidity sensor is available that can measure up to 100% humidity with more accuracy, and at the lower temperature points. The use of this probe can provide better control over the plenum humidity, and can provide the ability to map the low temperature side of the bell curve. This specific type of humidity probe may also be able to compensate for the lack of high relative humidity at high barometric pressure.

For these tests, the lack of mapping of the 45°F (7.2° C) points on the bell curve was not considered to be critical, since the objective was define a process and procedure to produce the desired RPM drops. This objective led to 50° F (10.0° C) being selected as the primary objective. If this test were to be performed on any fuel other than current D 910 aviation gasoline, the need to evaluate both tails of the bell curve would become more important. This is because it is documented, and this test replicates, that D 910 aviation gasoline has a worst case ice evaporation ice and venturi ice formation at 50° F (10.0° C). If a different spec fuel is used, the peak RPM drop may not be at the 50° F (10.0° C) point. The peak point could move up to a higher, or down to a lower temperature. Therefore more evaluation should be done at the points above and below the 50° F (10.0° C) to see if the curve has shifted.

If this test is to be run on any fuel besides a current D 910 aviation gasoline, it is also recommended that the barometric pressure be closely monitored, or controlled, as well. While the barometric pressure has more influence over the ability of the air to suspend water, any substantial difference in venturi temperatures caused by a D 910 fuel vs. any future fuel, could have a different influence on the ability of the air to retain the water in suspension inside the carburetor.

It is also recommended that data curves not be developed based on single runs at given temperature and humidity set points. The engines are tolerant enough of ice formation, to make a single prediction unreliable for a specific RPM loss on any given single run. The engines are generally designed not to form ice, thus on any given engine run, the engine may successfully defeat the ice formation, or successfully clear itself of ice formation. This is the same as Mean Time Between Failure (MTBF) data on engine components being intended to predict fleet averages, and not individual component failures. Curves for carburetor icing should be derived from a series of runs with times and RPM losses being averaged to develop a representative curve. The researchers on this project have concluded that this is most likely what the original Esso researchers had done in establishing the icing curves published in their report.
7. Recommendations

At some future point, a fully instrumented, windowed carburetor (or electronic video) should be constructed to be able to observe the location and characteristics of ice formation.

Future tests should incorporate an additional suite of measured inputs including such things as:
1. Redundant plenum humidity and temperature sensors for comparative measurement
2. Manifold pressure
3. Fuel flow
4. Venturi temperature
5. External carburetor area temperature
6. Carburetor casting internal temperature
7. Video recording of ice formation
8. High accuracy manifold pressure monitoring
9. High accuracy barometric pressure monitoring
10. Inlet plenum pressure control
11. Arrangements for fuel storage/handling should seek to minimize the opportunity for loss of light hydrocarbons/changes in volatility (‘weathering’) prior to test.

Note: Based on this testing the need for having the carburetor totally immersed in the conditioned air flow was noted, and the test set up was redesigned for future tests to make sure the carburetor remained immersed in the same conditioned air flow as the combustion inlet air flow.

There are other recommendations which come with pros and cons that must be considered.

- A determination may need to be made regarding the operation of the engine on a propeller vs. an eddy current dyno. There are pros and cons to each method. The eddy current dyno can provide a precise loading of the engine, however exact torque curves for the various speeds and unusual (conditions must be established and documented. The use of the approved propeller for this engine provides known, repeatable loads. Additionally, the availability and cost of an eddy current dyno for use as a screening test for fuel developers could be problematic. For engine performance and detonation testing, loading on an eddy current dynamometer is unarguably the best method, however for carburetor icing testing, more evaluation needs to be done to determine any real gain in information regarding the use of propeller load vs. eddy current load.

- A more robust and precise inlet air conditioning system improves repeatability of the icing, and the operation of the engine in an environmentally controlled cell can improve the effects of ambient weather and atmospheric conditions of the test. The CAS700 system provides good air processing for developing standard day conditions. However, the temperatures and humidity required for this test pushes this system to its limits. The addition of a higher volume, higher pressure steam injection system in the ductwork or plenum, instead of the internal steam injection system of the CAS 700, would provide the ability to run the full spectrum of temperatures on the ESSO curve from the +40° F (+4.4° C) to +60° F (15.5° C). The ability to control atmospheric pressure would also prove advantageous, given the barometric pressure
variable found in the study. However, the cost and large physical footprint of the atmospheric control systems is prohibitive for all except a few specialized test facilities.

