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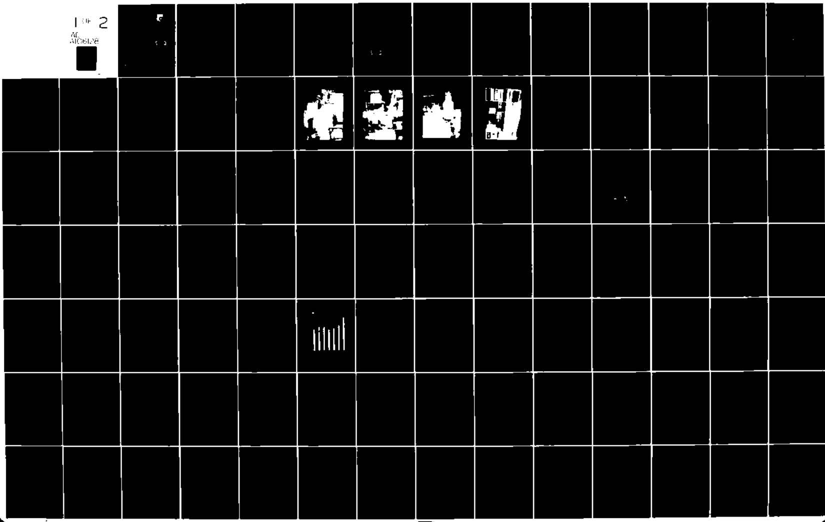

② LEVEL II

AD A106128

AFWAL-TR-81-2022

DEVELOPMENT OF THE AUTOMATED AFAPL ENGINE SIMULATOR TEST FOR LUBRICANT EVALUATION

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78284

May 1981

Final Report for Period: 1 May 1978-1 January 1981

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A description of an automated gas turbine engine simulator, designated the AFAPL engine simulator, and a discussion of the test results obtained using the simulator are presented. The No. 4-5 bearing compartment areas of a J57 turbine engine are used as the basic hardware for the simulator. The simulator is driven by a variable-speed drive system, through the —

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20. ABSTRACT (Cont'd)

accessory drive gearbox, providing simulator mainshaft speeds up to 10,000 rpm. Electrical resistance heaters are used to heat the air surrounding the oil-wetted areas within the No. 4-5 bearing compartment areas. The temperatures, pressures, and rpm are automatically controlled at predetermined levels and monitored throughout the 9120-6000 rpm speed cycling sequences and the soakback periods by a Hewlett-Packard mini-computer system, which is also programmed to automatically draw 5-hr interval test-oil samples, control test-oil sump level, provide safety shut-off protection, as well as print out and plot test information generated during each individual test. Simulator results obtained on eight turbine engine lubricants, for which full-scale engine data are available, show a very good correlation of the deposit ratings obtained using the AFAPL engine simulator and the deposit ratings from full-scale engine tests.

PREFACE

This technical report was prepared by the Mobile Energy Division of Southwest Research Institute (SwRI). The effort was sponsored by the Aero Propulsion Laboratory (APL), Air Force Wright Aeronautical Laboratories (AFWAL), Air Force Systems Command, Wright-Patterson AFB, Ohio, under Contract No. F33615-78-C-2012 for the period 1 May 1978 to 1 January 1981. The work herein was accomplished under Project 3048, Task 304806, Work Unit No. 30480605, "Modification of the AFAPL Engine Simulator for Automatic Operation," with Mr. L.J. DeBrohun, AFWAL/POSL, as Project Engineer. Mr. B.B. Baber of Southwest Research Institute was technically responsible for the work. The technical contributions of M.L. Valtierra, J.R. Eichelberger, J.A. Pasquali, and J.E. Wallace of Southwest Research Institute are acknowledged.

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INTRODUCTION

General

The development and evaluation of lubricants intended for use in current and future aircraft gas turbine engines have often been hampered by the lack of suitable bench tests which reasonably predict various aspects of lubricant performance from full-scale engine tests. This is particularly true regarding lubricant deposition and degradation. The use of an engine simulator was attempted a decade ago [(1)*], but the work was not carried far enough to indicate the usefulness of the approach.

There are several areas in the engine which produce problems due to lubricant deposition and degradation, namely:

- Carbon deposits around the seal-contact surfaces and springs of face-type, spring-loaded seals.

- Sludging in closed, restricted areas adjacent to the rotating shaft.

- Vapor-phase coking in breather lines and small heated passageways.

- Plugging of scavenge strainers.

The consensus is that the most critical oil deposits are formed in areas where the metal surface and/or air leakage temperatures are the highest, e.g., the area between the rear compressor and the turbine section [(2)]. Most deposits formed in this general area are hard, crusty, carbonaceous buildups around the heat-sink-type metal flanges in the oil-wetted areas.

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* Superscript numbers in parentheses refer to the list of references included in this report.

Oil vapor vent lines and connections may be plugged after extended operation. A plugged breather tube in the No. 4-5 bearing compartment can cause a pressure unbalance between the two bearing compartments and result in improper oil scavenging with the possibility of oil loss during flight [2].

Realizing the large expenditures of time and money necessary to obtain sufficient full-scale engine data, the Aero Propulsion Laboratory (APL) contracted with Southwest Research Institute (SwRI) in 1972 (Contract No. F33615-72-C-1097) to develop an engine simulator test that would minimize the need for conducting full-scale engine tests to determine the deposition and degradation characteristics of lubricants.

As a result of the contract, the AFAPL engine simulator was designed and developed [3] by SwRI. Deposition results from the AFAPL engine simulator using eight turbine engine lubricants for which full-scale engine data were available, show a very good correlation (90.4 percent correlation coefficient) of the deposit ratings obtained using the AFAPL engine simulator and the deposit ratings obtained from the No. 4-5 bearing compartment areas from the full-scale engine tests.

This report presents the results of a subsequent contract, F33615-78-C-2012, to automate the operation, control, and data management systems of the AFAPL engine simulator during test, and thereby significantly reduce the operating technician time required to run an engine simulator test.

A comparison of the costs for power to operate the AFAPL engine simulator versus fuel costs to operate the APL full-scale engine test indicates that the engine simulator costs approximately $330 for electrical power during a 100-hr test, while the APL full-scale engine requires over $100,000 for fuel to operate for 100 hr. Assuming the APL full-scale engine test remains as the final "pass" or "fail" criterion for candidate turbine engine lubricants, considerable savings in fuel costs, not to mention the conservation of fuel and the possibility of future fuel availability problems, can be realized by using the engine simulator as the last screening tool prior to full-scale engine testing.

Summary

The J57 turbojet is a continuous flow gas turbine engine employing a multistage reaction turbine to drive a two-spool multistage axial flow compressor. This basic engine is used in the B-52, KC-135, C-135A, F-100, F-101, F102, F-8, F-6, and the A-3 military aircraft. Due to the large population density of this engine in inventory, it was selected by APL for use in all full-scale engine tests conducted by APL. In addition, the No. 4-5 bearing compartment areas of the J57 engine were subsequently selected as the basic hardware for the AFAPL engine simulator. Figure 1, a simplified sketch of a J57, shows the location of the No. 4-5 bearing compartment area in relation to the compressor and turbine areas of the engine. It will be noted that the combustion chamber section surrounds the No. 4-5 bearing compartment areas. It is this area of the engine which is considered to be the most critical with respect to lubricant depositon and degradation due to the high temperatures in the oil wetted areas.

The simulator operates in the horizontal position and is driven by a variable-speed drive system through timing belts to the accessory drive gearbox thereby providing compressor shaft speeds up to 9,120 rpm. Filtered air is introduced into the No. 4 compartment and directed over finned air heaters. As in the full-scale engine, a portion of the incoming air passes through the conical section to the No. 5 compartment. The combined seal leakage of the Nos. 4 and 5 seals passes through the breather tube strut and is directed to a trap, demister, and precipitator. Electrical resistance heaters are used to heat the air in the No. 4 and 5 bearing-seal areas to realistic operating temperatures. In addition, electrical resistance heaters are used to provide additional heat, as required to the No. 4 bearing housing, the conical section, and the breather strut.

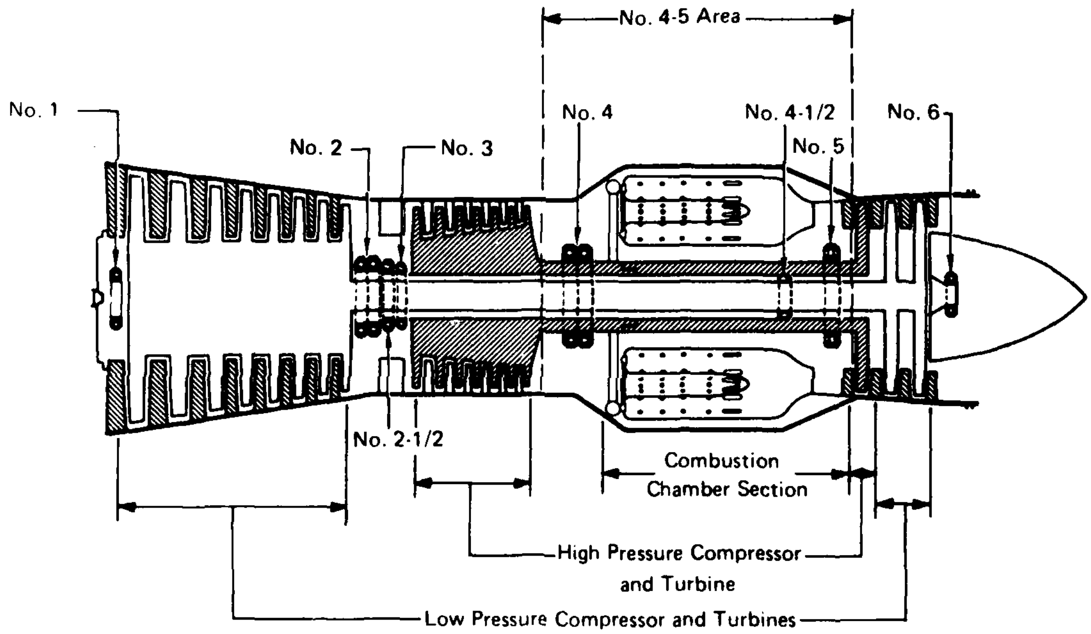


FIGURE 1. J57 TURBOJET ENGINE WITH BEARING LOCATIONS NUMBERED

An external test oil system provides lubricant to the simulator at the normal operating engine oil pressure. Approximately two-thirds of the test oil flow is provided to the internal oil system of the simulator. The remaining oil flow is jetted into the front and rear of the simulator gearbox to provide additional cooling to the gearbox. A heat exchanger is used to cool the oil flow to the gearbox. Additional heat exchangers are used in the simulator and gearbox oil return lines to the external sump.

The simulator test sequence was patterned after the cycling test procedure (25 min operation at 9120 rpm, followed by 6000 rpm operation for 5 min) used at APL for the full-scale engine test. A 1-hr soakback period (not counted as part of the test time) is performed after each 2.5 hr of test cycling. This 2.5 hr test cycle is repeated 40 times to complete a typical 100-hr simulator test.

Temperatures, pressures, and the simulator rpm are automatically controlled at predetermined levels and monitored throughout the 9120 and 6000 rpm speed cycling sequences and the soakback periods by a mini-computer system having a 64K semiconductor core memory. This computer system, used in conjunction with appropriate electronic interface devices, a CRT with keyboard, an X-Y plotter, a line printer with keyboard, and associated software programs provides for the automated operation of the simulator; extensive protection control and test rig shut-off limits for the various temperatures, pressures, etc. monitored; automatic sampling of the test oil each 5 hr; automatic measurement of the demister and precipitator fluid and its return to the sump; and automatic test-oil sump level control. The data from 63 sensors (temperature, pressure, rpm) are automatically monitored, averaged, and stored for the 9120 rpm and 6000 rpm speed cycles and later printed out to provide a section of the final test report. Temperature information from selected areas of the simulator are also monitored, averaged, and stored, for the 1-hr soakback periods. Average soakback temperature curves are generated by the X-Y plotter following each test. In addition, other information such as test-oil viscosity, neutralization number, and iron content; and, the numerical values of the visual inspection of the deposits of selected oil-wetted engine parts are manually input into the computer and then are used to compute and print out programmed information required for the test report.

Four automated AFAPL engine simulator tests were conducted following the conversion of the simulator control systems to computer control and the development of the related software programs. Two of the automated simulator tests were conducted to determine the correlation of the automated test data with test data generated earlier [3] using the manual controlled simulator test. Excellent correlation of the deposit ratings for lubricants 0-73-1, a "clean" oil, and 0-67-7, a "dirty" oil, was obtained using the two different test variable control methods. The remaining two tests were extended duration tests (one 250-hr, and one 350-hr duration), using lubricant 0-79-16, to determine the satisfactory repeated operation of the computer and its associated control equipment; and, to indicate the effect of extended test duration on the deposition and degradation characteristics of 0-79-16. Only two significant failures of the computer related equipment were obtained during the 850+hr automated operation (including check out operating time) during this contract period. These failures resulted in a cost of only approximately $1,000 and a down time of approximately 2.5 weeks (primarily delivery time of failed parts from the supplier) which is believed to indicate reasonable reliability of the various simulator systems. The deposit ratings for lubricant 0-79-16 showed significant increases when the test time was extended to 250-hr and then to 350-hr duration. An increase from 18 to approximately 23 was obtained in the deposit rating when the test time was extended to 250-hr from 100-hr duration. A further increase in the deposit rating to approximately 34 was obtained when the test was extended to 350-hr duration.

TEST EQUIPMENT AND PROCEDURES

Test Equipment

AFAPL Engine Simulator. The AFAPL engine simulator was designed to provide a relatively simple but flexible test facility with the capability of closely simulating the critical temperatures and oil flow variables experienced by the lubricant in the full-scale engine. Figure 2 illustrates the No. 4-5 bearing compartment areas of the J57-43 engine used as the heart of the simulator. The simulator is driven through the accessory gearbox by a variable-speed drive system providing simulator speed capabilities up to approximately 10,000 rpm. A maximum design temperature of 800°F (427°C) for the heated air in the No. 4 compartment and 850°F (454°C) in the No. 5 compartment is provided by finned electrical resistance heaters. The No. 4 bearing housing and the conical section are heated by band type electrical resistance heaters while the breather tube strut is heated by an open wire electrical resistance heater.

It will be noted in Figure 2 that the low pressure compressor drive rotor, the inner shaft shown in Figure 1, and the No. 4-1/2 bearing are not included in the simulator. Since these parts are not included, modifications were required to some of the standard hardware parts. For example, 4 holes in the rear shaft, normally used as return oil passages from the No. 4-1/2 bearing, were welded closed in order to provide a sealable air system within the simulator. In addition, the hub and rear shaft were modified to remove excessive weight and to allow additional room for air heaters. Plugs were incorporated into the ends of the hub and rear shaft to minimize air flow through the shaft and thereby provide the same air flow paths as those in the full-scale engine. Following the modifications to the hub and rear shaft, the complete rotating assembly was dynamically balanced. The No. 4 bearings are normally thrust loaded in the engine due to forces from the turbine section. In the simulator, the No. 4 bearings are preloaded during assembly to prevent the possibility of ball skidding

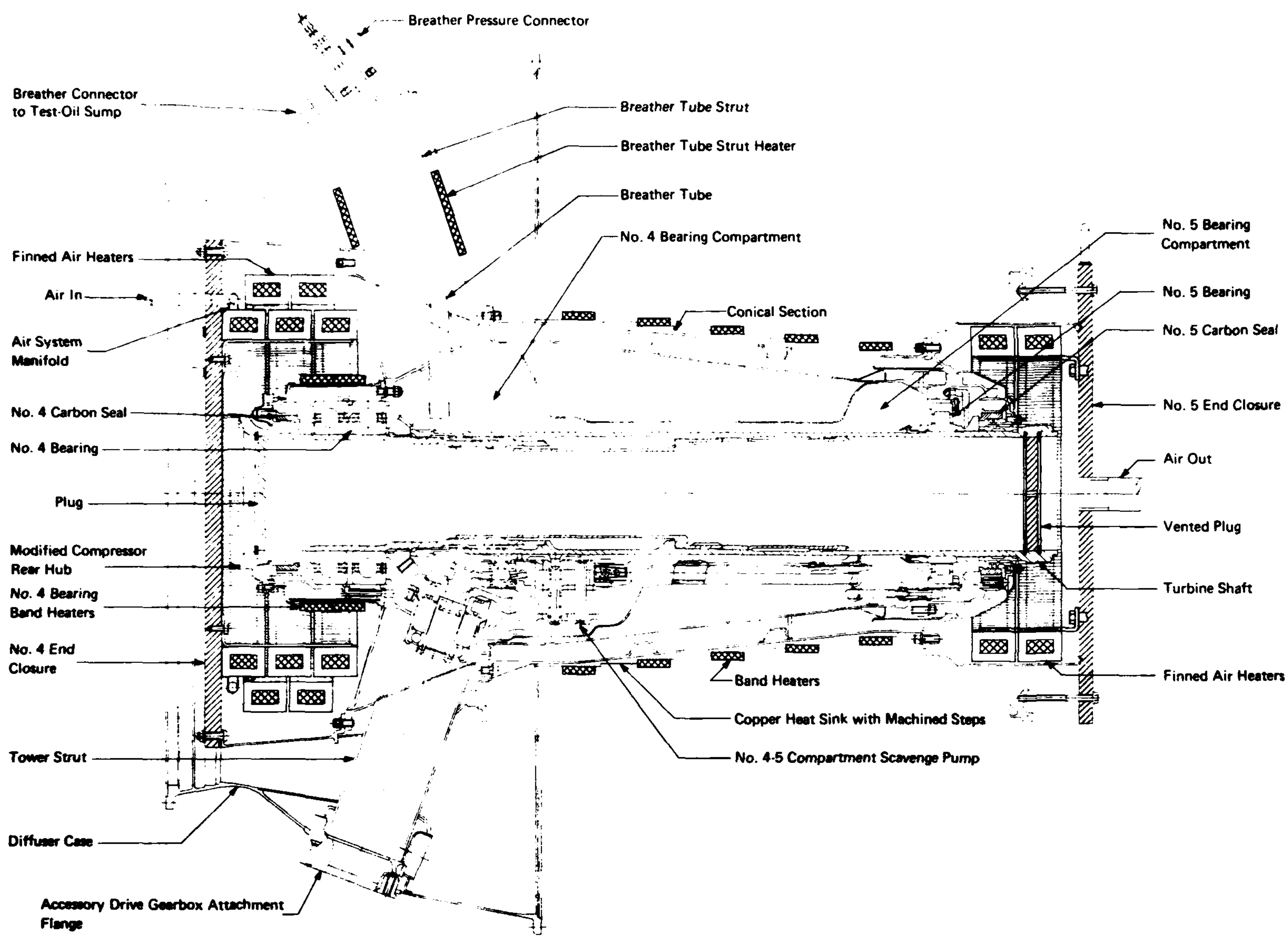


FIGURE 2. CROSS SECTION OF AFAPL ENGINE SIMULATOR

during operation. The preload is accomplished by changing the thickness of one of the bearing spacers. End closures were provided for the No. 4 and 5 compartment areas to provide a pressure tight system and to provide attachment points for the finned air heaters.

Three views of the AFAPL engine simulator are presented in Figures 3, 4, and 5. Figure 3 presents a view of the simulator with the external test-oil system shown at the extreme right. As noted in the background, bottled air is provided on standby in the event house air becomes inoperative during a test. Figure 4 shows a view of the simulator variable speed drive system. Figure 5 shows the external test-oil system including the automated test-oil sampling system, the demister, precipitator, and pour-back sump.

