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THE STATE-OF-THE-ART IN OIL QUANTITY GAGING ON U.S. MILITARY AND COMMERCIAL AIRCRAFT

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September 1974

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This report reviews the principal design techniques used in oil quantity gaging systems for U.S. military and commercial aircraft. The most pertinent design details of four oil quantity gaging systems are discussed and the author's opinion as to the merits of certain characteristics of each design is given based upon the potential of the basic design while operating in military environments. An attempt is made to rate each of the four designs in the following areas: Adequacy of Performance, Vulnerability to Military Aircraft (Cont)

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Environments, Simplicity of Design and Reproducibility, and Maintainability. The reliability area was omitted inasmuch as the reliability of a design is subject to many variables, most of which are introduced and/or controlled by the manufacturer. The controversial subject of mass versus volumetric gaging is also discussed and important questions are raised. The magnetic float voltage ratio and the digital systems were considered to have the greatest potential for low maintenance and satisfactory operation in military aircraft environments. The report recommends the use of volumetric type oil quantity gaging systems on all military aircraft and recommends the initiation of a program to determine the nominal dielectric constant and density of engine oil which is procured to military specifications to improve the credibility of capacitance type systems.

PREFACE

This report was prepared by John W. Long, Chief, Propulsion Instruments Branch, Instruments Division, Directorate of Airframe Engineering, Wright-Patterson Air Force Base, Ohio. The information was prepared between 1 February and 31 July 1974 at the request of Lieutenant Colonel D. L. Scott USAF, Chief, Instruments Division. No formal project or task was assigned this effort. Acknowledgement is given to Transonics, Inc., The General Electric Company and General Nucleonics, Inc. for the use of information on and photographs and drawings of their equipment. Also, valuable assistance was given by Mr. James M. Planet of the Propulsion Instruments Branch who read the manuscript and provided several constructive suggestions.

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SECTION I INTRODUCTION

A. Liquid Quantity Gaging

Many problems confront the designer of liquid quantity gaging systems for current aircraft applications. The increase in complexity over stationary liquid quantity gaging systems is due primarily to the extreme environments, the unusual shapes of the containers, the relative freedom of the liquid to change its position within the containers with changes in aircraft attitude, the increased probability of contamination, the characteristics of the subsystem which requires the liquid, and the necessity to provide some type of warning when the quantity is reduced to some predetermined low limit. Some design techniques require a considerable amount of information as to the physical and chemical characteristics of the liquid to be measured and how these characteristics change with temperature, with use and from one batch to another from the same or from a different supplier. The dimensions and shapes of the containers (tanks) must be accurately specified within relatively small tolerances if accurate gaging is required.

If the quantity must be displayed, either continuously or on demand, to flight personnel, some standard unit of quantity or increment of capacity must be chosen. This choice is dictated to some degree by the accuracy desired and by the cost and complexity the user is willing to accept. Also associated with this choice is the dilemma of "Mass Versus Volumetric" gaging. Maybe the term "dilemma" is not quite appropriate but, in some applications, an intelligent decision requires very close scrutiny of tradeoffs. This subject will be discussed in some detail in Section II and in more detail in Sections III and IV.

Although this brief introduction to liquid quantity gaging was not intended to cover all of the problems and assessments which must be considered in the design of the system, it is believed that the uninitiated can better appreciate the magnitude of the effort necessary for accurate gaging of liquids on aircraft.

B. Characteristics of Aircraft Engine Oil

Aircraft engine oil is generally procured to performance type specifications which place relatively few restrictions on the chemical composition of the oil, or on various additives such as antioxidants, anti-foam agents, metal deactivators, load carrying additives, etc. Once a supplier is qualified, however, he must obtain approval to change the composition of his oil. Characteristics such as dielectric constant and density are not specified or controlled. Relatively wide variations therefore may exist in these characteristics among suppliers. It has been established that these characteristics vary also with temperature which further complicates the gaging problem depending on the gaging technique used. Additional variations are found between new and used oil of the same batch. It has been further determined from tests on oil which meets the performance requirements of Military Specification MIL-L-7808, that the dielectric constant may vary as much as five percent between new and used oil. Oil temperature on some current engines may be as high as 177°C (350.6°F). An oil temperature of 150°C (302°F) frequently occurs on many engines. Engine oil pressures normally range below 100 pounds per square inch differential as measured between the engine breather pressure and oil accessory housing pressure. Transient overpressures may reach 200 PSI or higher on some engines. In addition to the various additives mentioned above, engine oil usually contains minute metal particles a few microns in diameter. Oil quantity gage system designers must be aware of these characteristics and conditions and should be guided by them in the choice of a design. As we discuss system design techniques in Section III, we will frequently refer to some of these characteristics and their effects on the various designs.

SECTION II OIL QUANTITY GAGING

A. Why we need it

The basic purpose of lubricants is the prevention or deceleration of wear, scoring, or seizure of mating surfaces by providing a film of the lubricant between the surfaces to reduce friction. It logically follows then that the reduction of friction reduces the amount of energy necessary to sustain dynamic conditions while increasing the useful life of the mating parts. Gas turbine engines used on most military and commercial aircraft require engine lubrication in amounts varying from a few quarts to some thirty quarts, depending on the size of the engine and the auxiliary and accessory equipment which must be supplied engine oil for lubrication, hydraulic actuation, or cooling. Continuous oil quantity gaging provides the pilot or other flight personnel the earliest possible warning that oil is being lost, so that either the engine is shut down, in the case of multiengine aircraft, or a safe landing is accomplished with single engine aircraft, before serious engine damage or loss of aircraft occurs. Low-level warning systems do not provide this early warning; consequently, when the low level warning is observed, there is usually one or two alternatives left: shut down the engine or land immediately with limited choice of the landing site. In some instances the pilots of single engine aircraft may have to leave the aircraft and parachute to safety. In the absence of continuous oil quantity indication, oil pressure may be observed to aid in the detection of critical oil losses unless the malfunctioning of some accessory which requires engine oil provides an earlier warning. It can be shown however, that the oil pressure indicator will maintain almost normal pressure indication as long as a reasonable head pressure is maintained at the oil pump inlet and down stream leakage is at a relatively low rate. Under these conditions a significant loss of oil is indicated by the oil pressure indicator only after pump starvation is underway. The low level warning is usually activated before this condition is reflected in the oil pressure indication.

Oil gulping of gas turbine engines by hiding oil in lines, nozzle actuators, gear boxes, or other accessories is a common problem for oil quantity gage designers. With continuous oil quantity indication abnormal engine characteristics in this regard may be detected; however, these characteristics must be known for each engine type to aid in differentiating between permanent oil loss and temporary engine gulping.

B. Mass Versus Volumetric Gaging

Weight or mass indication of oil quantity more accurately shows the amount of lubricant available. Some basic liquid quantity gaging techniques are inherently mass structured and can be used to indicate mass quantity with a minimum amount of compensation for changes in the characteristics of the liquid. Other techniques require compensation for changes in several characteristics to provide the same level of accuracy when measuring mass. This raises the question whether there are any truly mass oil quantity gaging systems in use on U.S. military or commercial aircraft. If a container partially filled with engine oil is placed on a very accurate weighing device, its weight or mass would not be affected by changes in temperature, density, dielectric constant, volume, etc. Nor would it be necessary to provide any type of compensation to maintain the original indication of mass while operating at reasonable aircraft altitudes. This device would provide a mass quantity indication. Techniques requiring compensation for changes in such characteristics as noted above are basically volumetric gaging systems which are compensated for changes in other than the mass of the medium. It can be said however, that a mass quantity indicating system provides a more accurate indication of useful lubrication than a simple volumetric system which is not fully compensated for various changes in the fluid characteristics. Likewise, the mass quantity indicating systems are generally more costly, more complex, and less reliable than the uncompensated or partially compensated volumetric system. The advantages or disadvantages of one system versus the other will depend on the accuracy and reliability requirements of the application and on the tradeoffs among accuracy, reliability, and cost of ownership (life cycle costs). The information given in table I for JP-4 fuel is typical of the information required on engine oil to determine mass when the oil is used as the dielectric of a capacitor.

TABLE I. CHARACTERISTICS OF JP-4 FUEL

Temp °C	K	K-1	Variations of K-1 With Temp $\frac{K-1}{(K-1)_o}$ 1/	D Pounds/ Gallon	Variations of Density With Temp $\frac{D}{D_o}$ 2/	Error in Uncompensated System using K-1 as D % 3/
-70	2.19398	1.19398	1.09398	7.00227	1.07085	2.16
-60	2.17934		1.08055	6.93609	1.06073	1.87
-55	2.17202		1.07384	6.90300	1.05567	1.72
-50	2.16470		1.06713	6.86991	1.05061	1.57
-40	2.15006		1.05370	6.80372	1.04048	1.268
-30	2.13542		1.04028	6.73754	1.03036	0.962
-20	2.12077		1.02685	6.67136	1.02024	0.647
-10	2.10614		1.01341	6.60518	1.01012	0.325
4/ 0	2.09150	1.09150	1.00000	6.53900	1.00000	0.000
10	2.07686		0.98659	6.47282	0.98988	0.333
20	2.06222		0.97317	6.40664	0.97976	0.674
30	2.04758		0.95976	6.34046	0.96964	1.020
40	2.03294		0.94635	6.27427	0.95952	1.373
50	2.01830		0.93294	6.20809	0.94939	1.734
55	2.01098		0.92623	6.17497	0.94433	1.920
60	2.00366		0.91952	6.14191	0.93927	2.102
70	1.98902	0.98902	0.90611	6.07573	0.92915	2.480

NOTES:

1/ Variations of K-1 with temperature variations using nominal fuel characteristics at 0°C as basis for design. For integral compensation, the ultimate total sensor output in $K-1/(K-1)_o$ must be made to agree with D/D_o.

2/ Variations of density with temperature variations.

3/ Percent error introduced by temperature variations in an uncompensated system using K-1 variations as direct indication of density variations.

4/ Nominal fuel characteristics for design purposes.

