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OPERATION OF A T63 TURBINE ENGINE USING F24 CONTAMINATED SKYDROL 5 HYDRAULIC FLUID

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14. ABSTRACT
The objective of the investigation was to determine the potential effects on engine operability and the likelihood for accelerated turbine blade and nozzle wear while operating on fuel contaminated with Skydrol 5 hydraulic fluid. An Allison A 250 T63 turboshaft engine located in the Air Force Research Laboratory (AFRL) Aerospace Systems Directorate, Turbine Engine Division, Mechanical Systems Branch (RQTM) Engine Environment Research Facility (EERF) at WPAFB was used to conduct the research. Two situations were evaluated using fuel adulterated with the Skydrol 5 hydraulic fluid consisting of 1 and 5% concentration for each investigation. The 5% concentration of Skydrol 5 and F-24 aviation kerosene was evaluated while operating the T63 engine for 5 continuous hours at normal rated power. The one percent concentration was operated for a total of 25 hours at normal rated power over the course of three days. The results of this effort are detailed with operability information and borescope photos that documented the conditions of the turbine section components before and after the 5- and 25-hour assessments.

15. SUBJECT TERMS
Skydrol, hydraulic fluid, F-24, engine

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1 Introduction

The Skydrol series of phosphate ester hydraulic fluids were originally developed by the Douglas Aircraft Company during the 1940s to reduce fire risk from leaking high pressure mineral oil-based hydraulic fluids on potential ignition sources. The Skydrol series of hydraulic fluids has evolved over the years to meet the increasing thermal load demands in modern hydraulic systems and reduced density to lower weight impact on the aircraft. Eastman Chemical is the current producer of Skydrol hydraulic fluids after a series of acquisitions through the years from Monsanto and Solutia. (Specification, December 2014)

Modern aircraft use the fuel system as heat sink medium prior to the fuel being consumed in the combustion process resulting in propulsion for the aircraft. The hydraulic system, required to maintain control of the aircraft, contains heat exchangers located within the tanks in direct contact with fuel to remove heat generated during hydraulic actuation process. An unexpected leak in these heat exchangers of the hydraulic fluid has the potential to comingle with the aircraft fuel and the resulting contaminated fuel being burned in the turbine engine during flight operations.

The Skydrol 5 hydraulic fluid was chosen since it contained the highest concentration of phosphorus compared to other fluids considered for this experiment. The others fluids considered include Skydrol LD4, Skydrol, PE-5, Skydrol 500B-4, Hyjet IV-A PLUS, and Hyjet V.

2 Experimental

The same F-24 (POSF 12360) fuel was used for the all of the research conducted during these experiments for continuity throughout the entire course of the testing. The phosphorus content of this base fuel was determined using ASTM D7111. The concentration of phosphorus was <0.10 mg/kg for POSF 12360 fuel.

Initially a visual miscibility assessment was carried out using 50 mL of Skydrol 5 and 50 mL of F24 fuel to determine if any separation of the components were visible to the naked eye. The two components with mixed vigorously and allowed to sit undisturbed for 3 days after which no visible separation was evident. A gallon of 5% Skydrol and F-24 was then mixed and 100 mL was tested using ASTM D 4809-13 to determine the net heat of combustion. The reported results were a net heat of combustion of 42.6 (MJ/kg). A 1% and 5% Skydrol with F-24 (POSF 13260) was mixed for use with the T63 engine and phosphorous content determined using ASTM D7111.

3 Discussion

3.1 Pre-operation inspection

The combustion section of the engine used for these experiments was visually inspected and photographically documented prior to being operated. The turbine section schematic is shown in Figure 1, courtesy of the Allison Turbine Engine Training school manual, details the location of specific turbine section components discussed through this document.