Computer Control System. The automated AFAPL engine simulator control console is shown in Figure 6. The simulator is controlled by a Model 40 Hewlett-Packard (H-P) 1000E, Series 2113, General Purpose Disc Based Mini-Computer System, including a 2648A graphics terminal, a 7900A disc (5M byte), an RTE-II-III real time driver, a 7245A printer/plotter, and a 2635A printing terminal. This computer system, used in conjunction with appropriate interface devices, sensors, and software programs provides for the automated operation of the simulator as shown in Figures 7, 8, and 9. These simplified schematic diagrams show the 12 separate process loops which must be controlled, and five of the on-off type controls which must be reset periodically, based upon time. In addition to extensive protection control and shut-off limits for the various temperatures, pressures, etc. monitored for safety, information from 63 sensors (temperature, pressure, rpm) are automatically monitored, stored, and averaged for the 9120 rpm and 6000 rpm speed cycles and later printed out to provide a section of the final test report. Temperature information from selected areas of the simulator are also monitored, stored, and averaged for the 1-hr soakback periods. Average soakback temperature curves are generated by the X-Y plotter following each test. In addition, other information such as test-oil viscosity, neutralization number, and iron content; and, the numerical values of the visual inspection of the deposits of selected

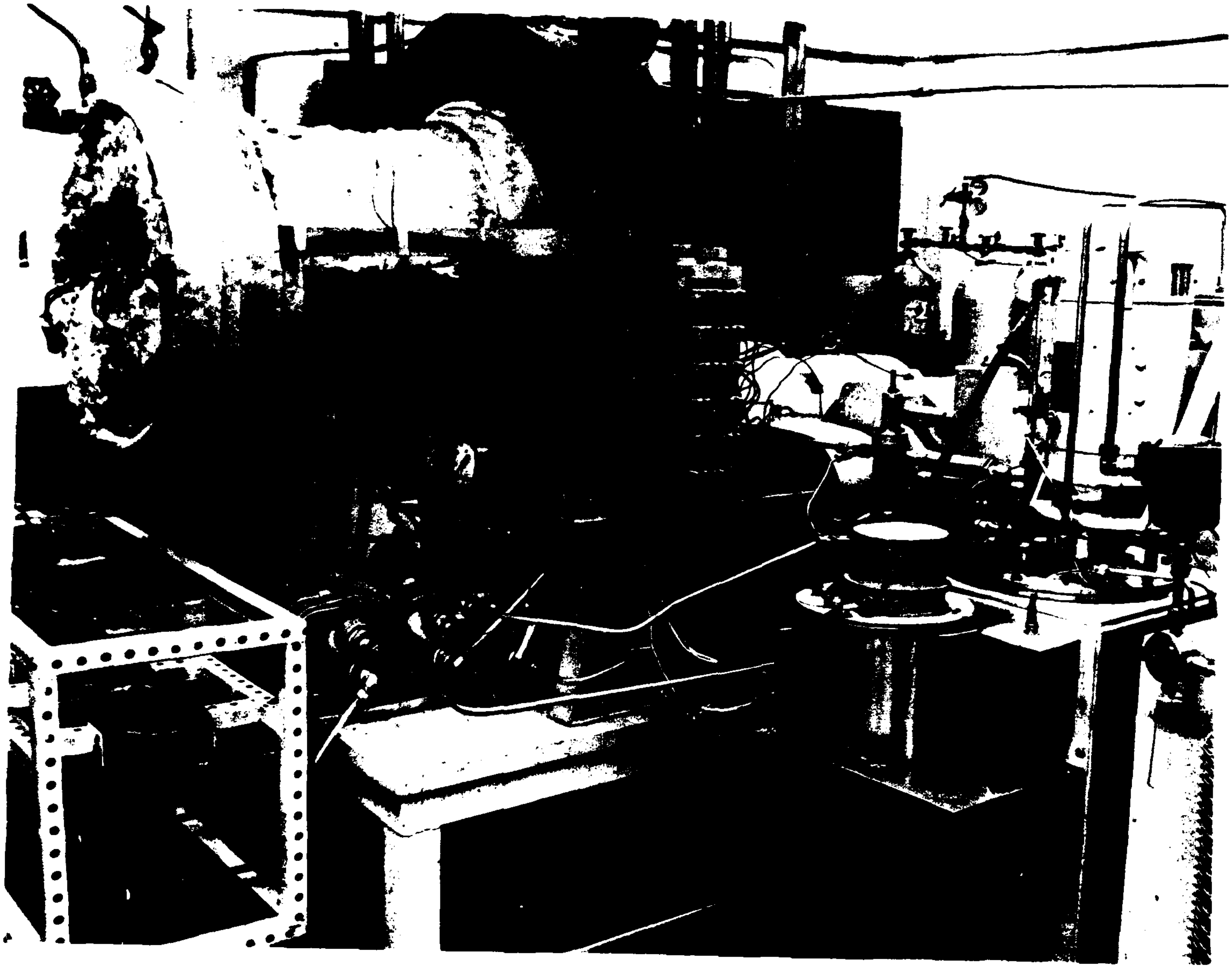


FIGURE 3. AFAPL ENGINE SIMULATOR WITH EXTERNAL TEST OIL SYSTI

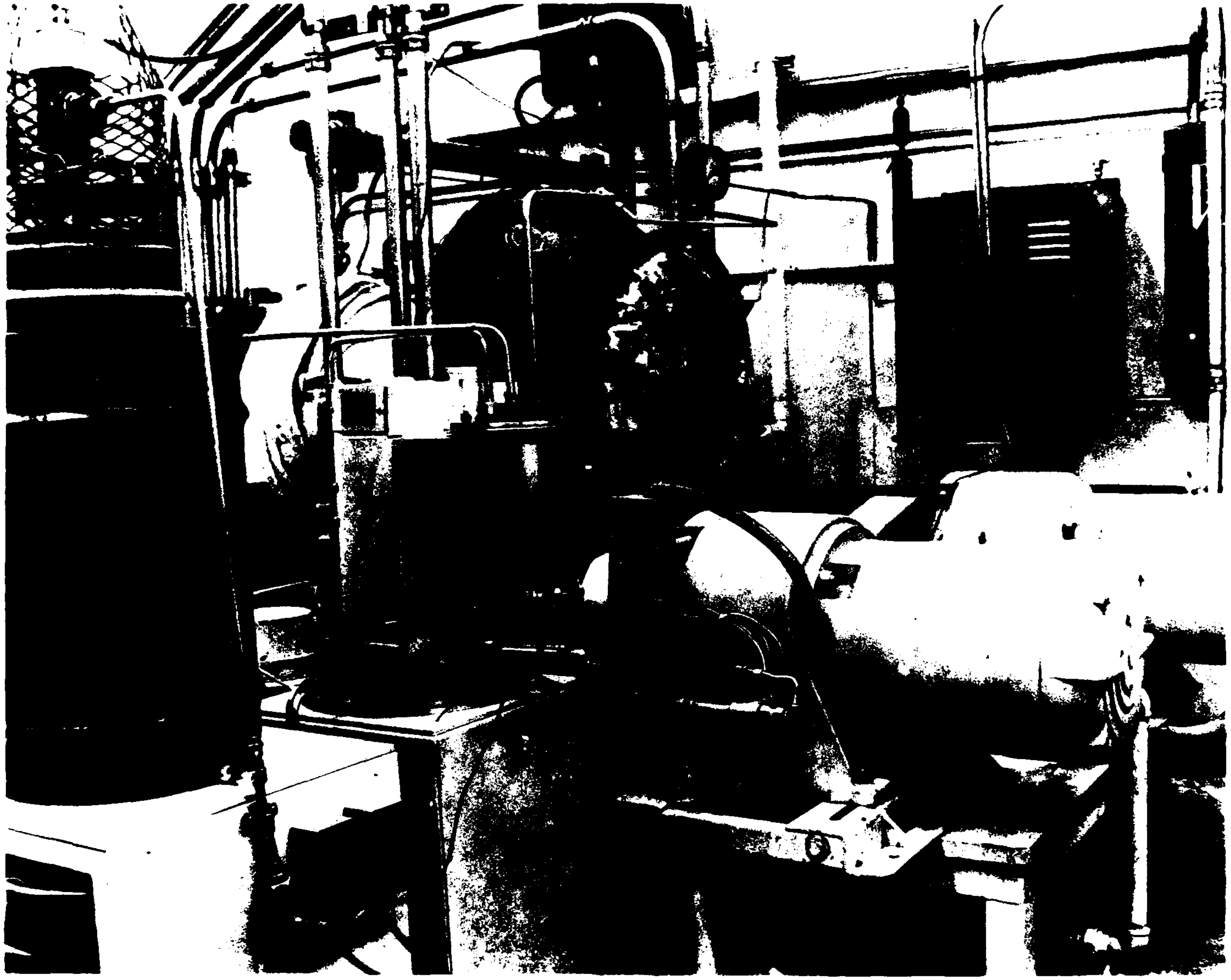


FIGURE 4. AFAPL ENGINE SIMULATOR VARIABLE SPEED DRIVE SYSTEM

FIGURE 5. AFAPL ENGINE SIMULATOR TEST-OIL SYSTEM

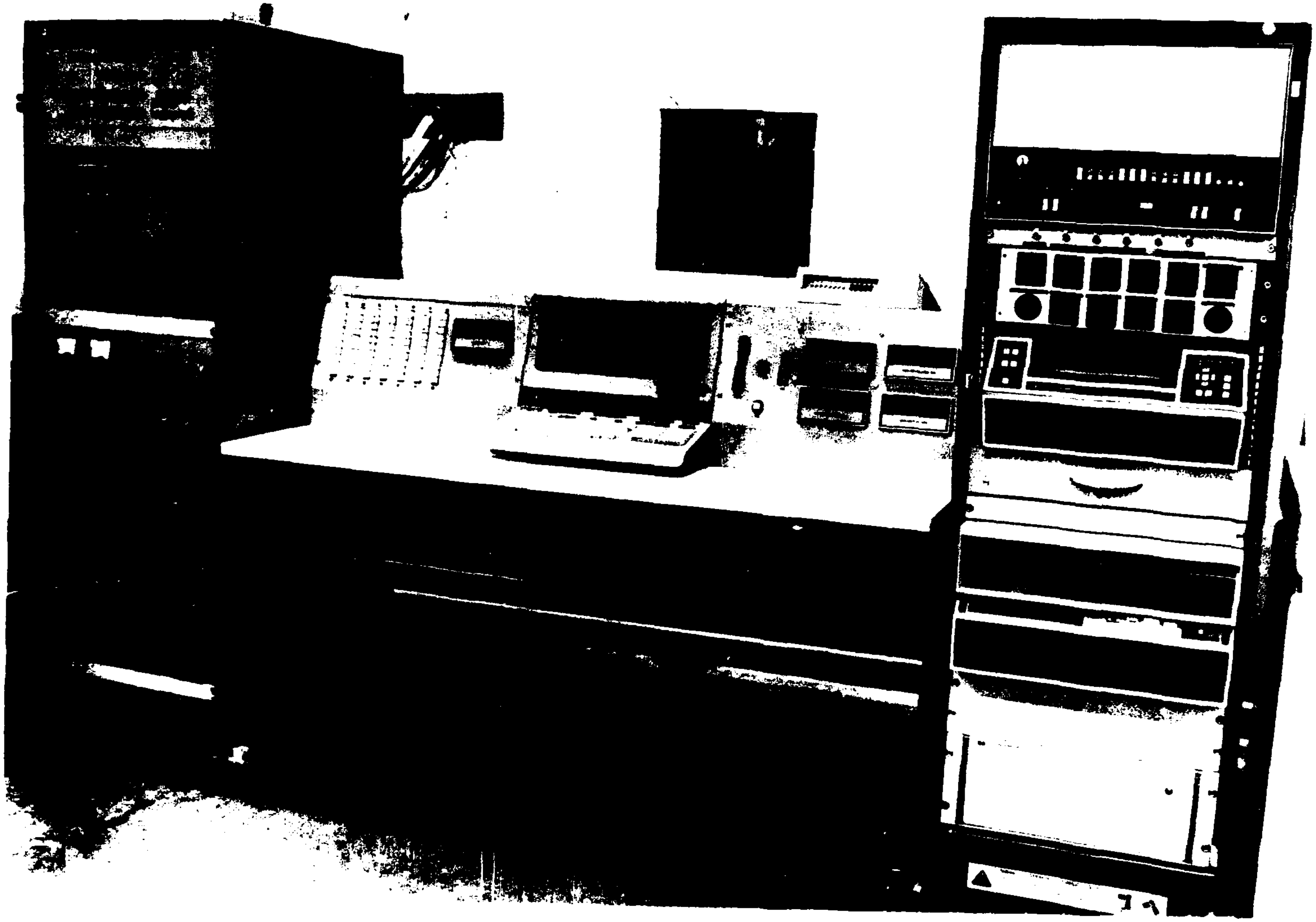


FIGURE 6. AFAPL ENGINE SIMULATOR CONTROL CONSOLE

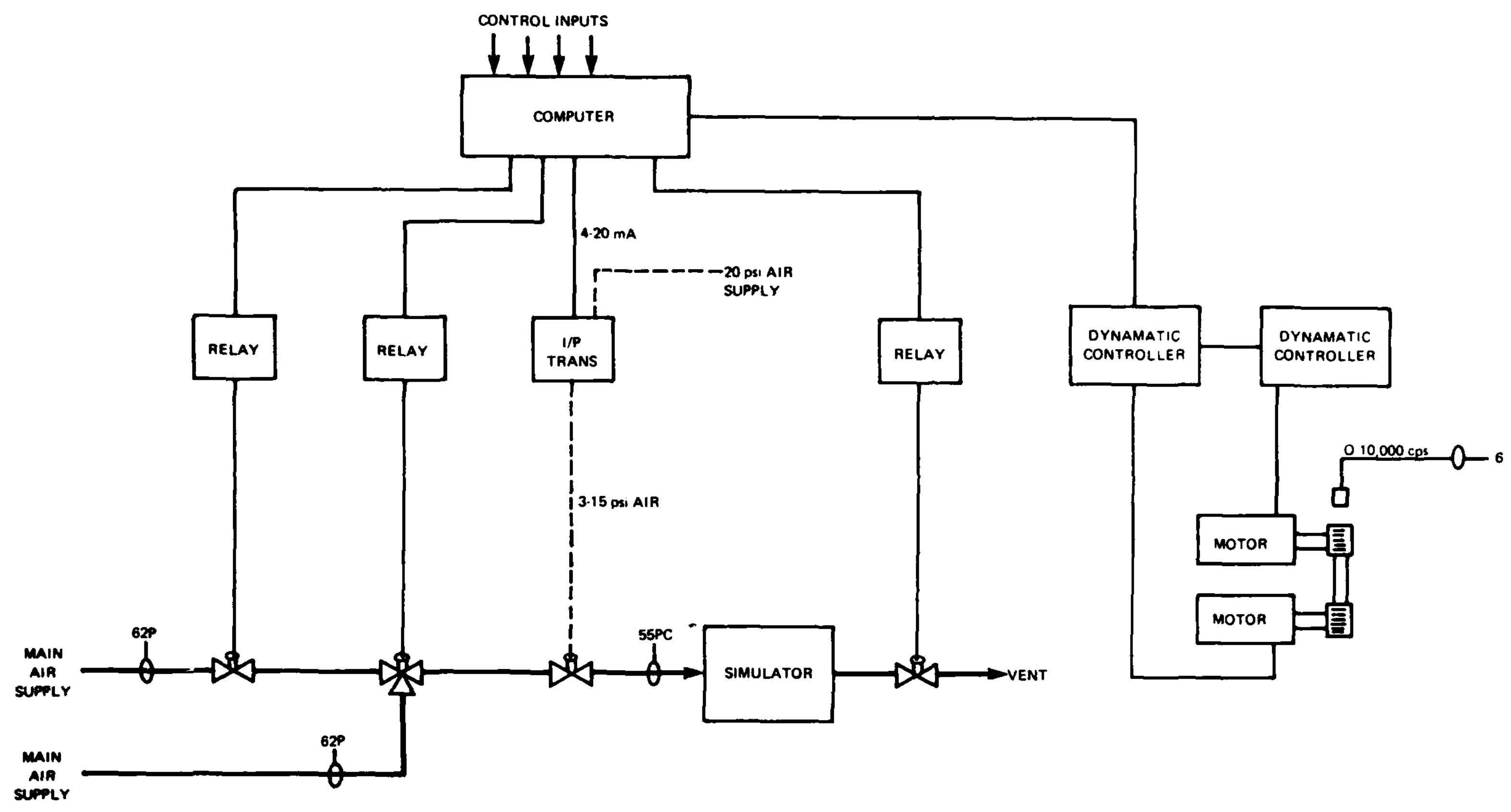


FIGURE 7. SCHEMATIC OF THE AUTOMATED AIR FLOW AND SPEED CONTROL SYSTEM

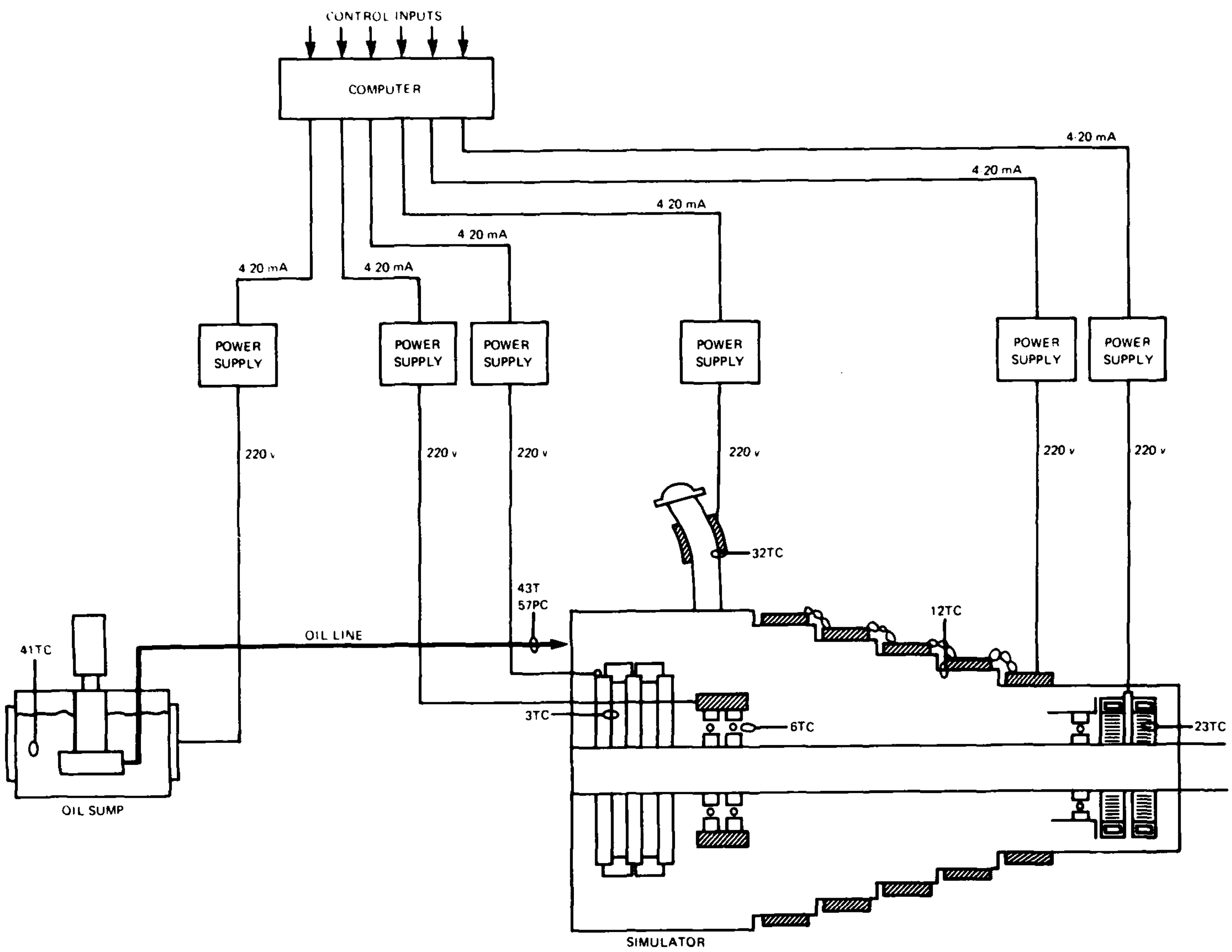


FIGURE 8. SCHEMATIC OF THE AUTOMATED HEATER CONTROL SYSTEM

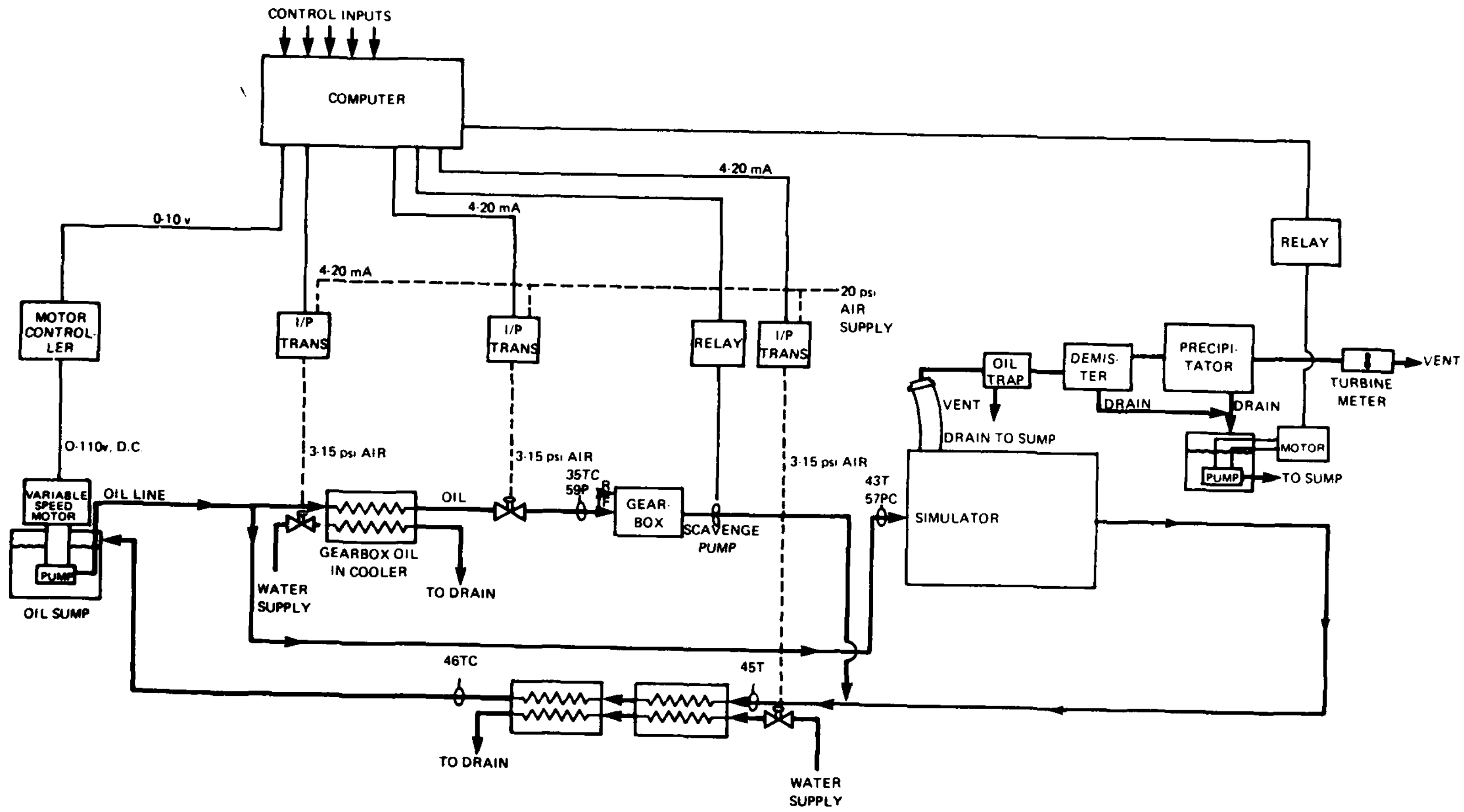


FIGURE 9. SCHEMATIC OF THE AUTOMATED OIL TEMPERATURE AND FLOW CONTROL SYSTEM

oil-wetted engine parts are manually input into the computer and then are used to compute and print out programmed information required for the test report.

