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AIRCRAFT FUEL SYSTEMS
HAZARDOUS CONDITION INDICATOR STUDY

By

George H. Custard
John K. Hobbs

February 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-70-C-0057
FALCON RESEARCH AND DEVELOPMENT COMPANY
DENVER, COLORADO

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This report, which was prepared by Falcon Research and Development Company under the terms of Contract DAAJ02-70-C-0057, covers a comprehensive engineering analysis and evaluation of devices and systems leading to a development of an aircraft fuel systems hazardous condition indicator.

The technical monitor for this contract was Mr. Rocco Fama, Safety and Survivability Division.

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USAAMRDL Technical Report 72-5
February 1972

AIRCRAFT FUEL SYSTEMS HAZARDOUS CONDITION INDICATOR STUDY

Final Report

By

George H. Custard

John K. Hobbs

Prepared by

Falcon Research and Development Company
Denver, Colorado

for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SUMMARY

The work done for the aircraft fuel systems hazardous condition indicator project was divided into several different tasks. The first task involved a comprehensive literature survey which provided data relative to useful phenomena occurring during the ballistic penetration of a fuel cell, and determined available means of detecting these phenomena. The literature survey provided a basis for suggesting four candidate phenomena. Pressure effects and fluid agitation were selected as being the most promising approaches which were worthy of further study.

The pressure and fluid agitation effects and the means of detecting their presence during a ballistic penetration were compared for overall system applicability in the UH-1B helicopter. A preliminary design for the hazardous condition indicator was developed employing each approach for this aircraft. This was the second major task of the project.

The final project task was to select the most advantageous system and construct a portable demonstration model showing the significant features and technical feasibility of the approach. The approach selected utilized the apparent fuel level fluctuations caused by fuel agitation during a ballistic penetration. The method of sensing the fuel level variations employed a standard capacitive fuel tank unit and discrimination circuitry sensitive to the pulse characteristics produced by a ballistic penetration.

Testing was conducted to investigate the signal produced on a UH-1B fluid level sensor during a ballistic penetration. Cal. 30 ball rounds were fired into a 2-foot self-sealing fuel cell containing the UH-1B tank unit. Parameters investigated in these preliminary tests included the fuel depth, the bullet velocity, the shot line offset distance, and the fuel flow restriction to and from the tank unit. The results achieved were consistent and show promise for this approach to the development of a hazardous condition indicator.

FOREWORD

The work for this project was conducted under Contract DAAJ02-70-C-0057 during the period 15 June 1970 to 15 November 1971. Technical direction for the project was provided by the following U. S. Army Air Mobility Research and Development Laboratory personnel: Mr. William Sickles, Chief, Safety and Survivability Division; Mr. James T. Robinson, head of Aircraft Vulnerability Section; Mr. Rocco Fama, Project Engineer; and Mr. Charles Pedriani.

The study was conducted by the Falcon Research and Development Company under the guidance of Mr. Charles E. Eppinger, President. Mr. George H. Custard served as Project Supervisor, and Mr. John K. Hobbs was the project engineer responsible for most of the technical work at Falcon Research. Other persons assisting in the project include Mr. James T. McFadden, Mr. Howard H. Iwata, Mr. Donald C. Saum, and Mrs. Kathleen A. Klemp.

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A. NEED FOR A HAZARDOUS CONDITION INDICATOR

The ballistic penetration of fuel tanks is a leading cause of aircraft combat losses due to ground fire. Yet a recent study* has shown conclusively that such penetrations must be accepted as a condition of light aircraft employment. An earlier study of the Ballistic Research Laboratories reached the same conclusion.** Thus, the type of hazardous condition indicator sought in this program would serve a vital need and could provide Army pilots with information needed to reduce both personnel and aircraft losses.

An indication of a first hit is particularly necessary, since many first hits do not cause fires even when the bullet is an incendiary type. The first hit invariably spills some fuel, and this spilled fuel greatly increases the fire hazards from subsequent impacts. The hazardous condition indicator could alert the pilot to the urgent need for reducing aircraft exposure to enemy fire. Timely knowledge of this increased hazard could be very useful in many situations where it is feasible to take alternative courses of action. Thus, the hazardous condition indicator is a logical new item of equipment for the increased survivability of combat aircraft.

B. ARMY AIRCRAFT FUEL AND OIL TANKS FOR PROTECTION

The Army aircraft to be considered in this study are the UH-1B, OH-6, and CH-47 helicopters. These three aircraft are shown in Figures 1, 2, and 3, which provide details of the fuel tank locations and configuration. Each of these aircraft has two separate but interconnected fuel tanks.

The tanks of the UH-1B hold approximately 120 gallons of JP-4 each and are of combined self-sealing and non-self-sealing

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*Custard, George H., "Study of Aircraft Fuel Protection Systems" (U), USAAVLABS Technical Report 66-15, April 1966, AD 373247 (SECRET).

**Harris, John C., and Bernier, Roland G., "Passive Defense for Aircraft Fuel Tanks" (U), BRL Memorandum Report No. 1159, AD 302156 (CONFIDENTIAL).

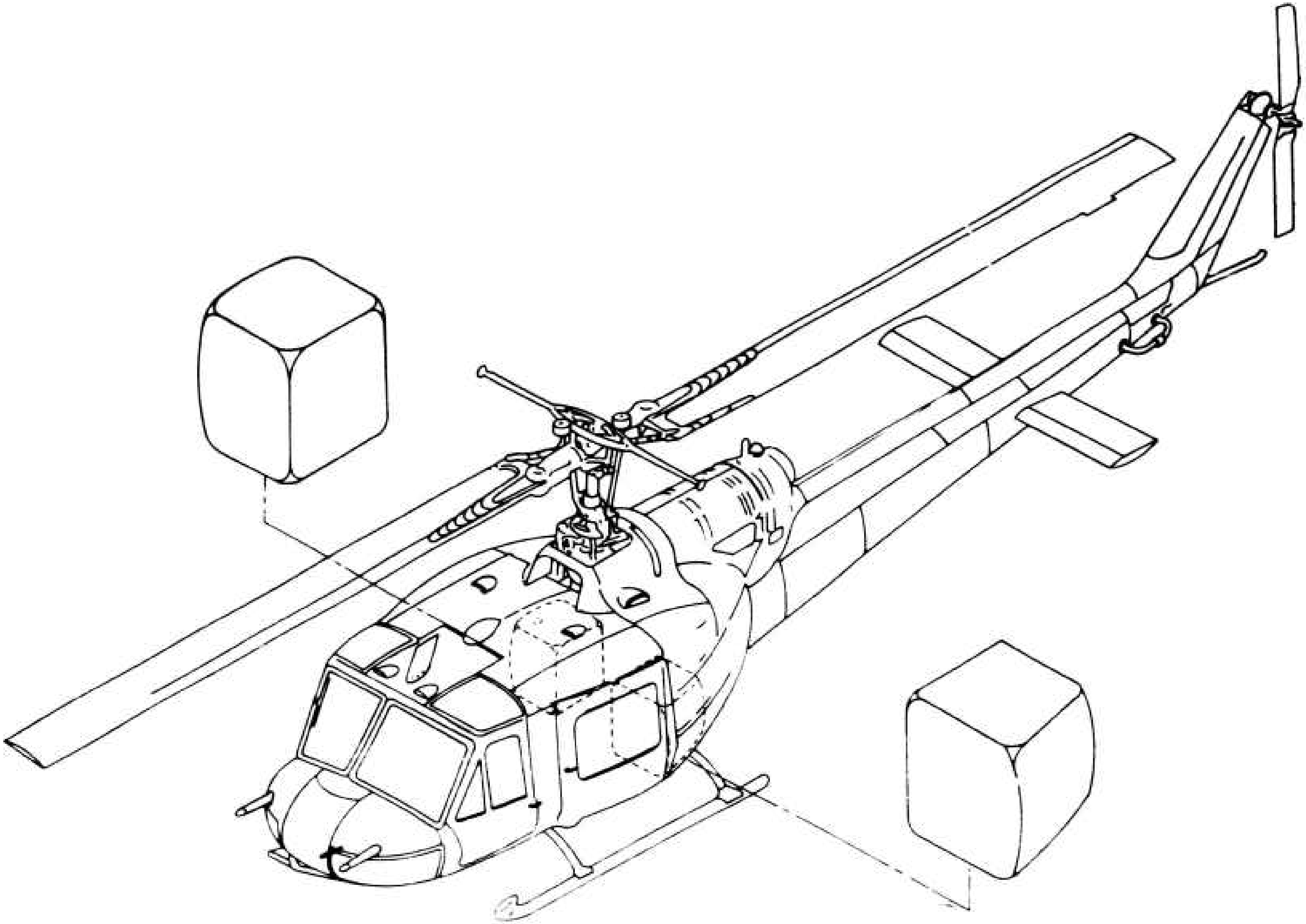

Figure 1. Fuel Tank Configuration and Location for the UH-1B Aircraft.

