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Effects of Increased Jet Fuel Freeze Point on Cold Start Ability

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In the interests of jet fuel availability, the Canadian commercial wide cut fuel specification has recently been relaxed by allowing an increase in the freeze point. An increased freeze point implies an increased low-temperature viscosity and associated cold starting difficulties. To identify the amount of cold start degradation to be expected with such fuels, the Canadian Forces commissioned testing at the National Research Council of Canada to examine the cold start ability of an Allison T63-A-700 turboshaft helicopter engine using four fuels including typical in-service samples of kerosene Jet A-1 and NATO wide cut F-40, as well as two intermediate wide cut fuels having freeze points corresponding to exact specification values. For the engine under test, the relaxed wide cut fuel produced a 20°C degradation in cold start capability compared to the typical NATO F-40 fuel.

Introduction

AS a result of the demands being placed on a diminishing resource, changes will occur in the availability and characteristics of crude oils used to produce future liquid hydrocarbon fuels. In addition, synthetic crude will increasingly constitute a higher percentage of refinery base stock (already a fact in Canada with syncrude being produced from tar sands). As a result, to avoid prohibitive refining costs and to increase aviation fuel availability, current fuel specifications will need to be altered, as concluded in several international studies.[1,2] It is generally accepted that these future aviation fuel specifications will be relaxed primarily in terms of increased aromatics content (or lower hydrogen content), and higher final boiling points, which will lead to fuels with higher freeze points. This paper is concerned primarily with identifying the effect of an increased freeze point wide cut fuel on the cold start capability of a small helicopter engine.

As an example of the potential increase in fuel availability which may result from such a specification change, a 1976 United States Air Force study,[3] based on the 1975 United States crude supply and product demand mix, showed that a freeze point increase of 8°C had the potential to increase JP4 (equivalent to NATO F-40) wide cut fuel production by 24.3%. Similarly, a 1976 study by the Canadian Government Specification Board (CGSB),[4] estimated that the potential improvement in Canadian commercial wide cut fuel availability for a freeze point increase of 7°C could be as high as 15%.

Effects of High Final Boiling Point

A higher final boiling point produces a fuel with a higher freeze point. In addition, the fuel distillation curve tends to be shifted, producing a fuel with a higher viscosity and lower volatility. These two fuel properties impact on the design and operation of an aircraft engine and fuel system in primarily two areas; fuel pumpability and distribution, and ignition characteristics, especially under low-temperature conditions.

Most studies examining the effects of a freeze point relaxation have dealt only with the fuel storage and distribution problems; that is, the potential for fuel freezing (or wax separating from the fuel) in aircraft tanks and fuel systems during long duration flights at high altitude. There are many parameters which can affect tank fuel temperature, such as time of year, route, duration of flight, initial fuel temperature, cruise Mach number and altitude, and aircraft design. Figure 1 illustrates the range of typical fuel tank temperatures. Because of the potential flight safety hazards, this problem has been given a great deal of study and most specification relaxation proposals have considered it in detail.

The effect of an increased freeze point on ignition characteristics, primarily cold start, has been given far less consideration. This is understandable, since the requirement for starting with both cold soaked engines and fuel does not occur very frequently, especially in commercial operations. However, in Canada and other northern regions, the situation can present itself, especially for deployed aircraft or helicopter operations. Similarly, very little information is available on the startability of wide cut fuels (as opposed to kerosene fuels) because they are primarily military fuels and generally not thought of as causing cold start problems due to their relatively high volatility.

While higher boiling point fuels would be slightly less volatile than "unrelaxed" fuels, lowered fuel volatility was not considered to be a major factor in the low-temperature

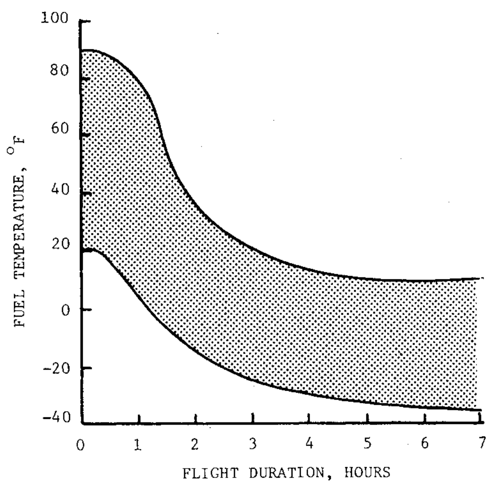

Fig. 1 Typical range of in-flight fuel temperatures.[4]