Drive System. As shown in Figure 4, the simulator is driven by two 50-hp (37.3kw) variable speed Dynamatic drive units coupled through timing belts to the accessory drive gearbox extension shaft. This drive system provides an infinitely variable speed range up to approximately 10,000 rpm for the simulator main shaft assembly, and allows the simulator to be slowly accelerated to the maximum operating speed without damaging any portion of the drive system.

The accessory drive gearbox extention shaft was modified to allow ball bearing pillow blocks to be used to support the shaft. A 2:1 pulley ratio is used between the Dynamatic drive units and the accessory drive gearbox extension shaft. The gear ratio between the gearbox shaft extension and the simulator main shaft is approximately 1.43:1. The combination of these two step-up speed ratios provides an overall ratio between the Dynamatic drive unit and the simulator main shaft of 2.86:1. This overall step-up speed ratio allows the simulator main shaft to rotate at the normal maximum speed of 9,120 rpm with an input speed of only approximately 3,200 rpm from the Dynamatic drive units.

In actual engine operation, the accessory drive gearbox shaft extension is enclosed in a tube connected to the accessory gearbox which allows oil to return to the accessory gearbox. Since the accessory gearbox and the connecting tube are not used with the simulator, it was necessary to provide an oil seal around the accessory drive gearbox shaft extension to prevent oil loss, and to provide an external oil scavenge pump to return test oil from the gearbox to the sump.

Test-Oil System. The general configuration and location of the test-oil system with respect to the simulator is shown in Figure 5. The primary emphasis placed upon the design of the test-oil system was to provide a versatile system which would duplicate the temperatures and pressures in the J57 engine lubrication system, plus having sump temperature capabilities exceeding those normally encountered in J57 engine operation. The test-oil sump was designed to maintain a maximum controlled inlet oil temperature to the simulator of 450°F (232°C). By providing the increased temperature capability, elevated temperature tests, simulating advanced turbine engine operating conditions, can be performed using the AFAPL engine simulator in the future when the need arises.

Figure 10 presents a schematic of the automated AFAPL engine simulator test-oil system. All items of the system which are exposed to the lubricant are constructed of stainless steel with the exception of the test oil pressure pump and the gearbox scavenge pump. The O. D. of the stainless steel sump is copper-metallized for a distance extending approximately 6 in. (15.2 cm) from the sump bottom to provide improved heater efficiency and temperature uniformity. The copper clad is applied to a thickness of approximately 5/16 in. (0.8 cm) and machined smooth to a final thickness of 3/16 in. (0.5 cm). Heat is provided to the test-oil sump in the area of the copper clad by three 1500-watt band heaters conforming to the sump diameter.

A positive displacement gear pump (Brown and Sharpe 3S) is used in conjunction with a 3-hp variable-speed motor to provide test oil at a controlled 45 psi (310×10^3 Pa), to the simulator and gearbox. As shown in Figure 10, the pump is mounted inside the test-oil sump below the level of the test oil. A mechanical carbon seal is used to seal the pump shaft at the sump lid in order to permit measurement of seal air leakage in the simulator. The test-oil flow from the pressure pump passes through a 100-mesh screen filter and approximately 6 gal/min (22.7 l/min.) is directed to the oil inlet fitting of the simulator. The oil is scavenged from the No. 4-5 bearing compartment by the standard internal scavenge pump of the J57 engine and is returned to the test-oil sump after passing through an oil cooler and a 100-mesh screen filter.

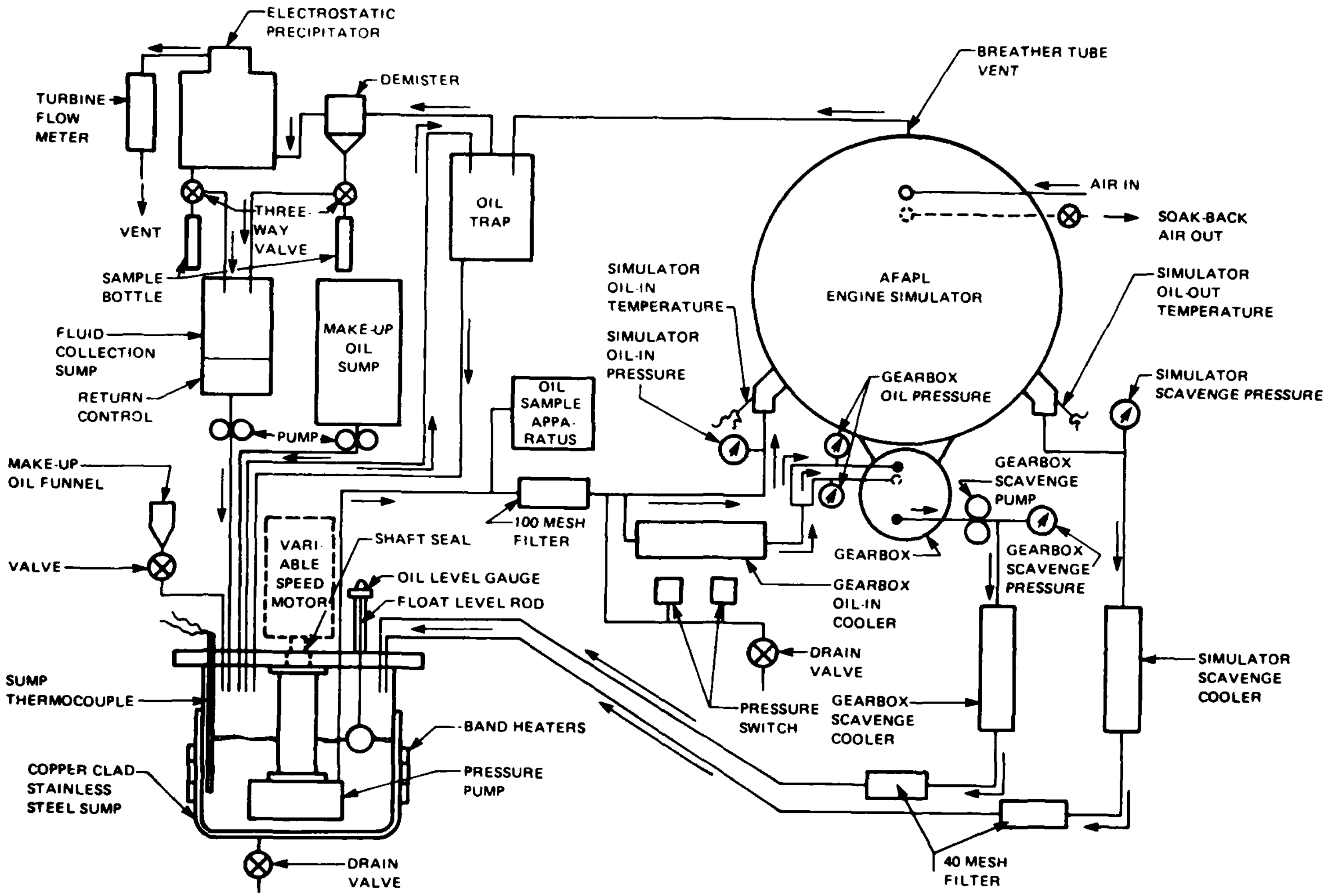


FIGURE 10. SCHEMATIC OF AUTOMATED AFAPL ENGINE SIMULATOR EXTERNAL TEST-OIL SYSTEM

Since the simulator is driven through the accessory drive gearbox, additional oil is supplied to the gearbox to provide increased cooling to the gears and bearings within the gearbox. Approximately 3 gal/min (11.4 l/min) of the oil flow from the pressure pump is utilized to provide the increased cooling for the gearbox. As shown in Figured 10, a portion of the oil flow from the 100-mesh screen filter (in the pressure line) is directed through an oil cooler and then to the gearbox. An external scavenge pump (Brown and Sharpe 2S), mounted on the bedplate below the level of the gearbox, returns the oil through an oil cooler and a 100-mesh screen filter to the test-oil sump.

The oil system within the simulator is the standard internal oil system (passages, fixed jets, and scavenge pump) used in the No. 4-5 bearing compartment area of the J57-43 except for the following changes:

- As stated previously the No. 4-1/2 bearing is not included in the AFAPL engine simulator; therefore, the normal oil flow from the No. 4-1/2 bearing is not included in the oil scavenged from the simulator. (The normal oil flow to the No. 4-1/2 bearing is supplied from the No. 6 bearing area which is not included in the AFAPL engine simulator and, therefore, is of no concern to the oil flow requirement of the No. 4-5 bearing compartment.)

- Since the J57-29 engine used at APL for the full-scale engine tests does not use two oil jets to lubricate the No. 5 carbon seal as does the J57-43 engine, the top oil jet to the No. 5 carbon seal in the simulator was capped in order to privide approximately the same amount of oil flow to the No. 5 carbon seal area as that obtained in the APL full-scale J57-29 engine. As discussed in a later section of this report, the oil flow from the top jet to the No. 5 carbon seal was redirected through a 0.076 in (0.193 cm) jet onto the main shaft towards the No. 4 sump. Redirecting this oil flow in the simulator provides cooling oil to the area of the I.D. of the conical section approximating the oil flow through the shaft, in this same area, from the No. 4-1/2 bearing in the full-scale engine.

The test-oil sump is sealed in order to permit the measurement of the No. 4-5 breather tube pressure in the test-oil system. The air leaking past the carbon seals into the test-oil section of the simulator is removed from the simulator by the over capacity scavenge pumps or is vented through the No. 4-5 compartment breather tube vent, as shown in Figure 10. The air-oil mist from the breather tube vent is directed to an oil trap which collects and gravity returns any oil droplets to the test-oil sump. The test-oil sump is also vented to the top of the oil trap. From the oil trap, air and oil vapors are directd to a demister, which removes approximately 1/2 of the air borne liquid from the vapors and then to an electrostatic precipitator which removes the remaining liquid from the vapors. The air from the electrostatic precipitator is then directed to a turbine type flow meter where measurements of air flow are taken periodically. Drains are provided on both the demister and the precipitator to enable the fluid removed from the vapors to be collected in a common fluid collection sump. The fluid thus collected, is returned automatically to the test-oil sump by a computer controlled pump which is activated by a signal from a pressure transducer located in the return control system of the fluid collection sump. Samples of either the demister or precipitator fluids can be taken manually, if desired, by use of the three-way valves provided.

Test-oil samples (40 ml each) are automatically taken from the oil pressure line, leading from the sump to the 100-mesh filter, approximately three minutes prior to each 5-hr shutdown for soakback. Two sample bottles are used for each sample period. The first sample bottle is filled with a 40-ml sample which is a purge of the lines and not a representative sample of current test oil and should be discarded. The second sample bottle is filled with a 40-ml sample which is a representative sample of the current test-oil. The samples taken are used to monitor viscosity, neutralization number, and iron content. Make-up oil is added automatically to the test-oil sump from the make-up oil sump (see Figure 10), approximately five minutes after the 5-hr shutdown for soakback, to compensate for loses resulting from normal consumption and the samples drawn.

In addition to the safety shut-down limits continuously monitored and controlled by the computer, mechanical/electrical high and low pressure switches are located in the test-oil pressure line as a redundant safety system to automatically shut the simulator off in the event of an excessively high or low test-oil pressure.

Air System. Filtered laboratory air is directed through the No. 4 end closure (see Figure 2) to a manifold ring, made of 1/2-in. (1.3 cm) diameter tubing, having a mean diameter of 18-1/4 in. (45.7 cm). Twenty-eight, evenly spaced, 1/16 in. (0.16 cm) diameter holes are used in the manifold ring to distribute the incoming air over the finned air heaters in the No. 4 bearing area. The air exits the simulator through the test-oil system and the No. 4-5 bearing compartment breather tube vent previously described.

An emergency air blow down system has been provided for the engine simulator facility. This system is designed for use in the event that the laboratory air system becomes inoperative. Four high pressure air bottles, 220 ft^3 (6.23 m^3) size, are manifolded together. In the event laboratory air is lost, the bottled air is automatically turned on by the computer. The quantity of emergency air available is sufficient to operate the simulator for approximately 2 hr, perform a 1-hr soakback, or, cool the simulator down during an emergency stop, if required. Without the emergency air system an entire test could be lost due to excessive temperatures in oil wetted areas within the simulator if laboratory air was lost during a scheduled or unscheduled stop.

Breather Tube. The J57 engine uses a rather complex configuration for the No. 4-5 bearing area breather tube (see Figure 2) by utilizing one of the diffuser case struts. Plates are welded at both the upper and lower portions of the strut. A tube is welded near the center of lower plate of the strut and extended downward into the No. 4 bearing compartment. This is the basic breather tube design. One serious problem related to this basic design is that it is almost impossible to completely clean the teardrop-shaped strut, primarily due to the inability to get a cleaning tool into the teardrop portion of the strut.

In an effort to alleviate cleaning of the basic breather tube design Pratt and Whitney designed a "slip-in breather tube." This change and others are included in T.O. 2J-J57-854, dated 14 October 1966, and entitled "Installation of Heat Sheilding and Thermal Blankets Nos. 2, 3, 4, and 5 bearing Compartments and Installation of Diffuser Slip-In Breather Strut Tube and Oil Jet J57-P/F-43W, -43B, and P59W Engines."

This "slip-in breather tube" modification is used in the AFAPL engine simulator and greatly simplifies the cleaning of the tube since it can be easily removed from the diffuser case strut.

Heating System. As previously discussed, it is necessary to add heat and control the temperature in the following areas of the simulator:

- No. 4 bearing-seal area
- Conical section

- No. 5 bearing-seal area
- Breather strut

Specific information related to these temperature controlled areas are discussed in the following paragraphs.

No. 4 Bearing-Seal Area. The No. 4 compartment is heated by five finned air heating elements (Figure 2) utilizing monel sheath and fins capable of a maximum surface temperature of 1050°F (566°C). These heaters have a combined maximum capacity of 25.6 kW. By carefully directing the air entering the No. 4 bearing-seal area through the manifold ring across the finned heating elements the desired maximum air temperature of 800°F (427°C) is attained. The heater rings are attached to the No. 4 end closure. The heater rings were formed at the factory by curving straight elements to the desired radius. Since the exact desired lengths are not available as off-the-shelf-heaters, each ring is made up of two standard length elements. Tabulated below are the heater elements used in the No. 4 area:

Chromalox finned air heating elements, 1-3/8 x 2-in. (3.3x5.1 cm) fins, maximum wattage: 30 W/sq. in., 240 V.

Qty	Part Number	Approx. Overall Length, in. (cm)	Inside Diameter of Bent Heaters, in. (cm)	Location	Max. Watts, ea.
6	SEF-250	25-1/2 (64.8)	14-1/8 (35.9)	inside ring	2400
4	SEF-300	30-1/2 (77.5)	17-3/8 (44.1)	outside ring	2800

Two band heaters are clamped around the No. 4 bearing housing assembly to assist in producing bearing outer race temperatures similar to those obtained in the APL full-scale engine test. These heaters are specified as follows:

Chromalox chrome steel sheath band heater for temperatures up to 1200°F (649°C). One-piece construction, two terminals at one end, heater cross section 3/8-in. (1.0 cm) wide, 750W, 240V, P/N SE-3307, inside diameter of band 10-1/4 in. (26.0 cm).

Conical Section. The outside surface of the conical section is heated by five band heaters. In order to provide a more uniform flow of heat to the conical section, a 3/8 in. (1.0 cm) thick layer of copper was metallized to the entire outside surface of the tapered portion of the conical section. Cylindrical steps were then machined in the copper layer to accomodate the five band heaters. Each band heater is made up of two standard length strip heaters which are formed to the desired radius at the factory. Tabulated below are the heater elements sized to fit the machined copper steps of the conical section:

Chromalox chrome steel sheath band heaters for temperatures up to 1200°F (649°C) heater cross section 3/8-in (1.0 cm) thick x 1-1/2 in (3.8 cm) wide, 240V.

Qty	Part Number	Approx. Overall Length, in. (cm)	Inside Diameter of Bent Heaters, in. (cm)	Max. Watts, ea.
2	SE-2507	25 (63.5)	16-3/8 (41.6)	750
2	SE-2405	23-1/4 (59.0)	15-3/8 (39.0)	500
2	SE-2405	23-1/4 (59.0)	14-3/4 (37.5)	500
2	SE-2007	20-1/2 (52.1)	14-3/8 (36.5)	750
2	SE-2007	20-1/2 (52.1)	13-3/8 (34.0)	750

No. 5 Bearing-Seal Area. Approximately one-half of the heated air in the No. 4 bearing-seal area flows through the heated annulus of the conical section to the No. 5 bearing-seal area; therefore, only a small amount of heat, to make up for heat losses, is required for the No. 5 bearing-seal area.

The No. 5 compartment is heated by two, 12-5/8 in. (32.1 cm) inside diameter, finned air heating elements, similar to those used in the No. 4 compartment, having a combined maximum capacity of 8.2 kW. The heater rings are attached to the No.5 end enclosure and fit inside the turbine nozzle inner case (Figure 2) upon assembly of the simulator.

The following heater elements are used to make up the ring heaters for the No. 5 compartment:

Chromalox finned air heating elements, 1-3/8 x 2-in. (3.3 x 5.1 cm) fins, monel sheath and fin for 1050°F maximum sheath temperature, maximum wattage: 30 W/sq. in., 240 V.

Qty	Part Number	Approx. Overall Length, in. (cm)	Location	Max. Watts, ea.
2	SEF-210	21 (53.3)	outside ring	1900
2	SEF-240	23-3/4 (60.3)	outside ring	2200

Breather Tube Strut. The breather tube strut is heated by means of a clam-shell type open wire electric resistance heater. The heater enclosure is trapezoidal shaped to fit around the strut. Approximately 1 kW is required to maintain a controlled strut skin temperature of 650°F (343°C).

Operating Procedures

General. The AFAPL engine simulator test is patterned after the 100-hr, 9120-6000 rpm cycling test procedure used at APL for the full-scale engine tests. Temperatures are controlled in slected areas of the engine simulator in order to approximate the temperature profiles obtained in APL full-scale engine tests. The standard test duration is currently considered to be 100 hr in order to allow comparison of the engine simulator test results with the results obtained from full-scale APL engine test results. However, extended-duration tests of up to 350 hr have also been conducted using the engine simulator. Selected oil wetted parts within the engine simulator are visually rated for deposits and color photographs are taken at the end of test. Samples of test oil are drawn periodically and the viscosity and neutralization number determined. A detailed description of the AFAPL engine simulator test is presented in the following paragraphs.

Test Preparation. A number of preliminary steps are performed prior to starting an engine simulator test. All of the oil wetted parts in the engine simulator and test-oil system are thoroughly cleaned and air dried prior to assembly of the components. The heat exchangers used in the test oil system are pressure checked after cleaning to insure that no leaks exist between the oil to water heat transfer tubes. The oil filter screens used for the simulator oil in, simulator oil out, and the gearbox oil out are cleaned, weighed, and their weights recorded. New thermocouples are made and installed in the engine simulator. Thermocouples located in the air and test-oil systems are checked and replaced as necessary. The No. 4 and No. 5 carbon face seals are checked for flatness of the sealing face and lapped if necessary. The height of the carbon seal face of both the No. 4 and No. 5 carbon seals is measured at three indexed locations, 120° apart, and recorded. The seal plates used with the No. 4 and No. 5 carbon seals are visually inspected for nicks, dents, and smearing of the chrome plated sealing surface. The seal plates are then checked for flatness of the sealing surface and lapped if necessary. The complete seal assemblies are then individually checked for leaks using a special test fixture (similar to the PWA-650-51 test facility). The leak check is conducted using air at 80 psi (552 kPa). The total air leakage must be less than three cfm (1.4×10^{-3} m^3/s) for each seal assembly to be acceptable for use in accordance with T.O. 2J-J57-56. Following these specific inspections and a visual inspection of all parts within the simulator, the simulator is assembled in accordance with T.O. 2J-J57-56. The test-oil system is assembled and the lubricant to be evaluated is added to the test-oil sump.