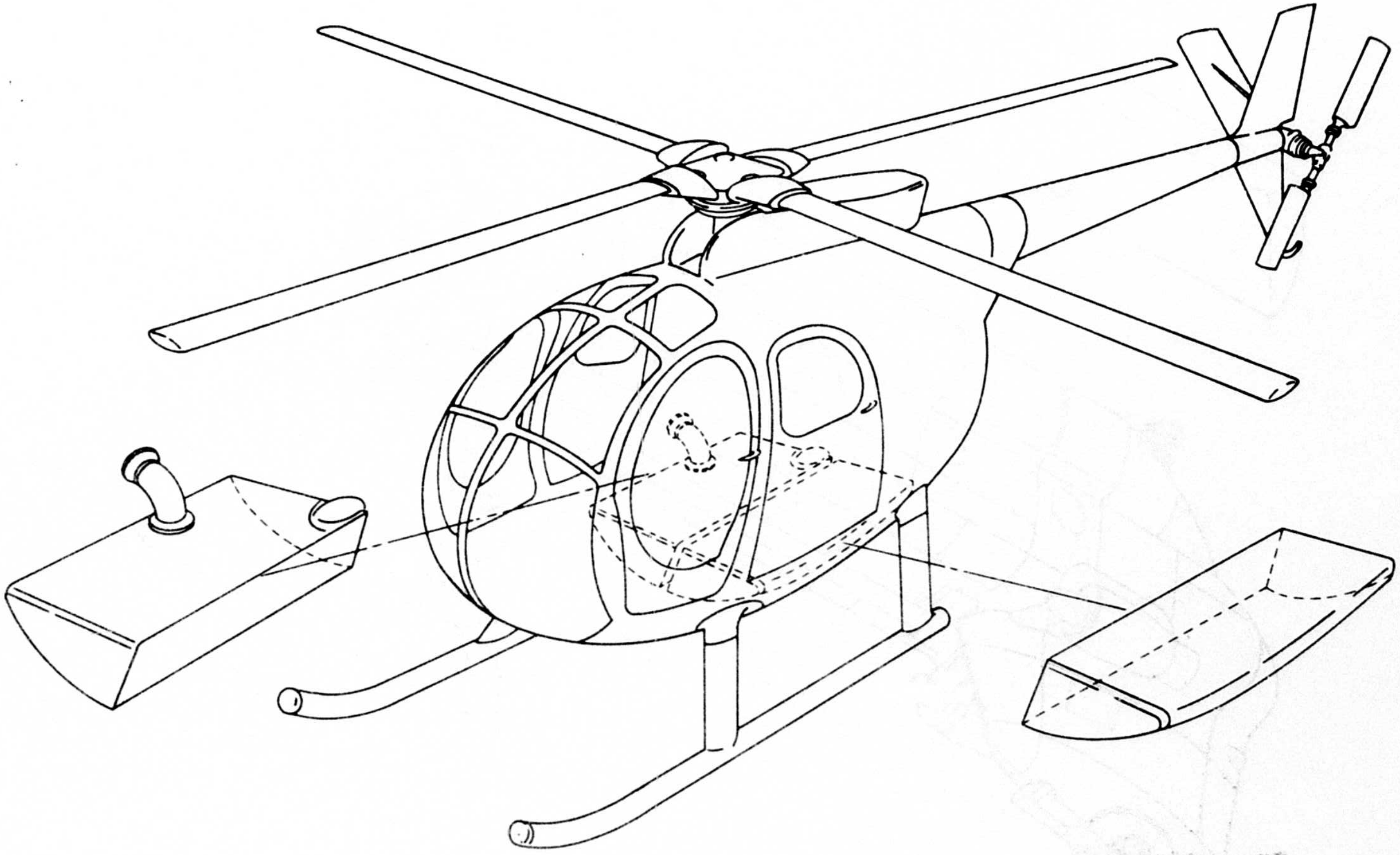

Figure 2. Fuel Tank Configuration and Location for the OH-6 Aircraft.

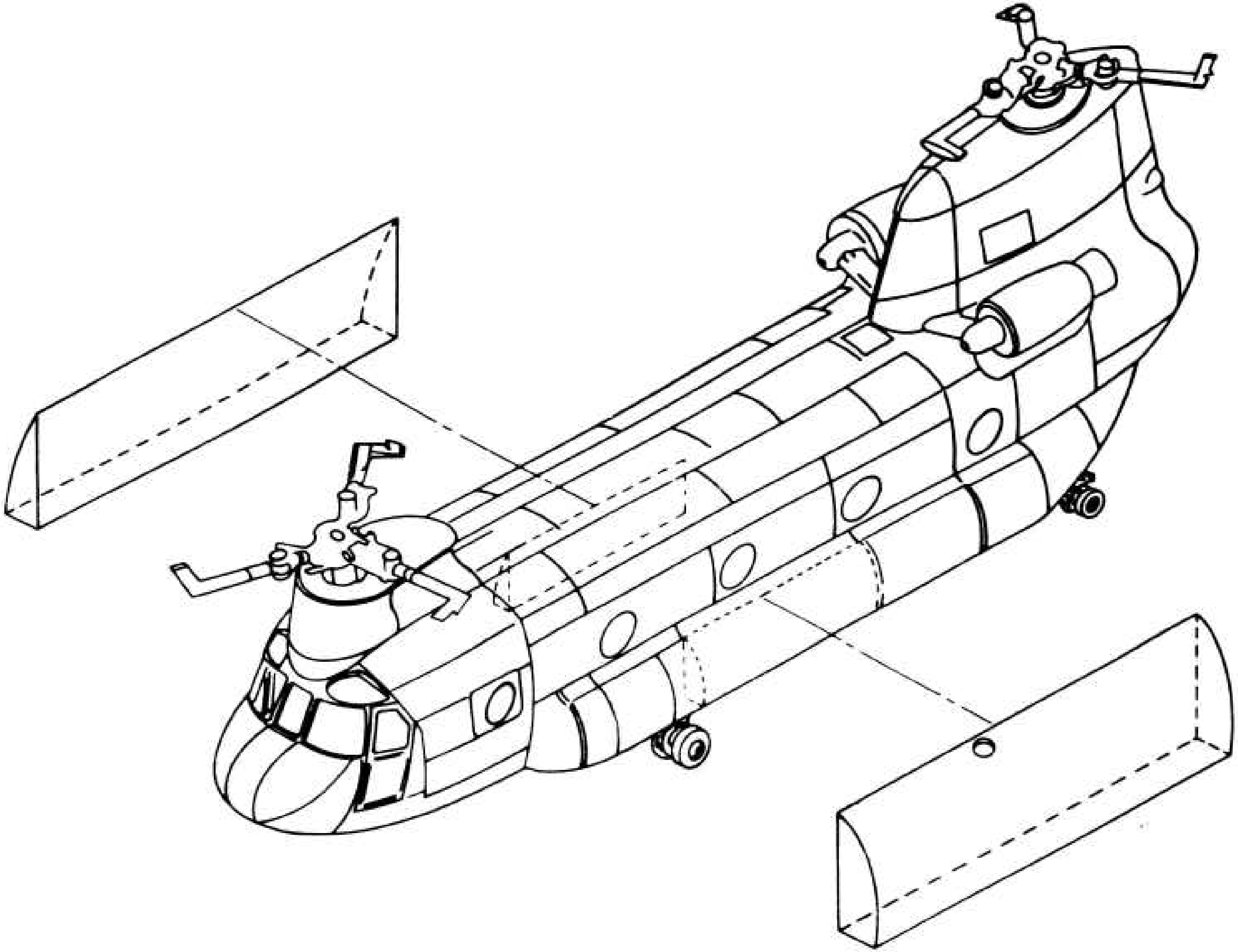

Figure 3. Fuel Tank Configuration and Location for the CH-47 Aircraft.

construction. The lower 60 percent of each tank is fabricated from a cal. 50 rated self-sealing material. Each tank provides approximately 39 square feet of surface area which may be perforated.

The tanks of the OH-6 hold approximately 33 gallons each and are very similar in construction to the tanks of the UH-1B. The lower 60 percent of the tank surface is again fabricated from a cal. 50 rated self-sealing material. These tanks provide approximately 19 square feet of surface area each.

The tanks of the CH-47 hold 315 gallons each and are again fabricated from a combination of materials. The lower half of these tanks is self-sealing, conforming to MIL-T-5578, while the upper half is non-self-sealing, conforming to MIL-T-6396. Each of these tanks provides nearly 100 square feet of surface area for ballistic perforation.

In each of these aircraft, the fuel tanks are behind and below the crew positions; thus the visual detection of a fuel leak would be unlikely unless the leakage rates were very high.

The oil reservoirs on these aircraft are very small by comparison with the fuel tanks but are vital to continued engine operation and are capable of producing fires. The oil reservoir on the UH-1B is of approximately 2 gallons capacity and is located on the right side of the aircraft near the engine. Oil reservoirs on the CH-47 are an integral part of the turbine engines. Fuel reservoirs are at the rear of these engines and contain approximately 3 gallons in each unit.

C. BALLISTIC THREATS FOR CONSIDERATION

All of these fuel and oil reservoirs can be readily perforated by bullets from any of the common types of combat small-arms weapons available throughout the world today. Further, hits on the self-sealing tank materials will prevent fuel loss only part of the time, since many types of combat hits will not fully seal even after several minutes of fuel leakage.

The ballistic threat against which the hazardous condition indicator must work will include shell fragments and a range of small-arms projectiles up to at least the 14.5 mm (cal. 60) size. In reality, any indicator capable of sensing the smaller projectiles will probably have nearly unlimited sensing ability on larger projectiles because their greater energy and greater mass would make them very "visible" no matter what sensing phenomenon was employed.

The 7.62 mm (cal. 30) ball projectile, or a bullet very similar to it, represents the most frequent threat to the fuel tanks of these helicopters. A typical cal. 30 bullet has a mass of 150 grains and a muzzle velocity of 2,750 ft/sec. This velocity falls to about 2,500 ft/sec at 100 yards range and to 2,100 ft/sec at 200 yards. The maximum useful range for such rounds is at the 300- to 500-yard distance, where velocity has fallen to 1,500 to 1,000 ft/sec. While hits can be achieved at substantially greater distances, the rounds become easily deflected by light structure and are much less likely to cause serious tank wounds.

The larger cal. 50 projectile weighs 700 grains, and the 14.5 mm weighs at least 1,000 grains. These bullets have excellent tank penetration capabilities to ranges of 1,000 yards and beyond because of their greater mass and greater kinetic energy.

D. KINETIC ENERGY EXCHANGE

The most obvious phenomenon associated with ballistic perforations of fuel tanks is a violent kinetic energy exchange between the high-velocity projectile and the stationary fluid mass. A bullet begins to lose its kinetic energy through an interaction with the cell contents immediately upon impact. Bullet impacts into the liquid-filled portion of the tank are the most common and the most hazardous. These perforations cause a violent agitation of the liquid, a sharp increase in pressure within the tank, and a substantial flexing of the entire tank structure. Strikes which pass through only the vapor space are less violent and generally less hazardous. This is true because of the lesser kinetic energy exchange with the lighter fluid (air) and because dangerous fuel leakage is improbable from such impacts. It is probable that perforations of the vapor space can be detected if required.

Bullet impacts into the liquid fuel are most probable because of the high frequency of ground-to-air small-arms fire. Since such interactions always provide at least some upward vector to the bullet and since gravity keeps the fuel in the lower portion of the tank, it becomes difficult to secure tank perforations from below which do not pass through some liquid fuel. Oil reservoirs tend to be nearly full under most conditions, and thus oil tank hits must be expected to be into the liquid for virtually all attack aspects.

It is clear that the kinetic energy associated with ballistic impacts is dramatic and has a characteristic time-pressure pattern, or "signature", which is unlike any other set of forces acting on the aircraft. While this energy exchange is not the only phenomenon associated with the tank perforation, it is the most obvious and has been used in the past to activate an impact sensor.