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Table 1 Selected properties of wide cut fuel specifications

Property	Canadian commercial, CAN 2-3.22	ASTM Jet B	MIL-T-5624, (JP-4) NATO F-40
Initial boil point, °C	Report	Report	Report
Fuel Recovered			
10% vol., °C, max.	Report	Report	Report
20% vol., °C, max.	143	143	143
50% vol., °C, max.	188	188	188
90% vol., °C, max.	243	243	243
End point, °C	Report	Report	Report
Loss, %	1.5	1.5	1.5
Specific gravity, 60/60°F	0.751 to 0.802	0.751 to 0.802	0.751 to 0.802
Reid vapor pressure, psi	2.0 to 3.0[a]	Max 3.0	2.0 to 3.0
Freezing point, °C	−51	−50	−58
Option	−58	b	None
Viscosity[c]			

[a]Minimum limit may be waived if purchaser agrees. [b]Lower freeze points may be agreed upon between supplier and purchaser. [c]A low-temperature viscosity requirement is not specified for these fuels.

Table 2 Analysis of wide cut test fuels

	Test Fuel		
Property	1 Standard CAN 2-3.22	2 Low freeze point CAN 2-3.22	3 Typical F-40 sample
Freezing point, °C	−50	−57	−66
Initial boiling point, °C	62	57	64
10% recovered, °C	120	108	90
20% recovered, °C	146	132	102
50% recovered, °C	192	179	145
90% recovered, °C	241	231	209
End point, °C	254	250	245
Loss, %	0.3	0.2	1.2
Reid vapor pressure, psi	1.8	2.1	2.4
Specific gravity, 60/60°F	0.780	0.779	0.764
Viscosity, centistokes			
At −18°C	2.94	2.43	1.63
At 0°C	1.99	1.70	1.21
At 20°C	1.40	1.23	0.93
At 38°C	1.10	0.98	0.75

starting ability of wide cut fuels. Rather, the increased low temperature viscosity was projected to be a dominant factor. For satisfactory ignition and starting, fuel must be injected into the combustion chamber in the correct quantity, spray pattern, and droplet size to ensure proper fuel vaporization and primary zone fuel/air ratio. Increased fuel viscosity can affect all these requirements by producing a larger pressure drop through the fuel system, as a result of greater friction losses, which in turn reduces the volume flow of fuel. In addition, fuel droplet size is increased due both to the higher viscosity and lower fuel delivery pressure.

In 1978, the CGSB, following the Ref. 4 study, relaxed the freeze point from −58 to −51°C for commercial wide cut fuel produced to CAN2-3.22 specification (similar to ASTM Jet B, complete equivalency of fuel specifications is given in Table 1). Although a −58°C freeze point fuel option was retained, the Canadian Forces (CF) were concerned that fuel meeting the wide cut NATO F-40 specification (the standard Canadian military jet fuel with a −58°C freeze point) might become limited in availability or require custom refining at a premium price.

For these reasons, the CF instituted a test program to determine the cold start capability of representative engine types using fuels with different freeze points. The test fuels were three wide cut fuels with freeze points varying from −51 to −66°C and one kerosene type aviation fuel (−49°C freeze point). The subject of this paper is the testing of the first engine, an Allison T63-A-700 turboshaft.

Testing

The CF contracted the National Research Council of Canada (NRCC) Engine Laboratory, Ottawa, Ontario, Canada, to coordinate the test program. The active engine testing was subsequently subcontracted to a local consulting engineering firm, Davis, Eryou and Associates Limited, while blending and analysis of the test fuels were carried out at the NRCC Fuels and Lubricants Laboratory.

Test Fuels

As stated, one aviation kerosene and three wide cut fuels were used in the test programs. Two wide cut fuels were blends of wide cut F-40 and a distillate fuel to produce fuels with freeze points of −51°C and −58°C which are respectively the maximum freeze point requirements of the new Canadian commercial wide cut fuel specification and a lower freeze point option. The third wide cut fuel was an unblended representative sample of F-40 fuel obtained from CF sources, which had a freeze point of −66°C. The aviation kerosene was CGSB 3-GP-23 (ASTM Jet A-1) obtained from commercial sources and was included to illustrate the effects of a different, less volatile fuel type with expected worse starting characteristics. Test fuel properties, as analyzed by the NRCC Fuels and Lubricants Laboratory, are listed in Tables 2 and 3.