Test Temperatures. A total of 54 temperatures are continuously monitored and recorded during an engine simulator test. Figure 11 presents the general locations for the 34 thermocouples inside the engine simulator. Thirteen thermocouples are placed in various locations throughout the test-oil system. Three thermocouples are placed under bolt heads located on the front, rear, and top (near bearing outer races) of the gearbox. The remaining four thermocouples are located on the two drive motors and the input shaft pillow block bearings.

Controlled Test Temperatures. Temperatures are controlled in selected areas of the engine simulator in order to approximate the temperature profile obtained in APL full-scale engine tests. The location and the temperature or the controlled temperature areas of the engine simulator during test, are as follows:

Location	Thermocouple Number	Controlled Temperature, °F (C)
No. 4 Air	3	800 (427)
No. 4 Bearing Heater	5	800 (427)
Concial Outer Surface	12	800 (427)
No. 5 Air	23	850 (454)
Breather Tube Strut	32	650 (343)
Test Oil Sump	41	300 (149)

Measured Test Temperature. In additon to recording the temperatures of the controlled areas within the engine simulator and the test-oil sump, the location and average measured test temperatures during operation at 9120 rpm for the remaining 48 uncontrolled temperature areas are presented in Table 1.

Test Sequence. As mentioned earlier, the test sequence used with the AFAPL engine simulator is patterned after the 100-hr, 9120-6000 rpm

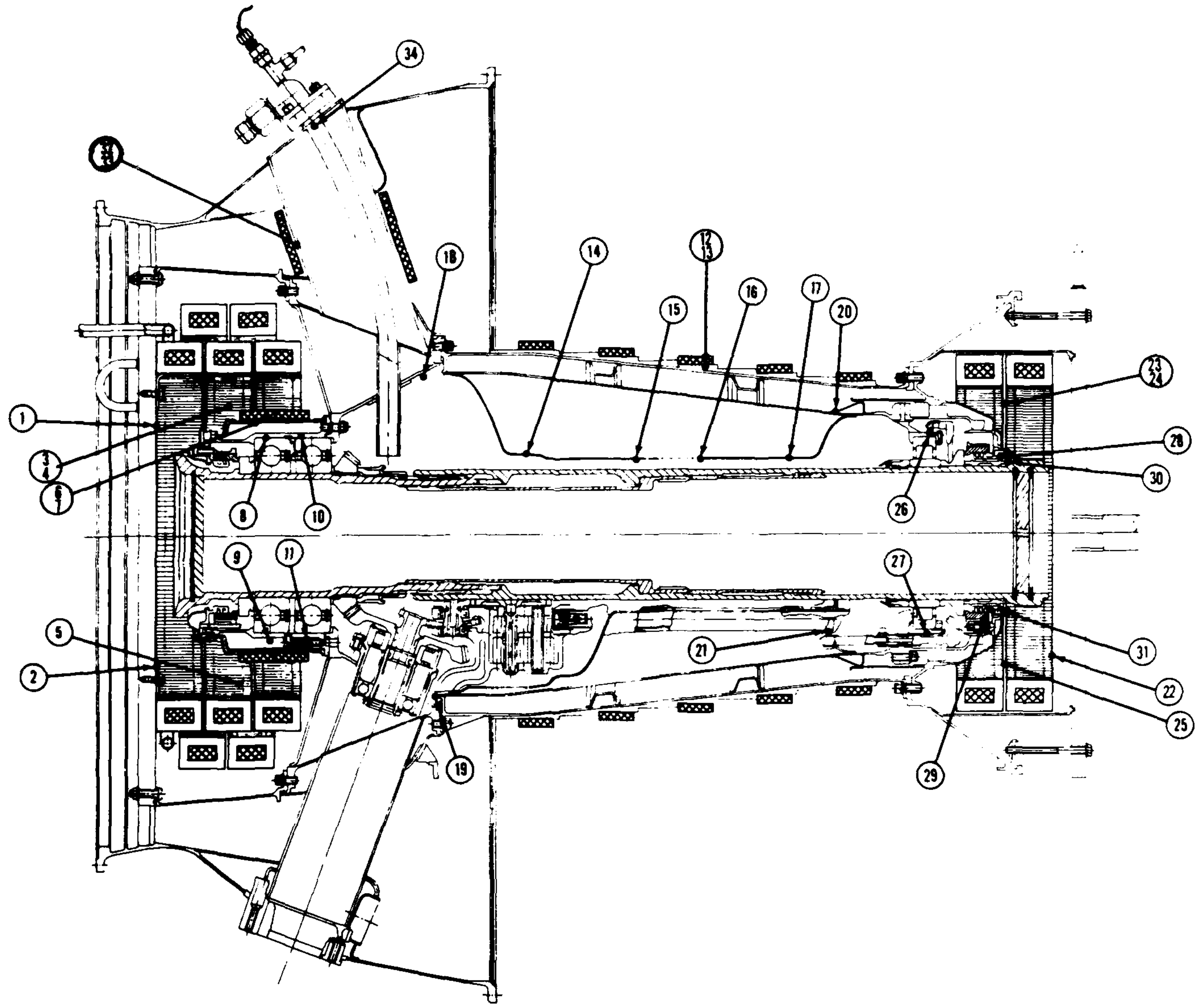


FIGURE 11. AFAPL ENGINE SIMULATOR THERMOCOUPLE LOCATIONS

TABLE 1. LOCATION AND AVERAGE MEASURED TEST TEMPERATURES FOR UNCONTROLLED AFAPL ENGINE SIMULATOR AREAS

Location	TC No.[a]	Temperature, °F (°C)
NO. 4 AREA		
Air Heater (Inside)	1	630 (332)
Air Heater (Outside)	2	626 (330)
Air (T)[b]	4	766 (408)
Air (B)[c]	5	713 (378)
Bearing Heater	7	753 (400)
Bearing (Fwd T)	8	329 (165)
Bearing (Fwd B)	9	324 (162)
Bearing (Aft T)	10	316 (158)
Bearing (Aft B)	11	323 (162)
CONICAL AREA		
Heater	13	784 (418)
Hub Area (Fwd)	14	328 (164)
Hub Area (Mid-Fwd)	15	316 (158)
Hub Area (Mid-Aft)	16	316 (158)
Hub Area (Aft)	17	307 (153)
Sump (Fwd T)	18	352 (178)
Sump (Fwd B)	19	339 (171)
Sump (Aft T)	20	350 (177)
Sump (Aft B)	21	342 (172)
NO. 5 AREA		
Air Heater (B)	22	942 (506)
Air (T)	24	816 (436)
Air (B)	25	736 (391)
Bearing (T)	26	391 (199)
Bearing (B)	27	391 (199)
Seal Ring Housing (T)	28	679 (360)
Seal Ring Housing (B)	29	626 (330)
Washer (T)	30	680 (360)
Washer (B)	31	665 (352)

Location	TC No.	Temperature, °F (°C)
BREATHER AREA		
Heater	33	622 (328)
Tube Air	34	228 (109)
GEARBOX AREA		
Oil-In	35	186 (86)
Oil-In	36	194 (90)
Oil-Out	37	298 (148)
Bearing (T)	38	279 (137)
Bearing (Fwd)	39	229 (109)
Bearing (Aft)	40	265 (129)
OIL SYSTEM AREA		
Oil Sump	42	296 (147)
Simulator Oil-In	43	299 (148)
Simulator Oil-Out	44	343 (173)
Simulator HE Oil-In	45	340 (171)
Simulator Scav. HE Out	46	307 (153)
Simulator Scav. HE Out	47	312 (156)
Gearbox Scav. HE Out	48	271 (133)
Gearbox Scav. HE Out	49	271 (133)
MISCELLANEOUS		
Left Drive Motor	50	76 (24)
Right Drive Motor	51	76 (24)
Drive Shaft Bearing	52	132 (56)
Drive Shaft Bearing	53	139 (59)
Oil Sump Heater	54	332(167)

Temperatures measured during operation at 9120 rpm.

(a) Thermocouple number.
(b) Top
(c) Bottom

cycling test procedure used at APL for the full-scale engine tests. Briefly, the test oil system heaters, the air heaters, the No. 4 bearing heaters, the conical outer surface heaters, and the breather tube strut heater are all turned on and preheated for a short period of time (approximately 20 min). The test-oil pressure pump and gearbox scavenge pump are started. Within approximately 15 seconds from the time the test-oil pressure pump is started, the drive system of the simulator is started and the simulator speed brought up to 9120 rpm and the air pressure is increased to 20 psi. These conditions are maintained for 25 minutes. The speed is then reduced to 6000 rpm for a period of 5 minutes. This speed cycle is repeated three times for a total heated operating period of two hours. At that time the power to all heaters is turned off and one speed cycle is run without heat. At the end of the 30-minutes operating period without heat, the simulator is stopped and a 1-hr temperature soakback is made. The valve in the air-out line on the No. 5 end cover is opened and the air pressure is reduced to 6 psi for the first 30 minutes of the soakback period and then further reduced to 3 psi for the remaining 30 minutes of the soakback period. The 1-hr soakback period is not counted as operating test time. The 2.5-hr operating test cycle and 1-hr soakback are repeated 40 times to complete a 100-hr simulator test.

It should be mentioned that the temperatures, air pressures, oil pressures, simulator rpm, and test times are all controlled automatically by the computer once the test has been initiated by the operator. A complete step-by-step operating procedure and a copy of all of the software programs, including program documentations were submitted to the APL Project Engineer.

At the end of test, whether 100-hr or an extended duration test, the simulator is disassembled and color photographs of the rated items are taken prior to the visual deposit inspection.

Test Termination. Simulator tests are normally conducted for 100-hr, or for longer predetermined periods, as required. However, a test may be terminated early if the 5-hr test-oil sample indicates a 37.8°C viscosity increase of 50 percent or the neutralization number exceeds 10 mg KOH/g.

Test Procedure Variations. Numerous minor variations were made to the test procedure used with the manually operated AFAPL engine simulator. These variations were made in an effort to, (1) improve the temperature profile within the engine simulator such that it provided a better approximation of the temperature profile within the APL full-scale engine tests, (2) adapt available J57-43 engine parts as necessary to simulate the oil flows in the J57-29 engine (used in the full-scale engine tests), and (3) obtain correlation of the engine simulator used oil analyses with those obtained during the full-scale engine tests.

The following variations (A through E) to the basic test procedure were used with the manually operated AFAPL engine simulator:

Procedure A

1. The initial test-oil sump charge was 5 gal.

2. The standard internal oil system in the No. 4-5 bearing compartment area of the J57-43 was used. Since the No. 4-1/2 bearing is not included in the simulator, the normal oil flow from the No. 4-1/2 bearing was not included.

3. A forced oil make-up schedule, scaled to the oil make-up normally required by the full-scale engine test, was used.

4. The fluids collected in the demister, precipitator, and oil trap were sampled for viscosity and neutralization number determinations but were not returned to the test-oil sump.

Procedure B

1. The test-oil system was modified such that the oil from the oil trap in the engine simulator vent line was continuously returned to the sump. The fluids collected in the demister and precipitator were sampled for viscosity and neutralization number determinations and the fluids remaining after sampling were returned to the sump.

2. All other test conditions were the same as Procedure A.

Procedure C

Same as Procedure B except initial test-oil sump charge was incresased to 6 gal.

Procedure D

1. The initial test-oil sump charge was 6 gal.

2. The standard J57-43 internal oil system was modified by capping the top oil jet to the No. 5 carbon seal, thereby approximating the oil flow to the No. 5 carbon seal area in the APL full-scale J57-29 engine.

3. The forced oil make-up schedule was not used. Test oil was added at each 5-hr test interval, after samples were drawn and the fluids from the demister and precipitator were returned to the sump, to compensate for losses resulting from consumption and the samples drawn.

Procedure E

Same as Procedure D except for the following:

1. The oil from the top oil jet to the No. 5 carbon seal was redirected through a 0.076 in. jet onto the main shaft towards the No. 4 sump in the area of the No. 17 thermocouple. Redirecting this oil flow provides oil to the area of the I.D. of the conical section approximating the flow through the shaft from the No. 4-1/2 bearing in the full-scale engine.

2. A plug was placed in the I.D. of the main shaft in the No. 5 seal area in an effort to reduce the temperature of the main shaft. A 1/8 in. hole was drilled in the plug to relieve any possible pressure increase within the shaft.

Procedure Auto I

This procedure represents the automated version of Procedure E, in that, the computer control software was written to duplicate, as nearly as possible, the earlier manual operation of the simulator temperature, pressure, and speed controls. No known differences were designed into the operating portion of the test. The only differences are in the mechanical methods the 5-hr samples are taken and the test-oil make-up is added to the sump.

Deposit Demerit Rating Procedure

Upon completion of an engine simulator test the engine simulator is disassembled and selected oil wetted parts are visually rated for deposits.

The deposit demerit rating system used by APL for full-scale engine testing is also used to numerically describe the lubricant deposits which accumulate on the rated parts of the engine simulator. The demerit rating numbers used to describe the different types and thicknesses of deposits obtained in the full-scale engine tests conducted at APL and the AFAPL engine simulator test are summarized in Table 2.

The following 17 oil wetted engine simulator parts are rated for deposits:

- No. 4 Forward Bearing
- No. 4 Aft Bearing
- No. 5 Bearing
- No. 4 Seal
- No. 5 Seal
- No. 4 Sump
- No. 5 Bearing Support Forward and Aft
- No. 4-5 Scavenge Pump
- No. 4 Compartment
- No. 5 Compartment
- No. 4-5 Scavenge Pump Screen
- No. 4-5 Breather Tube
- No. 4-5 Breather Tube Elbow
- Tower Shaft
- Tower Shaft Strut
- Conical Section I.D.
- Rear Shaft

Figure 12 presents an illustration of a typical rating worksheet used when visually rating the simulator. Normally only the numerical description of the deposit and the percent area covered by that deposit is all that needs to be recorded on the rating worksheet since only these data are entered into the computer which then calculates all the needed

TABLE 2. DEMERIT RATING NUMBERS USED
FOR NUMERICALLY DESCRIBING DEPOSITS

Deposit Description	Demerit Rating Number
Clean	0.0
Very light varnish - straw colored	1.0
Light varnish - amber colored	1.2
Medium varnish - tan colored	1.4
Heavy varnish - brown, 0.001 in. (0.0025 cm) depth	1.7
Very heavy varnish - black <0.002 in. (0.005 cm) depth	2.0
Light soft sludge - wipes easily, little depth	1.5
Medium soft sludge - wipes with pressure, <0.016 in. (0.040 cm) depth	1.8
Heavy soft sludge - difficult to wipe, >0.016 in. (0.040 cm) depth	2.2
Light hard sludge - <0.016 in. (0.040 cm) depth	2.5
Medium hard sludge - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	3.0
Heavy hard sludge - >0.062 in. (0.159 cm) depth	3.5
Light gritty deposit - <0.016 in. (0.040 cm) depth	4.0
Medium gritty deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	5.0
Heavy gritty deposit - >0.062 in. (0.159 cm) depth	6.0
Light smooth or wavy deposit - <0.016 in. (0.040 cm) depth	5.5
Medium smooth or wavy deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	7.0
Heavy smooth or wavy deposit - >0.062 in. (0.159 cm) depth	8.5
Light blistered deposit - <0.016 in. (0.040 cm) depth	6.5
Medium blistered deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	8.0
Heavy blistered deposit - >0.062 in. (0.159 cm) depth	9.5
Light flaked deposit - <0.016 in. (0.040 cm) depth	9.0
Medium flaked deposit - 0.016 in. (0.040 cm) to 0.062 in. (0.159 cm) depth	12.0
Heavy flaked deposit - >0.062 in. (0.159 cm) depth	15.0

values, stores the results, and prints out a four page summary of the input data and calculations for the test report. Numerical values are included in Figure 12 to facilate a complete description of the rating method and calculations used to determine the deposit rating of the lubricant at the end of an engine simulator test. It will be noted in Figure 12 that the rated areas of the bearings are divided into four sections: inner race, outer race, retainer, and balls or rollers. These sections are in turn broken down into specific areas to be rated. The exposed surfaces of the inner and outer bearing races, front and rear, and wear track are rated. The bearing retainers are rated on the front, rear, I.D. and O.D. surfaces. Due to the type construction of the No. 5 bearing, no rating is made of the O.D. of the roller retainer or the outer race wear track. The rated areas of the No. 4 seal are divided into three sections: springs, support, and carbon assembly. Only the oil wetted area of the seal support (excluding the ring groove area) is rated for deposits. The entire oil wetted areas of the springs and carbon assembly are rated. The rated areas of the No. 5 seal are the same as those of the No. 4 seal with one added area -- the seal ring housing (P & W No. 348950) which is not applicable to the No. 4 seal. The remaining 12 items rated are not divided into sub areas for deposit rating purposes.

The deposit rating for each part or area rated is obtained by selecting a demerit rating number or numbers, ranging from 0 to 15 (Table 2), to describe the types and thicknesses of deposits present on the part. The demerit number is then multiplied by the estimated percent area covered by that deposit. In the event that more than one type or thickness of deposit is present on the area being rated, the rating for that part or area is the total of the individual ratings. The inspection accounts for 100 percent of each oil wetted part or area being inspected. When the part being rated is broken down into various sub items and rated areas, such as the No. 4 bearings, inner race, outer race, retainer, and balls, the average rating is obtained for each sub item and the overall average

NO. 4 BEARING

	FORWARD			AFT		
	Deposit × % Area	Total	Avg	Deposit × % Area	Total	Avg
INNER RACE Front	1.4 × 100 = 1.40	1.40	1.33	1.4 × 100 = 1.40	1.40	1.33
Rear	1.4 × 100 = 1.40	1.40		1.4 × 100 = 1.40	1.40	
Track	1.2 × 100 = 1.20	1.20		1.2 × 100 = 1.20	1.20	
OUTER RACE Front	1.4 × 100 = 1.40	1.40	1.36	1.4 × 100 = 1.40	1.40	1.33
Rear	1.7 × 30 = 0.51 1.4 × 70 = 0.98	1.49		1.4 × 100 = 1.40	1.40	
Track	1.2 × 100 = 1.20	1.20		1.2 × 100 = 1.20	1.20	
RETAINER Front	1.5 × 50 = 0.75 1.2 × 50 = 0.60	1.35	1.25	1.2 × 100 = 1.20	1.20	1.22
Rear	1.2 × 100 = 1.20	1.20		1.2 × 100 = 1.20	1.20	
I.D.	1.5 × 20 = 0.30 1.2 × 80 = 0.96	1.26		1.5 × 20 = 0.30 1.2 × 80 = 0.96	1.26	
O.D.	1.2 × 100 = 1.20	1.20		1.2 × 100 = 1.20	1.20	
BALLS	1.4 × 100 = 1.40	1.40	1.40	1.4 × 100 = 1.40	1.40	1.40

AVERAGE NO. 4 BEARING FWD 1.34 AFT 1.32

NO. 5 BEARING

	Deposit × % Area	Total	Avg
INNER RACE Front	1.7 × 100 = 1.70	1.70	1.60
Rear	1.7 × 100 = 1.70	1.70	
Track	1.7 × 40 = 0.68 1.2 × 60 = 0.72	1.40	
OUTER RACE Front	1.4 × 100 = 1.40	1.40	1.40
Rear	1.4 × 100 = 1.40	1.40	
RETAINER Front	1.0 × 100 = 1.00	1.00	1.00
Rear	1.0 × 100 = 1.00	1.00	
I.D.	1.0 × 100 = 1.00	1.00	
ROLLERS	1.4 × 30 = 0.42 1.2 × 70 = 0.84	1.26	1.26

AVERAGE NO. 5 BEARING 1.32

TOTAL BEARING RATING (NO. 4 & 5 BRG'S) = 3.98

COMPARTMENT

	Deposit × % Area	Total
NO. 4 (POT)	1.4 × 10 = 0.14 1.2 × 90 = 1.08	1.22
NO. 5 (AIR SEAL)	1.4 × 25 = 0.35 1.2 × 75 = 0.90	1.25

TOTAL COMPARTMENT RATING 2.47

SEALS

	NO. 4		NO. 5	
	Deposit × % Area	Total	Deposit × % Area	Total
SPRINGS	1.7 × 50 = 0.85 1.4 × 50 = 0.70	1.55	4.0 × 10 = 0.40 1.7 × 30 = 0.51 1.4 × 60 = 0.84	1.75
SUPPORT	2.2 × 10 = 0.22 2.0 × 15 = 0.30 1.7 × 40 = 0.68 1.4 × 35 = 0.49	1.69	12.0 × 40 = 4.80 5.5 × 15 = 0.82 1.7 × 20 = 0.34 1.4 × 25 = 0.35	6.31
CARBON	1.4 × 100 = 1.40	1.40	1.4 × 35 = 0.49 1.2 × 65 = 0.78	1.27
SEAL RING HOUSING	N/A		12.0 × 40 = 4.80 2.0 × 15 = 0.30 1.7 × 20 = 0.34 1.4 × 25 = 0.35	5.79

AVERAGE NO. 4 SEAL 1.55 NO. 5 SEAL 3.78

TOTAL SEAL RATING (NO. 4 & 5 SEALS) 5.33

BREATHER

	Deposit × % Area	Total
NO. 4-5 ELBOW	0 × 100 = 0	0
NO. 4-5 TUBE	2.0 × 50 = 1.00 1.0 × 50 = 0.50	1.50

TOTAL BREATHER RATING 1.50

SCREEN

	Deposit × % Area	Total
NO. 4-5	1.7 × 50 = 0.85 1.4 × 50 = 0.70	1.55

TOTAL SCREEN RATING 1.55

MISCELLANEOUS

	Deposit × % Area	Total
TOWER SHAFT	1.4 × 50 = 0.70 1.2 × 50 = 0.60	1.30
TOWER SHAFT STRUT	1.7 × 100 = 1.70	1.70

TOTAL MISCELLANEOUS RATING 3.00

SUMPS AND PUMP

	Deposit × % Area	Total
NO. 4 SUMP (Diffuser)	1.2 × 100 = 1.20	1.20
NO. 5 BRG. SUPPORT (Conical fwd)	1.0 × 100 = 1.00	1.00
NO. 5 BRG. SUPPORT (Conical aft)	1.0 × 100 = 1.00	1.00
NO. 4-5 PUMP (Scavenge)	1.7 × 75 = 1.28 1.4 × 25 = 0.35	1.63

TOTAL SUMPS AND PUMP RATING 4.83

CONICAL I. D.