II. BALLISTIC PENETRATION PHENOMENA AND CANDIDATE APPROACHES TO THE HAZARDOUS CONDITION INDICATOR

The penetration of a fuel cell by a projectile produces several transient phenomena which can be sensed and uniquely determined to have originated from the penetration. These phenomena include, but are not limited to, shock waves (both in liquid and vapor), hydrodynamic pressure, a change in liquid level, or apparent change of fuel volume within the cell, and physical changes in the shape and size of the cell. Other transient phenomena which can be sensed include capacitive effects, inductive effects, and resistance changes associated with the penetrating object. The following sections discuss these phenomena and indicate the possible sensing elements, circuits, and devices which could respond to them.

A. MAGNETIC EFFECTS

When a metallic object passes through a magnetic field, the free electrons of the metal begin to orbit in a direction such that the resultant currents produce a magnetic field in opposition to the original field. This disturbance in the original magnetic field can be detected as a transient change in the magnitude of the driving current required for the established static field. While the magnitude of such effects is small, they can readily be detected and used to indicate the presence of a moving metal object such as a bullet. A magnetic field can conceivably be designed, through precise placement of the excitation coils, which will be largely confined to the interior of an aircraft fuel cell. One device which may be applicable to this sensing scheme is found in U.S. patent number 3,473,110, issued to J. T. Hardin et. al. and entitled "Electronic Conductor Detector and Indicator." The device detects the presence of conducting objects through the use of an electromagnetic sensor. The sensor is a coil wound on a ferromagnetic core and excited by an alternating voltage. The coil is in a resonant circuit whose impedance controls the amplitude of an oscillator. As a conducting object approaches the sensing coil, eddy currents are induced in the object and the resultant energy dissipation changes the inductance of the sensing coil which changes the impedance of the resonant circuit. The amplitude change of the oscillator voltage is then an indication of the proximity of the conducting object to the sensor. This device could be used as a ballistic penetration detector providing the sensing coil could be made sensitive enough to detect objects the size of bullets or shell fragments. The system would have to be designed such that the proximity of the conducting parts of the airplane would have no effect on the sensing coils, and the space seen by the sensing coil would be largely confined to the interior of the fuel cell so that a projectile passing near the cell but not penetrating it could be discriminated and not cause a hazardous condition alert.

A variation of the magnetic influence system can employ the earth's magnetic field as the static field and consider local transient forces produced by the high-velocity projectile as it passes near a sensor. Just as a ferrous metal object will cause a compass needle to deflect, a bullet can cause a more sensitive indicator to signal its presence. In detecting localized disturbances in the earth's magnetic field due to the projectile, a sensor similar in principle to a magnetic influence fuse for antitank mines may be applicable. Through a study of the literature, it has been found that magnetic influence fuses of this type, in general, employ a movable vane within a permanent magnet controlling system. When the fuse is in position, the controlling magnets align with the local earth's magnetic field, and the vane lags behind the movement of the magnet positioning system; thus it can close an electrical contact if the rotation of the positioning system is rapid and of sufficient magnitude.

The passing of a ferrous object locally disrupts the earth's magnetic field and causes the positioning system to rotate. When the local disturbance is sufficient, the vane makes electrical contact. The operation of a sensor of this type is greatly affected by characteristics of the object to be detected, such as speed and weight. For example, when the speed is too great, the positioning system will not respond rapidly enough to take full advantage of the disturbed magnetic field. When the speed is too low, the vane tends to move with the positioning system and not provide a switching action.

To use this type of device for detecting small, high-speed, ferrous objects such as bullets or shell fragments, major modifications would be needed. The most significant modification would require a great reduction in the mass of the positioning system to provide the increased rate or response necessary for the detection of high-speed objects. There is also a need for increased sensitivity because of the relatively small local disturbance to the earth's magnetic field produced by a small object such as a bullet.

These two factors alone tend to indicate that a magnetic influence sensor of this type, capable of detecting a passing bullet or shell fragment, would be an extremely delicate instrument and not entirely suitable for the environment of an aircraft fuel cell. The in-flight motion of the aircraft itself is a factor which would require elaborate compensation. Since the aircraft is mostly metallic materials and contains electric motors and some ferrous material, additional compensation of the sensor must be anticipated to balance these forces.

B. PRESSURE WAVE SYSTEMS

The best general description of the events taking place within a fuel cell which has experienced a ballistic penetration is given by a Douglas Aircraft Company report.* A brief summary of the hydraulic pressure effects (or the "hydraulic ram" effect) is given with reference to Figure 4, which is a pressure-time diagram taken from that report.

The impact shock occurs when the tank wall is first penetrated and is a pressure impulse of very large magnitude. The result is a shock wave which propagates outward from the point of the localized high pressure, but whose pressure attenuates rapidly with distance. Although the shock pressure is too weak to cause damage at the other tank walls, it may be of sufficient magnitude to cause damage to the wall near the impact point. Because the impact shock is of such short duration and its pressure attenuates greatly with distance, extremely sensitive and delicate instrumentation is needed to monitor its characteristics. The Stanford Research Institute has developed a piezoresistive pressure gage of ytterbium foil which has the sensitivity and response needed to measure the pressure and rise time of the impact shock. However, this device is so delicate that it is itself destroyed by the shock. For the purpose of indicating a ballistic penetration, the detection of the impact shock would probably be the most definite way of insuring that spurious pressure variations within the tank would not result in an indication. However, because of the

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*"Fuel Tank Vulnerability Reduction - Final Report," H. F. Winchester et. al., Report No. MDCJ-0044, Douglas Aircraft Co., April 1970.

delicate nature and probable cost of the equipment required, utilizing this phenomenon for the hazardous condition indicator does not appear to be the most feasible approach.

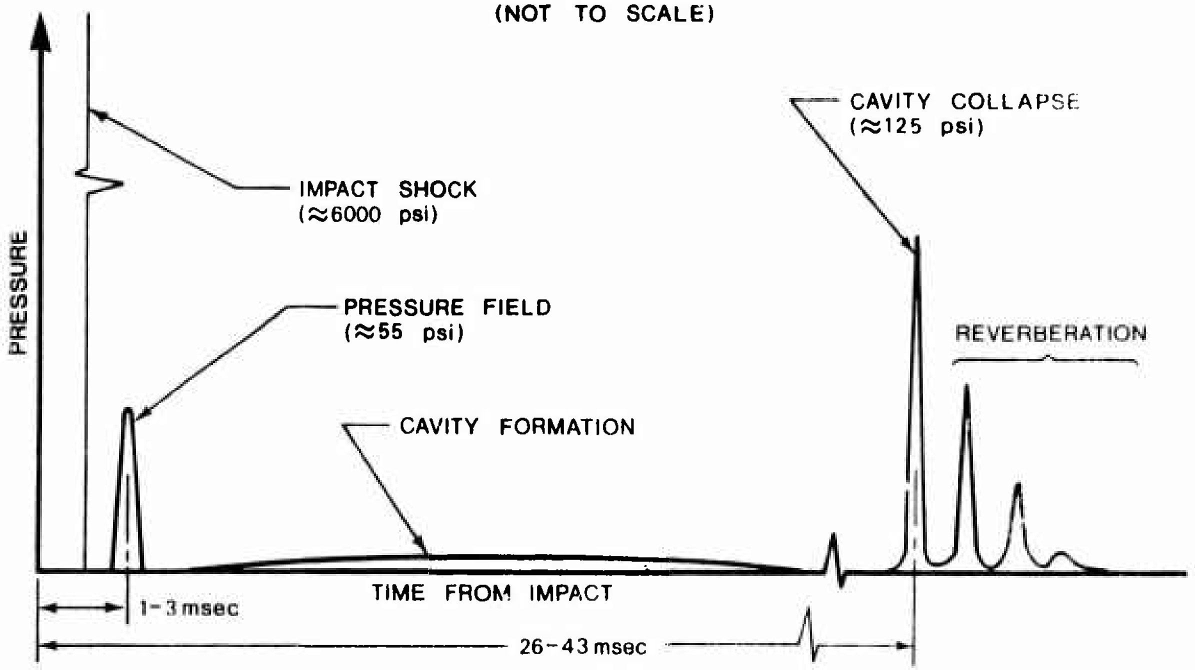

Figure 4. Pressure-Time Characteristics of the Fuel Within a 200-Gallon Fuel Cell Penetrated at the Center of One Wall by a Cal. 50 Bullet at Service Velocity.

The pressure field (refer to Figure 4) is the result of the movement of the projectile through the fluid, and the pressure at a given wall is dependent upon the projectile's distance from that wall. The experimentally measured values are for a projectile approximately 18 inches from a side wall. Equipment required for measuring a pressure pulse of this type is fairly simple and readily available, thus making this phenomenon a more likely candidate for use in a penetration indicator.

This pressure pulse may not be as unmistakably a result of a ballistic penetration as the impact shock, but it could possibly be used in conjunction with the cavity collapse pulse (to be discussed) in a system which requires, for example, an arming pulse followed by a trigger pulse within a fixed period of time for operation. Using this pressure pulse combination would reduce the probability of other fluid pressure variations simulating a ballistic penetration.

The cavity formation in the fluid is a relatively slow process, and the pressure at the tank walls is relatively low depending upon the size of the tank. The test tanks used by Douglas were 200 to 260 gallons in volume, resulting in the cavity formation characteristics as shown by the figure. However, initial tests conducted by the Stanford Research Institute with 1.5-foot by 1.5-foot tanks showed that the cavity formation was the cause of a catastrophic failure of the tank. Generally, it appears that the cavity formation phase will be suitable for use in the hazardous condition indicator only if its slower pressure rise time and the low magnitude of pressure for larger tanks can be distinguished from normally occurring tank forces.

The cavity collapse phase begins when the fluid pressure caused by the resistance of the tank walls to expansion becomes great enough to stop the cavity expansion. The cavity then collapses approximately radially, resulting in the generation of a high-pressure pulse which propagates outward radially. The pressure pulse at the wall is of the order of 100-200 psi with a width of approximately 500 microseconds. This pulse should be suitable to use alone to give an indication of a ballistic penetration, or as previously discussed, it can be used in conjunction with the pressure field pulse.

The data presented by the Douglas Aircraft Company for the hydraulic pressure effects associated with the ballistic penetration of a fuel cell is generally supported by the data presented in the report from the North American Rockwell Corporation* for similar experiments.

There exists a wide range of pressure sensing devices which would be applicable for the fuel cell hazardous condition indicator. In addition to numerous piezoelectric type transducers which would be suitable, the following U.S. patents describe devices employing different principles of operation. These devices can be used with the proper modifications as the sensor of a ballistic penetration.