The tradeoff is that a test cell with ideal barometric control, eddy current dynamometers, and an ideal steam generation system, may be beyond the means of a new fuel developer, when all that is required is a screening test where a new proposed fuel can be compared to an existing fuel baseline.

On the other hand a more robust control of the air inlet conditions can provide a better determination of a skewing of the ice curves left or right. For current, avgas, used in this study the ideal icing condition centers around a +48°F (+8.9° C) to +50° F (+10.0° C) temperature point. Equipment that can provide the 97% relative humidity, and controlled atmospheric pressure, in a range from +40° F (+4.4° C) to +70° F (21.1° C) would be ideal, since the characteristics of heat lost due to evaporation of future, non-avgas fuels may not be the same as current avgas, and that point of most heat loss may be higher or lower than the currently known +48°F (+8.9° C) to +50° F (+10.0° C).

- A better understanding of the relationship of vapor pressure to icing is needed for future testing. The relationship between vapor pressure and icing is detailed in the V.I. Nazarov, et al report, “Calculation Method for Determination of Carburetor Icing Rate”. The current test may have correlated to the tables in the Nazarov article given that the current test fuel may have had a lower vapor pressure than the historical fuels, and displayed a tendency not to easily form carburetor ice.

Since previous tests seem to show some effect of fuel properties (including volatility or front end distillation temperature) on icing, it seems logical that the fuels used for these series of tests would be analyzed, in order to provide data with which to correlate new tests with any historical tests, and/or to eliminate variability for test variations. This should be standard protocol for any future testing.

Despite the limitations given in the conclusions and recommendations, the researchers believe that this test is viable as an affordable screening test, as was set forth at the onset as the project goal, where there may be limited funds available for future fuel developers needing to evaluate large numbers of multiple formulations in a standardized manner. Affordable, standardized screening tests are an asset to a fuel developer or fuels laboratory researcher, where iterations of formulations need to be evaluated at the early stages of fuel creation. Fuels passing a screening test, may then need to be evaluated on a more complex test rig, with greater control the parameters of the engine and combustion air.
8. References


*Note this is the correct spelling per the publication name


## Appendix I – Esso report excerpt

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<td>18</td>
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2. Light Aircraft Carburetor Icing

One of the recognized hazards of personal aircraft operation is the formation of ice in the carburetor; as emphasized by Civil Aeronautics Board surveys which indicated that 30% of the 1,330 light plane engine mishaps occurring during 1947 and 1948 could be attributed to carburetor icing.

a. Mechanism and Manifestation of Carburetor Icing

Light aircraft engines are generally equipped with updraft, float-type carburetor, which mixes fuel with air within the venturi. Icing occurs when the evaporation of fuel in the intake air stream at the carburetor extracts sufficient heat from the air and surrounding metal surfaces to reduce the temperatures below freezing, so that, as shown in Figure 5, water vapor in the air may condense and frozen on the metal surfaces to an extent which can become critical to engine operation. This phenomenon takes place when ambient conditions are within the icing range, i.e., in a cool atmosphere (30-65°F) where the relative humidity is high (above 50%). In formations similar to that shown in the sketch on the underside of the throttle, have actually been observed through a Lucite window in the wall of the carburetor during laboratory icing tests in a Continental 95 HP aircraft engine.