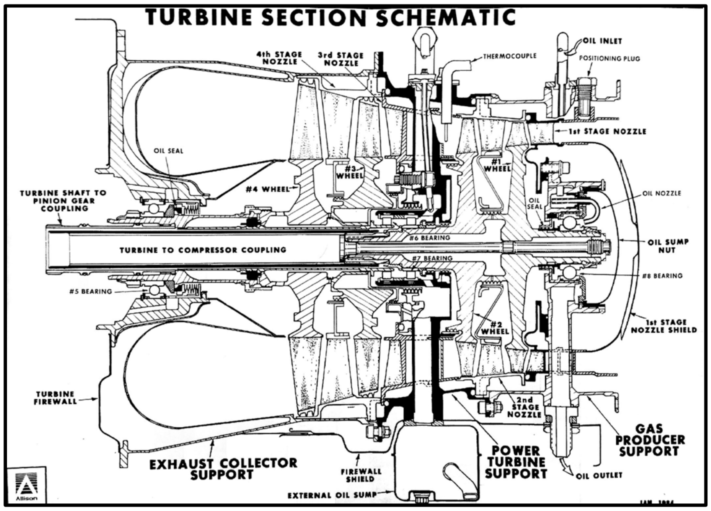


Figure 1. T63 Turbine Section Diagram

(Allison Turbine School Training Manual 250-C20B Series Engine page 80.)

The engine was reassembled with a plastic media blasted clean combustor liner, first stage heat shield, and ultrasonically cleaned fuel nozzle depicted in Figure 2. The inspection included photo documentation of the first stage nozzle and #1 turbine condition from the rear of the engine with the combustion liner removed shown in Figure 3. Additional inspections of the second stage nozzle, #2 turbine, and third stage nozzle were carried out by removing combustor thermocouple and using a borescope depicted in Figures 4 and 5. The #4 turbine and fourth stage nozzle were accessed through the exhaust ports of the engine with the borescope Figures 4 and 5. SEM results indicated the first stage nozzle was comprised of 49.2% (wt.) cobalt.

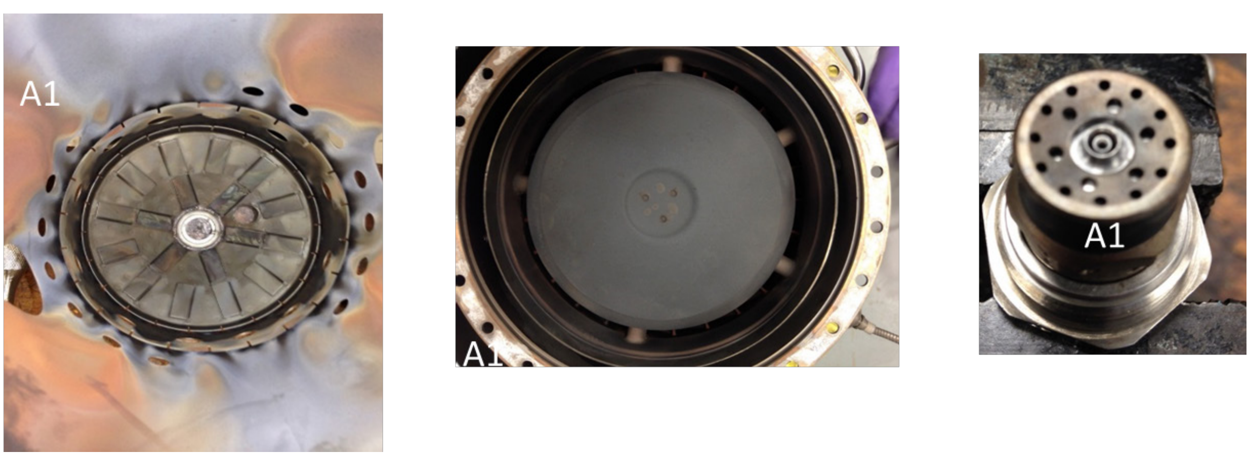


Figure 2. Combustor Liner, First Stage Heat Shield and Fuel Nozzle Prior to Operation of T63 Engine

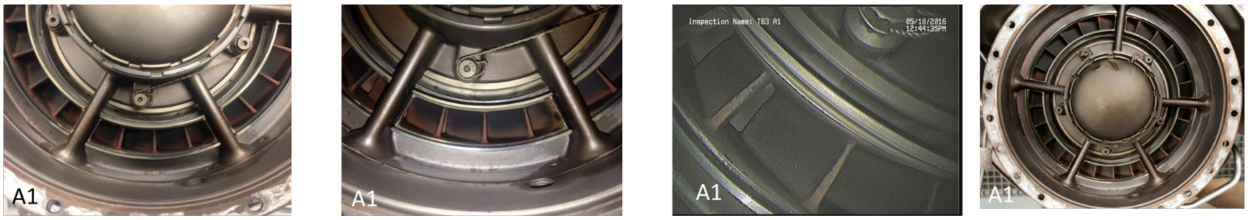


Figure 3. First Stage Nozzle Condition Prior to Engine Operation on Hydraulic Contaminated Fuel