	Deposit × % Area	Total
CONICAL I. D.	1.7 × 25 = 0.42 1.4 × 75 = 1.05	1.47

TOTAL CONICAL I. D. 1.47

REAR SHAFT

	Deposit × % Area	Total
REAR SHAFT	1.7 × 25 = 0.42 1.4 × 75 = 1.05	1.47

TOTAL REAR SHAFT 1.47

FIGURE 12. ILLUSTRATION OF TYPICAL WORKSHEET FOR AFAPL ENGINE SIMULATOR DEPOSIT RATING

rating is obtained for each sub item and the overall average rating for the part determined by averaging the ratings obtained for each sub item. For example, in Figure 9 the No. 4 bearing, forward, is shown to be broken down into four rated items (the inner race, the outer race, the retainer, and the balls). The inner race is further broken down into three rated areas (front, rear, and track). Only one type deposit was found on the inner race front, medium varnish which has a demerit rating number of 1.4 (Table 2). The same was true for the inner race rear. The track had only light varnish which has a demerit rating of 1.2. Therefore, the average rating for the inner race is shown to be the average of 1.4 + 1.4 +1.2 or 1.33. The outer race front and track are shown to have the same deposits as the inner race, 1.4 and 1.2 respectively. However, the outer race rear had two deposit types apparent upon inspection; 30 percent of the rated area was covered with heavy varnish which has a demerit number of 1.7 and 70 percent of the rated area was covered with medium varnish which has a demerit number of 1.4. The rating for the outer race rear is therefore (1.7 X 0.30) + (1.4 X 0.70) or 1.49, as shown. The average rating for the outer race is then obtained from the average of 1.40 + 1.49 + 1.20 or 1.36. The rating is continued for the retainer and balls as shown in Figure 12. The average rating for the No. 4 bearing forward is obtained by averaging the ratings obtained for the four items which make up the bearing, which in this case is the average of 1.33 + 1.36 + 1.40 or 1.34. The rating process is continued as shown in Figure 12 until all items have been rated. The overall engine simulator rating is then obtained by adding the following individual ratings:

	Example
Total bearing rating	3.98
Total seal rating	5.33
Total sumps and pump rating	4.83
Total compartment rating	2.47
Total screen rating	1.50
Overall engine simulator rating =	18.11

It will be noted that the ratings obtained for the breather (No. 4-5 elbow and No. 4-5 tube), miscellaneous (tower shaft and tower shaft strut), conical I.D. and rear shaft are not included in the overall engine simulator rating. These parts are not rated in the APL full-scale engine tests; therefore, they are not included in the overall engine simulator rating but are reported for added information.

Test Data Reported

A test report is generated by and printed out by the computer after manual inputs are completed by the operator at the end of each test. A typical test report (Test Report for automated AFAPL Engine Simulator Test No. 24) is presented in Appendix A of this report. It will be noted that the test report includes the following information:

- Test summary data sheet
- Test lubricant consumption data
- Filter weight data
- Viscosity data at 5-hr intervals
- Neutralization number and iron content at 5-hr intervals
- Plot of viscosity versus test time
- Plot of neutralization number versus test time
- Detailed deposit rating
- Average data (temperature, pressure, rpm) from 63 individual sensors
- Carbon seal wear measurements
- Test-oil system filter weights
- Average soakback temperature plots
- A listing of the low and high, inner and outer limits for the 63 individual temperature, pressure, and rpm sensors

In additon to the aforementioned data, color photographs (not included in the Appendix) of the following 16 simulator parts are included in each report submitted to APL:

- No. 4 bearing, forward
- No. 4 bearing, aft
- No. 5 bearing
- No. 5 bearing seal support
- No. 4 carbon seal
- No. 5 carbon seal, No. 5 seal plate, No. 4 seal plate
- No. 4 sump diffuser
- No. 4-5 sump pump
- Conical section, forward
- Conical section, aft
- No. 5 seal ring housing
- No. 5 bearing seal housing
- No. 4-5 breather elbow
- No. 4-5 breather tube
- Tower shaft strut
- Tower shaft

System Safety Analysis Report. The system safety analysis report (SSAR) for the automated AFAPL engine simulator is included in Appendix B of this report. The SSAR identifies and describes all of the recognized hazards, the effects, and the hazard control recommended for all of the engine simulator systems.

TEST LUBRICANTS

Eleven lubricants have been evaluated to date in the AFAPL engine simulator. APL full-scale engine test data were available for eight of the eleven lubricants evaluated. The full-scale engine tests were conducted, in some cases, on different batches of the same lubricant formulation as noted in later sections of this report. Table 3 presents a description of the lubricants included in the program along with their respective initial viscosities and neutralization number data.

TABLE 3. DESCRIPTION OF TEST LUBRICANTS

Oil Code	Viscosity, cs 100°F (37.8°C)	210°F (98.9°C)	Neut. No., mg KOH/g	Description
0-62-6	17.8	4.7	0.29	MIL-L-7808E
0-67-7	17.3	4.6	0.28	Different batch of 0-62-6
0-67-20	13.5	3.2	0.21	MIL-L-7808G
0-67-21	12.9	3.2	0.24	MIL-L-7808G
0-67-23	13.5	3.3	0.46	Different batch of 0-67-20
0-68-7	13.8	3.8	0.15	MIL-L-7808G
0-68-13	14.6	3.6	0.23	MIL-L-7808G
0-70-2	13.9	3.7	0.26	MIL-L-7808G
0-71-2	13.4	3.3	0.03	MIL-L-7808 Type
0-72-2	33.2	6.0	0.16	MIL-L-27502 Type
0-72-8	14.0	3.7	0.24	Different batch of 0-70-2
0-72-9	15.3	3.6	0.12	MIL-L-7808 Type
0-72-13	14.7	3.5	0.12	MIL-L-7808 Type
0-73-1	33.8	6.1	0.04	Different batch of 0-72-2
0-74-2	13.6	3.4	0.05	Different batch of 0-68-7
0-76-1	13.5	3.6	0.26	Different batch of 0-70-2
0-79-16	13.4	3.2	0.21	Different batch of 0-67-20
ATL-6040	13.1	3.4	0.24	Different batch of 0-70-2
ATL-8152	13.9	3.3	0.04	MIL-L-7808 Type

TEST RESULTS AND DISCUSSION

General

Eleven lubricants have been evaluated to date using the AFAPL engine simulator. A total of 22 tests have been conducted, accumulating over 3400 test hours on the engine simulator rig, during the various evaluations conducted on the 11 lubricants.

Numerous short duration tests (8 hr or less) to check the general operation of the simulator hardware and manual control systems, including the soakback procedure, conducted in the early operating period of the simulator and reported in Reference 3 will not be repeated in this report. However, all of the standard, manually controlled simulator lubricant evaluations conducted earlier are included in this report to provide a complete set of AFAPL engine simulator data in one report.

Lubricant Evaluation Tests

As mentioned earlier, 22 AFAPL engine simulator tests have been conducted to date. Eighteen of these tests were conducted using the manual control system originally developed for the simulator, while the last four tests (850 hours) were conducted using the H-P 1000 computer to manage and control all of the simulator systems which were earlier manually controlled by trained technicians.

Eleven lubricants have been evaluated in the AFAPL engine simulator to date, using the test procedures described earlier in this report. Eight of the 11 lubricants evaluated were selected on the basis of APL full-scale engine test data being available on them, thereby making it possible to compare the results obtained with the engine simulator with those obtained from full-scale engine tests.

A summary of the results obtained from the 22 AFAPL engine simulator tests is presented in Table 4. The different test procedure variations used during the course of evaluating the different lubricants are noted in Table 4. A discussion of the results obtained using the various manual operating procedure variations was included in the earlier report [3] and will not be repeated here. It should be mentioned that procedure variations D, E, and Auto 1 do not vary greatly from each other; and, as such can be considered to be essentially the same for the purpose of test result comparisons.

Two lubricants were selected to be run using the automated AFAPL engine simulator to provide results which could be compared with those obtained earlier using procedures D and E. Based upon the deposit ratings obtained earlier, lubricants 0-73-1, a "clean" oil, and 0-67-7, a "dirty" oil, were selected to represent the two extreme conditions of interest. The results obtained for 0-73-1 using Auto 1 procedure (Test No. 23) are for all practical purpose the same as those shown for Test 11 conducted earlier using procedure E. The end of test results shown for 0-67-7 using the Auto 1 procedure (Test No. 24) appears to provide a significant difference in the results shown for the lubricant viscosity and neutralization number compared with Test No. 14. However, if the 5-hr lubricant sample values (included in the individual 20-page test report for each test, as shown in Appendix A for Test No. 24) are reviewed, it will be noted that the 80-hr lubricant sample, just 10 hr before the test was terminated, provided viscosity and neutralization number values, -20.2 percent viscosity change and +4.16 neutralization number change, much the same as those shown in Table 4 for 0-67-7 using procedure E. One additional set of data that may be used to show correlation of the manually operated procedures and the automated procedure is presented for lubricant 0-79-16 after 250-hr operation. This test (Test No. 25) may be compared with the results from the 250-hr values shown for Test No. 6 using lubricant 0-67-23. As shown in Table 3, lubricants 0-67-23 and 0-79-16 are different batches of the same lubricant formulation. The results from these two extended duration

TABLE 4. SUMMARY OF AFAPL ENGINE SIMULATOR TESTS

Lubricant	Test Procedure Variation	Test Time, hr	Deposit Rating	100°F Viscosity Change, %	Neut. No. Change, mg KOH/g	Sump Iron Content, ppm max(a)	Test No.
0-67-7	E	100	24.4	-18.8	+0.60	48 (95)	14
0-67-21	D	100	19.7	+10.7	+0.29	10 (100)	9
	D	250	21.8	+12.7	+0.63	10 (105)	9
0-67-23	A	100	17.3	+6.9	-0.16	10 (80)	3
	D	100	18.2	+5.6	-0.19	4 (85)	6
	D	250	21.1	+8.9	+0.07	5 (120)	6
0-68-13	E	100	18.5	-3.6	+0.37	54 (100)	12
	E	225(b)	20.3	-0.2	+1.42	130 (225)	12
0-70-2	D	90(c)	18.8	+78.1	+35.14	48 (90)	8
	E	75(d)	17.2	+46.2	+23.98	50 (75)	10
0-71-2	B	100	19.9	+9.7	+1.17	68 (45)	4
	C	100	18.6	+7.4	+0.81	4 (30)	5
	D	90(c)	23.0	+1434.6	+51.16	90 (90)	7
0-72-8	E	150(e)	25.3	-0.5	+2.29	2750 (65)	17
0-72-9	E	100	19.0	+6.2	+0.19	58 (95)	15
	E	147.5(f)	21.2	+9.1	+0.31	120 (147.5)	15
0-72-13	E	100	20.0	+6.7	+0.33	80 (100)	16
	E	250	19.7	+11.1	+0.63	80 (100)	16
0-73-1	E	100	16.0	+5.1	+0.45	40 (100)	11
	E	250	19.8	+17.1	+1.30	195 (250)	11
0-74-2	E	100	18.0	+7.4	+0.45	48 (100)	13
	E	250	19.7	+14.3	+2.40	115 (250)	13
0-76-1	E	61(g)	23.0	-12.6	+0.83	1200 (61)	18
ATL-6040	F	100	19.2	+1.0	+1.31	82 (100)	19
ATL-8152	F	100	18.9	+8.0	+0.17	57 (95)	22
0-73-1	Auto 1	100	15.7	+5.2	+0.89	23 (100)	23
0-67-7	Auto 1	90(h)	27.4	+44.3	+39.29	48 (75)	24
0-79-16	Auto 1	250	25.4	+10.4	+0.81	36 (105)	25
0-79-16	Auto 1	350	34.3	+14.6	+1.23	270 (350)	26

Test Procedures

A. Sump 5 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids not returned.
B. Sump 5 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids returned.
C. Sump 6 gal., standard J57-43 oil system, forced oil make-up, collected vent fluids returned.
D. Sump 6 gal., capped No. 5 top seal jet, no forced oil make-up, collected vent fluids returned.
E. Sump 6 gal., No. 5 top seal jet oil directed to I.D. of conical, no forced oil make-up, collected vent fluids returned.
Auto 1. Same as E except computer management of all simulator control systems.

(a) Number in parentheses indicates the earliest test time at which maximum concentration occurred.
(b) Test terminated at 225 hr due to repeated cracks occurring in conical section front flange.
(c) Test terminated at 90 hr due to excessive increases in viscosity and neutralization number of sump sample.
(d) Test terminated at 75 hr due to excessive increases in viscosity and neutralization number of sump sample.
(e) Test terminated at 150 hr. No 100-hr intermediate inspection made.
(f) Test terminated at 147.5 hr due to fatigue spall in outer race of the No. 4 forward bearing.
(g) Test terminated at 61 hr due to excessive cage wear of No. 4 aft bearing.
(h) Test terminated at 90 hr due to excessive increase in viscosity and neutralization number of sump sample.

tests are reasonably close for both the deposit rating and the lubricant performance data indicating reasonable test repeatability. However, additional data will be required from the engine simulator before the test repeatability can actually be determined.

Correlation of Simulator and Engine Test Results

Due to the limited amount of data available from both the AFAPL engine simulator and full-scale engine test, only very general statements can be made with respect to correlation of test results.

Repeat test data from APL full-scale engine tests are available on only one lubricant, 0-67-20 (an earlier batch of 0-67-23), since the numerical rating system has been in use at APL. Four APL full-scale engine tests on lubricant 0-67-20 gave the following deposit ratings:

Test No.		Total Engine Deposit Rating
1		83.1
2		79.4
3		89.4
4		86.4
	Avg =	84.6

These four engine deposit ratings provide a standard deviation of 4.3 and a 95 percent confidence interval about the mean of ± 4.2. These data indicate an excellent repeatability capability of the full-scale engine test. However, additional data would be required using other lubricants before an overall test repeatability statement could be reliably estimated.

Seven lubricants, 0-67-21, 0-67-23, 0-67-13, 0-70-2, 0-71-2, 0-73-1, and 0-74-2, which have been evaluated in the AFAPL engine simulator have also been evaluated in the APL full-scale engine. One lubricant, 0-67-7, also has engine data available, but was run in the full-scale engine prior to the use of the numerical rating system. Therefore, only general data are available for 0-67-7 with respect to full-scale engine deposit ratings.

Table 5 presents a comparison of the 100-hr AFAPL engine simulator deposit ratings with the 100-hr full-scale engine deposit ratings. The engine simulator deposit ratings shown in Table 5 are from tests using only the test procedures D and E which represent data from tests using the best approximation of actual J57-29 oil flows and temperature profiles. The deposit ratings shown for the full-scale engine are presented in two columns. One column shows the deposit rating of just the 4-5 bearing area from the engine test, and the second column shows the total deposit rating for all the rated areas of the full-scale engine. The deposit rating shown for the engine simulator can be compared directly with the ratings shown for the 4-5 area of the engine test since the rated areas included in both ratings are exactly the same. Figure 13 presents a plot of the AFAPL engine simulator deposit ratings versus the deposit ratings of the 4-5 area from full-scale engine tests. The degree of correlation, shown in Figure 13, is based on the calculated correlation coefficient[4], expressed as a percent value. This statistic is a measure of the collinearity of data, with 100 percent representing exact correlation (not necessarily at a 1:1 ratio) and 0 percent indicating no correspondence. The equation used to obtain the correlation coefficient statistic (γ) is given as

$$\gamma = \frac{(n\Sigma xy - \Sigma x\Sigma y)\ 100}{\sqrt{\left[n\Sigma x^2 - (\Sigma x)^2\right]\left[n\Sigma y^2 - (\Sigma y)^2\right]}}$$

where n is the number of data pairs.

TABLE 5. COMPARISON OF AFAPL ENGINE SIMULATOR DEPOSIT RATINGS WITH FULL-SCALE ENGINE DEPOSIT RATINGS

	Deposit Rating		
		Full-Scale Engine	
Lubricant	Simulator	4-5 Area[a]	Total[b]
0-67-7 (0-62-6)	24.4	(c)	(c)
0-67-21	19.7	17.6	68.5
0-67-23 (0-67-20)	18.2	18.9[d]	84.6[d]
0-68-13	18.5	16.6	81.6
0-70-2	18.0[e]	16.0	65.5
0-71-2	23.0	24.6	97.3
0-73-1 (0-72-2)	16.0	15.5	75.2
0-74-2 (0-68-7)	18.0	17.8	66.2

Lubricant code in parentheses indicate code of engine test lubricant if different from simulator test lubricant code.

(a) Deposit rating for the 4-5 area of the full-scale engine test.
(b) Total deposit rating for all rated areas of the full-scale engine test.
(c) Engine test performed prior to the initiation of the numerical rating system at APL.
(d) Average of four engine tests.
(e) Average of two simulator tests.

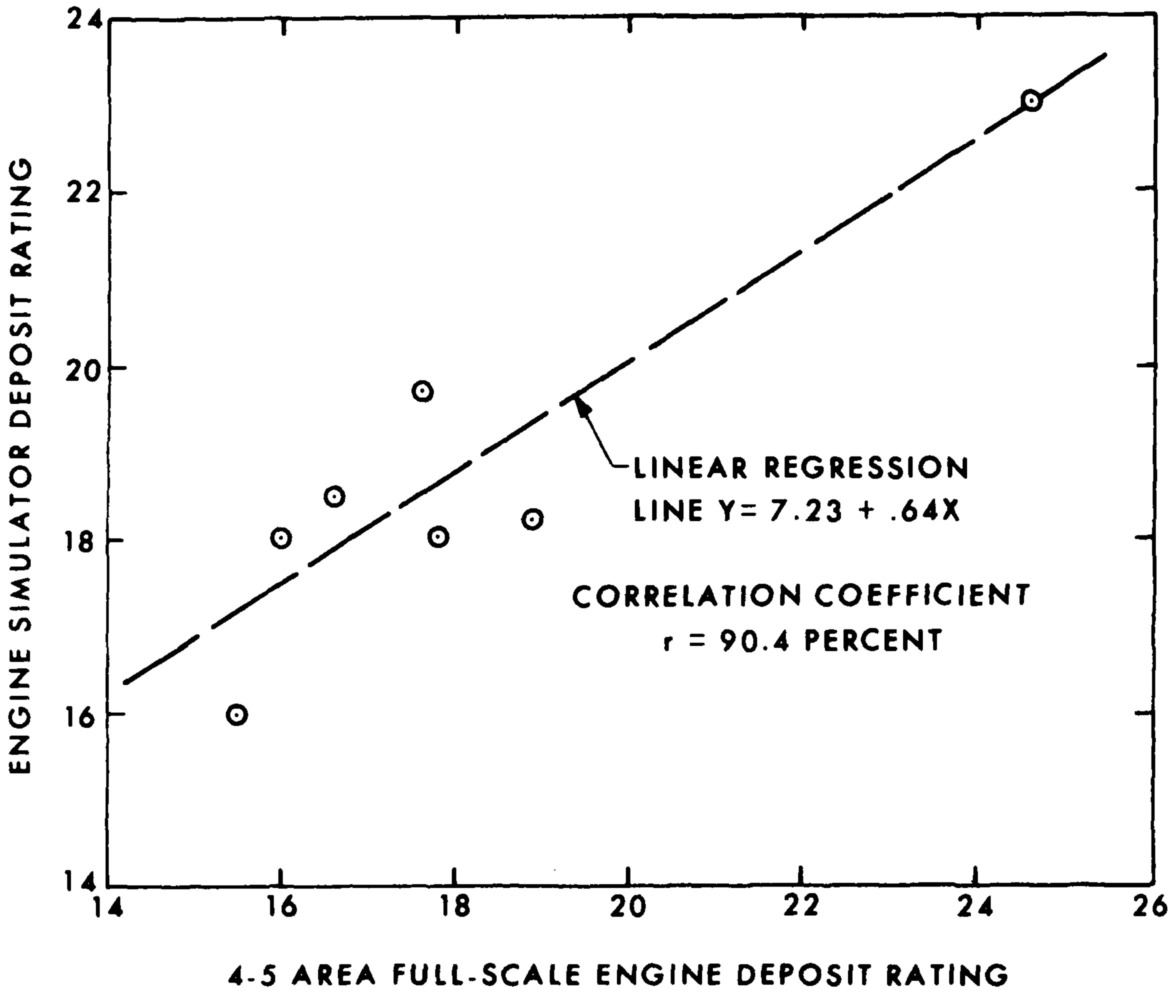


FIGURE 13. AFAPL ENGINE SIMULATOR DEPOSIT RATINGS VERSUS DEPOSIT RATINGS OF THE 4-5 AREA FROM FULL-SCALE ENGINE TESTS

The dashed line in Figure 13 is the linear regression line for the data pairs plotted. The calculated correlation coefficient is shown to be 90.4 percent, which indicates very good correlation to the engine simulator deposit ratings with the 4-5 area deposit ratings from full-scale engine tests.