SECTION III SYSTEM DESIGN TECHNIQUES

A. Nucleonic Systems

The scattering of gamma photons and the absorption of these photons by the atoms (nuclei) of the material through which they pass bear a direct relationship to the mass of the intervening material. This is the basic principle on which nucleonic oil quantity gaging was developed. The source of the gamma photons on military aircraft is the isotope, Krypton 85, and the intervening material of primary interest is the engine oil. Gamma radiation is electromagnetic radiation emitted by the nuclei of atoms undergoing radioactive decay. In passing through matter gamma radiation behaves as though it consisted of particles moving at the speed of light. These would be particles are called photons. A photon behaves as though it has a mass, m, and a velocity, c. It carries momentum mc and energy mc^2. The photons are inelastically scattered and absorbed as they pass through matter. Scattering consists primarily of collisons with electrons. Part of the photon energy is imparted to the electron; the scattered photon thus has less energy and a longer wave length than prior to the collision. Other photons are absorbed by the nuclei of atoms. In this case, the energy of the photon is used up in ionizing the atom and ejecting electrons. The ionized atom decays to its ground state by emitting X-rays and by recapturing electrons. The energetic electrons produced by the scattering and absorption processes lose energy by radiating continuous X-radiation or "bremsstrahlung". As a result of these processes, the radiation which reaches the detector after traversing the oil is very heterogenous. It consists of primary radiation or gamma photons which had collisions with electrons and whose energies have been reduced, characteristic X-radiation from excited atoms, and continuous X-radiation or bremsstrahlung emitted by energetic electrons. The response of the detector is a function of the energy or wave length of the incident radiation. The signal generated depends mostly on the higher energy components, or the primary and scattered gamma photons. In practice, the radiation source is usually housed in an aluminum tube, is specially configured, and is mounted on one or more sides of the oil tank to radiate the total volume of the tank, thus, the number of gamma photons reaching the detector, which is mounted on the opposite side of the tank, is a linear function of the mass of the oil in the tank. The detector is a Geiger-Müller tube which is activated by the photons which are not captured by the nuclei of the oil as they pass through the tank. These photons generate pulse trains in the anode of the tube. In the case of small oil tanks, the pulse rate is usually an exponential function of the mass, inasmuch as only one small source is normally used. Figure 1 shows the relative positions of sources and detectors as used on some military aircraft.

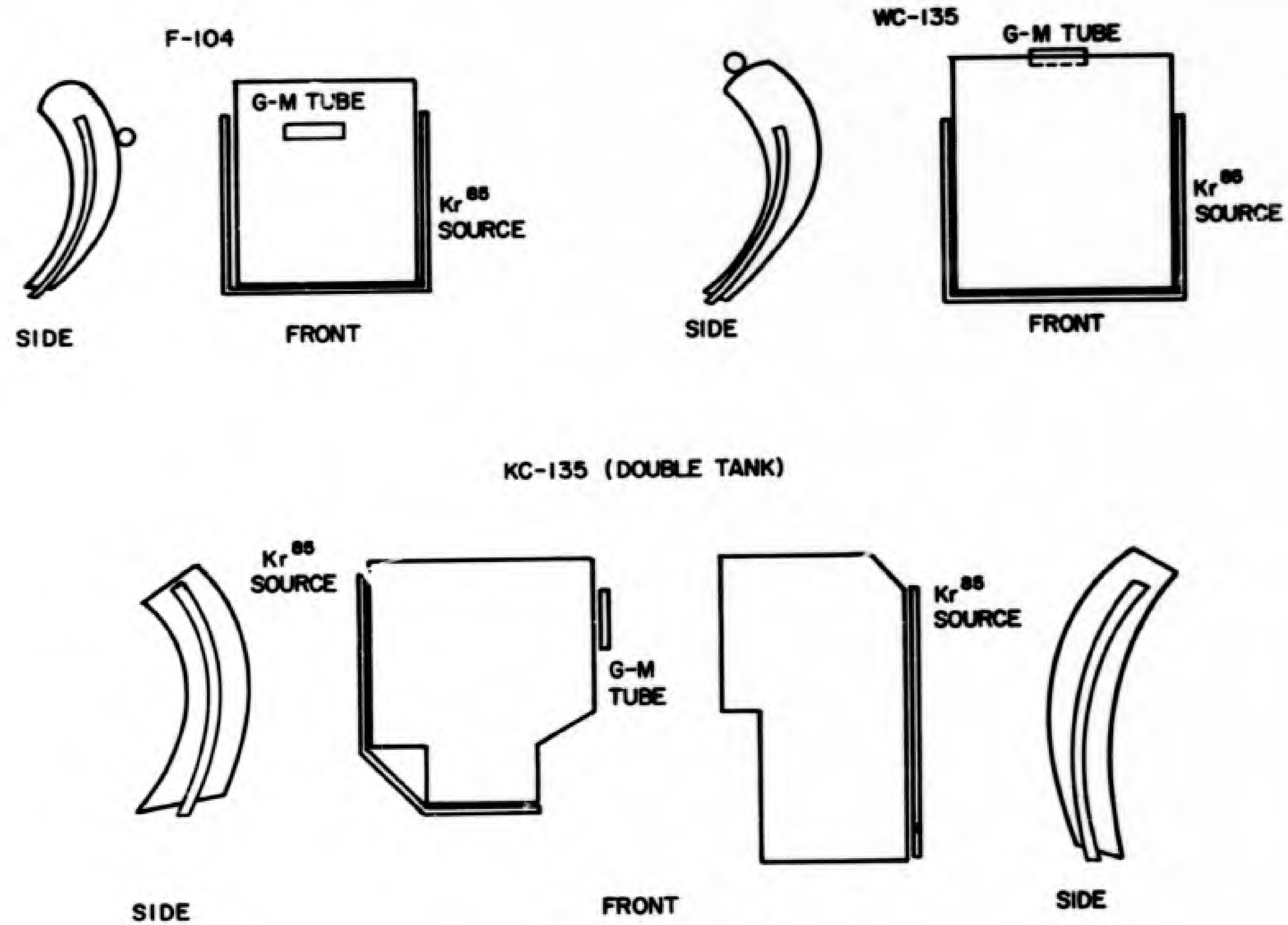
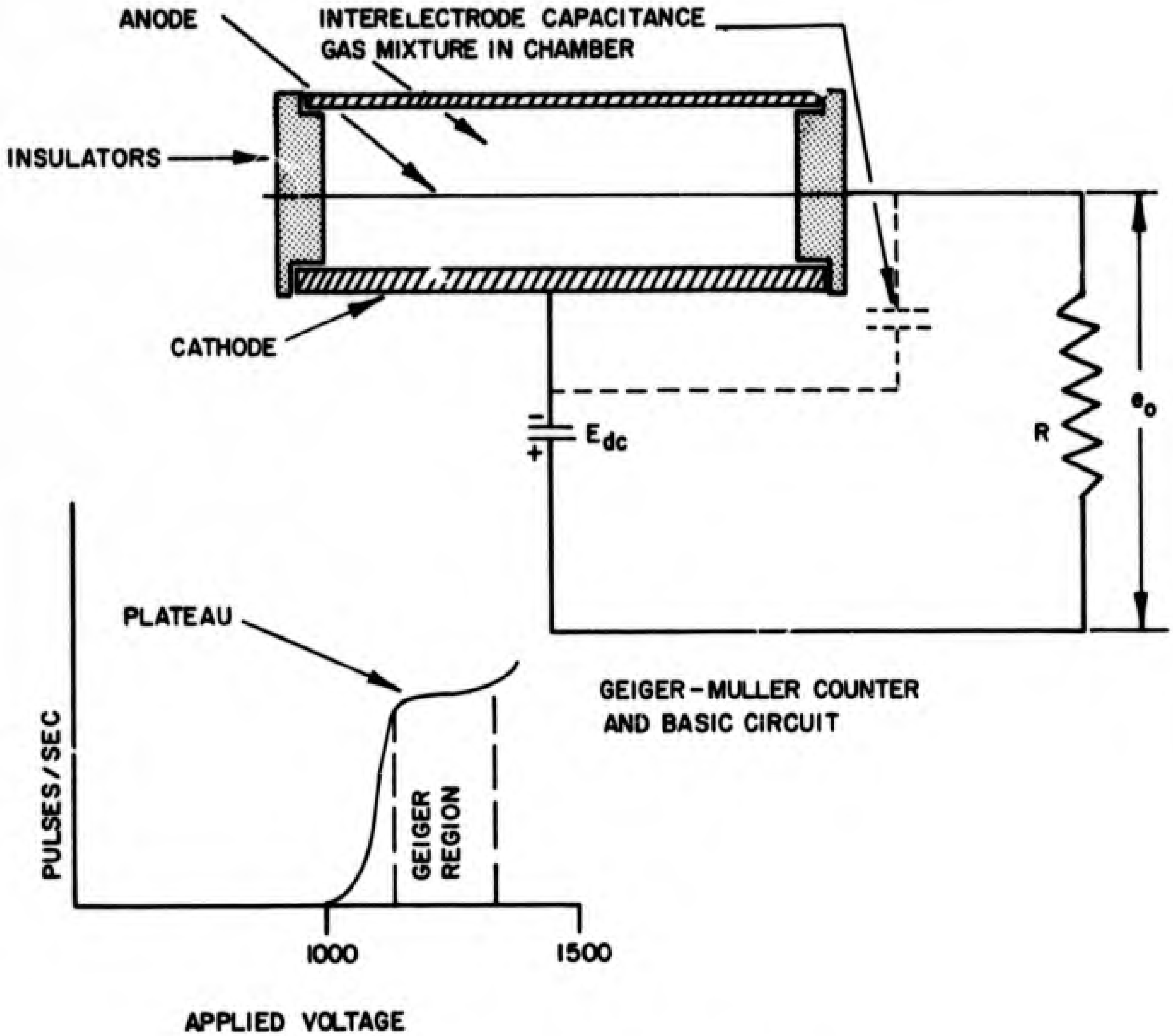


FIG 1.

SOURCE AND DETECTOR LOCATIONS FOR VARIOUS ENGINE OIL TANK

The common form of Geiger-Müller counter is shown schematically in Figure 2. The anode consists of a thin or small diameter tungsten or platinum wire held by insulators within a cylindrical cathode. The walls of the cathode are made thin or a window is provided to permit the gamma photons to enter the tube. The counter is filled with an inert gas such as argon to which is added a small amount of polyatomic gas. The pressure within the counter may be a few centimeters of mercury or it may approach atmospheric pressure. A voltage is applied through a resistance R and causes an electric field to be developed around the anode. Four modes or regions of operation can be distinguished as a result of ionization, depending primarily upon the magnitude of the applied voltage. They are: ionization chamber region, region of proportionality, region of limited proportionality and the Geiger region. We shall limit our discussion to the Geiger region. The characteristic property of a counter operated in the Geiger region is the appearance of output pulses that are all of the same size independent of the number of ions initially formed by an ionizing particle or gamma photon. An incident ionizing particle produces an electron-ion pair upon collision with the cathode. The electron drifts toward the anode and within a narrow region around it causes ionization by collision and the formation of an avalanche. Before the avalanche is collected at the electrodes, a second phenomena takes place. Light emitted from the first avalanche causes photoionization of the gas molecules and the liberation of new electrons which cause further avalanches. The light emission proceeds in every direction, but only in the vicinity of the anode is the field strength high enough to facilitate the formation of new avalanches. The discharge spreads along the wire until the entire anode is surrounded by a small diameter cylinder of ions and the discharge becomes self-sustaining. To terminate this situation one of three methods of quenching is used: resistance quenching by setting the time constant of an RC circuit to prevent reignition of the ion discharge; electronic quenching by using the output pulses of the counter to remove the applied voltage momentarily and then recharge the counter; and self-quenching by using a mixture of say 10% polyatomic gas such as methane and 90% argon to prevent reignition of the discharge. Some of the quenching agent is decomposed in each discharge. Thus, the life of the counter is limited by the decomposition of the quenching agent. The performance of the counter may show variations at low temperatures where condensation of the quenching agent may occur. The pulse size of Geiger counters is usually between 1 and 10 volts but may be higher. The amplification factor is in the range 10^7 to 10^9. Counters vary in length from 2 to 40 inches and in diameter from about 0.125 to about 2 inches. Figure 3 shows a typical early design which was used on F-104 aircraft. It is now obvious that the pulse rate is highest with an empty tank (fewer photon absorptions by the oil and more photons reaching the detector) and is lowest with a full tank (maximum photon absorption by the oil and fewer photons reaching the detector). The remainder of the system is usually housed in the oil quantity gage indicator which is mounted on the aircraft instrument panel. This indicator incorporates the high voltage supply for the detector, the linearization, discrimination, signal conversion, amplification, output circuitry, etc.,



GEIGER-MULLER COUNTER AND BASIC CIRCUIT

COUNT RATE VS APPLIED VOLTAGE

FIG 2.