The formation of ice in the carburetor or intake manifold has the effect of reducing engine power output by restricting the flow of combustible mixture to the cylinder. Icing in actual flight consequently manifests itself as a decrease in engine speed, and may subsequently cause an accident. For example, if ice has been formed in the carburetor during some part throttle operation, the engine may stall during a subsequent normal, closed-throttle glide approach for a landing due to the long-over of the idle jet, or it may be impossible, due to restriction by ice of the intake system, to obtain sufficient power for climbing from an unsuccessful landing attempt. An alternate
FIGURE 2

SCHEMATIC DIAGRAM OF LIGHT AIRCRAFT CARBURETOR

TYPICAL ICE FORMATION SHOWN GREY
Intake air supply duct, jacketed by the exhaust manifold, as provided a "carburetor heat" on light aircraft for preventing carburetor icing. Safety in flight depends on proper and timely application of carburetor heat by the pilot during icing conditions. The use of a fuel which is capable of preventing carburetor icing would add safe operation in the event of lost engine in applying heat.

b. Development of Laboratory icing Test

For the study of the light aircraft carburetor icing problem and how it might be solved, an 85 HP Continental engine has been employed at simulated flight conditions. In this test, icing is simulated by a disc in engine speed with the throttle setting remaining fixed in its initial position, the amount of ice accumulated being reflected in the magnitude of the disc loss. In standardizing the test for use in evaluating the icing tendencies of various fuel blends it was desired to choose the conditions which would result in rapid accumulation of most carburetor ice possible, based on the premise that the carburetor condition would then be the most dangerous in any subsequent aircraft operations. The test variables investigated are discussed below:

(1) Effect of Carburetor Cooling Air Temperature

The temperature of the air surrounding the carburetor affects the rate of ice formation within the carburetor; the lowest temperature being more severe as could be predicted on the basis of the air being less available to the metal parts of the carburetor. Its effect is shown by the framed curves in Figure 4 for three different carburetor vicinity temperatures and is summarized below:

<table>
<thead>
<tr>
<th>Temperature of Air Surrounding Carburetor, °F</th>
<th>Initial Speed, RPM</th>
<th>After 3 Minutes</th>
<th>After 10 Minutes</th>
</tr>
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<tbody>
<tr>
<td>80</td>
<td>1790</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>60</td>
<td>1790</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>1790</td>
<td>250</td>
<td>85</td>
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</tbody>
</table>

In view of these results, the air surrounding the carburetor for the standard laboratory icing test is maintained at an intake air temperature employed since this is the lowest cooling air temperature which could be encountered near the carburetor on the engine of a plane.
in actual flight.

(2) Effect of Intake Air Temperature and Humidity

Since, for constant relative humidity, the temperature of the intake air determines its water vapor content increasing intake air temperature increases carburetor icing severity until a temperature is reached where the higher heat content of the air induces evaporation of the greater amount of water made available for freezing. Data at various intake air temperatures are plotted for two levels of relative humidity in Figure 3, and the results for the more severe high humidity conditions are summarized in the following table:

**Carburetor Icing in Laboratory Continental Engine**

<table>
<thead>
<tr>
<th>Intake Air Temperature, °F</th>
<th>Intake Air Relative Humidity, %</th>
<th>Des in Speed Due to Icing After 1 Minute, Δ RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>97 + 3</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>97 + 3</td>
<td>3</td>
</tr>
<tr>
<td>55</td>
<td>97 + 3</td>
<td>5</td>
</tr>
</tbody>
</table>

On the basis of these results, 50°F. and 97 + 3% relative humidity were concluded to be the most severe intake air conditions for carburetor icing in these laboratory studies. It is possible that operating in an actual fog (> 100% relative humidity) could be much more conducive to ice formation, but control difficulties prevented testing at any condition above 100% relative humidity.

(3) Effect of Throttle Setting

The choice of throttle setting giving an initial engine speed of 1750 RPM in the work reported above was based on one previous study of various throttle settings, employing somewhat less critical conditions than those described above. Carburetor ice formed in much larger quantities at part-throttle, intermediate speed conditions typical of those employed in an aircraft in descending from one altitude to another, than at nearly closed-throttle, 1/4 speed settings, such as might be employed as a final glide approach for landing. This effect is shown in the following summary table:

(Data on following page)
FIGURE - 5

CARBURETOR ICING IN LABRADOR CONTINENTAL ENGINE

EFFECT OF INTAKE AIR CONDITIONS ON ICING SEVERITY.
FUEL: ESSO WAT ON GADE 80
CONDITIONS: INITIAL ENGINE SPEED 750 RPM.
TEMPERATURE OF AIR SURROUNDING CARBURETOR MATCHES INTAKE AIR TEMPERATURE FOR EACH RUN.