The results of the fuel analysis indicated that the F-40 and Jet A-1 samples were representative of those fuels as typically found in service. The analysis of the blended wide cut fuels

Table 3 Selected properties of kerosene fuel specification and analysis of test fuel

Property	Specification requirements CGSB 3-GP-23 (equivalent to ASTM Jet A-1)	Analysis of test fuel (fuel 4)
Freezing point, °F	−48	−49
Initial boiling point, °C	204 max.	150
10% recovered, °C	...	181
20% recovered, °C	...	191
50% recovered, °C	Report	208
90% recovered, °C	Report	231
Final boiling point, °C	300 max.	250
Reid vapor pressure, psi	No requirement	0.1
Specific gravity, 60/60°F	0.775-0.840	0.8049
Viscosity, centistokes		
At −20°C	8.0 max.	4.65
At −18°C	...	4.32
At 0°C	...	2.71
At 20°C	...	1.81
At 38°C	...	1.37

Table 4 Summary of fuel properties and engine test results

		Wide cut fuel		Kerosene fuel
	Fuel 1	Fuel 2	Fuel 3	Fuel 4
Fuel freeze point, °C	−50	−57	−66	−49
Minimum cold start temperature, °C	−10	−20	−30	0
Fuel viscosity at start, centistokes	2.4	2.6	2.2	2.7

indicated that both these fuels failed by a narrow margin to meet some of the CAN2-3.22 requirements (freeze point was 1°C too high in both cases). However, this was not considered to be serious enough to invalidate any conclusions; for all practical purposes they were representative of fuels that would just barely meet the specifications.

Engine Testing

Engine Description

The Allison T63-A-700 engine is the military version of the commercial 250-C18. This family of engines enjoys widespread usage in the Bell Jet Ranger helicopter series and in Canadian military service it is installed in the Kiowa helicopter. The engine is a small (317 hp), free turbine turboshaft with a combustion chamber utilizing a single duplex pressure atomizer fuel nozzle. The engine model had proven sensitive to fuel type in cold starting during previous testing.[5]

Test Description

All testing was performed at a cold chamber in the NRCC Low Temperature Laboratory. A comparative test program was developed to enable a resolution of 5°C in the cold start temperature for each test fuel, a successful start being defined as "a start during which the engine rotor is accelerated to idle speed from rest using the approved starting procedure provided that the engine stays within operating limits and the time specified in applicable technical manuals." A satisfactory starting capability was defined as "two consecutive successful starts being obtained after cold soaking at the specified temperature between start attempts." For the purposes of these tests, a "cold soak" was defined as "the condition that exists after temperatures of the cold chamber air, fuel, engine gear case, and fuel pump are maintained within 1°C, and the oil tank temperature within 2°C, of the test temperature for at least 20 minutes prior to the start attempt."

All start attempts were made using a motor driven ground power unit for starting power and thus the results should not be considered representative of the batter-powered cold start

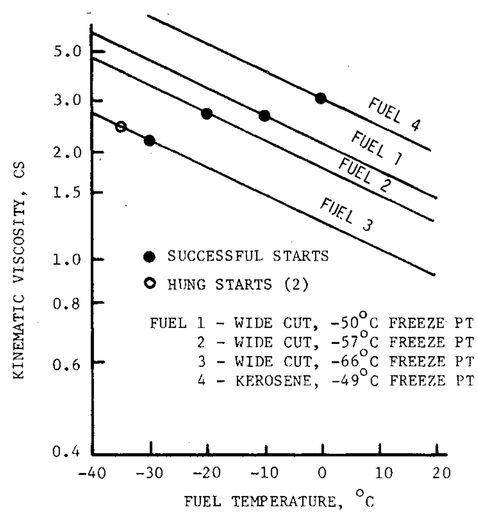

Fig. 2 Test fuel viscosity/temperature relationships.

capability of an engine installed in a helicopter. The engine contained lubricating oil to MIL-L-23699 specification, rather than the lower viscosity MIL-L-7808 which is recommended for low temperature operations. Previous low temperature qualification testing by the CF with this engine installation indicated that oil type had a very small influence on starting capability when using a ground power unit, although for battery starts, successful starts could be expected at temperatures up to 10°C colder when using the lower viscosity oil.[6]

Test Results and Discussion

Starting results are presented in Table 4, with the differences in starting ability between test fuels being clearly evident. As stated previously, fuel viscosity effects can be a dominant factor in obtaining successful ignition and starting under low temperature conditions. Figure 2 illustrates the test fuels' viscosity/temperature characteristics determined during the fuel analysis. On it are superimposed points representing the minimum successful starting temperature for each fuel. Note that successful starts were obtained in a fairly narrow fuel viscosity band, regardless of fuel type.