TYPICAL GEIGER-MULLER DETECTOR

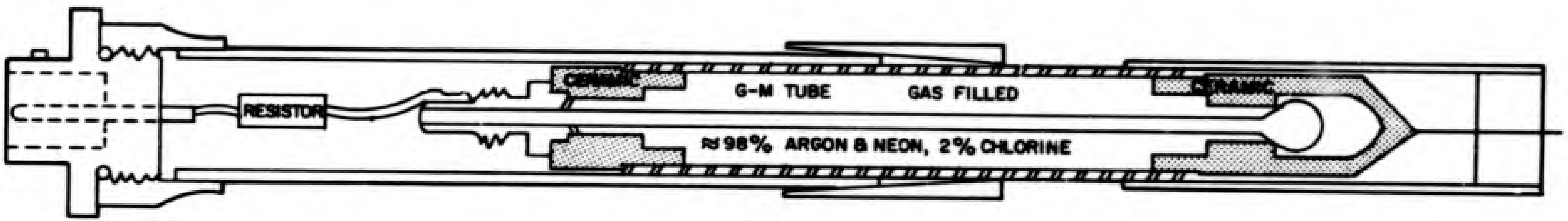


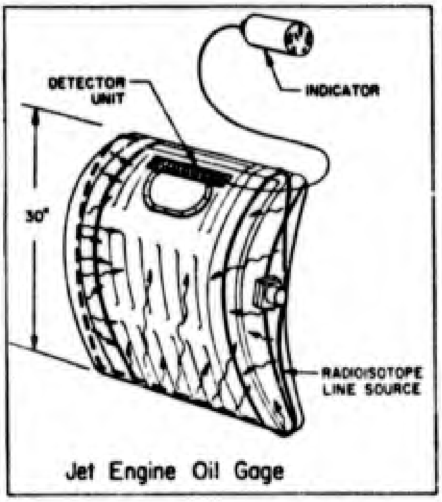
FIG 3.

AN EARLY DESIGN OF F-104 GEIGER-MULLER DETECTOR as necessary, to provide the oil quantity display. The shape or placement of the source tube is dictated by the permissible attitude error caused by the shifting of the position of the oil with various pitch and roll angles of the aircraft. This constraint is more exacting on the larger tanks and requires a partial "wrap-around" source configuration or the use of several sources. The typical pulse count rates for the detector tubes used on F-104 aircraft are 400HZ with an empty tank and 200HZ with a full tank. The time constant for the F-104 system is approximately 6 seconds. The dose rate at the detector is approximately 2 milli-roentgens per hour for a full tank. Figure 4 shows the F-104 installation and a block diagram of a typical system. Now that we have a general idea of how the Nucleonic Oil Quantity Indicating System (NOQIS) operates, it is considered necessary to look at one of the basic equations commonly used to relate the gamma photon count rate at the detector to the unattenuated gamma radiation of a collimated or point source. Thus, $CR = CR_o e^{-\mu\rho X}$. Where CR is the count rate of photons at the detector, CR_o is the count rate at the source, μ is the absorption coefficient of the oil, ρ is the oil density and X is the distance travelled by the photons. From this equation it can be seen that variations in either μ, ρ, or X will vary CR, the count rate at the detector. The absorption coefficient of the oil will vary with use, from one supplier to the next, with the type and quantity of additives used, etc. Changes with use result from chemical changes which take place in old oil. Also, old oil and fresh oil will be mixed. Density changes of significance will result from temperature changes although minor changes will be associated with most of the conditions which affect the absorption coefficient. Installations which utilize large tanks and a single small source and detector will experience changes in X during various attitudes of the aircraft. Although changes in μ, ρ and X will partially cancel each other, there remains an error which is difficult to predict or compensate under the conditions described above. The difficulty of the problem is increased several orders of magnitude when we go from a point source to radiation in all directions as is the practical case. Indeed, an elaborate computer program may be required to design a system to meet the accuracy requirements specified in Military Specification MIL-O-38338, for nucleonic oil quantity gaging systems.

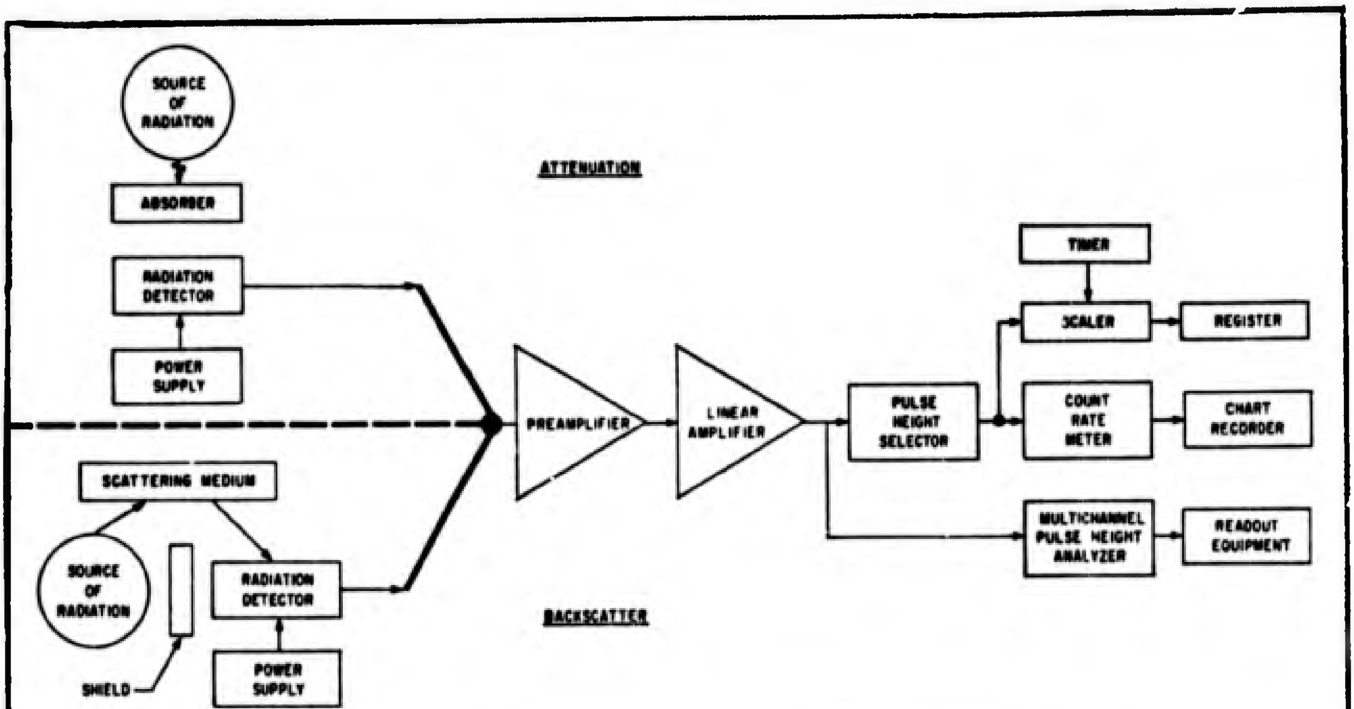
1. Advantages of the Nucleonic System

a. The nucleonic system is mass structured by the very nature of the photon absorption process. Mass quantity gives a more accurate indication of the amount of lubrication available and may be used to compute operating time remaining, given the use rate.

b. The system installation does not require physical contact between the oil and the sensor, thus avoiding contamination, elaborate electrical insulation, etc.



DRAWING ILLUSTRATES F-104 radioisotope oil-gaging system. Gamma rays emitted by line source around tank are attenuated by molecules of oil. The number striking the radiation detector is a direct measure of oil quantity, which is displayed on indicator.



TYPICAL RADIOISOTOPE counting system as used for measuring radioisotopes either attenuated by a substance like fuel or oil or scattered back from a medium, as in air density measurements.

FIGURE 4. F-104 INSTALLATION AND TYPICAL SYSTEM DIAGRAM

c. The output signal of the detector is relatively large (several volts) which reduces amplification problems and eliminates the necessity for conductor shielding or coaxial conductors between the detector and the cockpit mounted indicator.

d. The system has the potential for the development of a mass quantity gage with accuracies considered adequate for all known airborne applications.

2. Disadvantages

a. Krypton 85 poses a minor health hazard and requires licensing by the U.S. Atomic Energy Commission for its use.

b. The system design is complex and requires expertise in many disciplines to provide a reliable system.

c. More than one radiation source or a wrap-around configuration may be required with large oil tanks. This further complicates the design and may increase the health hazard.

d. Special shielding, electrical compensation, and the use of more than one detector may be required for satisfactory operation on the resumption of atmospheric nuclear weapon testing. The added weight and complexity necessary for proper operation of the system in an atmosphere of gamma activity from fission products, as found in radioactive clouds a few hours after detonations, all but exclude this technique from the realm of general applications for oil quantity gaging.

e. Somewhat elaborate field test equipment is required to support the system and periodic calibration adjustments are necessary due primarily to source depletion and to quench gas depletion.

f. The cost of the system is relatively high.