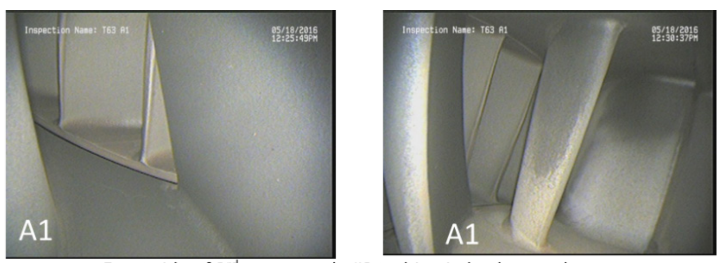
Upstream side of #1 turbine blades

Downstream side 4th stage nozzle

Downstream side #4 turbine blades

Downstream side #2 turbine blades-Note TC in upper right of photo

Figure 4. Turbine Section Component Borescope Photos



Front side of 3rd stage nozzle #3 turbine in background

Figure 5. Turbine Section Component Borescope Photos

3.2 T63 Turbine Section

The T63 engine was reassemble and installed in the EERF facility. The engine was operated and inspected for leaks for 60 minutes at normal rated power using F-24 fuel. (POSF 12360). The engine operated within normal parameters witnessed from earlier operability during lubrication oil qualifications and emissions experiments. The only leak observed was an extremely small oil leak at a Swagelok connection located on the oil cooler. This leak was easily remedied with adequate torque applied to the ½ inch fitting.

3.3 Operation with 5% Skydrol 5 with F-24

The investigation dictated the 5% Skydrol contaminated fuel characterization was to be the first fuel evaluated. A 5% concentration mixture of Skydrol 5 was achieved by mixing 567.8 liters of F-24 with 30 liters Skydrol 5. Samples were taken for quality assurance and contingent testing dependent on the engine operability and mechanical condition after the evaluation.

The fuel system of the engine was flushed with the 5% Skydrol/F-24 mixture which was visually confirmed by the presence of purple colored fuel flowing from the fuel pressure relief port. The engine was then operated for 300 minutes (five hours) at normal rated power minus 15 minutes total at idle condition to inspect engine for leaks, exchange auxiliary tanks, and a two minute cooling off period prior to engine shutdown. A total of 285 minutes at normal rated power was achieved during this initial 5% Skydrol/F-24 investigation. The phosphorus content of the 5% Skydrol mixture was determined using ASTM D7111 and determined to be 7609 ppm.

The composition of Skydrol 5 is proprietary, but the MS-DS states that it is 60-100% tri-isobutyl phosphate ($C_{12}H_{27}O_4P$). Tri-isobutyl phosphate is 11.6 mass% phosphorus. From the MS-DS, the density of Skydrol 5 is 0.97-0.98. The density of the jet fuel used is 0.814 (and by analysis has a very low phosphorus content). So, using the blending volumes discussed above, 30 L of Skydrol 5 added 29.25 kg of phosphorus to 567.8 L of jet fuel (462.2 kg). After a bit of math, this would lead to a blend containing 0.69 mass% phosphorus (assuming Skydrol 5 is 100 % tri-isobutyl phosphate). Thus, the D7111 measurement of 0.76 mass% phosphorus is in the ballpark.

The engine was removed from the EERF and transferred to the build room for post operation disassembly and inspection. The combustion liner and fuel nozzle were removed and photographed in Figure 6. The first stage heat shield indicated no visible change after operating on the 5% Skydrol/F-24 fuel.

Figure 6. Combustor Liner and Fuel Nozzle after 5 Hours of Operation Using a 5% Skydrol/F-24 Fuel

Carbon deposits were apparent on the inner air baffles at the 1 and 4 o'clock position on either side of the ignitor. These type of deposits are not unusual and have been documented on occasions when operating on F-24 fuel during additive testing. SEM results indicated the deposits consist of predominately carbon see Figure 7. The combustor liner was uncharacteristically coated with carbon soot black streaking down the sides of the liner. The fuel nozzle also exhibited an unusual carbon like build up in the 3 o'clock position which coincided with position of the ignitor used for starting the engine.

Additional inspection included the same areas of the turbine section examined prior to operation on the 5% Skydrol/F-24 fuel mixture. The first stage nozzle condition is presented in Figure 9 exhibiting a purplish shade on the surface of the nozzle. No cracks were discovered in the first stage nozzle during the inspection.