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*"Survivable Fuel Tank Systems Selection Technique, R. & D. Design Handbook Report" (U), Vol. I, F. M. Cooper and W. A. Reinsch, Technical Report AFFDL-TR-70-43, North American Rockwell Corporation, March 1970.

1. No. 2,485,515, G. P. Sutton et. al., "Pressure Pickup"

This pressure sensor consists basically of a flexible diaphragm mounted in an insulating structure in close proximity to a stationary metal plate. The force of pressure on the diaphragm changes the spacing between the diaphragm and the stationary metal plate, thus changing the capacitance of the arrangement. The capacitance change results in a frequency change of an oscillator which is used to give an indication of the applied pressure. The device as described in the patent is compact and rugged and seems well suited to an aircraft environment. The diaphragm flexibility can be chosen to respond only to the pressure surge characteristics of a ballistic penetration.

2. No. 2,661,460, J. W. Matthews, "Transient Pressure Detector"

The device consists of a magnetic circuit whose air gaps are varied by the force of a pressure on a bellows. Connected to the bellows is the armature of the circuit which moves laterally as the bellows moves. The armature moves between two pole pieces which are cut at an angle off the axis of motion of the armature so that as the armature moves, one air gap will decrease as the other increases. Coils wound on the pole pieces are utilized in a measuring circuit which will give an indication of the pressure applied to the bellows by measuring the change in the air gap of the magnetic circuit. The pressure range can be varied by changing the initial separation of the pole pieces. This device would be fairly well suited to the aircraft environment because it could be made lightweight and rugged.

3. No. 3,455,165, P. Huet, "Pressure Sensitive Devices"

The basic pressure-sensing element described in this patent is a diaphragm coated with a thin layer of conducting material. As the diaphragm is deformed, the resistivity of the conducting layer changes, and this can be used to give an indication of the pressure applied to the diaphragm. In use, the diaphragm has conducting areas on both sides so that one surface experiences a compression while the other experiences an expansion with a deformation. This adds to the sensitivity of the device with the resistance elements placed in a bridge arrangement. The degree of unbalance in the bridge circuit is then proportional to the magnitude of force applied to the diaphragm. This device could be used to monitor the pressure inside an aircraft fuel cell either directly or through a mechanical linkage to another diaphragm-type pressure sensor mounted within the tank.

C. FLUID AGITATION AND CAPACITIVE EFFECTS

During the cavitation phase of a ballistic penetration, the surface of the liquid in the cell becomes violently agitated, with the apparent liquid level increasing roughly at the same rate as the cavity formation. This level change can be monitored for the purpose of giving a hazardous condition indication and can be separated from spurious level changes because the rate of cavity formation is fairly constant. The most convenient means of monitoring the fuel level in the fuel cell for the purpose of detecting a ballistic penetration is through the existing fuel quantity gage or at least through the sensor for such a fuel gage system. The level monitoring device is a capacitor which operates in the following manner.

A voltage applied to two plates which are separated by a nonconducting layer establishes a capacitance. The magnitude of the capacitance varies with several parameters, including plate area, properties of the separating medium, applied voltage, and distance between the plates. For the case of the capacitive fuel gage, the fuel and/or vapor of the fuel cell provides the separating medium. Thus, as the ratio of fuel to vapor changes within the tank and between the plates of the capacitor, the capacitance of the fuel gage changes. This change is sensed and used through calibrating circuitry to indicate fuel level.

An advantage for this type of indicating system is that the presently used capacitive fuel gage can be used as the primary sensor, with additions to the monitoring circuitry, to detect the unique properties of the ballistic penetration. It is believed possible to add this type of indicating system to the present fuel gage circuit without any change to the fuel level indicator. The present fuel level indicator uses a highly buffered or damped capacitive signal to prevent constant changes in the fuel level indication with sloshing of the fuel. The undamped signal must exist on the plates of the sensor and therefore must be potentially available for recognition. This type of capacitive response to ballistic penetration is particularly attractive from the standpoint of ease of retrofit installation and minimum dollar and weight costs for all installations.

Another effect on the capacitive fuel gage is the interaction of the actual cavity produced in the fuel by the ballistic penetration with the gage itself. If the path through the fuel cell of the penetrating particle is near the fuel gage, and if the cavity produced by the penetrating particle is large, the cavity (fuel vapor) will try to envelop the fuel gage. If this event occurs, "bubbles" of fuel vapor may be present between the plates of the capacitive fuel gage, and a resulting fuel level fluctuation will be indicated regardless of the condition of the surface of the fuel in the remainder of the fuel cell. The hazardous condition indicator circuitry can be made to accept such fuel level fluctuations as the indication of a ballistic penetration.

D. FUEL CELL DISTORTION EFFECTS

The fuel cell distortion resulting from the initial impact and penetration is a result largely of the high-pressure shock wave, and is localized in the area immediately surrounding the point of entry. The short-duration shock can transfer considerable outward momentum to the tank wall, causing relatively large localized distortion. The remaining tank walls are affected primarily by the fluid pressure rises accompanying the cavitation phase. These distortions can also be used as a basis for the indication of bullet entry through a variety of methods. Two of the most effective methods involve the use of strain gages and accelerometers probably mounted directly on the fuel cell walls. The acceleration rates and strain rates associated with ballistic perforations are high and thus can be used to discriminate this type of occurrence from other forces associated with aircraft operation. These types of sensors are inherently simple and the system, including circuitry, can be designed to discriminate effectively against extraneous signals.

Another approach to the detection of a fuel cell ballistic penetration is through sensors requiring the break or make of an electrical circuit. Sensors of this type are attractive because they are positive, simple, and require a minimum of associated circuitry. However, they are inherently "one-shot" devices and may be difficult to replace when a hit is recorded.

A ballistic penetration detector which requires an electrical closure (make-circuit) can be constructed by surrounding the fuel cell with conducting layers of foil separated by a thin layer of insulating material. Thus a ballistic penetration would at least momentarily cause an electrical connection between the conducting layers and result in a hazardous condition indication.

A detector requiring an electrical opening (break-circuit) can be constructed of a continuous loop of narrow conducting material covering essentially the entire surface area of the fuel cell. A ballistic penetration would then break this conductor and subsequently result in an indication.

Either the make or the break circuit can be mounted in one of several configurations. Of these configurations, two of the easiest and probably most economical would be to attach the circuit directly to the exterior of the cell, or to the fuel cell compartment backing boards. Other perhaps more costly means would involve including the circuits in the original construction of the fuel cell. One disadvantage of this approach would be the need of replacing the entire fuel cell after a single hit to maintain the integrity of the ballistic penetration warning system.

E. APPLICABILITY OF FLUIDIC APPROACH

Fluidic sensors would be primarily applicable for the detection of either a specific pressure level or a rate of pressure change of the fuel in the fuel cell. In either case, the sensor would have to be biased by a continuous flow; this might either be an air system, a JP-4 fuel system with feedback from the fuel pump, or a flowing oil system which would employ the high-pressure oil in the aircraft. Any of these approaches could sense pressure levels on the order of 50 to 300 psi or could be established as a differentiating system which would sense a high rate of change of pressure.

The fluidic approach appears attractive for the detection of the shock wave and resultant sharp rise in pressure within the fuel cell following ballistic penetration, assuming that a suitable fluidic pressure sensing device can be produced. This may be especially applicable to the UH-1B helicopter, which has been fitted for fluidic systems testing. The Aerospace Division of Honeywell Incorporated carried out a fluidic reliability program* for the U. S. Army Aviation Materiel Laboratories, wherein one fluidic control system was tested on the UH-1B helicopter under conditions simulating actual flights. The most applicable results of that program are summarized as follows:

1. There are no catastrophic failure modes inherent in fluidic systems.

2. Failures are not random as in electronics, but of a wear-out mode.

3. Environments do not increase the number of failures (other than those causing material damage).

4. The components and feasibility system performed as expected, in that they demonstrated a high reliability and tolerance for various grades of contaminated fluid.

5. There was no detectable material wearout trend.

These conclusions indicate that a fluidic system as applied to the hazardous condition indicator would exhibit a high degree of reliability and is highly compatible with the aircraft environment.

These general conclusions are supported by the work done independently at the Harry Diamond Laboratories on fluidic devices and systems.

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*Contract DAAJ02-67-6-0003, Honeywell, Inc., Aerospace Division, Minneapolis, Minnesota.

III. ENGINEERING ANALYSIS OF THE RECOMMENDED SYSTEMS

Two approaches to the hazardous condition indicator system were chosen from the four approaches discussed in Section II as being the most feasible for use in an aircraft warning system. The basis of this selection was an evaluation of the following aspects as applied to each of the four systems:

1. Potential reliability of the system.
2. System effectiveness.
3. System cost in dollar and weight units.
4. Ease of retrofit to existing aircraft.
5. Ease of new installations.
6. Maintenance requirements.
7. Multiple hit capability.
8. Preflight checkout capability.
9. Durability in an aircraft operating environment.

The rating system devised and applied to the evaluation indicated the best overall system to be the fuel level monitoring system and the second best to be the pressure sensing system.

The following is the evaluation of the four approaches utilizing the above engineering aspects.

A. POTENTIAL RELIABILITY OF THE SYSTEM

1. Pressure Sensing System

The nature of the pressure variations following the impact shock within a fuel cell which has experienced a ballistic penetration has been shown to be fairly constant for 0.30 and 0.50 cal. and 20 mm penetrators. The peak pressures achieved within the cell may be different for each projectile, but the rates of pressure rise and the period of the pressure oscillations are similar. Thus, for a pressure sensing system, good reliability can be achieved if the circuitry is to respond to a predetermined rate of pressure rise which is characteristic of the most common type of projectile. Further reliability of this system can be gained through the use of multiple input triggering circuitry which would depend upon a fixed sequence of pulses from the sensor corresponding to the pressure oscillations.

2. Liquid Level Monitoring System

The fuel level fluctuations following a ballistic penetration of the fuel cell are believed to be proportional to the pressure variations within the fuel, and they follow closely the oscillations of the pressure. The level monitoring device and circuitry will, in the same manner as the pressure sensing system, respond to a rate of level increase or series of level increases which is characteristic of the ballistic penetration. Thus, the fluid level monitoring system should be able to achieve good reliability in detecting a ballistic penetration.