B. Capacitance Systems

Oil quantity gaging systems which utilize engine oil as the dielectric of a capacitor are generally referred to as "capacitance systems." Dielectrics, liquids and solids, must be essentially non-conductors to facilitate the development of the electrostatic charge across the dielectric. The value of the capacitance is a function of the dielectric constant which is the ratio of the capacitance with oil as the dielectric to the capacitance with air or vacuum as the dielectric, using the same dimensions and configuration of the plates of the capacitor in both instances. This technique has been used extensively in fuel quantity gaging for approximately two decades with reasonably good results. It is basically a volumetric type gage which is used to indicate mass quantity by developing the statistical relation between the density and dielectric constant of the fuel and providing compensation for varying conditions. It has been determined that the expression (K-1)/D which relates the dielectric constant to density must be instrumented such that the value remains constant with changes in the dielectric constant and density in order to provide accurate mass quantity gaging. This term is called the <u>capacitance index</u> and the instrumentation required is called the "capacitance index compensator". In fuel quantity gaging an equation of the form (K-1)/D = A (K-1) +B has been instrumented to provide sufficient compensation for most conditions. (K-1)/D forms the ordinate and (K-1) is plotted along the abcissa of Cartesian coordinates:

Where K = dielectric constant of fuel (oil in this case)
D = density in lbs/gallon
A = slope of the line
B = (K-1)/D intercept

The (K-1) term is derived from the fact that the dielectric constant of air or vacuum is considered 1 and represents the dielectric constant with an empty tank. Inasmuch as K represents the dielectric constant of the fuel or oil, the increase in the dielectric constant between an empty tank and a full tank is K-1. However, the use of such an equation requires information on the variation of density and dielectric constant with temperature and among suppliers.

In Section I.B. it was stated, in essence, that engine oil for aircraft is not procured to specific requirements for density and dielectric constant and that a variety of additives are used by various suppliers. In view of this situation capacitance type instrumentation for accurate indication of oil mass must rely on accurate information on the range of the densities, and dielectric constants of the oil and compensation techniques must be used based upon some nominal values of the variables. Likewise accurate indication of volume must depend on a knowledge of the variations in the dielectric constant and density with temperature and among suppliers in order to provide adequate compensation. Therefore, some nominal dielectric constant and density values must be used and compensation must be provided for the range of deviations anticipated. In view of the several additives used, accurate compensation for changes in density and dielectric constant will be very difficult, particularly for an accurate indication of mass quantity.

Finally, the capacitance probe must be profiled to the oil tank configuration and there will be attitude errors due to aircraft pitch and roll angles during normal flight. The magnitude of these errors will normally be small due to the stillwell design used by some suppliers but will vary with the probe design, installation, and tank size. The remainder of the system is a panel-mounted indicator which incorporates the electronics for the various computations and compensation and provides a display of oil quantity for flight personnel. It may be said that the complexity of the system increases exponentially with increases in accuracy requirements as we go from the uncompensated volumetric to the fully compensated volumetric or mass quantity gage. Figure 5 shows the major components of a typical capacitance type oil quantity gaging system.

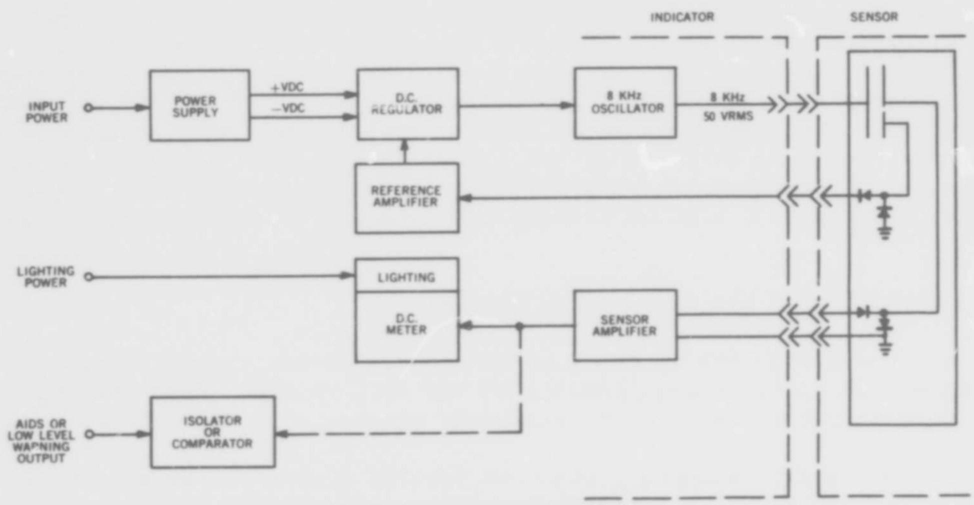
In the capacitance system the quality of the tank unit and the dielectric resistance of the oil are of utmost importance. Leakage paths which result in shunt resistances and series noise signals may seriously affect the performance of the system. Figure 6 is an equivalent circuit of the main section of the tank unit (excluding the compensator). The relative values of R1 and $X_c = 1/(\omega C)$ determine the dissipation factor (DF) of the probe as expressed by the equation $DF = 1/(\omega R1C)$, where R1 = dielectric resistance of the oil, $\omega = 2\pi F$, and C = probe capacitance. The shunting action of R1 due to oil impurities and/or poor insulation resistance would obviously increase DF and subsequently result in phase shift and reduce the signal-to-noise ratio of the output signals of the probe at the HI-Z terminal. Depending on the severity of this situation, the display of oil quantity may be sluggish in response, have relatively large dead bands, or may even cease to change. Of lesser importance, but not to be ignored, are the obvious effects of R2, C2 and R3, C3 which represent contamination resistances and capacitance coupling from the high and low impedance conductors of the probe capacitor to ground. Some capacitance systems are designed to operate from a relatively high frequency power supply to reduce the effects of contamination by decreasing the dissipation factor, $1/(\omega R1C)$, and by increasing signal strength in the same ratio as the frequency increase. Several manufacturers have produced capacitance systems which operate from 8 kilohertz power supplies. These have been designed for oil and fuel quantity gaging. Another refinement used by at least one manufacturer is the signal conversion from ac to dc at the sensor to eliminate the troublesome coaxial cable and connectors, so widely used in fuel quantity gaging systems, to protect the small ac signals between the fuel probes and the cockpit indicator.

1. Advantages of the Capacitance System

a. The system can be designed to measure either volume or mass, depending on the accuracy requirements of the application. When used to measure volume, the design can be relatively simple.

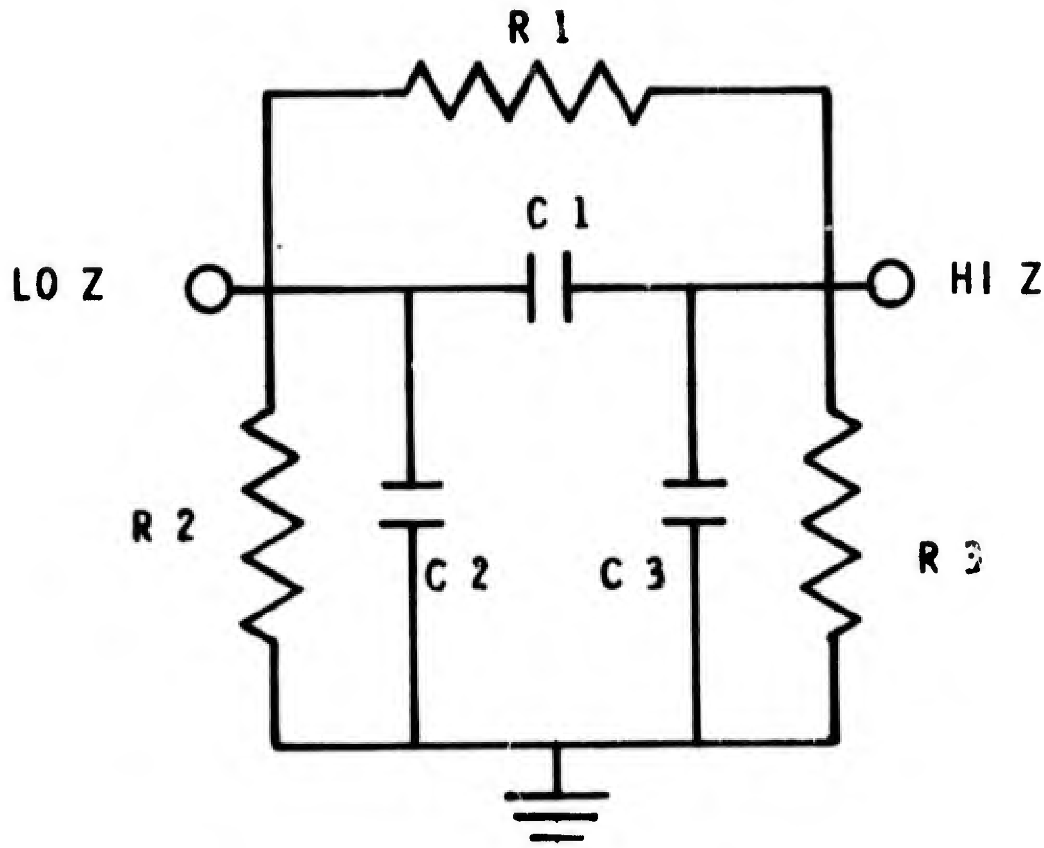
b. The basic technology required for the design of the system is known to many suppliers including fuel quantity gage suppliers and has been used on military and commercial aircraft for approximately two decades.

INTERNAL MOUNTING SENSOR FLANGE MOUNTING SENSOR



SYSTEM BLOCK DIAGRAM

FIGURE 5. INDICATOR, SENSORS AND CAPACITANCE SYSTEM BLOCK DIAGRAM



C 1 - CAPACITANCE PROBE

FIGURE 6

EQUIVALENT CIRCUIT OF CAPACITANCE PROBE

c. The system is compatible with nuclear survivability requirements.

2. Disadvantages

a. When the oil is heavily contaminated or after prolonged use, the probes may require flushing with a detergent or solvent to remove sludge.

b. Accurate indication of mass quantity requires the use of information on oil characteristics which is not readily available and which may change without the new information being made available either to the Government or to the instrument suppliers.

c. The system is moderately complex in design when mass quantity is measured to accuracies on the order of 2 to 3% of full scale due to the amount of compensation required.

d. The probe must be installed in the oil tank or a standpipe arrangement must be used.

e. Contaminants may affect the dielectric resistance and hence the operational accuracy and stability of the output signal.