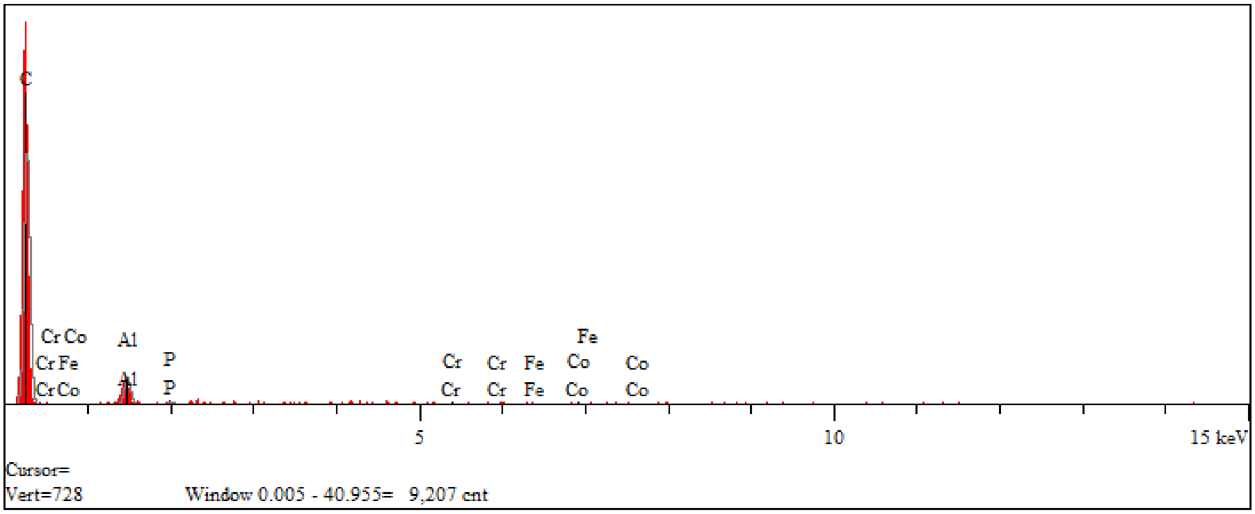


Figure 7. Carbon Deposit SEM Results

Elt.	Line	Intensity (c/s)	Conc	Units	Error 2-sig	MDL 3-sig	
C	Ka	43.30	96.473	wt.%	2.996	0.940	
Al	Ka	5.07	3.252	wt.%	0.394	0.410	
P	Ka	0.49	0.275	wt.%	0.273	0.400	
			100.000	wt.%			Total

Figure 8. Elemental SEM Determined Distribution of Carbon Deposit

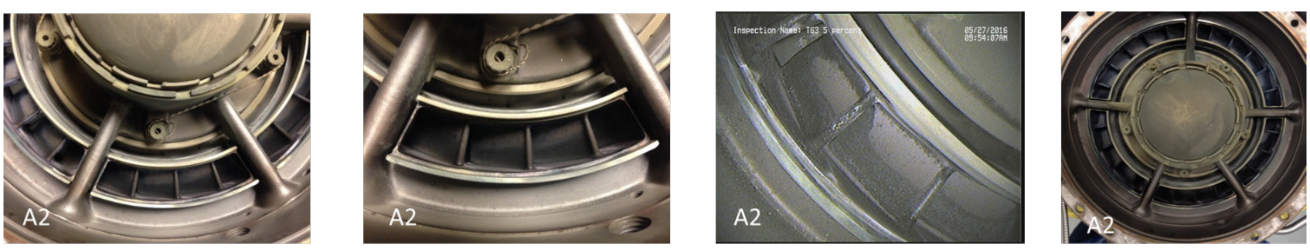
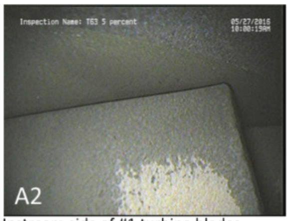
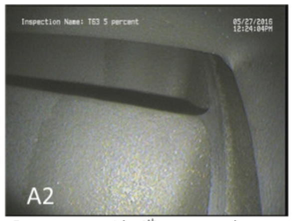


Figure 9. First Stage Nozzle Condition after Engine Operation on 5% Skydrol Contaminated Fuel