3. Make or Break System

The reliability of the make or break system will depend upon the method of construction of the sensor circuit. For a make circuit, the separation of the conducting layers is important, in that the closer together the layers are, the greater is the probability of the penetrator's causing a connection between them. In practice, the conducting layers can be fabricated with a very thin insulating layer separating them, and the result will be good reliability for detection of a penetrating projectile. The method of construction is also important for the break circuit sensor. Good reliability is achieved for this system when the conducting strip is narrow enough to insure being completely broken when a projectile passes through, and the neighboring strips are close enough together on the fuel cell surface area to prevent a projectile from passing through without breaking the conductor.

4. Strain Gage or Accelerometer System

The reliability of the strain gage system will be determined by the percentage of the surface area of the fuel cell effectively seen by the strain gages. The sensors must be placed at locations on the fuel cell which are sufficiently close together to have overlapping boundaries within which the tank wall strain due to a ballistic penetration can be detected. The circuitry for this system will respond to a high rate of change of tank wall strain to allow for the change in shape of the tank as fuel is consumed. The accelerometer system will depend upon the acceleration experienced by the tank walls during ballistic penetration. For good dependability, the system must be adjusted to not respond to accelerations experienced by the aircraft itself but still well within the range of acceleration experienced by the tank wall due to penetration.

B. SYSTEM EFFECTIVENESS

1. Pressure Sensing System

The pressure sensing system will be effective with most forms of ballistic penetrators due to the similarity of the rate of pressure increase and pressure oscillations for any high-velocity particle passing through a fluid. The effectiveness of the system will decrease as the fuel level within the tank reaches a minimum due to the possibility of the sensor's being out of the fuel at times because of sloshing.

2. Liquid Level Monitoring System

The effectiveness of the level monitoring system has been judged approximately equal to that of the pressure sensing system because of the apparent dependence of the fluid level fluctuations on the internal pressure in the fuel cell. However, the effectiveness of this system may decrease when the fuel cell is completely full and there are no fuel level fluctuations to be monitored.

3. Make or Break System

The make or break system is subject to possible malfunctioning in cases where the fuel cell has been hit but not penetrated by a projectile. The resulting stress and motion of the tank wall can cause the conductor circuits to break or short, giving a false indication of a hazardous condition. Otherwise, the make or break system will be effective for all types of penetrators.

4. Strain Gage or Accelerometer System

The strain gage or accelerometer system suffers from the same problem as the make or break system by possibly allowing a false indication to be given when the tank is hit but not penetrated. However, with sufficient coverage of the fuel cell surface area, the strain gage or accelerometer system will respond effectively for all tank penetrators.

C. SYSTEM COST IN DOLLAR AND WEIGHT UNITS

The dollar cost of the electronics required for the signal processing and indicating system will be approximately constant regardless of the sensing method employed. All associated circuitry including cables, connectors, housings, etc., is estimated to cost $150 to $200 per unit for each system. The weight of the electronics is estimated to be no more than 20 to 25 pounds per unit for each system, and will be determined largely by the housing and mounting required for the indicator. The dollar cost of the various sensing arrangements is difficult to estimate accurately at this time, but the arrangements will be listed below according to their relative cost, including installation on or in a fuel cell, with the least expensive first and most expensive last:

1. Liquid Level Monitoring
2. Pressure Sensing
3. Strain Gage or Accelerometer
4. Make or Break Circuit

D. EASE OF RETROFIT TO EXISTING AIRCRAFT

1. Pressure Sensing System

The modifications required to install the pressure sensing system in existing aircraft are primarily changes in the fuel cell door. These changes consist of openings and bolt holes through which connections to the sensor mounting assembly can be made. Thus, only the fuel cell door need be removed and machined for installation of the pressure sensor.

2. Liquid Level Monitoring System

For this system no fuel cell modifications are required if the cell contains a fuel quantity sensor. This capacitive sensor can be utilized as the sensor for the hazardous condition indicator without hindering its operation as a fuel quantity sensor.

The only modifications required to retrofit the system to an existing aircraft are to tap into the fuel quantity indicator for the undamped fuel quantity sensor signal, which is further processed without affecting the fuel quantity indicator.

3. Make or Break System

Installation of the make or break system in an existing aircraft will require the complete removal of each fuel cell to be protected. The system must surround the vulnerable areas of the fuel cell (all sides except, perhaps, the top) and can be placed either on the fuel cell compartment backing boards or directly on the fuel cell itself. This will require little actual modification to the fuel cell or its compartment, but will result in considerable effort in the retrofit process.

4. Strain Gage or Accelerometer System

Installation of these systems in an existing aircraft will also require the complete removal of each fuel cell to be protected. However, the sensors must be mounted directly to the fuel cell walls through some means such as using a strong adhesive.

E. EASE OF NEW INSTALLATIONS

1. Pressure Sensing System

Since the only major modifications are made to the fuel cell door, a new pattern for the door can be made, resulting in the majority of the work being done when the fuel cell door is fabricated. Mounting of the sensor can be done when the fuel cell is assembled.

2. Liquid Level Monitoring System

A modification of the fuel quantity indicator is required in production which will make available a connection for the hazardous condition indicating circuitry. Thus, in new installations, no change of fuel cell assembly procedures will be required.

3. Make or Break System

The make or break system would be made an integral part of the fuel cell at the time of its fabrication. The fuel cell installation procedures would then remain the same.

4. Strain Gage or Accelerometer System

The requirements for the strain gage and accelerometer system are much the same as those for the make or break system, as this system can become an integral part of the tank at the time of its fabrication, thus requiring no special installation procedures.

F. MAINTENANCE REQUIREMENTS

The maintenance requirements for the electronics of any system are minimal, because it is anticipated that solid-state components with long lifetimes will be used. The maintenance of the various sensor systems will require that they be inspected for damage after the fuel cell has been penetrated, but under normal operating conditions no inspection will be required. The make or break system is the only one which must be replaced after a ballistic penetration, because it depends upon a short circuit which may be permanent and a break in the circuit which is permanent for operation. The other systems have a good probability of surviving a ballistic penetration.

G. MULTIPLE HIT CAPABILITIES

All sensor systems except the make or break system are capable of responding to second and subsequent penetrations, provided they do not take a direct hit from the penetrator or are damaged due to extreme distortions of the fuel cell during ballistic penetration.

H. PREFLIGHT CHECK-OUT CAPABILITY

An optimum preflight check-out of the hazardous condition indicator might involve a simulation of a fuel cell ballistic penetration. This may be rather difficult and impractical in an operating aircraft. As an alternative, a signal injected into the indicating circuitry which duplicates the signal expected from the sensor during a ballistic penetration could provide system check-out. The sensor can also be checked for static continuity, but this is not a true test of dynamic response capability except for the case of the make or break system. It must be assumed that the other sensor systems are operable if they pass the static preflight check-out through a signal simulation procedure.

I. DURABILITY OF SYSTEM IN AIRCRAFT ENVIRONMENT

In an operating aircraft environment, each system can be made to withstand the abuse to the same degree required by all other systems of the aircraft.

Based on the above discussion of the relative merits of each proposed hazardous condition indicator approach, a rating system has been developed to give an immediate comparison of all approaches. Within this simple system, the highest number for each category A through I represents the best quality, and the highest overall number represents the best indicator approach. The system contains the numbers 1, 2, 3 and 4 with their connotations as follows:

4: Good, low cost, light, etc.
3: Fair
2: Poor
1: Bad, high cost, heavy, etc.

Inspection of Table I shows that the level monitoring and pressure sensing systems rate the highest of the four systems. These two systems are recommended as being the most promising for design and analysis of installation in the UH-1B, OH-6A, and CH-47 helicopters.

TABLE I. COMPARISON OF THE FOUR APPROACHES TO THE HAZARDOUS CONDITION INDICATOR SYSTEM

Systems	Engineering Aspects									
	A	B	C	D	E	F	G	H	I	Total*
Pressure Sensing	4	4	3	3	4	4	4	3	4	33
Level Monitoring	4	4	4	4	4	4	4	3	4	35
Make or Break	4	3	1	1	3	2	1	4	4	23
Strain Gage or Accelerometer	4	3	2	1	3	4	3	3	4	27

*The highest total score indicates the best overall system.

IV. SYSTEM DESIGNS FOR THE UH-1B HELICOPTER

The pressure sensing system and the fuel level monitoring systems have been designed for operation in the UH-1B helicopter. The designs of the two systems incorporate basically the same signal processing and alarm circuitry, and differ somewhat in actual sensor mounting and requirements of connection to the aircraft's existing electrical circuitry. The design of each sensor includes the following two phases:

1. Detail description of sensor mounting within each fuel cell of the aircraft (if required).

2. Detail description of means of tapping into existing aircraft electrical circuitry.

A third design phase includes a detail description of the complete hazardous condition indicator circuitry, including power requirements.

A. PRESSURE SENSING SYSTEM

The block diagram of Figure 5 shows the components of the pressure sensing system. A pressure sensor of the strain gage type is mounted in both the left and right side fuel cells. The sensor is a resistor which varies with the pressure of the surrounding medium and forms one arm of a resistance bridge such that the output voltage of the bridge is proportional to the pressure. The bridge output from each fuel tank is fed into a mixing circuit whose function is simply to sum the voltages prior to amplification. The amplifier stage has a large bandwidth to minimize distortion of the voltage pulse expected from the sensor during a ballistic penetration, and a gain to be compatible with the aircraft's existing 28V DC power system. The amplified sensor signal is then fed to the discriminating circuitry, which is similar for the pressure sensing system and the liquid level monitoring system. The function of this stage is to separate the signal which is characteristic of a ballistic penetration of the fuel cell from the continuous signal variations due to in-flight agitations of the fuel which result in minor pressure variations. A discussion of the operation of the signal processing and alarm circuitry follows in Part C of this section.