C. Magnetic Float Voltage Ratio Systems

This system, like the capacitance system, consists of an internally mounted tank probe and a panel-mounted indicator. Also, it is basically a volumetric type system which requires probe resistance characterization or profiling to the tank configuration for accurate volume measurements. With proper compensation for changes in density, the system can be designed to measure the mass of a liquid. The probe is basically a tube with openings to allow the liquid to rise within the tube, and housing a tapped potentiometer, reed switches and a magnetic float. One contact of each reed switch is connected at a tap of the potentiometer and the other contacts of the reed switches are electrically connected together and to the negative of a 28V dc power supply. The ends of the potentiometer are connected to the ends of a center tapped coil which is connected to the + of the 28V dc supply at the center tap of the coil. The closing and opening of the switches is controlled by the vertical position of the buoyant magnet assembly. When the assembly is opposite a particular switch, the magnetic field of the permanent magnet in the float draws the contacts closed. When the magnetic float moves to a higher or lower level, the switch returns to its normally open position and another switch is closed. This is repeated at each new position of the buoyant magnet assembly. The resistance on either side of the potentiometer tap at a closed switch determines the voltage ratio across the sections of the coil and consequently the currents through the coil. A pivoted magnet in the indicator to which the pointer is connected aligns itself with the resultant magnetic field by rotating clockwise or counterclockwise depending on the strength and polarities of the magnetic fields of the sections of the coil. The position of the potentiometer and reed switch assembly is fixed so that the signals produced in the coil, as a result of the vertical position of the magnetic float, are proportional to the level of the liquid in the tank. Characterizing to the configuration of a tank may be accomplished by varying the resistance of the potentiometer between taps, and/or the distance between taps to obtain the nonlinear relationship between liquid height and volume for irregular shaped tanks. Mass quantity indication can be obtained by sensing the density and temperature of the liquid and compensating or biasing the output accordingly. However, designs based upon a nominal density with temperature compensation may be adequate for most applications. A functional system schematic is shown in Figure 7. System components are shown on Figure 8. The basic design is used for fuel and oil quantity gaging on military and commercial aircraft. In applications requiring high accuracy, a voltage-ratio servo amplifier arrangement may be substituted for the design shown.

1. Advantages of the Magnetic Float Voltage Ratio System

a. Performance is unaffected by additives and most contaminants.

b. The design utilizes elementary technology.

c. The test equipment required to maintain the system can be simple in design.

d. The design is compatible with nuclear survivability requirements.

e. The design has the potential for high reliability and low maintenance costs.

2. Disadvantages

a. The probe must be installed in the tank or a standpipe arrangement must be used.

b. When the oil is heavily contaminated or after prolonged use, the probe may require flushing with a solvent or detergent to remove sludge.

D. Discrete Level Sensing and Warning Systems

1. Thermistor Sensors

Thermistor sensors have been used with capacitance type fuel and oil quantity gaging to provide a warning when the level of the liquid is decreased below the level at which the thermistor is installed. This level is generally considered hazardous to flight and requires the pilot to assess immediately his ability to reach a safe landing site. General practice is to connect the

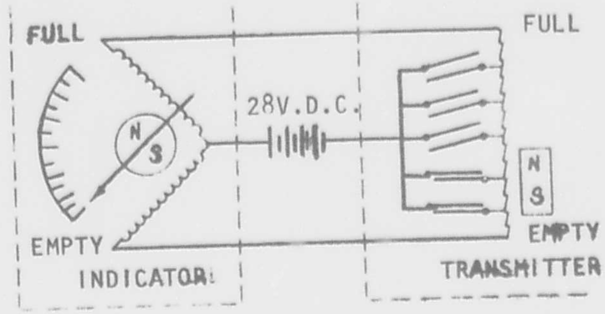


FIGURE 7. FUNCTIONAL SCHEMATIC OF MAGNETIC FLOAT VOLTAGE RATIO SYSTEM

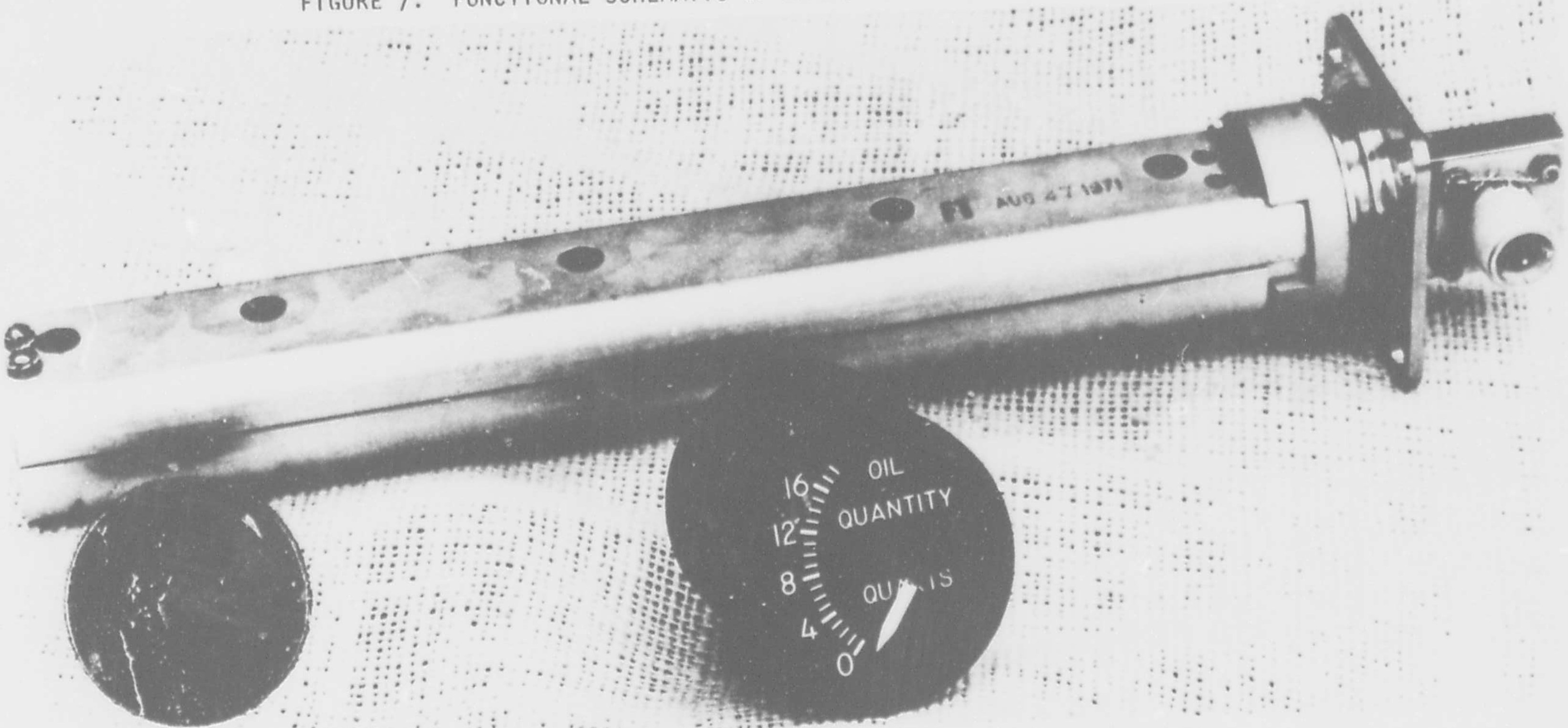


FIGURE 8. MAGNETIC FLOAT VOLTAGE RATIO SYSTEM COMPONENTS

thermistor in some type of bridge circuit with power applied such that a small current flows through the thermistor when it is submerged. So long as the thermistor is submerged in the liquid, the heat transfer to the liquid keeps the thermistor relatively cool and consequently the resistance of the thermistor relatively high (negative temperature coefficient of resistance). The bridge can be designed to remain substantially balanced over a range of temperatures as long as the thermistor is submerged. When the liquid level drops and exposes the thermistor, the heat transfer coefficient of the air and vapor above the liquid is insufficient to cool the thermistor. The temperature of the thermistor increases rapidly. The resistance decreases rapidly as a result. The unbalanced signal of the bridge increases and exceeds the level necessary to operate a relay or other device to provide a warning. The mass of the thermistor can be very small to provide a rapid temperature response. See Figures 9 and 10. The resistance change is usually exponential with temperature. Similar uses of thermistors to provide discrete level indication such as full, 7/8, 3/4, 5/8, 1/2, 3/8, 1/4, 1/8 etc. in oil quantity gaging would not result in a substantially lower cost system than the volumetric type capacitance or magnetic float voltage ratio systems. The number and quality of thermistors required and the circuitry necessary to provide a reasonably accurate and linear display, say 3 to 5 percent of full scale accuracy, may result in costs quite comparable to the cost of the systems mentioned above with a lower reliability.

a. Advantages when using thermistors

(1) Performance is not heavily dependent on the characteristics or content of the oil.

(2) Small size.

(3) Low level warning could be provided with a minimum of additional circuitry and components.

(4) Low power consumption.

b. Disadvantages

(1) Relatively slow response (several seconds).

(2) Moderately complex instrumentation is required to integrate and linearize the outputs for a display with 3 to 5 percent accuracy.

(3) Aging and temperature cycling cause significant changes in the resistance of the thermistor at various operating temperatures. The presence of minute quantities of impurities and the heat treating effect of the temperature cycling are primarily responsible for these changes in resistance.

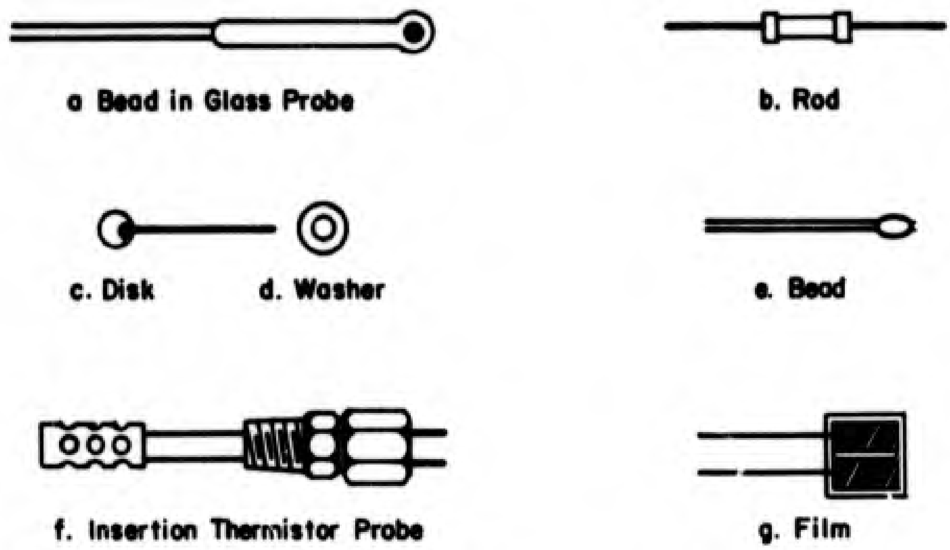


FIG 9.