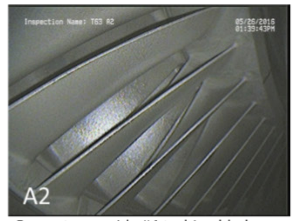
The turbine assembly inspection continued with the removal of the T5 thermocouple located in between the #2 turbine and the third stage nozzle (see Figure 1). The T5 temperature is used for combustion temperature measurement to meter fuel flow. This temperature is critical so as not to overheat the combustion section beyond the operation limits of the alloys used in the turbine section components. The condition of the #1 turbine, the fourth stage nozzle, #4 turbine, and #2 turbine are represented in Figure 9. Slight purplish discoloration is present on the surfaces. The turbine and nozzles indicate no major loss of blade/nozzle material. The condition of the #3 turbine and nozzle are revealed in Figure 10 and exhibit similar conditions as described for Figure 9.



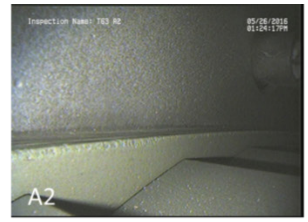
Upstream side of #1 turbine blades



Downstream side 4th stage nozzle

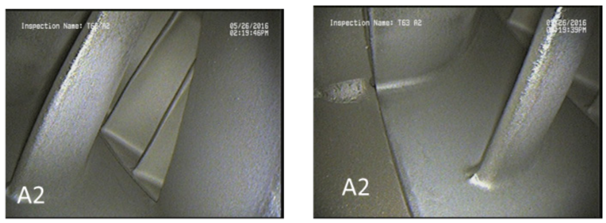


Downstream side #4 turbine blades



Downstream side #2 turbine blades-Note TC in upper right of photo

Figure 10. Turbine Section Component Borescope Photos after 5 Hours Operation Using 5% Skydrol/F-24



Front side of 3rd stage nozzle #3 turbine in background

Figure 11. Turbine Section Component Borescope Photos after 5 Hours Operation Using 5% Skydrol/F-24

The engine operability such as torque and operating temperature were within expected parameters when compared to historical operability data. Additionally the fuel consumption was within usual bounds when related to previous operations.

Figures 12 through 14 show SEM photos and data.

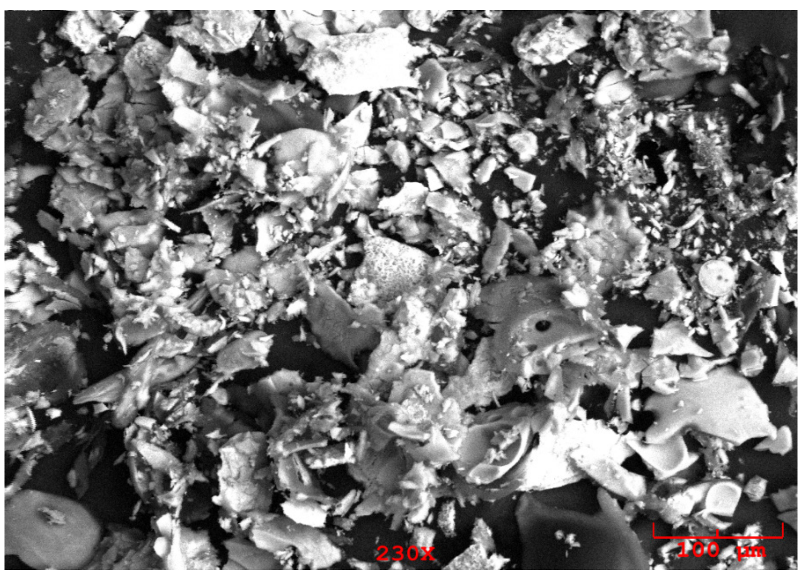


Figure 12. Soot Deposition Sample of 5% Skydrol/F-24 Scraped From Combustor Liner