LOSS IN ENGINE SPEED DUE TO ICING

RELATIVE HUMIDITY
- - 97 ± 3%
- - 85 ± 3%

INTAKE AIR TEMPERATURE, °F
Carburetor Icing in Laboratory Continental E-76

Fuel, 90 Octane; Intake Air, 73% Relative Humidity, 
40°F.; Carburetor Vicinity 40°F.

<table>
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<tr>
<th>Initial Throttle Setting</th>
<th>Engine Speed, RPM</th>
<th>Loss in Speed due to Icing, RPM</th>
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<td>3</td>
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The combination of the engine speed and throttle angle obtained with throttle setting number 2 appears to be most conducive to the build-up of a carburetor ice.

Based on the results of this icing test development work, the critical conditions for the rapid and substantial accumulation of carburetor ice have been established as:

- Intake Air Temperature, °F. 59
- Intake Air Relative Humidity, % 93 ± 3
- Air Surrounding Carburetor, °F. 51
- Initial Engine Speed, RPM 1750

While these conditions are reasonably suitable for demonstrating ice occurrence and prevention of carburetor icing in list aircraft engines, they do not necessarily simulate hazardous flight situations. To do so it has not been possible to cause stalling or to reach a condition where full power cannot be regained reasonably quickly by opening the throttle, probably because of limitations inherent in a laboratory operation of the engine.
Appendix II – Gasoline Water Content

The gasoline in the 25 gallon stainless steel engine fuel tank consisted of 2 different batches. The first batch was left over from previous engine runs and had sat in the tank for approximately 6 months, indoors in a repair shop environment, before it used in this test. This relatively short storage in an environment where the fuel tank had not been exposed to the elements, was deemed to be satisfactory for this test, and the fuel was considered “typical”. The first batch of fuel was used to verify the experimental procedures used in this test and was used for Runs 1 and 2. After this batch of fuel was used, a second batch was obtained from the local FBO and was used for Runs 3 and 4. Two different samples of each fuel were drawn using a 10ml pipette and placed into a 10ml sample tube. These samples were analyzed using Water by Volumetric Karl Fischer Titration per ASTM E203, by the labs at INTERTEK- Commodities, 725 Oakridge Dr., Romeoville, IL 60446.

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<th>Sample</th>
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It was determined that there were no meaningful difference in moisture content among the runs using the old and new fuel. In addition it was determined that there was no meaningful moisture in any of the fuel samples.
Appendix III – Fuel Characterization Data


These tables are combined with data from an analyses of the fuel, courtesy of ExxonMobil, in the late spring of 2015.

There are differences in the properties reported and nomenclature of the properties between the reports. The first column of the characterization tables provides the property being reported. The highlighted or darkened rows/cells indicate data from the 2015 ExxonMobil characterization. Non-highlighted or not darkened rows/cells indicate data taken from the Bureau of Mines reports. The Bureau of Mines reports contained tables covering the years 1949 through 1954. The current fuel is shown alongside both 80/87 octane fuel in the tables in this appendix.

Of note for this test is the vapor pressure. The historical reports provide vapor pressure as Reid Vapor Pressure (RVP) in “lb.”, and the 2015 analysis from ExxonMobil provides Dry Vapor Pressure Equivalent (DVPE) in kPa. The RVP’s ranged from 6.2 lb. to 6.5 lb. for the historical data, and 33.9 kPa in the ExxonMobil test. DVPE is given in ASTM D5591 as the total vapor pressure in a vacuum and RVP is given in ASTM D323 as the absolute vapor pressure at 100° F (37.8° C), and can include dissolved water. 40 CFR 4065.710 states that the intent is that DVPE to be equivalent to RVP for gasoline. That said, a direct numerical conversion of 33.9 kPa to pounds (psi) would equal 4.9 pounds. Based on this conversion there would appear to be some potential volatility difference between the historical gasoline and the current gasoline. In addition, T10% data indicate values over the 167°F (75 °C) maximum for ASTM D910 100LL Avgas. On this basis, it has been concluded that the 2015 test fuel could have suffered some weathering (loss of light hydrocarbons) during storage.
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*Table 8 - Summary data on tube 30-3.67 commercial aviation gasoline.*
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