THERMISTOR CONFIGURATIONS

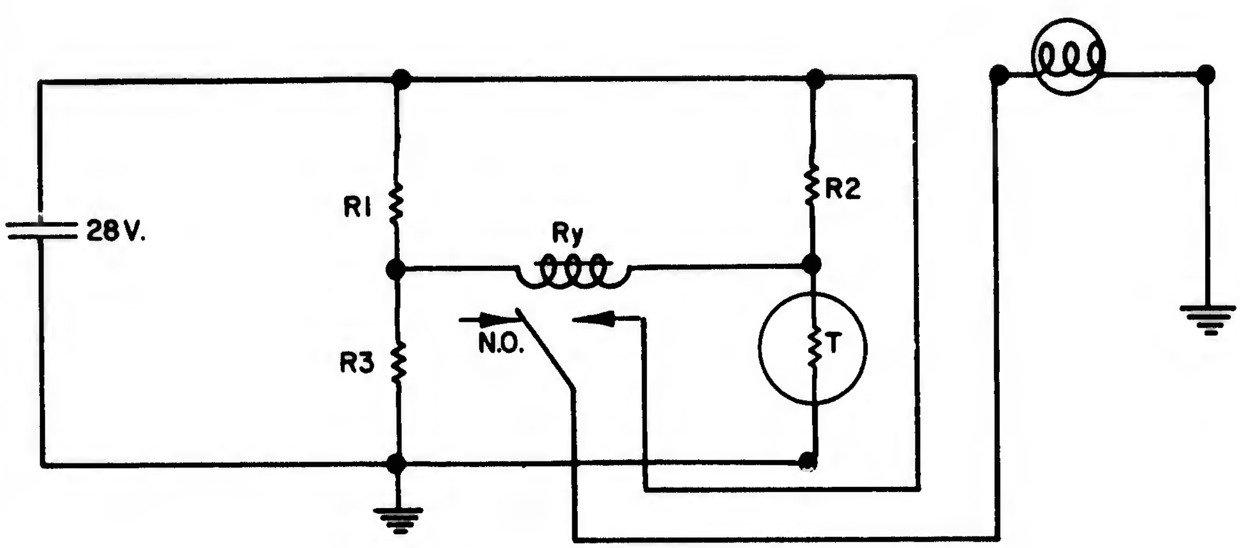


FIG 10.

SIMPLIFIED LOW LEVEL WARNING SYSTEM SCHEMATIC

(4) Thermistors in the upper half of the tank would be subjected to relatively high temperatures for long periods of time. This would reduce considerably the reliability of these thermistors.

2. Fluidic Devices

The application of fluidic technology to the measurement of liquid level has been limited primarily to stationary industrial applications and to laboratory experimentation. Although this general area of technology is rapidly gaining popularity due to the potential reliability of the sensor, the experimental nature of most of the designs (lack of standards) and the plumbing required make it less attractive and less practical than the other techniques described above. In general, the basic components of a fluidic system are: a calibrated pressure source, the necessary plumbing to compare the pressures and apply the resulting pressure signal to the transducer, a transducer, electronics for signal linearization and amplification, and a display for flight personnel. The use of the fluidic techniques in airborne installations would result in application problems greater by an order of magnitude than some of the other techniques described above.

3. Pressure Sensors

Pressure sensors have not been used extensively to indicate discrete levels of liquids or to provide low level warnings on military or commercial aircraft. In Section I it was shown that oil pressure indications can't be relied upon to provide timely indications of low oil levels. There are techniques however, which may be used with pressure transducers to provide low level warnings and to provide an indication of the mass of available oil. Three obvious techniques make use of the variable capacitor, the linear variable differential transformer, and the variable reluctance transducer. These may be used to weigh a column of oil of known diameter and variable length as a function of total oil mass. Needless to say, the contour of the tank must be known so that profiling or characterizing may be accomplished either electronically in the indicator or in the design of the tube. The distance between the plates of a capacitor may be varied as a function of pressure. The self inductance or mutual inductance of coils may be varied by inserting a magnetic probe to various depths within the coil as a function of pressure. Piezoresistive pressure transducers may also be used. Piezoresistive pressure transducers have been used to measure extremely low pressures including man's blood pressure. Although, to my knowledge, these techniques have not been used in liquid level or mass quantity gaging on military or commercial aircraft, they deserve investigation as new approaches to the difficult problem of mass quantity gaging of liquids.

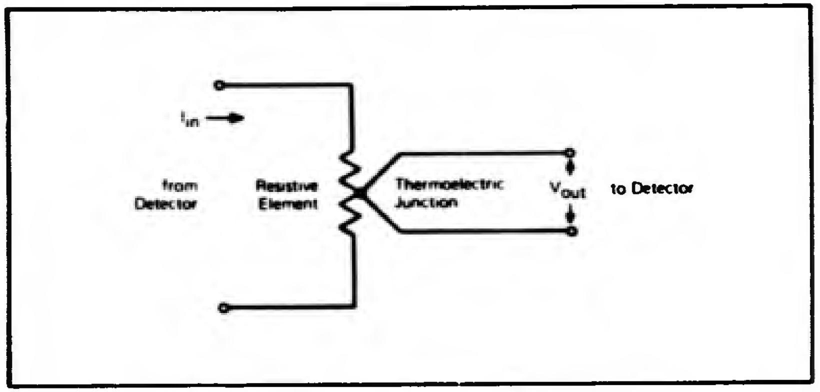
4. Float Switch

The float switch design as a low level warning device may vary from the simple switch, operated by the weight of the float when the liquid can no longer be reached, to very sophisticated designs. However, one current application of this type of device is in a still-well arrangement where the movement of the float is well defined. The still-well design is used in the magnetic float voltage ratio oil quantity gaging system described in Section III.C. above.

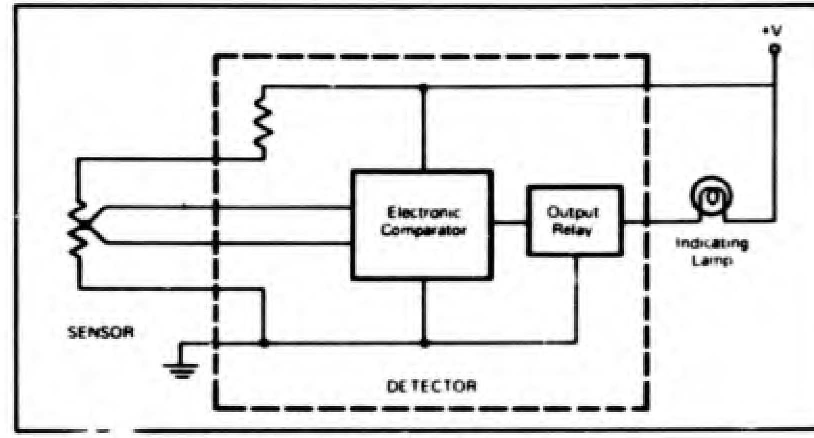
5. Digital Systems

Digital systems to indicate discrete levels of liquids are in use on commercial and military aircraft. The potential usefulness and reliability of this type of system deserve consideration. Representative of these systems is the Distat* Liquid Level Indicating System. The system may consist of only two components: a sensor and an indicator. The sensor is designed to accommodate several assemblies, each incorporating thermocouple junctions welded to electrical resistance wires through which is passed relatively low level currents. These assemblies are designed so that thermocouple junctions are at various levels in the oil tank. As long as the sensor is submerged in the oil, almost all of the heat generated in the resistance wire and the thermocouple junction is transferred away from the junction and only a small temperature increase results. When the oil level decreases and bares one or more thermocouple junctions, the heat transfer rate from the thermocouple junctions to the air and vapor above the oil is insufficient to maintain the previously low junction temperature. The result is an increase in the output of the thermocouple(s). In a typical installation, a sensor consists of four assemblies. The thermocouples are connected such that an even number of bared horizontal junctions cancel each other and only very small signals appear at the outputs. If an odd number of junctions are uncovered, relatively large signals are present at the outputs of the assemblies. The low output represents 0 in the digital code and the large signal represents 1. A four bit gray code is used to provide sixteen levels of oil quantity from "empty" to "full." Additionally, a low oil level warning circuit, a malfunction detection circuit, and a functional test switch are provided. Figures 11 and 11a show the basic sensing circuit, various configurations of multilevel sensing, low level warnings, and system connections. Figure 12 shows Distat sensors. The following table lists the gray codes for the sixteen oil levels:

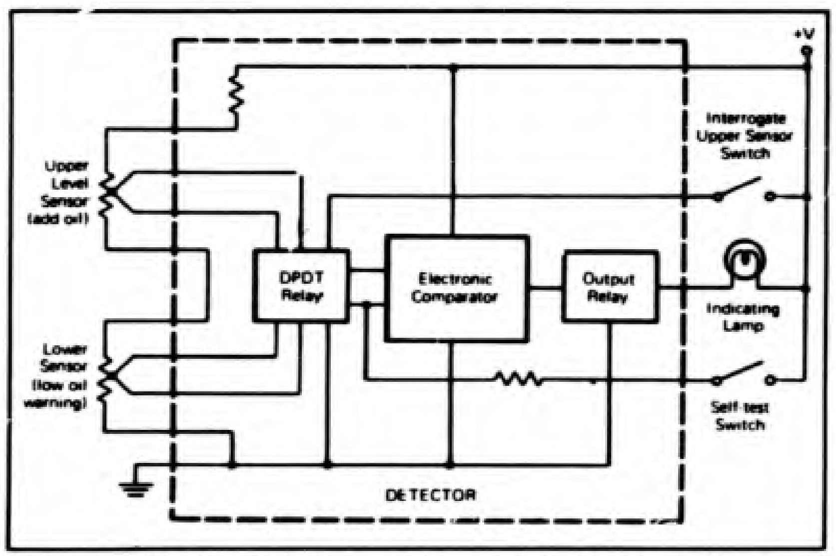
* Trademark of Transonics, Incorporated



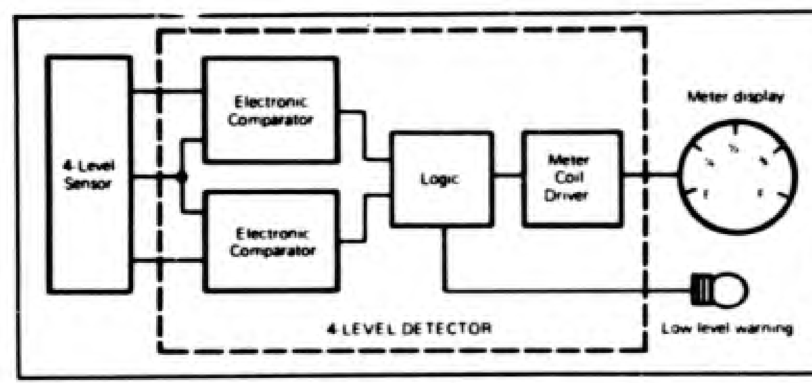
Single point Distat sensing circuit



Single point measuring system



Single Detector with switching to monitor two sensing levels.