It was shown earlier[3] that the 4-5 area of the full-scale engine contributed 20.3 to 26.9 percent of the total engine deposit rating with the overall average being 23.2 percent. If the only deposit ratings available were from the 4-5 area of the engine, a reasonable estimate of the total engine deposit rating could be made by multiplying the deposit rating for the 4-5 area by the reciprocal of .232, or 4.31. Further, since the AFAPL engine simulator ratings have been shown to provide a good correlation with the deposit ratings obtained from the 4-5 area of the engine, multiplying the engine simulator ratings by the same factor, 4.31, should also provide a reasonable estimate for the total engine deposit rating. The estimated total engine deposit ratings from the data available are shown in Table 6 along with the actual total engine deposit ratings. These data are compared graphically in Figure 14. According to APL engine test data, 0-71-2 is the only lubricant which has failed the full-scale engine test since the numerical rating procedure has been in use. All other lubricants included in Figure 14 have passed the APL engine test. The actual deposit rating number which is considered to indicate a failure to the APL engine test is still under study at APL: however, it must lie between 84.6, the highest deposit rating for any lubricant which passed the APL engine test, and 97.3, the deposit rating for 0-71-2 which failed the engine test. If it is assumed for this report that the upper total engine deposit rating limit for a "pass" is as low as 85, then the "pass-fail" line would be shown by the dashed line in Figure 14. Although the estimated total engine deposit ratings obtained from the AFAPL engine simulator data, or the 4-5 area data from the full-scale engine tests do not provide the same relative ranking for the lubricants which passed the APL engine test, the estimated total engine deposit ratings for these lubricants indicate they would all pass the full-scale engine test. The estimated total engine

TABLE 6. COMPARISON OF ESTIMATED AND ACTUAL TOTAL ENGINE DEPOSIT RATINGS

Lubricant	Estimated Total Engine Deposit Rating[a] Simulator	4-5 Engine Area	Actual Total Engine Deposit Rating
0-67-7	105.2	--	--
0-67-21	84.9	75.8	68.5
0-67-23	78.4	81.5	84.6
0-68-13	79.7	71.6	81.6
0-70-2	77.6	69.0	65.5
0-71-2	99.1	106.0	97.3
0-73-1	69.0	66.8	75.2
0-74-2	77.6	76.7	66.2

(a) Estimated total engine deposit rating obtained by multiplying the simulator deposit rating on the 4-5 engine area deposit rating by 4.31.

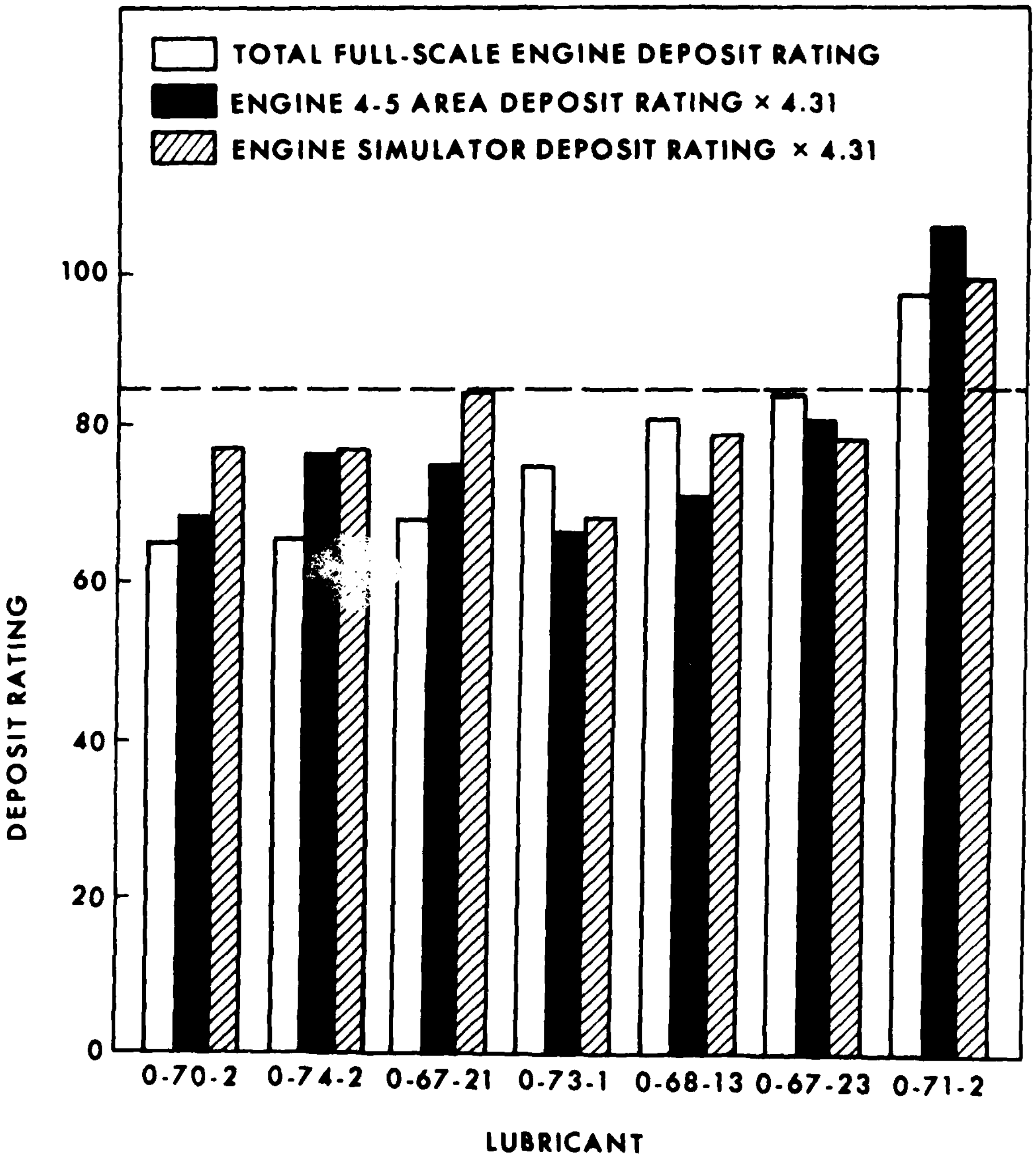


FIGURE 14. COMPARISON OF ESTIMATED AND ACTUAL TOTAL ENGINE DEPOSIT RATINGS

deposit ratings also indicate that lubricant 0-71-2 would fail the engine test, which is confirmed by the engine test results. In addition, the estimated total engine deposit rating of 105.2 for lubricant 0-67-7 (see Table 6), from the AFAPL engine simulator data, indicates that 0-67-7 would fail the APL engine test. This lubricant originally passed the engine test in 1962, prior to the use of the numerical deposit rating procedure, and was included in the Qualified Products List (QPL) for MIL-L-7808D lubricants. It is understood that the 0-67-7 formulations was included as a QPL lubricant until late 1967 when it was removed from the list due to its failure to meet the bearing deposition test requirements of the MIL-L-7808G specification. The bearing deposition test deposit ratings obtained by SwRI[5] for lubricants 0-62-6 and 0-67-7 were 90 and 97, respectively, while the MIL-L-7808G specification stated that the "overall deposit demerit rating shall not exceed 80."

Extended Duration Tests. Ten extended duration tests (over 100-hr duration) have been run to determine the effect of extended test time on the deposition characteristics of selected lubricants, as shown in Table 4. All of the extended duration tests except Test No. 26 on lubricant 0-79-16, were originally scheduled for 250-hr duration. It will be noted that three of the extended duration tests were terminated prior to 250 hr. Two of these tests were terminated due to mechanical problems, as shown in the footnotes of Table 4. Test No. 17 using lubricant 0-72-8, was terminated after 150 hr operation in the earlier contract [3] due to the contract period expiration.

The results from the extended duration tests show that the increase in deposit ratings from the values presented for the 100-hr inspection ranged from 1.7 for 0-74-2 to 3.8 for 0-73-1. The overall average increase in deposit rating after the 100-hr inspection, for the extended duration tests was 2.4 which represents an average increase of approximately 13.5

percent. Although 0-73-1 appears to have provided the largest deposit rating increase of 23.8 percent, if one considers the average 100-hr deposit rating of 18.7 for 0-67-23 and ATL-6040, different batches of the same lubricant formulation, and compares this average with the average 250-hr deposit rating, 23.2, for 0-67-23 and 0-79-16, the largest deposit rating increase will be approximately 25 percent for this lubricant formulation. Further, when the test duration was extended to 350 hr, the deposit rating was further increased to 34.3, or an 83 percent increase over that shown for 100-hr operation. It should be mentioned that the deposit rating shown for lubricant 0-79-16, Test No. 26, may be artifically high due to unnatural increases in the iron content noted after approximately 270 hr operation and continuing through approximately 310 hr operation; and, also a significant increase in breather air pressure during the last 10 hours of operation which did not change when the simulator was cycled from 9120 rpm to 6000 rpm, and then back to 9120 rpm.

With respect to viscosity and neutralization number increases during the extended duration tests, lubricant 0-73-1 showed the largest viscosity increase with 17.1 percent, lubricant 0-74-2 the largest neutralization number increase with 2.4 mg KOH/g. Neither of these values approached the arbitrary limits set for test termination.

CONCLUSIONS

An automated engine simulator test facility capable of closely simulating the critical temperature and oil flow variables experienced in a full-scale J57-29 turbine engine was designed, installed, and operated at SwRI. The simulator, designated the AFAPL engine simulator, uses a No. 4-5 bearing compartment area of a J57-43 turbine engine modified to allow air pressurization and electrical heating of the area surrounding the oil-wetted section of the No. 4-5 bearing compartment area. The AFAPL engine simulator is designed to allow controlled air temperatures to be varied up to 850°F (454°C) and test oil tempeatures up to 450°F (232°C) to be used. A variable speed drive system, driving the simulator through the accessory drive gearbox, provides compressor shaft speeds up to 10,000 rpm.

A test procedure patterned after the 100-hr, 9120-6000 rpm cycling test procedure used at APL for the full-scale engine tests was developed for the AFAPL engine simulator. Air and oil temperatures and flows within the simulator are controlled by a Hewlett-Packard 1000 computer in conjunction with associated hardware and software to approximate the temperature profiles obtained during full-scale engine tests at APL, including soakback temperatures upon engine shut-down.

A total of over 3,475 hr operation have been accumulated on the AFAPL engine simulator during the evaluation of 11 test lubricants. Approximately 800 hr of this total have been run using the computer controlled mode (Auto 1 test procedure) of operation. Eight of the 11 lubricants evaluated in the AFAPL engine simulator had previously been evaluated in the APL full-scale engine test. A comparison of the numerical deposit ratings obtained from the No. 4-5 area of the full-scale engine shown good correlation, with a calculated correlation coefficient of 90.4 percent. Further, the data from ten full-scale engine tests using seven different lubricants shows that the No. 4-5 area of the full-scale engine contributes an average of 23.2 percent of the total numerical engine deposit rating. Since good correlation is shown for the numerical ratings obtained from the engine simulator and the No. 4-5 area of the full-scale engine, multiplying a deposit rating obtained from the AFAPL engine simulator by the reciprocal of 0.232 provides a reasonable estimate of the total full-scale engine deposit rating for the same lubricant. The estimated total engine deposit ratings obtained in this manner did not provide the exact same relative ranking of the lubricants which passes the APL full-scale engine test. However, the estimated total engine deposit ratings obtained from engine simulator ratings did estimate a passing deposit rating, less than 85, for each of the six lubricants which had passed the APL engine test. The estimated total engine deposit rating for the one lubricant which failed the APL engine test was 99.1 compared with a deposit rating of 97.3 from the engine test. In addition, one lubricant which was removed from the MIL-L-7808 QPL list in 1967, due to its depositon characteristics, provided an estimated total engine deposit rating of 105.2 when evaluated in the AFAPL engine simulator test. A numerical deposit rating from the APL engine test run in 1962 is not available for this lubricant; but the estimated deposit rating of 105.2 indicates that this lubricant would certainly fail the current APL engine test requirements.

Extended duration tests, up to 350 hr duration, were conducted with the AFAPL engine simulator using eight different lubricants to determine the effect of additional test time on the physical properties and the deposition characteristics of the lubricants, since full-scale engine data are not available for test periods beyond 100 hr. It was found that the 250-hr deposit rating increase, when compared with the 100-hr deposit rating, ranged from essentially no change for lubricant 0-72-13 to a maximum of 25 percent increase for different batches of 0-67-20. The 350-hr deposit rating for 0-79-16, another different batch of 0-67-20, indicated an 83 percent increase over that shown for 100-hr operation.

RECOMMENDATIONS

The following recommendations are believed to be justified based upon the information generated with the AFAPL engine simulator over the last two contract periods:

1. All candidate turbine engine lubricant formulations should be evaluated in duplicate simulator tests of 100-hr each prior to being considered for full-scale engine testing.

2. A minimum of one extended duration simulator test, perhaps extending to 500 hrs, should be conducted on each turbine engine lubricant being considered for inclusion in a Qualified Products List.

3. In order to obtain an increased return on the money invested in the automated engine simulator system, it is recommended that a second set of 4-5 area hardware be obtained and be used for a second engine simulator set-up. In this manner, one set of 4-5 area hardware could be run by the computer while the second set was being torn down, rated, cleaned and prepared for the next test by the technicians. In this manner, the utilization of the expensive computer control hardware and software systems of the engine simulator, as well as the technicians trained for the simulator operation would be significantly improved.

4. It should be emphasized that the use the AFAPL engine simulator is not limited to the evaluation of lubricants of specific interest to only the Air Force; but, could be

used to evaluate lubricants of interest to the Navy and Army equally well. Due to the flexibility of the engine simulator control system, changes can be made in the operating conditions of the simulator such that practically any reasonable change, to satisfy a specific requirement, can be incorporated if it is desired.

REFERENCES

1. Bartholomaei, N.T., Marshall, H.T., and Taylor, H.N., "A Practical Approach to Jet Engine Lubrication Evaluation," SAE Paper 65018, 1965.

2. Reynolds, H.W., Jr., "Turbine Oil and Test Method Development Needed for Current and Future Engine," Proceedings of the USAF-SwRI Turbine Engine Lubrication Conference, February 1967.

3. Baber, B.B., Tyler, J.C., and Valtierra, M.L., "Development of the AFAPL Engine Simulator Test for lubricant Evaluation," AFAPL Technical Report 75-38, June 1975.

4. Brownlee, K.A., Industrial Experimentation, Chemical Publishing Co., New York, N. Y., 1952.

5. Baber, B.B., Cuellar, J.P., and Montalvo, D.A., "Deposition and Degradation Characteristics of Aircraft Turbine Engine Lubricants," AFAPL Technical Report 70-8, Vol. 1, June 1970.

APPENDIX A

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

LOCATION	100-Hr Deposit Rating Reference	Total
BEARINGS	--	4.73
SEALS	--	10.71
SUMPS & PUMPS	--	6.75
COMPARTMENTS	--	3.83
SCREEN	--	1.40
BREATHER	3.83	--
CONICAL I.D.	1.64	--
REAR SHAFT	1.34	--
MISCELLANEOUS	2.62	--

Total 100-Hr Deposit Rating........ 27.42

Lubricant P-1081(0-67-7)

Test Number 24

Deposit Rating 27.42

Test Duration, hr 90*

Test Procedure Auto 1

Oil Sump Temp, F(C) 300(148)

Date Started 3 JUNE 1980

Date Completed 26 JUNE 1980

Operator WALLACE-LEE-ALMOND

Approved by

LUBRICANT PERFORMANCE

Test Time, hr	Viscosity, cs at 37.8 C	Neut. No., mg KOH/g	Fe Content of Sump, ppm
0	17.30	.34	0.
25	14.56	.74	18.
50	14.11	1.64	34.
75	14.05	3.17	48.
100	*	*	*

REMARKS *Test terminated at 90 hrs due to excessive increase in viscosity and neutralization number values.

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

LUBRICANT CHARGE & CONSUMPTION

Oil Charge, ml 22710 - Total Consumption, ml 11730
Consumption, ml/hr (including sampling) 117.3
Sample Volume, Total 880 ml

Test Hrs	New Oil Added, ml	Test Hrs	New Oil Added, ml
5	680	55	0
10	340	60	85
15	595	65	765
20	1105	70	850
25	0	75	3060
30	595	80	0
35	1020	85	595
40	850	90	0
45	255	95	0
50	935	100	0

FILTER WEIGHTS

Filter Location	Total Accumulated Weight, gm
Test-Oil In (a)	1.00
Test-Oil Out (a)	.20
Gearbox Oil Out (a)	.30
No. 4 Bearing Strainer (b)	.30
Oil Suction Pump Strainer (c)	.70

SEAL WEAR

No. 4 Carbon Seal -.006 in.
No. 5 Carbon Seal -.005 in.

(a) 40-mesh Erdco line screen filter
(b) Engine item 16-72
(c) Engine item 18-26

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

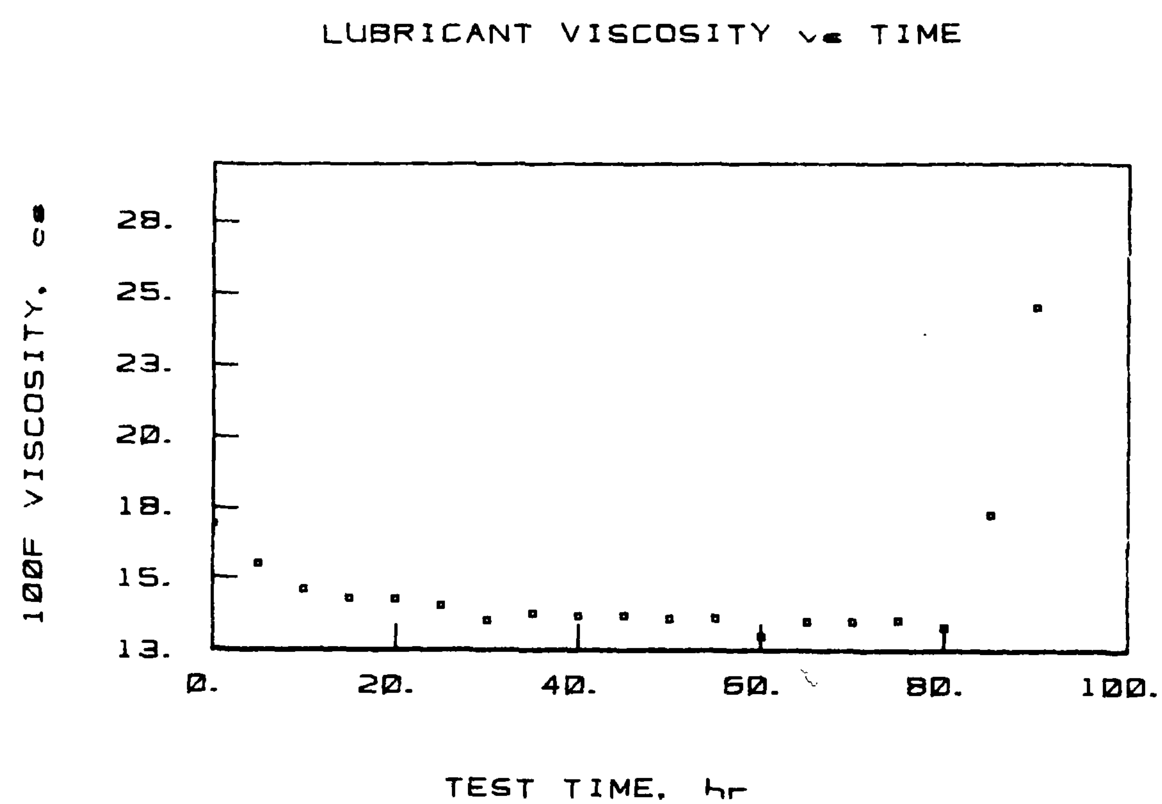
Test Hrs	LUBRICANT VISCOSITY 37.8C (100F) Viscosity, cs	Change, %
Can	17.30	-
Sump	17.39	-
5	16.02	-7.40
10	15.12	-12.60
15	14.81	-14.39
20	14.79	-14.51
25	14.56	-15.84
30	14.04	-18.84
35	14.28	-17.46
40	14.19	-17.98
45	14.21	-17.86
50	14.11	-18.44
55	14.12	-18.38
60	13.49	-22.02
65	14.01	-19.02
70	14.01	-19.02
75	14.05	-18.79
80	13.81	-20.17
85	17.76	2.66
90	24.97	44.34