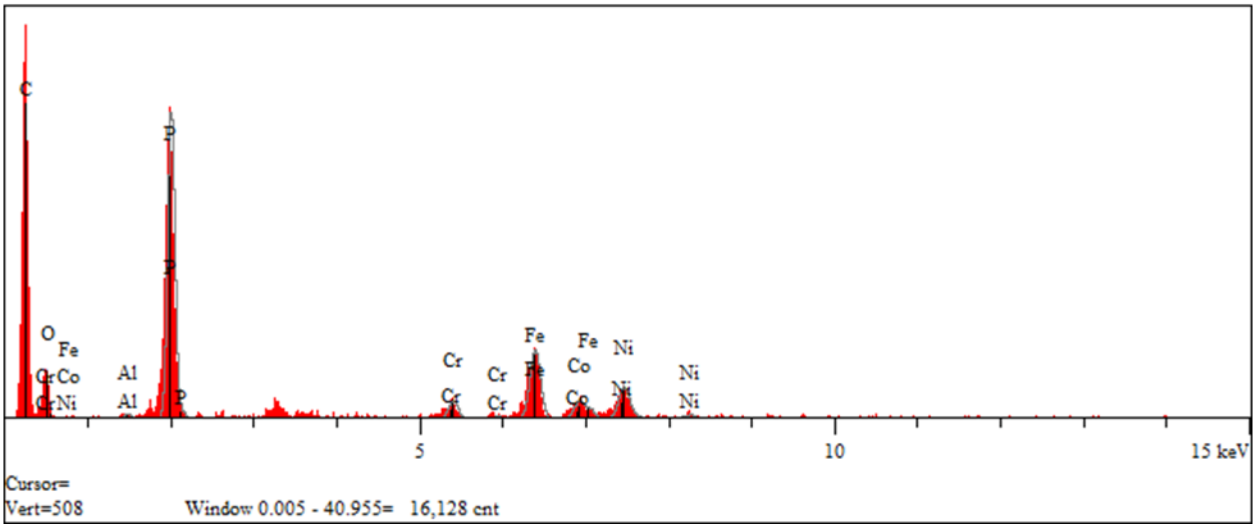


Figure 13. SEM Elemental Analysis of Deposition of Figure 12

Elt.	Line	Intensity (c/s)	Conc	Units	Error 2-sig	MDL 3-sig	
Al	Ka	0.71	1.250	wt.%	0.954	1.387	
P	Ka	41.42	51.517	wt.%	1.764	1.134	
Cr	Ka	3.26	4.312	wt.%	0.835	1.049	
Fe	Ka	13.41	22.280	wt.%	1.502	1.348	
Co	Ka	3.16	6.040	wt.%	1.165	1.449	
Ni	Ka	6.61	14.602	wt.%	1.509	1.521	
			100.000	wt.%			Total

Figure 14. Elemental Distribution of Figure 12 Soot Sample

3.4 Operation with 1% Skydrol 5 with F-24

The investigation then moved on to operation of the T63 engine for a period of 25 hours at normal rated power using a 1% Skydrol 5 concentration with F-24 fuel. The fuel mixture was accomplished mixing 2861.8 liters of F-24 with 27.4 liters of Skydrol 5. The fuel mixture was mixed and circulated for 24 hours to ensure uniformity in a 3785 liter clean storage tank located on the fuel farm at building 490 located at WPAFB. The engine was reassembled after cleaning combustion liner and fuel nozzle as described earlier. The T63 was reinstalled into the EERF and the fuel lines flushed using the 1% Skydrol 5 contaminated fuel. The 1% Skydrol phosphorus concentration was 1667 ppm determined using ASTM D7111.

Engine operation took place over 3 consecutive days. The first 2 days the T63 operated at normal rated power for 9 continuous hours for each day minus 4 minutes on each day, 2 minutes for initial startup leak check and 2 minutes for cool down before shutdown. The third day was comprised of 6 hours of operation at normal rated power minus the 4 minutes described previously. The 3-day run totaled up to 25 hours of engine operation using the 1% Skydrol 5 with F-24 for fuel. The preliminary results regarding a change in fuel consumption indicate no change compared to previous operation. Initial engine operability provided likewise results.

The engine was removed from the EERF and transferred to the build room for post operation inspection. The combustion liner, first stage heat shield and fuel nozzle were removed and photographed. The results are revealed in Figure 15. The combustor liner results provided a carbon deposit as seen with previous operation in the 2 o'clock position on the air baffle directly above the ignitor. The first stage heat shield yielded a distinct color with a greenish hue and the fuel nozzle displayed a much larger carbon like deposit as seen operating with the 5% Skydrol 5 fuel in the same 3 o'clock position.

Figure 15. Combustion Liner, First Stage Heat Shield, and Fuel Nozzle after 25 Hours of Operation Using a 1% Skydrol 5 with F-24 for Fuel

(Note: The fuel nozzle on the left depicts a clean nozzle for contrast to the 25 hour contaminated fuel nozzle on the right.)