Four-Level Sensing System

F/G. 11

SINGLE AND MULTILEVEL DIGITAL SYSTEM BLOCK DIAGRAM & SENSING CIRCUIT

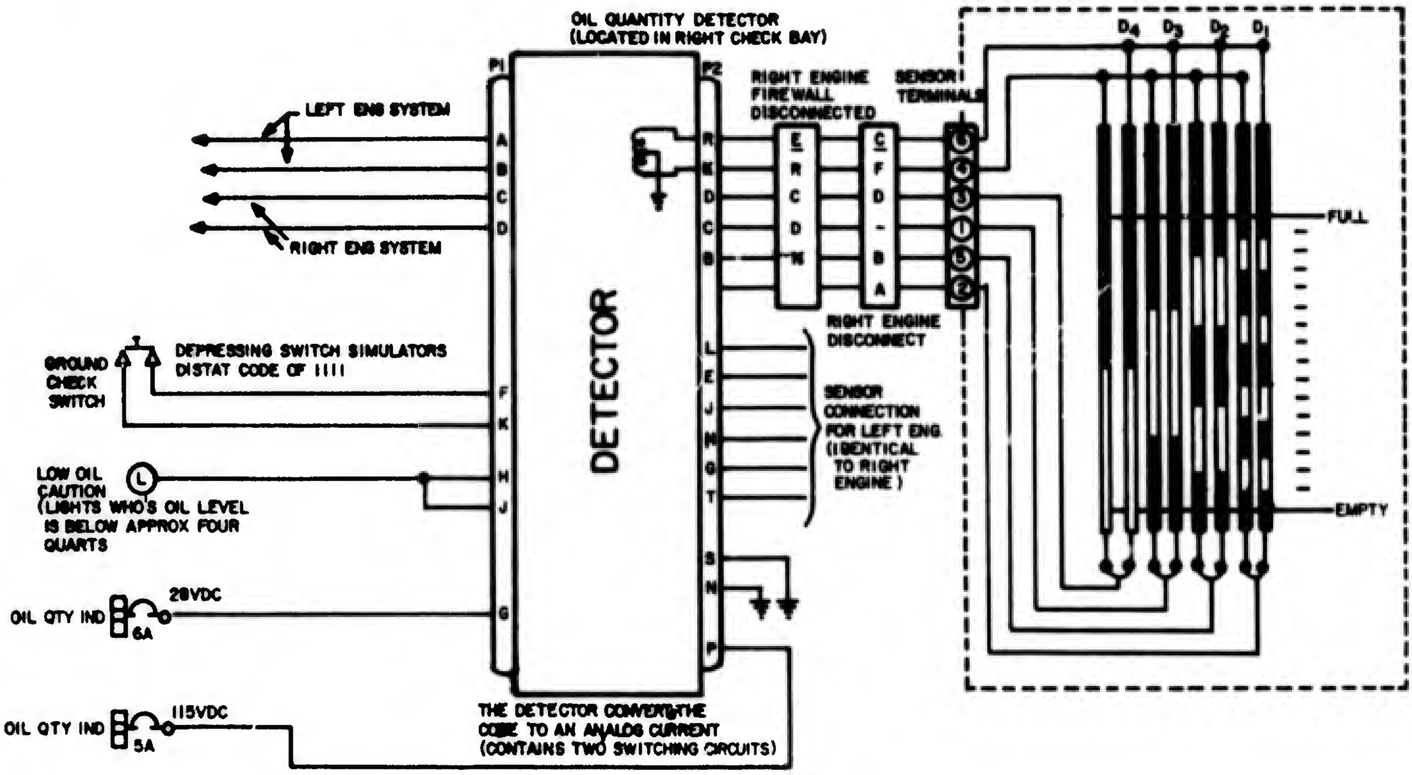


FIG 11A

TYPICAL DIGITAL SYSTEM INSTALLATION WIRING

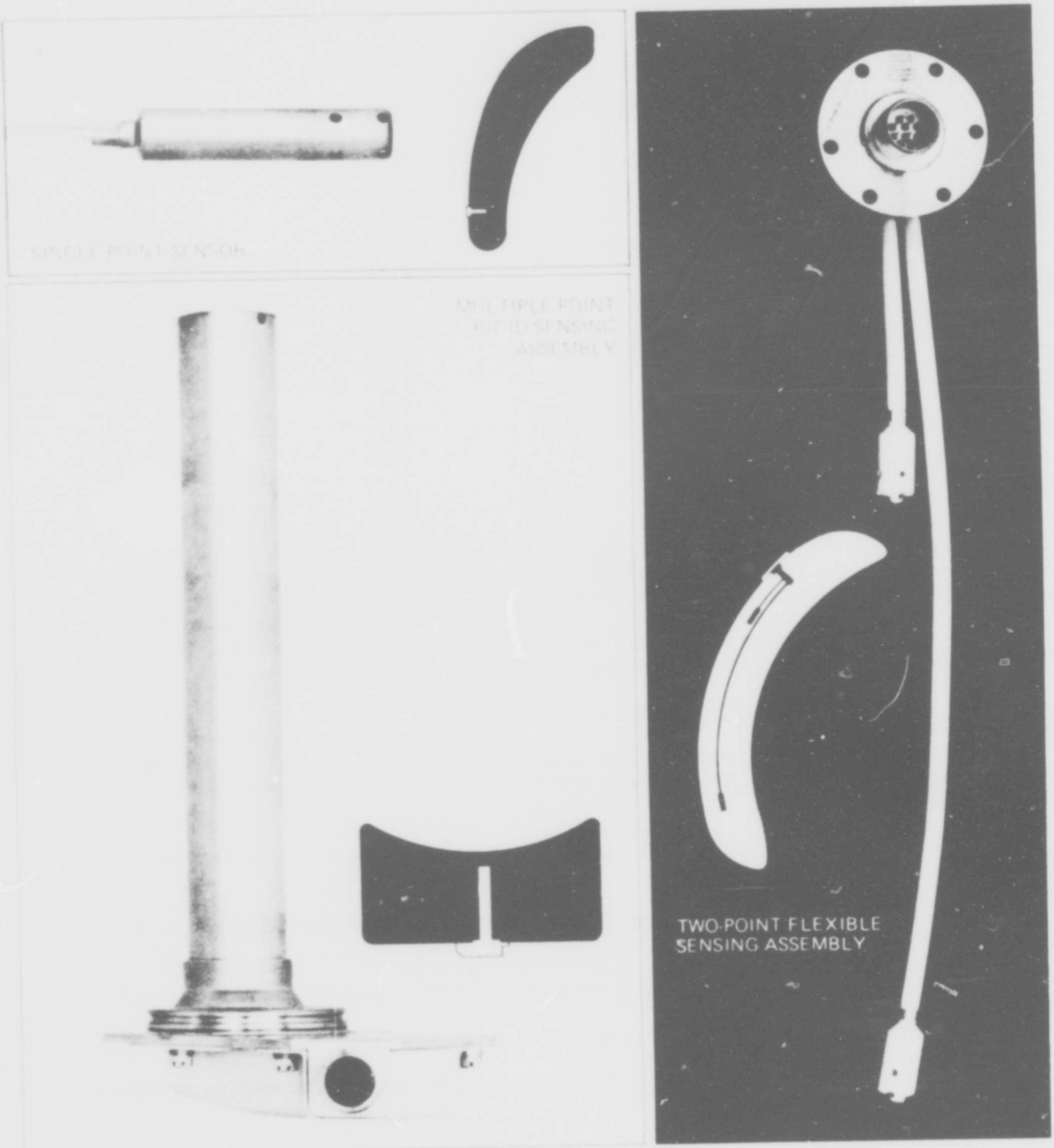


FIG. 12
DISTAL SENSORS

Sensor Level	Code
15	0000
14	0001
13	0011
12	0010
11	0110
10	0111
9	0101
8	0100
7	1100
6	1101
5	1111
4	1110
3	1010
2	1011
1	1001
0	1000

It is obvious from the description of the system and from the figure that the Distat System measures volume and that probe profiling or characterizing or electronic compensation is necessary for compatibility with irregular-shaped tanks. The electronics required includes logic circuits and digital to analog conversion to operate electromechanical display devices. The detector may be integrally housed in the panel mounted indicator.

a. Advantages of the Digital System

(1) The accuracy of the volume indication is virtually the same as the accuracy of the probe characterization and is not dependent on precise electronic signals.

(2) Relatively simple test equipment can be used to isolate malfunctions.

(3) The design is compatible with nuclear survivability requirements.

(4) The design has the potential for high reliability.

b. Disadvantages of the System

(1) The probe must be installed in the tank or a standpipe arrangement must be used.

(2) The system is moderately complex and must be carefully designed.

6. Electrical Resistance

This technique measures the electrical resistance or conductivity of the oil and is among the newest being designed.

SECTION IV CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Bases for Comparisons

So far, we have briefly discussed most of the techniques and basic designs found in instrumentation which is used to measure oil quantity on US military and commercial aircraft. Included were discussions of some of the characteristics considered advantageous and disadvantageous. Generally, these characteristics were evaluated against a background of environments and conditions known to exist on some military and commercial aircraft. Certainly, previous and current experience with instrumentation which utilizes some of these techniques and designs had some influence in the categorizations of advantages and disadvantages. However, it was not intended to infer that a design is useless or should not be used because of an undesirable feature, since all of the designs discussed had some undesirable characteristics. In some instances, the only alternative is the use of a different technique or design which has other more or less desirable features. This brings us to the selection of criteria by which a general unbiased assessment may be made of the various designs in use. It is hoped that this assessment can and will be used only as a general guide to the selection of oil quantity instrumentation for various applications. No attempt is made to evaluate every shade of differences among the various designs. The criteria listed below were chosen based on more than twenty years of experience with propulsion instruments from advanced development to maintenance and test equipment. The reliability area is conspicuously and purposely omitted in that the potential of the basic designs rather than a specific product of a manufacturer is evaluated. The reliability of a basic design is subject to many variables, most of which are introduced and controlled more or less by the various suppliers:

a. Adequacy of Performance
   Accuracy
   Response
   Sensitivity
   Damping

b. Vulnerability to Military Aircraft Environments
   Electromagnetic Radiation
   Vibration/Mechanical Shock
   Temperature/Temperature Cycling
   Contaminants in Oil
   Pressures
   Electrical Power Characteristics

c. Simplicity of Design or Reproducibility
   Technological Constraints

d. Maintainability
   Required Equipment for Functional Test
   Calibration Test Equipment
   Trouble Shooting and Repair
   Availability of Components
   Periodic Servicing

2. System Comparisons

a. Nucleonic Systems

(1) Adequacy of performance - It has been demonstrated on several installations that the accuracy, response, sensitivity, and damping of these systems are adequate. Although the response, 6-second time constant on F-104 installation, may be considered marginally adequate by some users, it can scarcely be rated inadequate for a quantity display. On this factor, a rating of "good" is in order.