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

LUBRICANT NEUTRALIZATION NO. AND IRON CONTENT

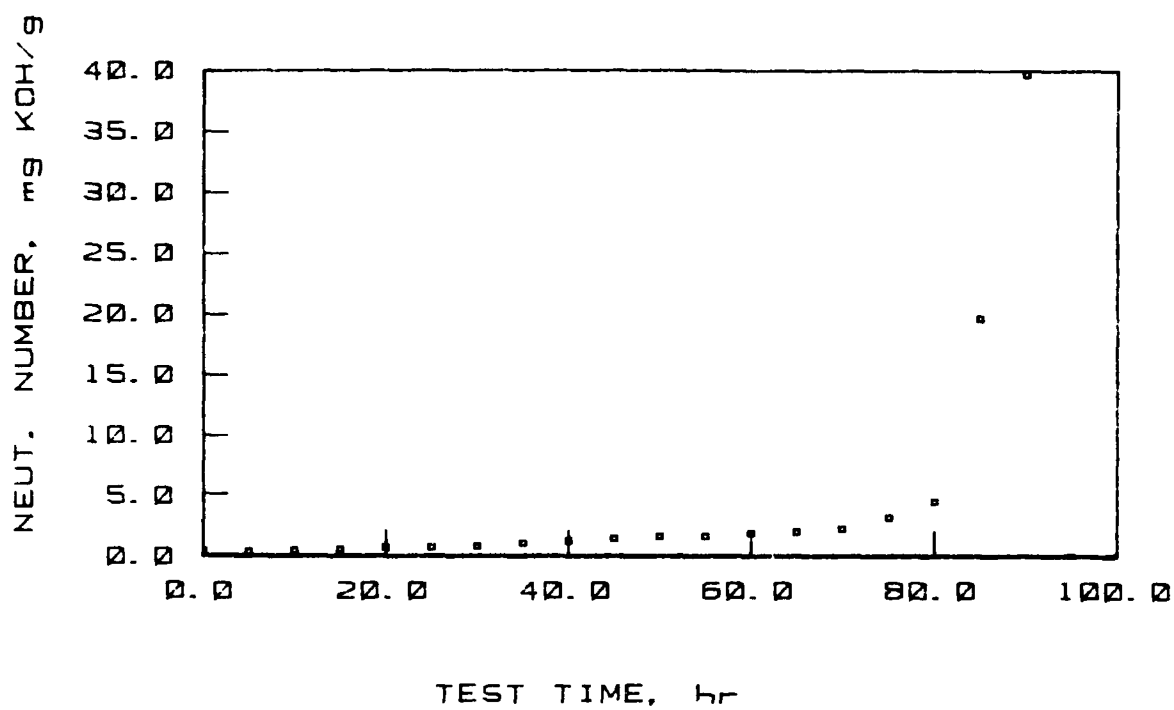
Test Hrs	Neutralization Sump	Neutralization Change	Iron Content, ppm
Can	.34	–	0.
Sump	.36	–	1.
5	.33	-.01	5.
10	.46	.12	11.
15	.56	.22	16.
20	.72	.38	19.
25	.74	.40	18.
30	.82	.48	24.
35	1.07	.73	27.
40	1.28	.94	33.
45	1.43	1.09	34.
50	1.64	1.30	34.
55	1.64	1.30	42.
60	1.89	1.55	43.
65	1.99	1.65	43.
70	2.25	1.91	47.
75	3.17	2.83	48.
80	4.50	4.16	43.
85	19.56	19.22	48.
90	39.63	39.29	40.

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24



AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

LUBRICANT NEUTRALIZATION NUMBER vs TIME



AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

DEPOSIT RATING

	No. 4 Bearing Forward		No. 4 Bearing Aft	
	Deposit X % Area	Total	Deposit X Area	Total
FRONT	1.4 X 5. = .07		1.7 X 5. = .08	
	1.2 X 95. = 1.14	1.21	1.4 X 20. = .28	
			1.2 X 75. = .90	1.26
REAR	1.4 X 5. = .07		1.7 X 5. = .08	
	1.2 X 95. = 1.14	1.21	1.4 X 20. = .28	
			1.2 X 75. = .90	1.26
TRACK	1.4 X 10. = .14		1.7 X 5. = .08	
	1.2 X 90. = 1.08	1.22	1.4 X 10. = .14	
			1.2 X 85. = 1.02	1.24
AVERAGE INNER RACE	....	1.21	....	1.25
FRONT	1.4 X 5. = .07		1.4 X 5. = .07	
	1.2 X 95. = 1.14	1.21	1.2 X 95. = 1.14	1.21
REAR	1.4 X 5. = .07		1.4 X 5. = .07	
	1.2 X 95. = 1.14	1.21	1.2 X 95. = 1.14	1.21
TRACK	1.7 X 5. = .08		1.7 X 5. = .08	
	1.4 X 10. = .14		1.4 X 10. = .14	
	1.2 X 85. = 1.02	1.24	1.2 X 85. = 1.02	1.24
AVERAGE OUTER RACE	....	1.22	....	1.22
FRONT	1.4 X 5. = .07		1.4 X 15. = .21	
	1.2 X 95. = 1.14	1.21	1.2 X 85. = 1.02	1.23
REAR	1.4 X 10. = .14		1.4 X 15. = .21	
	1.2 X 90. = 1.08	1.22	1.2 X 85. = 1.02	1.23
I. D.	1.4 X 20. = .28		1.4 X 10. = .14	
	1.2 X 80. = .96	1.24	1.2 X 90. = 1.08	1.22
O. D.	1.7 X 5. = .08		1.7 X 5. = .08	
	1.4 X 10. = .14		1.4 X 10. = .14	
	1.2 X 85. = 1.02	1.24	1.2 X 85. = 1.02	1.24
AVERAGE RETAINER	....	1.23	....	1.23
	1.2 X 100 = 1.20	1.20	1.2 X 100 = 1.20	1.20
AVERAGE BALLS	....	1.20	....	1.20
AVERAGE NO.4 BEARING	FWD.....	1.21	AFT....................	1.22

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

DEPOSIT RATING

	No. 5 Bearing Deposit X % Area	Total
TRACK	5.5 X 40. = 2.20	
	1.7 X 30. = .51	
	1.2 X 20. = .24	
	0.0 X 10. = 0.00	2.95
REAR	5.5 X 40. = 2.20	
	1.7 X 30. = .51	
	1.4 X 10. = .14	
	1.2 X 10. = .12	
	0.0 X 10. = 0.00	2.97
FRONT	1.4 X 20. = .28	
	1.2 X 80. = .96	1.24
AVERAGE INNER RACE.........................		2.39
FRONT	7.0 X 30. = 2.10	
	5.5 X 20. = 1.10	
	2.0 X 50. = 1.00	4.20
REAR	5.5 X 50. = 2.75	
	2.0 X 50. = 1.00	3.75
AVERAGE OUTER RACE.........................		3.97
FRONT	2.0 X 20. = .40	
	1.7 X 40. = .68	
	1.2 X 40. = .48	1.56
REAR	2.0 X 20. = .40	
	1.7 X 40. = .68	
	1.2 X 40. = .48	1.56
I. D.	1.7 X 80. = 1.36	
	1.2 X 20. = .24	1.60
AVERAGE RETAINER...........................		1.57
	1.7 X 10. = .17	
	1.4 X 20. = .28	
	1.2 X 70. = .84	1.29
AVERAGE ROLLERS............................		1.29
AVERAGE NO.5 BEARING.......................		2.30
TOTAL BEARING RATING (No.4 & 5)..............		4.73

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

DEPOSIT RATING

	No. 4 SEAL Deposit X % Area	No. 4 SEAL Total	No. 5 SEAL Deposit X % Area	No. 5 SEAL Total
SPRINGS	4.0 X 20. = .80		5.5 X 40. = 2.20	
	1.7 X 60. = 1.02		4.0 X 20. = .80	
	1.4 X 20. = .28	2.10	2.0 X 40. = .80	3.80
SUPPORT	8.5 X 50. = 4.25		8.5 X 55. = 4.67	
	5.5 X 50. = 2.75	7.00	7.0 X 30. = 2.10	
			5.5 X 15. = .82	7.59
CARBON	5.5 X 20. = 1.10		8.0 X 20. = 1.60	
	2.0 X 70. = 1.40		7.0 X 30. = 2.10	
	1.7 X 10. = .17	2.67	2.0 X 45. = .90	
			1.7 X 5. = .08	4.68
SEAL RING HOUSING			15.0 X 50. = 7.50	
			9.0 X 20. = 1.80	
			6.0 X 30. = 1.80	11.10

AVERAGE NO. 4 SEAL............. 3.92

NO. 5 SEAL......... 6.79

TOTAL SEAL RATING (NO. 4&5) 10.71

SUMPS & PUMP

NO.4 SUMP(DIFFUSER)		
	1.7 X 20. = .34	
	1.4 X 60. = .84	
	1.2 X 20. = .24	1.42
NO.4 BRG SUPPORT(CONICAL FWD)		
	1.7 X 15. = .25	
	1.4 X 85. = 1.19	1.44
NO.5 BRG SUPPORT(CONICAL AFT)		
	5.5 X 20. = 1.10	
	1.7 X 20. = .34	
	1.4 X 60. = .84	2.28
NO.4-5 PUMP(SCAVENGE)		
	1.7 X 70. = 1.19	
	1.4 X 30. = .42	1.61

TOTAL SUMPS & PUMP RATING... 6.75

COMPARTMENTS

NO.4 (POT)		
	1.7 X 10. = .17	
	1.4 X 20. = .28	
	1.2 X 70. = .84	1.29
NO.5 (AIR SEAL)		
	7.0 X 15. = 1.05	
	5.0 X 5. = .25	
	1.7 X 40. = .68	
	1.4 X 40. = .56	2.54

TOTAL COMPARTMENT...... 3.83

SCREEN

NO. 4-5		
	1.4 X 100 = 1.40	1.40

TOTAL SCREEN RATING.... 1.40

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

DEPOSIT RATING

(Reference Only - Not Included in Total Deposit Rating)

BREATHER

	Deposit X % Area	Total
NO.4-5 ELBOW	7.0 X 10. = .70	
	1.7 X 10. = .17	
	1.2 X 80. = .96	1.83
NO.4-5 TUBE	2.0 X 100 = 2.00	2.00
TOTAL BREATHER RATING..................		3.83

CONICAL INSIDE

	1.7 X 80. = 1.36	
	1.4 X 20. = .28	1.64
TOTAL CONICAL RATING....................		1.64

REAR SHAFT

	1.7 X 20. = .34	
	1.4 X 20. = .28	
	1.2 X 60. = .72	1.34
TOTAL REAR SHAFT RATING.................		1.34

MISCELLANEOUS

TOWER SHAFT	1.4 X 10. = .14	
	1.2 X 90. = 1.08	1.22
TOWER SHAFT STRUT	1.4 X 100 = 1.40	1.40
TOTAL MISCELLANEOUS RATING..............		2.62

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

NO. 4 AREA	SENSOR	9120 TARGET/ CONTROL	9120 AVERAGE	6000 AVERAGE
Air Heater (Inside)	1T	631	634	629
Air Heater (Outside)	2T	624	631	619
Air (Top)	3TC	800	790	785
Air (Top)	4T	768	772	768
Air (Bottom)	5T	705	687	678
Bearing Heater	6TC	800	742	734
Bearing Heater	7T	752	746	740
Bearing (Fwd Top)	8T	332	325	319
Bearing (Fwd Bottom)	9T	324	318	287
Bearing (Aft Top)	10T	316	310	281
Bearing (Aft Bottom)	11T	321	316	289
CONICAL AREA				
Heater	12TC	800	798	798
Heater	13T	784	798	799
Hub Area (Fwd)	14T	331	337	341
Hub Area (Mid-Fwd)	15T	316	315	290
Hub Area (Mid-Aft)	16T	316	315	290
Hub Area (Aft)	17T	310	311	280
Sump (Fwd Top)	18T	348	317	286
Sump (Fwd Bottom)	19T	339	333	307
Sump (Aft Top)	20T	350	346	327
Sump (Aft Bottom)	21T	344	333	307
NO. 5 AREA				
Air Heater (bottom)	22T		917	921
Air (Top)	23TC	800	825	835
Air (Top)	24T		822	828
Air (Bottom)	25T		718	721
Bearing (Top)	26T	394	383	345
Bearing (Bottom)	27T	394	383	345
Seal Ring Housing (Top)	28T		646	623
Seal Ring Housing (Bot)	29T		620	607
Washer (Top)	30T	687	678	678
Washer (Bottom)	31T		676	673
BREATHER AREA				
Heater	32TC	650	621	623
Heater	33T		570	561
Tube Air	34T		213	212

T, temperature, F.
TC, temperature controlled, F.

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

GEARBOX AREA	SENSOR	9120 TARGET/ CONTROL	9120 AVERAGE	6000 AVERAGE
Oil-In	35TC	190	189	186
Oil-In	36T	194	180	178
Oil-Out	37T	284	318	230
Bearing (Top)	38T	200	309	230
Bearing (Fwd)	39T	228	241	206
Bearing (Aft)	40T	254	295	223
OIL SYSTEM AREA				
Oil Sump	41TC	300	293	266
Oil Sump	42T	300	294	263
Simulator Oil-In	43T	300	297	270
Simulator Oil-Out	44T	339	444	302
Simulator HE Oil-In	45T	340	334	303
Simulator Scav. HE Out	46TC	300	304	290
Simulator Scav. HE Out	47T	318	298	285
Gearbox Scav. HE Out	48TC	300	282	228
Gearbox Scav. HE Out	49T	263	283	228
MISCELLANEOUS				
Left Drive Motor	50T	76	75	75
Right Drive Motor	51T	76	74	74
Drive Shaft Bearing	52T	130	129	124
Drive Shaft Bearing	53T	140	115	106
Oil Sump Heater	54T	335	354	349
AIR-OIL PRESSURES				
No. 4 Air-In	55PC	18	18	18
Breather Air	56P		1	2
Simulator Oil-In	57PC	45	44	45
Simulator Oil-Out	58P	35	34	32
Gearbox Oil-In	59P	44	43	43
Gearbox Oil Scav.	60P		1	1
Bottled Air Supply	61P	2000	2166	2166
House Air Supply	62P	100	111	110
DRIVE MOTOR				
Simulator Hub Speed	63SC	9120	9119	6011

T, temperature, F.
TC, temperature controlled, F.
P, pressure, psi.
PC, pressure controlled, psig

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

NO. 4-5 SEAL MEASUREMENTS, in.

	Seal Wear (Location) 1	2	3	Avg	Ring Gap (Location) Fwd	Aft
No. 4						
Before	1.083	1.083	1.082	1.083	.018	.018
After	1.076	1.076	1.076	1.076	.018	.018
Net	.007	.007	.006	.007	0.000	0.000
No. 5						
Before	1.081	1.081	1.081	1.081	.018	.018
After	1.078	1.078	1.078	1.078	.018	.018
Net	.003	.003	.003	.003	0.000	0.000

NO. 4-5 SEALS - INITIAL STATIC PRESSURE LEAK CHECK

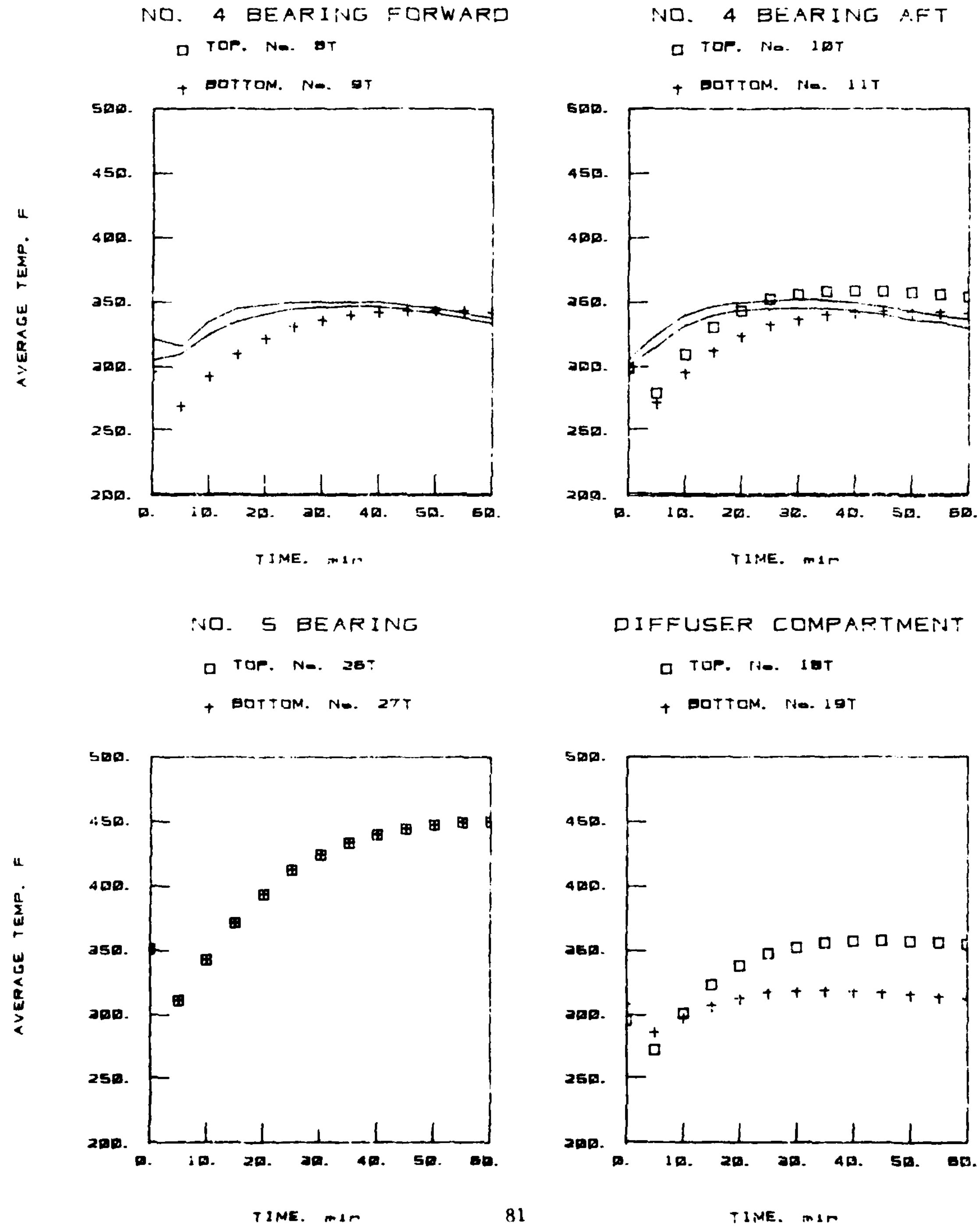
NO. 4 - 2.3 CFM NO.5 - 1.9 CFM

FILTER WEIGHTS, g

	Test Oil In (#1)	Test Oil Out (#2)	Gearbox Out (#3)	Strainer Jets (#4)	Scavenge Pump (#5)
BEFORE	8.00	7.70	7.70	58.50	32.90
AFTER	8.20	8.70	8.00	58.80	33.60
NET	.20	1.00	.30	.30	.70

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

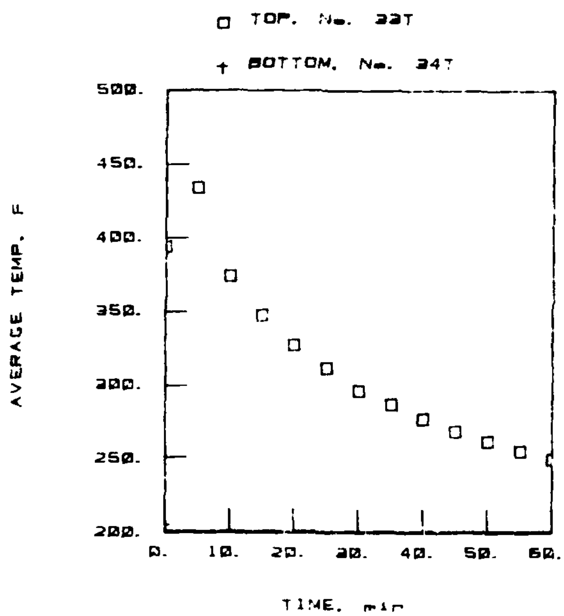
AVERAGE SOAK-BACK TEMPERATURES VERSES TIME



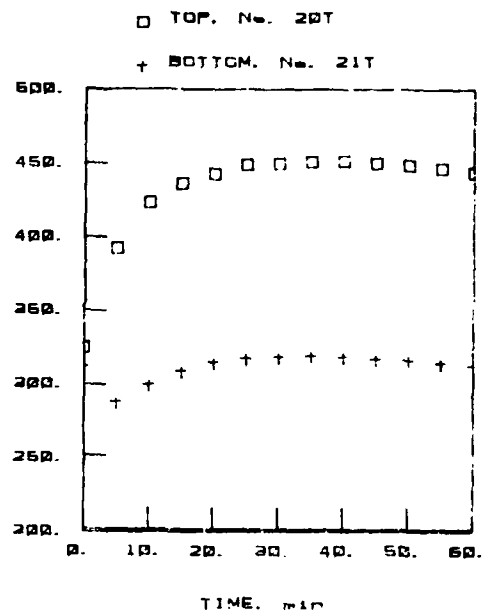
AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