Of interest is the fact that a fuel just meeting the −58°C freeze point F-40 specification resulted in a cold start temperature 10°C warmer than that for a typical F-40 fuel. It appears that fuels just meeting the F-40 specification could produce a different test result than average F-40 fuels, which historically have well exceeded the specification freeze point requirement. With relaxations being proposed to raise the freeze point, it may be assumed that more and more fuels will be encountered that more closely approach the specification value. Thus, use of a fuel just meeting existing specifications could result in the unexpected degradation in cold start capability of an engine which was previously qualified with an "average" fuel.

In earlier category II low-temperature testing by the CF,[6] cold soak starts with F-40 fuel were obtained as low as −40°C. As to why this particular engine did not start down to the previously demonstrated cold start temperature, the explanation is that the test installation did not incorporate the usual aircraft mounted fuel boost pump which provides a 5 psi head at the engine driven fuel pump. Instead, the test rig utilized a gravity feed system with only a 1 psi head. Main fuel pump delivery pressure was monitored to be within published limits before the ignition system was activated; however, the pressure would be less than that normally encountered in an installed engine operation. Operational experience has indicated that "hung" starts (although fuel ignition occurs, the engine does not accelerate beyond 20 to 30% rpm within time limits) are possible in cold temperatures with an inoperative boost pump. Referring to Fig. 2, note that two hung starts were obtained at −35°C with the F-40 fuel sample.

Ignition and starting behavior are hardware dependent and can vary from engine to engine. For this reason, the minimum start temperatures obtained in this test program are not necessarily applicable to other engine types; however, it is considered that the general trends noted would be valid.

A final comment is that previous limitations to cold starting of engines with wide cut fuels were not fuel dependent. Instead, especially for deployed operations with helicopters, limiting factors frequently included low cold battery output, oil viscosity, and gear gox or drive train drag. However, with a relaxation in fuel properties, it is quite conceivable that the fuel itself, even wide cut fuel, can become the limiting factor to successful cold starts.

Summary and Conclusions

It has been projected that future aviation fuel specifications will have higher freeze points (associated with higher final boiling points) than present fuels. While much discussion has dealt with the effects of this increase on fuel system pumpability problems in commercial aircraft service using kerosene type fuel, little consideration has been given to the effect of such a change on the cold start ability with higher volatility wide cut fuels.

Because wide cut fuels are of prime importance to the Canadian military, a test program was undertaken to determine the effect of wide cut fuel freeze point on the cold start ability of a small, free turbine, helicopter turboshaft engine (Allison T63-A-700). This was done by cold start testing with four fuels; three wide cut aviation jet fuels with freeze points varying from −51 to −66°C, and an aviation kerosene with a −49°C freeze point as the fourth test fuel.

For the T63-A-700 test engine, an upper limit of fuel viscosity for acceptable starting was determined, with all successful cold starts being obtained over a narrow range of fuel viscosity (2.2 to 2.7 centistokes). No effects on starting attributable to the volatility differences between the wide cut and kerosene fuel types were noted.

Test results with the two wide cut fuels with freeze points at the specification limits of −51 and −58°C indicated a 10°C lower cold start capability with the −58°C freeze point fuel. The sample of typical in-service wide cut fuel with a −66°C freeze point produced a 10°C improvement in cold start capability in comparison to the fuel just meeting the −58°C freeze point specification limit. Since fuels have historically well exceeded this parameter's specification limit, fuel related degradations in cold start ability may occur if fuels approach their specification limits due to availability reasons. When using wide cut fuels, previous cold start limitations were rarely fuel related. However, with lowered quality, or specification relaxations, the fuel itself may become the limiting factor to successful cold starts.

The extent of degradation observed in cold start ability during this test series reinforces the need to consider the effects on starting as well as wax separation or fuel pumpability problems whenever fuel freeze point relaxations are proposed. Several studies have concluded that to alleviate future fuel availability problems, both engine design and fuel specifications must change. Clearly, the gains projected in fuel availability due to higher freeze points indicate that such changes will occur. To cater for such an eventuality, engine manufacturers and users must be aware of all the possible operational implications of proposed fuel specification changes. Inevitably, engine developments must be made to preserve a certain starting ability (both cold start and altitude relight) with higher viscosity, lower volatility fuels.

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