The inspection continued with the examination of the first stage nozzle condition after the removal of the combustor liner and first stage heat shield. The condition of the first stage nozzle can be observed in Figure 11. The first stage nozzle did not exhibit any cracks and the number eight bearing cover remained a shade of green as seen earlier when operated on the 5% Skydrol concentration fuel. Upon closer examination of the first stage nozzle a color change was observed resulting in a pinkish purple hue coating the nozzle surface with washed out white patches. The washed out areas were also observed as seen in Figure 17 when inspecting the turbine section surfaces with a borescope through the thermocouple mounting port and behind the first stage nozzle on the #1 turbine. These surface color changes continued through the rest of the turbine section inspection observed in Figure 18

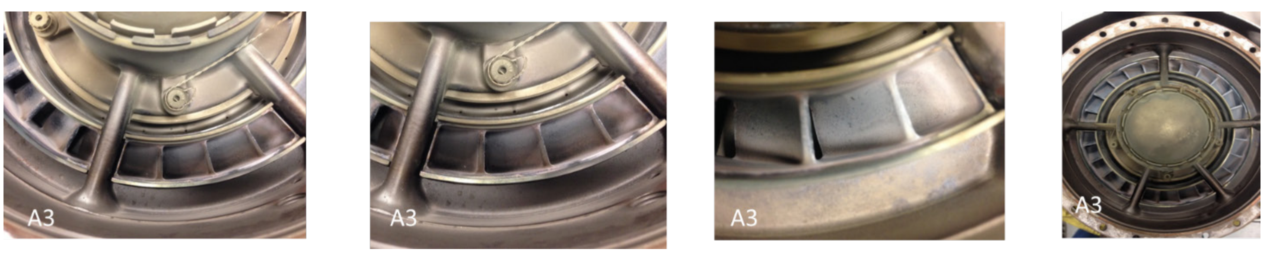
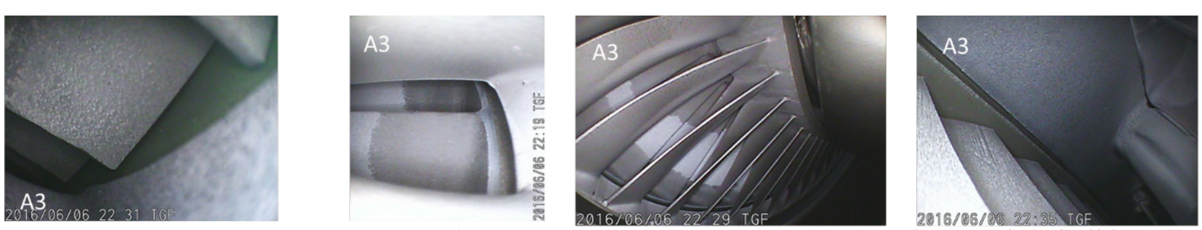
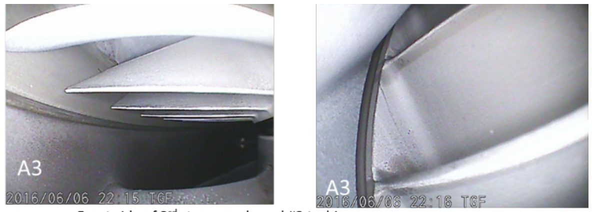


Figure 16. First Stage Nozzle after Operating on 1% Skydrol 5 with F-24 for Fuel for 25 hours



Upstream side of #1 turbine blades | Downstream side 4th stage nozzle | Downstream side #4 turbine blades | Downstream side #2 turbine blades-Note TC in lower right of photo

Figure 17. Turbine Section Component Borescope Photos after Operating on 1% Skydrol 5 with F-24 for Fuel for 25 hours



Front side of 3rd stage nozzle and #3 turbine

Figure 18. Turbine Section Component Borescope Photos after Operating on 1% Skydrol 5 with F-24 for Fuel for 25 Hours

4 Conclusion

The Skydrol 5 contaminated fuel did provide distinct color changes to the turbine components. The fuel nozzle did exhibit uncharacteristic build up on the surface for both concentrations of Skydrol 5 but no operability changes were observed prior to engine shutdown indicating a fuel nozzle issue. The T63 engine operated the entire time on both the 5% and 1% Skydrol 5 concentration contaminated fuel with little change in perceived engine operability.