AVERAGE SOAK-BACK TEMPERATURES VERSUS TIME

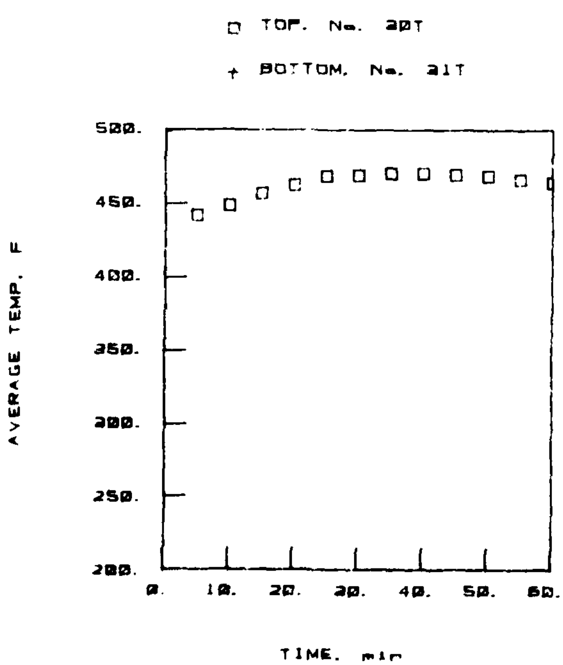
BREATHER STRUT



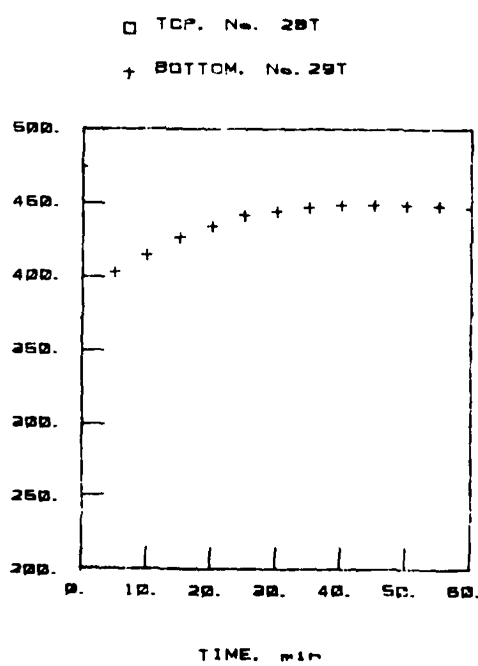
CONICAL SECTION



NO. 5 SEAL RING HOUSING



NO. 5 SEAL RING HOUSING



AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

NO. 4 AREA	SENSOR	OUTER LIMIT (LOW)	INNER LIMIT (LOW)	TARGET CONTROL POINT	INNER LIMIT (HIGH)	OUTER LIMIT (HIGH)
Air Heater (Inside)	1T	0	0	–	900	950
Air Heater (Outside)	2T	0	0	–	1000	1000
Air (Top)	3TC	0	0	800	815	825
Air (Top)	4T	0	0	800	820	835
Air (Bottom)	5T	0	0	–	820	835
Bearing Heater	6TC	0	0	800	815	825
Bearing Heater	7T	0	0	800	815	825
Bearing (Fwd Top)	8T	0	0	–	350	365
Bearing (Fwd Bottom)	9T	0	0	–	350	365
Bearing (Aft Top)	10T	0	0	–	350	365
Bearing (Aft Bottom)	11T	0	0	–	350	365
CONICAL AREA						
Heater	12TC	0	0	–	815	825
Heater	13T	0	0	–	815	825
Hub Area (Fwd)	14T	0	0	–	1000	1000
Hub Area (Mid-Fwd)	15T	0	0	–	1000	1000
Hub Area (Mid-Aft)	16T	0	0	–	1000	1000
Hub Area (Aft)	17T	0	0	–	1000	1000
Sump (Fwd Top)	18T	0	0	–	1000	1000
Sump (Fwd Bottom)	19T	0	0	–	1000	1000
Sump (Aft Top)	20T	0	0	–	1000	1000
Sump (Aft Bottom)	21T	0	0	–	1000	1000
NO. 5 AREA						
Air Heater (bottom)	22T	0	0	–	1020	1040
Air (Top)	23TC	0	0	800	860	870
Air (Top)	24T	0	0	800	860	870
Air (Bottom)	25T	0	0	–	860	870
Bearing (Top)	26T	0	0	–	415	450
Bearing (Bottom)	27T	0	0	–	415	450
Seal Ring Housing (Top)	28T	0	0	–	1000	1000
Seal Ring Housing (Bot)	29T	0	0	–	1000	1000
Washer (Top)	30T	0	0	–	1000	1000
Washer (Bottom)	31T	0	0	–	1000	1000
BREATHER AREA						
Heater	32TC	0	0	650	660	670
Heater	33T	0	0	650	660	670
Tube Air	34T	0	0	–	1000	1000

T, temperature, F.
TC, temperature controlled, F.

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

	SENSOR	OUTER LIMIT (LOW)	INNER LIMIT (LOW)	TARGET CONTROL POINT	INNER LIMIT (HIGH)	OUTER LIMIT (HIGH)
GEARBOX AREA						
Oil-In	35TC	0	0	190	220	230
Oil-In	36T	0	0	190	220	230
Oil-Out	37T	0	0	-	365	380
Bearing (Top)	38T	0	0	-	360	365
Bearing (Fwd)	39T	0	0	-	320	330
Bearing (Aft)	40T	0	0	-	310	315
OIL SYSTEM AREA						
Oil Sump	41TC	220	235	300	310	316
Oil Sump	42T	220	235	300	310	316
Simulator Oil-In	43T	220	235	300	310	316
Simulator Oil-Out	44T	0	0	-	370	375
Simulator HE Oil-In	45T	0	0	-	370	375
Simulator Scav. HE Out	46TC	0	0	300	350	365
Simulator Scav. HE Out	47T	0	0	300	350	365
Gearbox Scav. HE Out	48TC	0	220	300	330	345
Gearbox Scav. HE Out	49T	0	220	300	330	345
MISCELLANEOUS						
Left Drive Motor	50T	0	0	-	140	160
Right Drive Motor	51T	0	0	-	140	160
Drive Shaft Bearing	52T	0	0	-	210	220
Drive Shaft Bearing	53T	0	0	-	210	220
Oil Sump Heater	54T	0	0	-	810	820
AIR-OIL PRESSURES						
No. 4 Air-In	55PC	10	14	18	20	22
Breather Air	56P	0	0	-	10	15
Simulator Oil-In	57PC	40	43	45	47	50
Simulator Oil-Out	58P	20	25	-	60	65
Gearbox Oil-In	59P	25	30	-	50	55
Gearbox Oil Scav.	60P	10	14	-	45	50
Bottled Air Supply	61P	2700	2950	-	5000	5000
House Air Supply	62P	50	55	-	130	135
DRIVE MOTOR						
Simulator Hub Speed	65SC	8940	8950	9120	9155	9170

T, temperature, F.
TC, temperature controlled, F.
P, pressure, psiq.
PC, pressure controlled, psiq.

AUTOMATED AFAPL ENGINE SIMULATOR TEST NO. 24

Clean	0.0
Very light tarnish- straw colored	1.0
Light varnish- amber colored	1[illegible]
Medium varnish- tan colored	1.[illegible]
Heavy varnish- brown, 0.0254 mm(0.0001 in.) depth	1.7
Very heavy tarnish- black, 0.0508 mm(0.002 in.) depth	2.0
Light soft sludge- wipes easily, little depth	1.5
Medium soft sludge- wipes with pressure, <0.397mm (0.0156in.) depth	1.8
Heavy soft sludge- difficult to wipe, >0.397mm (0.0156in.) depth	2.[illegible]
Light hard sludge- <0.397mm (0.0156in) depth	2.[illegible]
Medium hard sludge- 0.397mm (0.0156in) to 1.588mm (0.0625in) depth	3.0
Heavy hard sludge- >1.588mm (0.0625in) depth	3.5
Light gritty deposit- <0.397mm (0.0156in)depth	4.0
Medium gritty deposit- 0.397mm (0.0156in) to 1.588mm (0.0625in)depth.	5.0
Heavy gritty deposit- >1.588mm (0.0625in) depth	6.0
Light smoth or wavy deposit- <0.397mm (0.0156in) depth	5.5
Medium smooth or wavy deposit- 0.397mm (0.0156in) to 1.588mm (0.0625in) depth	7.0
Heavy smooth or wavy deposit- >1.588mm (0.0625in) depth	8.5
Light blistered deposit- <0.397mm (0.0156in) depth	6.5
Medium blistered deposit- 0.397mm (0.0156in) to 1.588mm (0.0625in)	8.0
Heavy blistered deposit- >1.588mm (0.0625in) depth	9.5
Light flaked deposit- <0.397mm (0.0156in) depth	9.0
Medium flaked deposit- 0.397mm (0.0156in) to 1.588mm (0.0625in)depth.	12.0
Heavy flaked deposit- >1.588mm (0.0625in) depth	15.0

APPENDIX B

SYSTEM SAFETY ANALYSIS REPORT

for the

AUTOMATED AFAPL ENGINE SIMULATOR

SYSTEM SAFETY ANALYSIS REPORT
for the
AUTOMATED AFAPL ENGINE SIMULATOR

This system safety analysis report identifies and describes the system and component malfunctioning modes of the automated AFAPL engine simulator test facility. System safety features for operation of the simulator will be employed to prevent damage to the hardware or injury tc test personnel. This report satisfies the system safety requirements of Air Force Contract F33615-78-C-2012, Section F. Paragraph 5.1 safety system. In addition, the report is in accordance with Paragraphs 5.8.2.1 and 5.8.2.2 of MIL-STD-822A, dated 28 June 1977. The report also completes the requirement of Data Item Sequence No. 10 of the aforementioned contract.

The Hazard Analysis for the system rig hardware at both the system and component levels is presently in the following sections of this report. A brief description of each column of the Hazard Analysis form is as follows:

Column 1. Hazard

This column lists the applicable malfunction mode(s) for the component. All recognized hazard modes for the component are listed and each is a basic condition analyzed in columns 2 through 6.

Column 2. Operation Phase

This column lists the operational phases in which a malfunction constitutes a hazard.

Column 3. Effect(s)

The effect(s) of the components abnormal condition on its operation is shown.

Column 4. Hazard Class

The hazard mode is classified in accordance with MIL-STD-882A.

Category I	-	Catastrophic
Category II	-	Critical
Category III	-	Marginal
Category IV	-	Negligible

Column 5. Hazard Control

This column is used to list system features and/or procedures that may be employed to control hazardous conditions.

Column 6. Remarks

This column includes additional information needed to clarify or verify information in the other columns. Recommendations to improve system safety are also provided in this column.

The following listing is a summary of the general precautions which are taken to prevent damage to the simulator system and to prevent injury to test personnel:

- The facility is located in a building with restricted access.
- Operator personnel are inside our air-conditioned control room, separated from the engine simulator area by a wall containing a viewing window.
- Test area piping for air and fluid systems are designed in accordance with the American National Standard Code for pressure piping, ANSI B31.3-1973, "Petroleum Refinery Piping, Division A," and MIL-F-5509-C, "Military Spec. Fittings, Flared Tube, Fluid Connection."
- Fire protection is provided by water spray, fixed systems designed in accordance with NFPA No. 15 in both the simulator test area and the control room area. CO_2 hand-operated fire extinguishers are also available.

- The rotating drive system is protected by over-speed sensors. Other protection includes: low oil, high and low temperature warning systems, and water pressure warning signals.

HAZARD ANALYSIS

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Review by B. B. Baber **Issue Date** 12-14-78

ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic **SYSTEM** Automated Test Facility

1 **Hazard**	2 **Operational Phase**	3 **Effect(s)**	4 **Hazard Class**	5 **Hazard Control**	6 **Remarks**
<u>System Analysis</u>					
Computer short	System test run	Fire hazard to computer and test cell; loss of program control and loss of data.	III	• Computer circuit breaker • Automatic shutoff • Automatic fire protection • Circuit breaker for fan-out (alarm) • Mechanical interlock on system power shuts systems off system test run	
Power failure	System test run	Computer stops, engine simulator stops, overheats entire engine simulator (ES), thereby loss of entire test.	IV	• Automatic pneumatic bottled-air blowdown system cools engine, thereby saving test • Computer has automatic restart capabilities when power is restored.	

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic **SYSTEM** Automated Test Facility

1 **Hazard**	2 **Operational Phase**	3 **Effect(s)**	4 **Hazard Class**	5 **Hazard Control**	6 **Remarks**
System Analysis					
Loss of air, water, electricity and fire protection	Simulator test run	Loss of air causes a rapid increase of temperatures through the ES, creating excess deposits and possible seizing of bearings; loss of water causes a rapid increase in drive motor system temperature; loss of electricity could cause loss of test; loss of fire protection could cause loss of entire facility.	II	• Computer shuts off ES on loss of air, water and electricity • Automatic pneumatic bottled-air blowdown system actuated when support electricity and air is lost. • Drive system shuts down on low water pressure • No other fire protection	

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic **SYSTEM** Automated Test Facility

1 **Hazard**	2 **Operational Phase**	3 **Effect(s)**	4 **Hazard Class**	5 **Hazard Control**	6 **Remarks**
System Analysis					
Manual Operation	System checkout or experimentation	Damage of entire ES is possible if high or low limits set in automatic computer operation are exceeded; engineering judgment must be exercised during this operational phase.	II	• No computer control protection for high or low pressures, temperatures, currents, flows, and motor speeds • Electromechanical high and low shutoffs provided for air and oil systems • Drive motor system has low water pressure protection with high temperature protection and high current protection	Manual operation of the ES can be performed with ease and safety if good engineering judgment is used
Auto Operation	Actual system test run	Damage of entire ES is possible if high or low limits set in automatic computer operation are exceeded.	II	• Computer control protection for high or low pressures, temperatures, currents, flows, and motor speeds. Otherwise, same as manual operation	

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic **SYSTEM** Engine Simulator

1 **Hazard**	2 **Operational Phase**	3 **Effect(s)**	4 **Hazard Class**	5 **Hazard Control**	6 **Remarks**
System Analysis					
Structural damage or drive system or gear train *malfunction*	System test run	Degradation of lubrication system performance, excessive vibration due to misalignment of parts resulting in excessive damage to engine *simulator parts and fire hazard if conditions* are suitable to initiate and sustain combustion.	II	• Computer shut off *ES* on vibration reaching upper temperature limit • Stringent maintenance and inspection procedures • *Manual abort and* visual monitoring capabilities provided • Isolation of personnel provided • Fire suppression *system*	
Leakage of engine simulator end covers, flanges, *and tube con*nections	System test run	Incorrect air pressures, and flow rates, thereby affecting test results; leakage of hot air and oil and possible fire hazard if conditions persist.	II	• Seals on mating surfaces • Leak checks and repairs *on assembly* • Fire suppression system	
Gearbox overheat or oil flooded	System test run	Damage gears and bearings due to overheating; oil flooding could cause oil deposition to change, call for more oil and overload engine simulator drive system, burn out drive shaft seal	II	• Computer shut off on temperature reaching upper limit • Computer shut off on pressure reaching low limit in flooded condition - no oil	

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HAZARD ANALYSIS

Review by B. B. Baber **Issue Date** 12-14-78

ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Drive **SYSTEM** Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Drive System					
Drive motors overspeed	System test run	If overspeed condition allowed to exceed safe limit, the drive gearbox could rupture, drive shaft seal burn up, possible bearing seizure, and possible fire, possible gearbox and simulator rupture.	I	• Computer overspeed protection • Temperature limits on critical areas • Isolation of personnel by wall with safety window • Fire suppression system	
Drive motors overheating	System test run	Overheating condition raise motor current, possibly burning out drive motors, and wiring.	III	• Non-computer temperature control • Overload protectors stop drive motors	

HAZARD ANALYSIS

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ITEM Automation of AFAPL Engine Simulator SUBSYSTEM Automatic Oil SYSTEM Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Oil System					
High oil pressure	System test run	Rupture oil lines, possible fire hazard, possible lack of lubrication and cooling to engine.	VI	• Computer shut off on pressure reaching upper limit • Electromechanical shut off on pressure reaching upper limit • Computer shut off on temperature reaching upper limit	
Low oil pressure	System test run	Overheating of gears and bearings with resulting seizure of bearings and oil pump could result in considerable damage to engine simulator if not aborted in time.	II	• Computer shut off on pressure reaching low limit • Electromechanical shut off on pressure reaching low limit	
High oil sump temperature	System test run	Overheating of test oil would increase test oil deterioration and affect deposition results, possible fire hazard.	III	• Computer shut off on temperature reaching upper limit • Fire suppression system	
Low or high oil sump level	System test run	Extreme low oil level could starve pump resulting in no oil flow or pressure overheat resulting pump seizure and damage to all rotating ES parts; high oil level causes high temperature in ES.	II	• Computer controls oil level • Computer shut off on temperature reaching upper limit	

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DEVELOPMENT OF THE AUTOMATED AFAPL ENGINE SIMULATOR TEST FOR LU--ETC(U)
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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Oil **SYSTEM** Engine Simulator

1 **Hazard**	2 **Operational Phase**	3 **Effect(s)**	4 **Hazard Class**	5 **Hazard Control**	6 **Remarks**
<u>Oil System</u>					
Main oil pump scoring, erosion or leaking	System test run	Reduced and fluctuating oil supply pressure. Increased possibility of engine simulator gear and bearing problems. Oil leaking from oil pump goes back in sump.	III	• Stringent maintenance practice prior to pump assembly • System instrumentation monitors pressures. • Low oil pressure automatically shuts down ES	
Oil pump drive shaft breaks	System test run	Oil pump stops, ES temperatures increase, possible damage to all mechanical rotating parts.	IV	• Computer shut off on low oil pressure • Electromechanical shut off on pressure reaching low limit	
Clogged oil-in filter element	System test run	High oil pump pressure with possibility of line rupture. Starve ES and possible parts damage.	IV	• Computer shut off on low oil pressure • Electromechanical shut off on pressure reaching low limit	
Clogged filter elements: gearbox oil out and simulator oil out	System test run	High oil scavenge pressures on gearbox and simulator oil out; possible line rupture—backup oil in simulator—overheating.	IV	• Computer shut off on high oil pressure • Computer shut off on high temperature	Very unlikely

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ITEM Automation of AFAPL Engine Simulator SUBSYSTEM Automatic Oil SYSTEM Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Oil System					
Blockage of oil flow passages inside ES	System test run	Increased temperatures to gears and bearings with possible damage.	IV	• Stringent maintenance and inspection upon inital assembly • Computer shut off on temperature reaching upper limit	Very rare
External scavenge pump failure	System test run	Oil backs up into ES increasing drive torque requirements; oil is pumped out of sump rapidly; scavenge oil pressure drops.	III	• Computer shuts off on high torque requirement on drive system • Computer shuts off on low scavenge oil pressure	

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Oil **SYSTEM** Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
<u>Oil System</u>					
Tube assemblies become loose, get nicks, or cracks	System test run	Light leakage of oil and possible oil pressure fluctuation.	IV	• Visual inspection • Tubing supports in adequate numbers as required	
Contamination of lubrication system	System test run	Degradation of lubricant; would require ES unscheduled shut-down to investigate and repair	III	• Stringent maintenance and inspection	• Recommend iron content analysis be performed on each 5-hr oil sample • Recommend possible ferrographic analysis on each 5-hr oil sample

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Heat **SYSTEM** Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Heat System					
Excessive heat	System test run	Excessive heat to heaters can cause heater burnout, excessive deposits, wire burnout, possible fire, and loss of test.	II	• Computer shut off on temperature reaching upper limit	Each temperature control area has one additional backup thermocouple for double safety

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Air **SYSTEM** Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Air System High air pressure	System test run	Excessive air pressure could cause No. 4 and 5 end covers to separate from diffuser case with explosive force; possible damage to seals and oil trap; damage to facility and extreme hazard to personnel.	I	• Computer shut off on pressure reaching upper limit • Electromechanical shut off on pressure reaching upper limit • Safety rupture disc • Isolation of personnel provided	

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ITEM Automation of AFAPL Engine Simulator **SUBSYSTEM** Automatic Cooling **SYSTEM** Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
<u>Cooling System</u>					
Burn-up drive system	System test run	Overheating of automatic drive motors due to loss of water supply could burn up the drive system	III	• Non-computer water temperature control on each driver motor • Overload protectors stop drive motors • Computer shut off on dynamatic drive system on temperature reaching upper limit	

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ITEM Automation of AFAPL Engine Simulator SUBSYSTEM Automatic Soakback SYSTEM Engine Simulator

1 Hazard	2 Operational Phase	3 Effect(s)	4 Hazard Class	5 Hazard Control	6 Remarks
Soakback System					
Excessive heat	System test run or automatic emergency soakback	Loss of test due to excessive heat input to the various temperature control areas due to loss of controlled air into ES.	II	• Normally open air valves used on house air and emergency bottle air system • Computer shut off on temperature reaching upper limit	

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