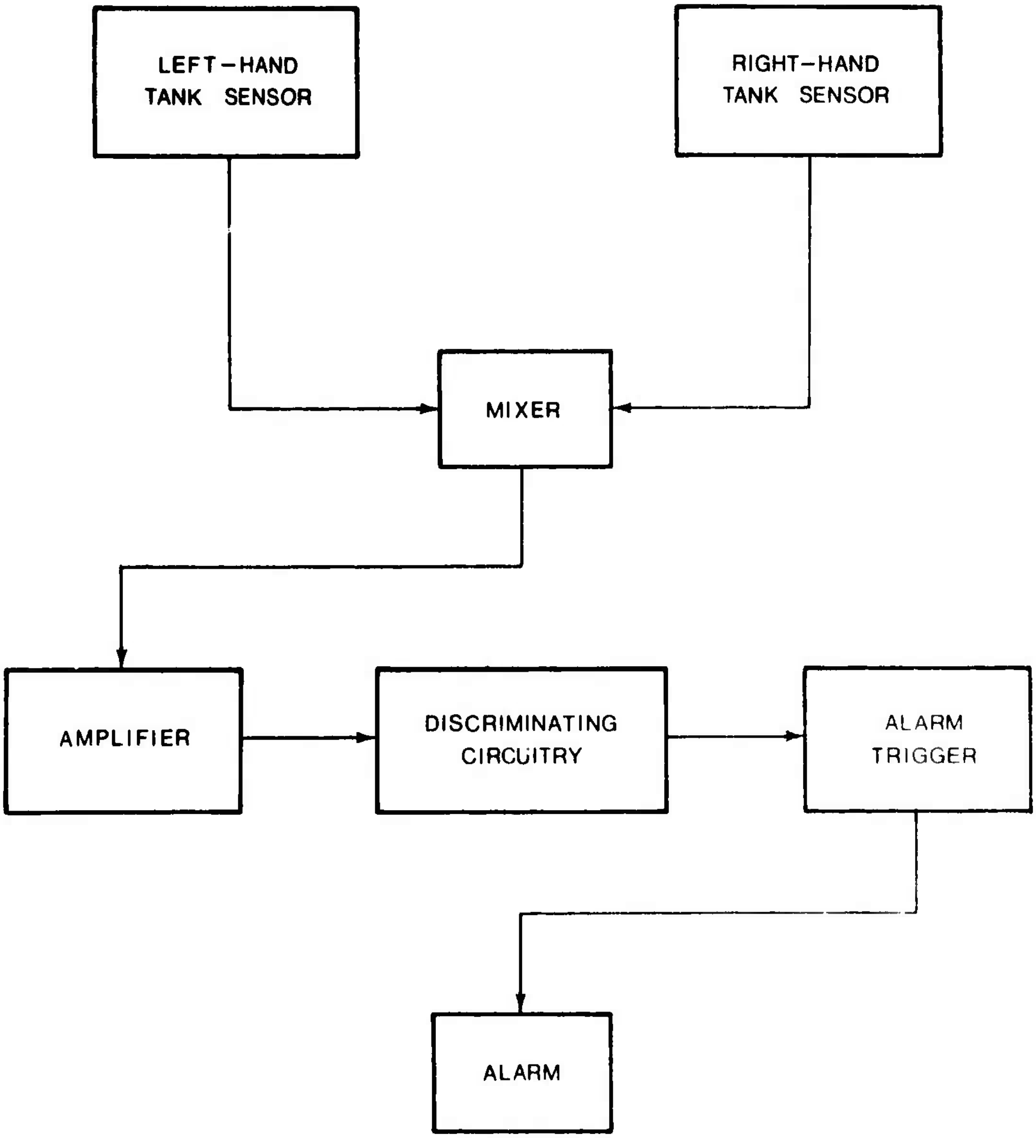


Figure 5. Block Diagram of Pressure Sensing Approach to the Hazardous Condition Indicator.

The pressure sensor is mounted in the fuel cell at approximately the level of the low fuel level warning switch. This location allows the sensor to remain submerged in the fuel as long as it is practically possible. To facilitate the pressure sensor mounting in existing fuel cells, the bracket (shown in Figure 6) is constructed so as to mate with the existing flange of the upper crossover assembly at its entry to each of the two fuel cells (refer to the sketch of the UH-1B fuel system in Figure 7). This bracket bolts between the modified crossover flange and the fuel cell and has support arms which extend through the fuel cell opening into the interior of the cell for the sensor mounting. For new fuel cell installations, a special opening can be fabricated in the new fuel cell in a location adjacent to the crossover assembly opening to accept a sensor mounting similar to that of Figure 6.

The pressure sensor itself is a sealed unit, and its cable is brought through the tank interior to the fuel cell access door, where it is terminated at a hermetically sealed bulkhead connector (see Figure 8). Connection is then made from this point to the first stage of the pressure sensing circuitry through a shielded cable. The first stage of the circuitry is shown in Figure 9 and requires only transducer excitation and amplifier power. However, the pressure sensing circuitry and sensor are powered from a self-contained power supply which produces the various DC voltages required. This power supply requires 115V AC, 400-cycle, single-phase power at a current of a few amps from the aircraft's main electrical system. No other electrical connections to or inputs from the aircraft's circuitry are required by the pressure sensing concept.

B. LIQUID LEVEL MONITORING SYSTEM

The basic concept of the liquid level monitoring approach to the hazardous condition indicator is to use the existing fuel quantity indicator tank unit of each tank as the sensor for a ballistic penetration. When a tank is experiencing a ballistic penetration, the fuel level will momentarily increase and thus the fuel quantity indicator tank unit voltage will change at the rate to which the alarm circuitry has been set to respond.

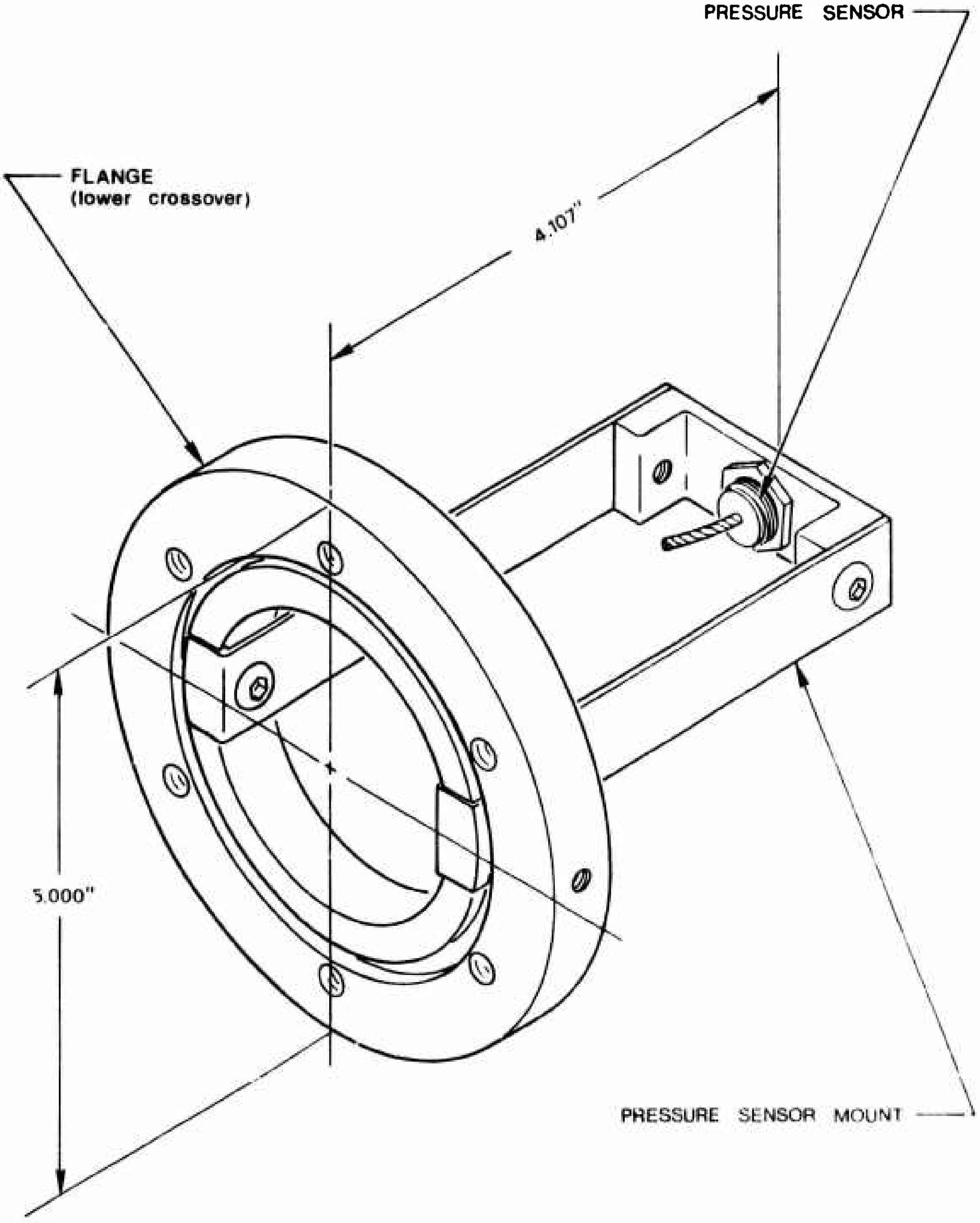


Figure 6. Hazardous Condition Indicator Pressure Sensor Mount, UH-1B.