(2) Vulnerability to aircraft environments - Electromagnetic radiation which includes radiation from fission materials of radioactive clouds would render the average system useless, temporarily; and the design necessary to alleviate this weakness would result in such added complexity, weight, and cost that it would not be competitive in other areas. The basic Geiger Muller Detector design is vulnerable to the combined vibration, shock, and temperature environments and requires expertise in several disciplines to design and reproduce detectors which are consistently reliable for several hundred or a thousand hours. Contaminants in oil, pressures and electrical power characteristics have little effect on these systems. Internal power supply regulation is generally required for most techniques and is not considered a significant penalty in these systems. On this factor only a "fair" rating can be given.

(3) Simplicity of design: Reproducibility - In reference to the discussion in Section III A. and to Figure 4, the nucleonic system is a complex system which requires expertise in several disciplines which is not generally available in most manufacturing organizations. As stated above, reproducibility to maintain consistent performance and reliability may not be demonstrated. Because of these liabilities, only a "fair" rating can be given this factor.

(4) Maintainability - Functional test equipment is required for aircraft installed systems and for laboratory or field bench tests. On the aircraft, this may be accomplished by merely applying electrical power to the system and comparing the indicator reading with the known oil quantity. However, on the bench, simulating the source and/or detector requires elaborate equipment. Calibration of system components independently and as a system and trouble shooting and repair also require elaborate equipment. Certain components such as Geiger Muller tubes of the quality required

for airborne use have limited availability. This situation is conducive to the development of not operationally ready supply (NORS) and reduced mission capability inasmuch as oil quantity is a major limiting factor on the range of the aircraft and engine operating time. Periodic servicing for calibration adjustments is required and results partly from source depletion and quench gas depletion. This factor is also rated "fair".

b. Capacitance Systems

(1) Adequacy of performance - The basic capacitance system is capable of adequate performance as to accuracy, response sensitivity and damping when used to measure either volume or mass quantity. The accuracy of the system as indicated in Section 3, is dependent upon the accuracy of the profiling or characterizing of the probe to the tank configuration. The performance characteristics of this basic design has been demonstrated in many fuel quantity gage applications. This factor is rated "good".

(2) Vulnerability to aircraft environments - The only aircraft environment to which the capacitance gage is known to be vulnerable is contaminated oil, specifically, contaminants which are electrolytes or conducting substances. However, small percentages of these substances can be tolerated through proper circuit and power supply design. Therefore, if it is assumed the percentages of these substances are kept relatively small, the capacitance system should be rated "good" on this factor.

(3) Simplicity of design: Reproducibility - The capacitance system design is only moderately complex. All parts of the conventional system are reproducible as to quality, dimensions, and performance within small limits. This has been demonstrated on thousands of fuel quantity gage systems. This factor is also rated "good".

(4) Maintainability - Functional test equipment, calibration test equipment, and trouble shooting and repair facilities can be readily obtained and similar equipment and facilities for fuel quantity gages are available at the AFLC logistic centers and in the using commands. Except for a special portable tester, special test equipment is not needed to perform these functions. Capacitance probes may require periodic flushing with a solvent or detergent. However, this is usually after hundreds or even thousands of hours of operation and is not considered an unusual maintenance burden. The associated indicator is capable of demonstrating mean times between failures in excess of 2000 hours. This factor is rated "excellent".

c. Magnetic Float Voltage Ratio System

(1) Adequacy of Performance - Although this is basically a volumetric type measurement system, with the addition of density compensation, mass can be measured to the required accuracy of all known military

applications. For maximum accuracy, a simple amplifier may be added and the meter movement may be replaced with a two-phase motor or dc torquer. Sensitivity, response and damping to meet all known requirements can be obtained with either the meter movement or the servo. This factor is rated "good".

(2) Vulnerability to aircraft environments - There are no aircraft environments associated with oil quantity gaging to which this system is vulnerable, assuming normal precautions are taken in the design for the various environments. No exotic design or construction techniques are necessary to meet the requirements. This factor is rated "excellent".

(3) Simplicity of design: Reproducibility - This is the simplest of the oil quantity gaging designs reviewed. The meter movement, the tapped potentiometer, the magnetic reed switches and the magnetic float assembly do require care in the design and selection of quality components and in the construction of the system. Nevertheless, the design is straightforward with no complex interfaces or critical components and dimensions. The electrical and electromechanical design utilize conventional techniques. Reproduction of any component or subassembly is not a critical task. For these characteristics this factor is rated "excellent".

(4) Maintainability - The meter movement or servo, the magnetic float, and the reed switch contacts are the only moving parts. With proper design and choice of quality components, this system is capable of operating several thousand hours maintenance free. No special test equipment is needed to troubleshoot and repair the system. However, a very simple tester and a container of liquid to operate the tank probe is all that is needed for complete system calibration. Components and material for the repair and production of the system are available. Flushing of the tank probe after thousands of hours of operation is the only periodic servicing necessary. The maintainability factor is also rated "excellent."

d. Digital Systems

(1) Adequacy of performance - Accuracy is never a problem in a truly digital system in that a condition either exists as indicated by a relatively large signal or it does not exist as indicated by a relatively small signal or no signal. The response of this system is limited only by the time constants of the circuits, including the thermocouples, and the power delivered to the meter operated display. It is adequate for all applications. The sensitivity and resolution are functions of the vertical spacing of the thermocouples and the temperature differential between immersed and exposed thermocouple junctions. The differential in output signal between the zero and one states of operation, 700 to 1000 microvolts, permits excellent

sensitivity with proper electronic design. Almost any level of damping desired can be provided with either a meter movement or servo. This factor is rated "good".

(2) Vulnerability to aircraft environments - Apparently this design is not vulnerable to the aircraft environments listed in 1b above. It should be noted that the techniques of nuclear hardening of conventional electronics are well known and that the electronics of this and the systems discussed above are not considered vulnerable to radioactive clouds of fission materials as described in Section III A. above. When properly designed this system should exhibit very high mean times between failures when subjected to the various environments. This factor is rated "excellent".

(3) Simplicity of design: Reproducibility - This design is considered to be moderately complex as may be determined from figures 11 and 11a and from the description of the basic design and operation. Signal converters and comparators (logic circuits) are necessary for multilevel sensing using a 4-bit gray code. However, the required circuitry is considered conventional due to its relatively widespread use and requires no exotic design; hence, the reproducibility of the system components is good. This overall factor is rated "good".

(4) Maintainability - Conventional laboratory test equipment may be used to functionally test, calibrate, troubleshoot, and repair the system with the aid of a container of liquid for the oil tank probe. However, a moderately complex portable tester may be designed to accomplish the various test and troubleshooting functions. Replacement of system components should be comparable to that of the capacitance and magnetic float voltage ratio systems. A rating of "excellent" is given this factor.

e. Table II summarizes the ratings of the various systems.

3. General Discussion

In Section II it was stated that the basic purpose of lubricants is the prevention or deceleration of wear, scoring, or seizure of mating surfaces by providing a film of the lubricant between the surfaces to reduce friction. Friction, stress, and temperature are the major enemies of gas turbine engines but all three are, by design, necessary for engine operation. It was further indicated that decreases in oil pressure indication, as a result of dangerously low oil levels, often gave too little information too late to avoid the extreme emergency of having to land a single engine aircraft immediately with little or no choice of the landing site. Even low level warning systems that are designed to give adequate warning to avoid accidents or extreme emergencies are not adequate for situations where the rate of oil loss is very high. It logically follows that for single engine aircraft continuous oil quantity indication with a low level warning should be a firm uncompromising requirement, and that preferably the warning light should be in the indicator to enable the

TABLE II SUMMARY OF RATINGS

FACTORS	NUCLEONIC				CAPACITANCE				MAGNETIC FLOAT VOLTAGE RATIO				DIGITAL (DISTAT)			
	POOR	FAIR	GOOD	EXC.	POOR	FAIR	GOOD	EXC.	POOR	FAIR	GOOD	EXC.	POOR	FAIR	GOOD	EXC.
1. Adequacy of Performance			X				X				X				X	
2. Vulnerability to Aircraft Environments		X					X					X				X
3. Simplicity of Design Reproducibility		X					X					X			X	
4. Maintainability		X						X				X				X

pilot to determine immediately when there is a relatively rapid reduction in oil quantity. This would differ from the present concept of choosing some level at which to provide the warning and would give considerably more time for deliberations.

On multiengine aircraft, this concept of warning when a steady loss of oil occurs would, in almost every instance, avoid engine damage where flight personnel have the option to shut down the engine and continue the mission or choose a safe alternate destination with one less engine operating. A similar arrangement with or without cockpit indication could be used advantageously on remotely controlled vehicles such as drones and guided missiles.

In Section II there was a brief discussion of mass versus volumetric indication of oil quantity. It is a fact that at temperatures of 150 to 175 degrees Centigrade, the volume of aircraft engine oil procured to military specifications may be 10 to 15 percent greater than it is at zero degrees centigrade. It's just another way of saying that the density of the oil changes 10 to 15 percent. This change is in the unsafe direction in that with volumetric indication we may be given a false sense of oil security, unless this situation is considered when low level warnings are specified. Almost all low level warnings are volumetric. If this low level warning is considered the most important oil quantity information from the standpoint of flight safety, then the question arises why isn't volumetric indication adequate for a tank 1/2, 3/4 or full of oil? If it is known that the maximum expansion is 15 percent, why can't we fill the tank 85 percent full at outside ambient temperature and use a simpler, cheaper and more reliable volumetric oil quantity gage? At most, assuming a nominal 12.5 percent expansion, we would be only 2.5 percent high or low in oil quantity indication when the engine reaches normal temperature with either a 10 or a 15 percent expansion. This would be indicated by an accurate volumetric gage. If we agree that this type of gage is adequate, how can we simplify some of the designs discussed in Section III to get the advantages mentioned above? The nucleonic gage is mass structured by its very design. There are no simplifications to be had. Further, the nucleonic gage is considered the least desirable of the designs discussed, see Table II. With the capacitance system the design to obtain the statistical relation between density and dielectric constant with temperature could be omitted. Inasmuch as the dielectric constant does vary with temperature and among batches of oil, it will continue to be necessary to compensate for deviations in the dielectric constant from the nominal for volume indications. The uncompensated magnetic float voltage ratio and the digital (Distat) systems are volumetrics as currently used and would undergo no simplifications. Other discrete level sensors are likewise volumetric devices.

B. Recommendations

1. The following are recommended:

(a) That continuous or discrete level oil quantity gaging including an integral warning light for continuously decreasing oil levels and low oil levels be provided for all military aircraft engines. The indication should cover the range from empty to full.

(b) That oil quantity gages which are designed to measure the volume of oil be considered adequate unless it can be conclusively demonstrated that the mass of the oil must be known and displayed to flight personnel.

(c) That a program be initiated to determine the ranges of the dielectric constants and densities of engine oil procured to military specifications in order to establish nominal values for the design of capacitance type oil quantity gaging systems.

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