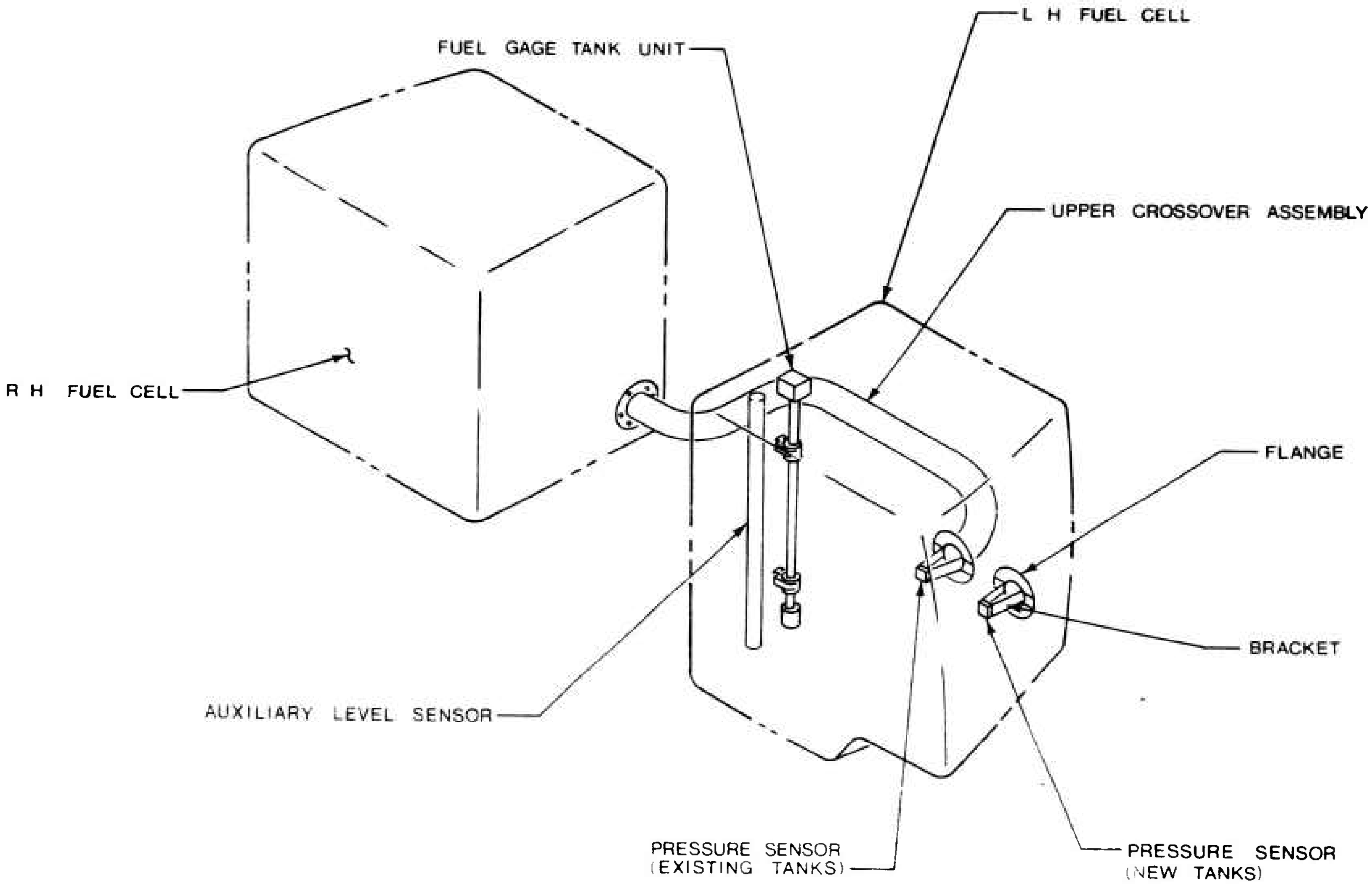


Figure 7. Location of Hazardous Condition Indicator Sensors, UH-1B Fuel System.

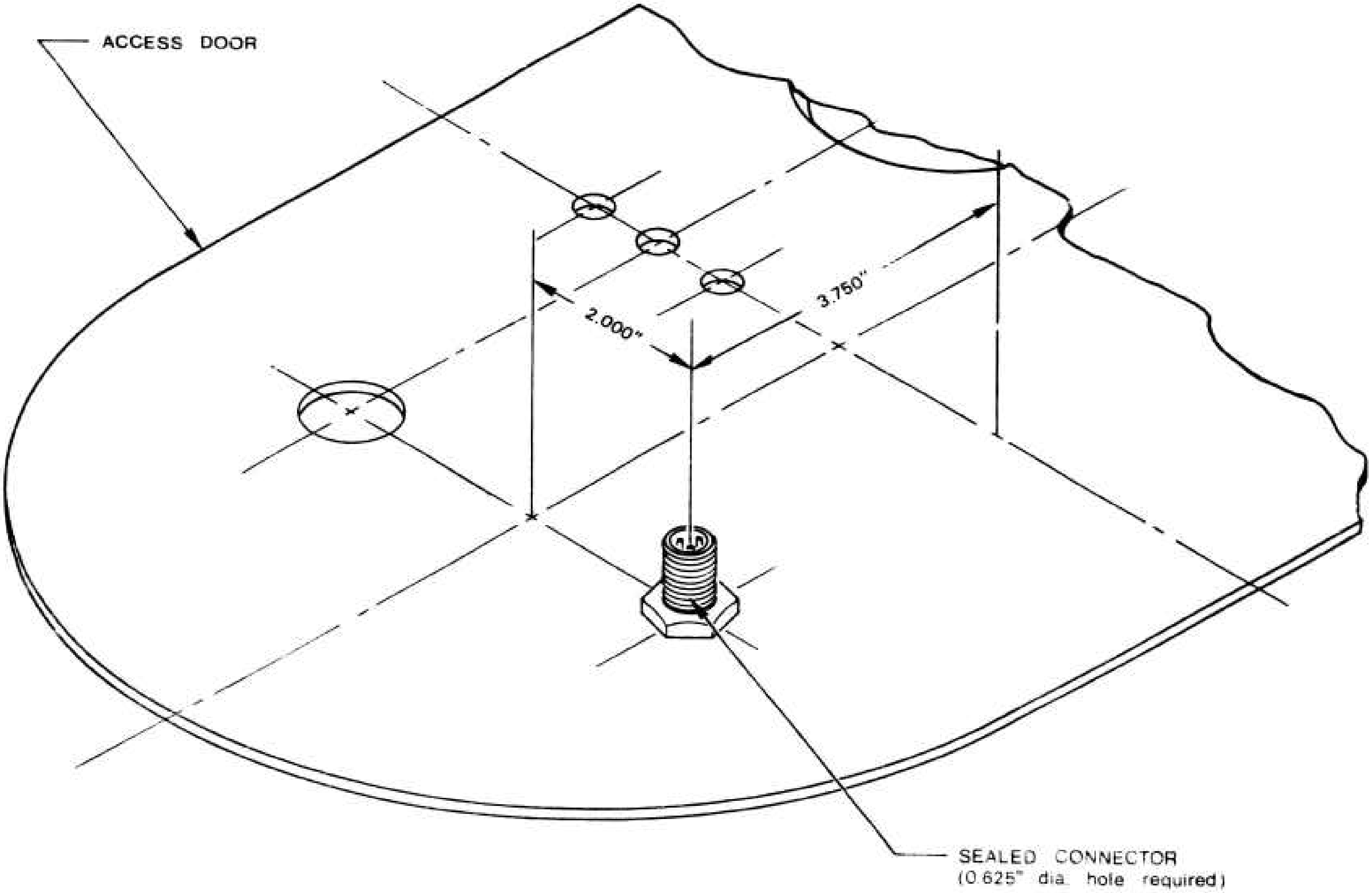


Figure 8. UH-1B Fuel Cell Access Door, Showing Location of Bulkhead Connector Required for Pressure Sensing System.

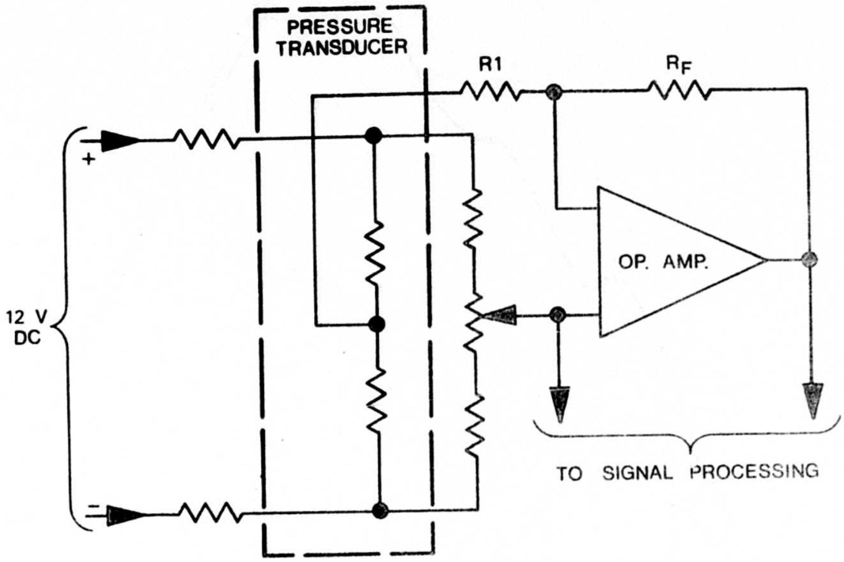


Figure 9. First State of Amplification for the Hazardous Condition Indicator Pressure Sensing Unit.

Figure 10 shows a block diagram of the fuel level monitoring approach. The fuel quantity indicating system tank units consist of concentric cylinder capacitors which are divided into shielded and unshielded components for each fuel cell. External to the two fuel cells of the UH-1B aircraft, the shielded components are electrically combined and the unshielded components are electrically combined to effectively place the capacitive tank units in parallel.

The signal from this parallel combination is fed through the junction box to the fuel level monitor sensing unit of the hazardous condition indicator shown in Figure 11. The sensing unit consists of a high input impedance amplifier and the first state of signal processing. The combination of D1, C1 and R2 forms an envelope detector whose output is a DC voltage with an amplitude varying as the change in signal from the fuel quantity indicator tank unit. Thus, when the fuel cell experiences a ballistic penetration, this DC voltage will undergo a rapid amplitude change. This signal is then sent to the signal processing and alarm circuit.

The hazardous condition indicator junction box of Figure 12 shows the connections to the existing aircraft circuitry necessary for operation of the hazardous condition indicator. The

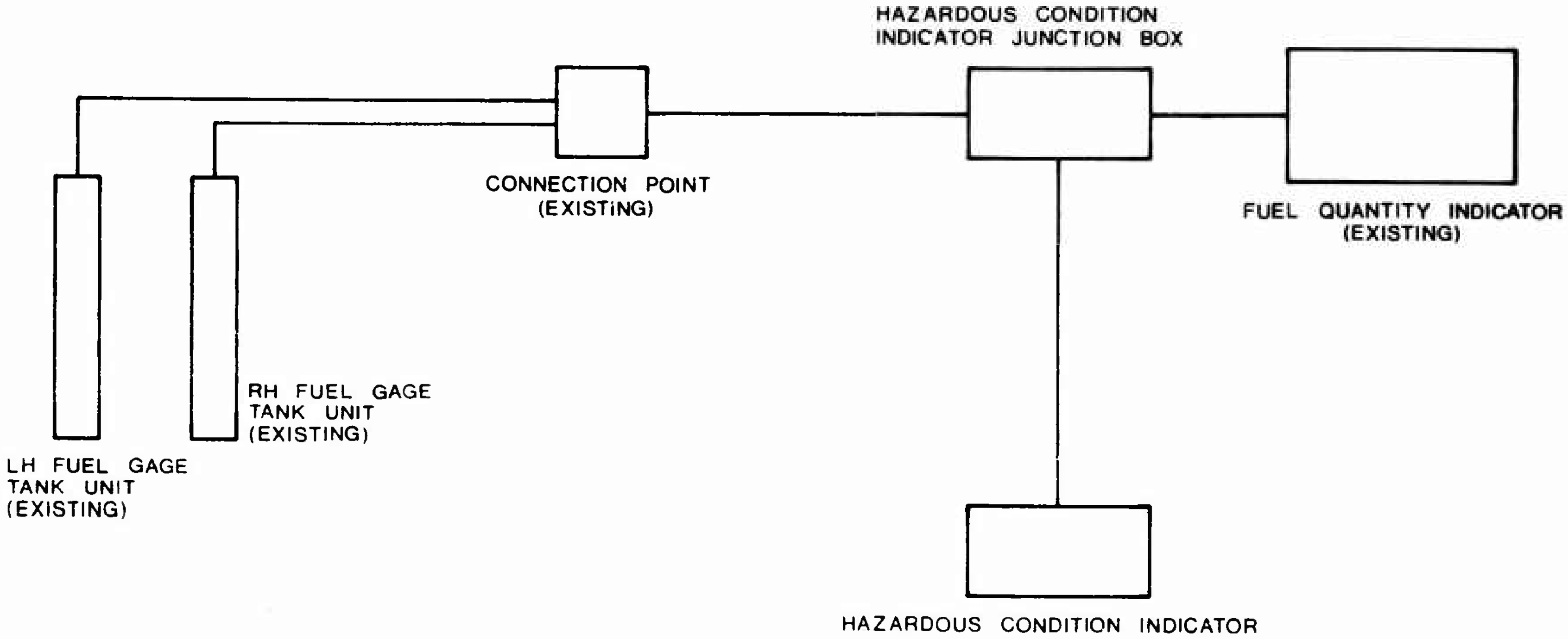


Figure 10. Block Diagram of Hazardous Condition Indicator System Utilizing the Existing Capacitive Fuel Quantity Indicating System of the UH-1B Helicopter.

junction box as shown is simply inserted between the fuel quantity indicator and its present connector and serves as a "T" to bring electrical connections to the hazardous condition indicator. Referring to Figure 12, the connection to pin H and the coaxial cable form the sensor input, which is the combination of the right and left tank unit unshielded components and shielded components respectively. Connections to pins B and J supply the 115V AC, 400-cycle power for the alarm circuitry. Physically, the junction box attaches directly to the fuel quantity indicator connector at one end. The connector for the hazardous condition indicator cable is on one side.

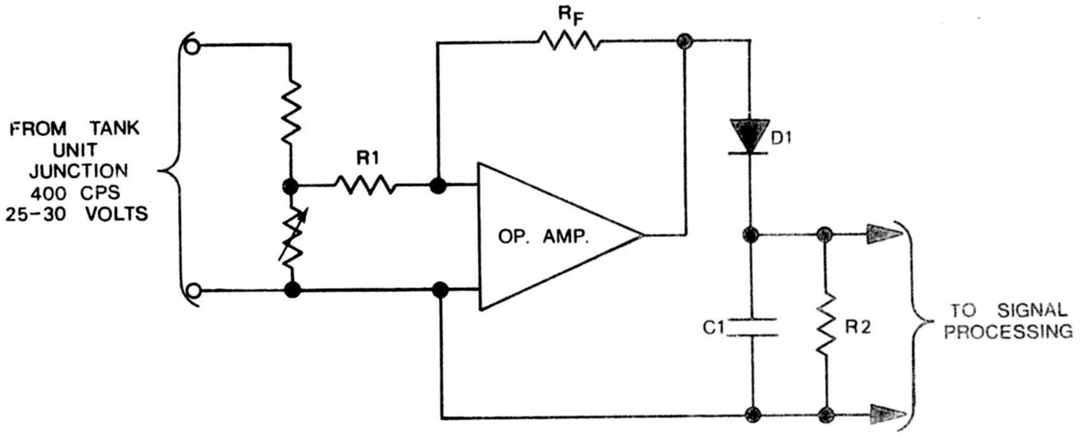


Figure 11. First State of Amplification for the Hazardous Condition Indicator Liquid Level Monitor Sensing Unit.

The present design of this concept calls for the incorporation of the fuel quantity indicator tank unit without modification to either the tank unit or the fuel cell. However, if future testing of the system shows that the tank unit is unsuitable for the hazardous condition indicator, then an auxiliary sensor will be installed. The auxiliary sensor is identical in size, shape and mounting to the fuel quantity indicator tank unit, but it has a response time adequate to respond to the fuel level change of a ballistic penetration. Electrical connection to the auxiliary sensor is made in the same manner as that of the pressure sensor (through an insulated, sealed, feed-through connector on the fuel cell door), and no electrical connections to the aircraft's existing fuel quantity indicating circuitry are needed. The only electrical input required for this case is that of the power supply power from the main electrical system.

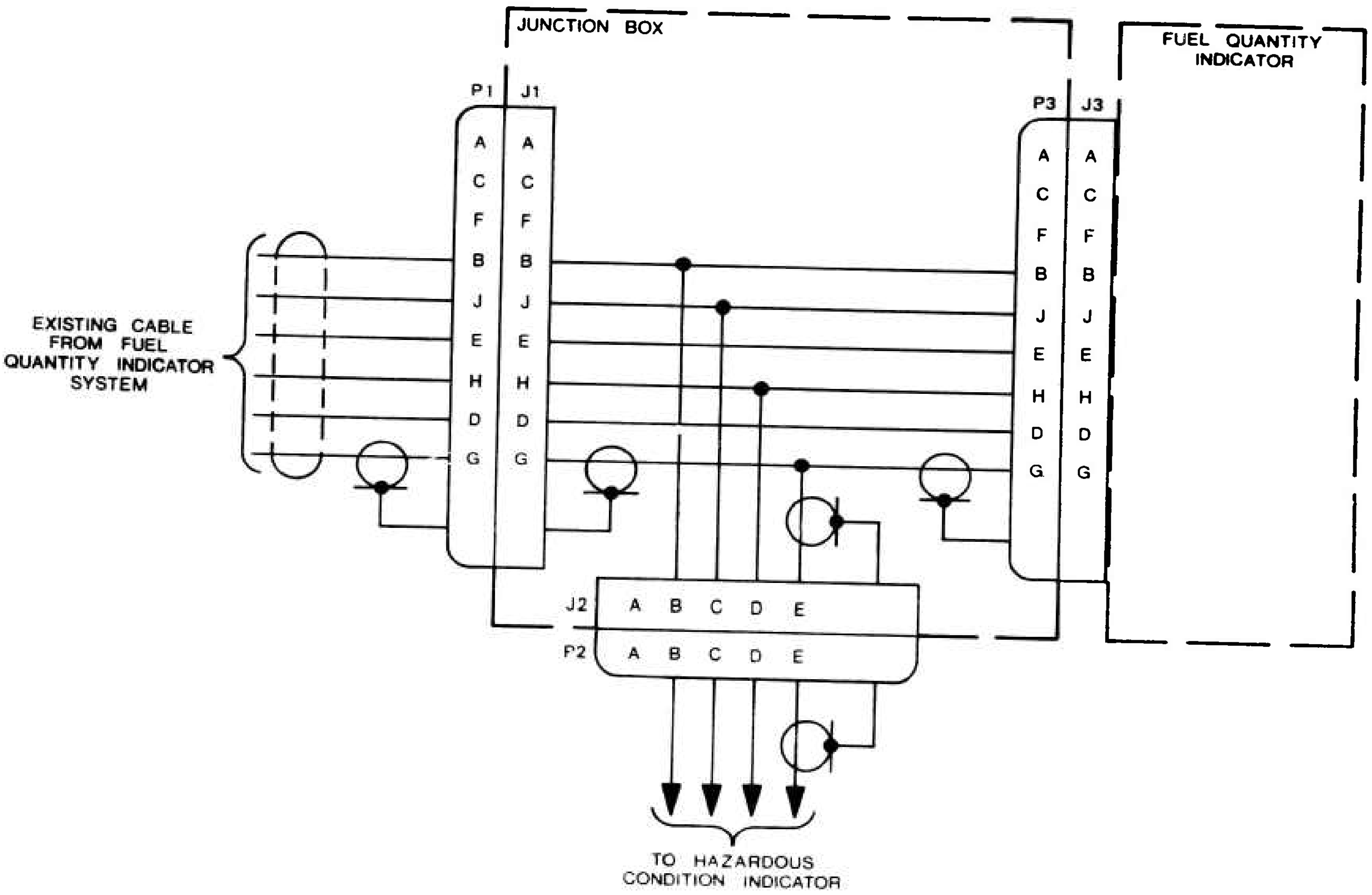


Figure 12. Hazardous Condition Indicator Junction Box, Liquid Level Monitoring System, UH-1B.

Referring to Figure 13, the UH-1B fuel cells are shown approximately as they appear in the aircraft, and the fuel gage tank units are shown in their approximate locations within each fuel cell. The signal cable from each fuel gage tank unit is brought to the connection point, where the capacitive elements of the tank units are combined, in parallel, to yield a single signal as an indication of the total amount of fuel within the two fuel cells. The cable from the connection point then normally goes to the fuel quantity indicator in the cockpit. It is between the connection point and the fuel quantity indicator that the hazardous condition indicator junction box is installed.

C. SIGNAL PROCESSING AND ALARM CIRCUITRY

The signal processing and alarm circuits are the same regardless of the sensor used to supply the triggering signal. Either the pressure sensing circuit of Figure 9 or the level monitoring circuit of Figure 11 can supply the input for the signal processing circuit of Figure 14, as they will both supply similar signals during a ballistic penetration of the aircraft's fuel cell(s). The signal processing circuit is essentially a discriminator which is designed to give a response to a pulse of a predetermined rise time, amplitude and duration, and ignore all other pulses or signal variations. The operation of the circuitry is briefly as follows:

The input stage of the signal processing circuit formed by R1, C1 and C2 (see Figure 14) is a differentiating circuit which determines the rate of rise of voltage from the sensing units to which the alarm will respond. The differentiating circuit along with the Schmidt trigger formed by transistors Q1 and Q2 eliminates the possibility of extraneous signals activating the alarm by being "tuned" to the rise time associated with a ballistic penetration of a fuel cell. Thus, when the DC voltage level of either sensing unit changes at the proper rate, the Schmidt trigger activates SCR1 which in turn activates relay K1. This relay supplies voltage to the oscillating alarm circuit with the audible and visual indicators as shown, and provides a short circuit across SCR1 so that it can return to a nonconducting state when the gate signal is removed. This action allows for the reception of subsequent fuel cell penetration signals once the acknowledge switch has been depressed; this switch deactivates the relay and turns off the alarm.

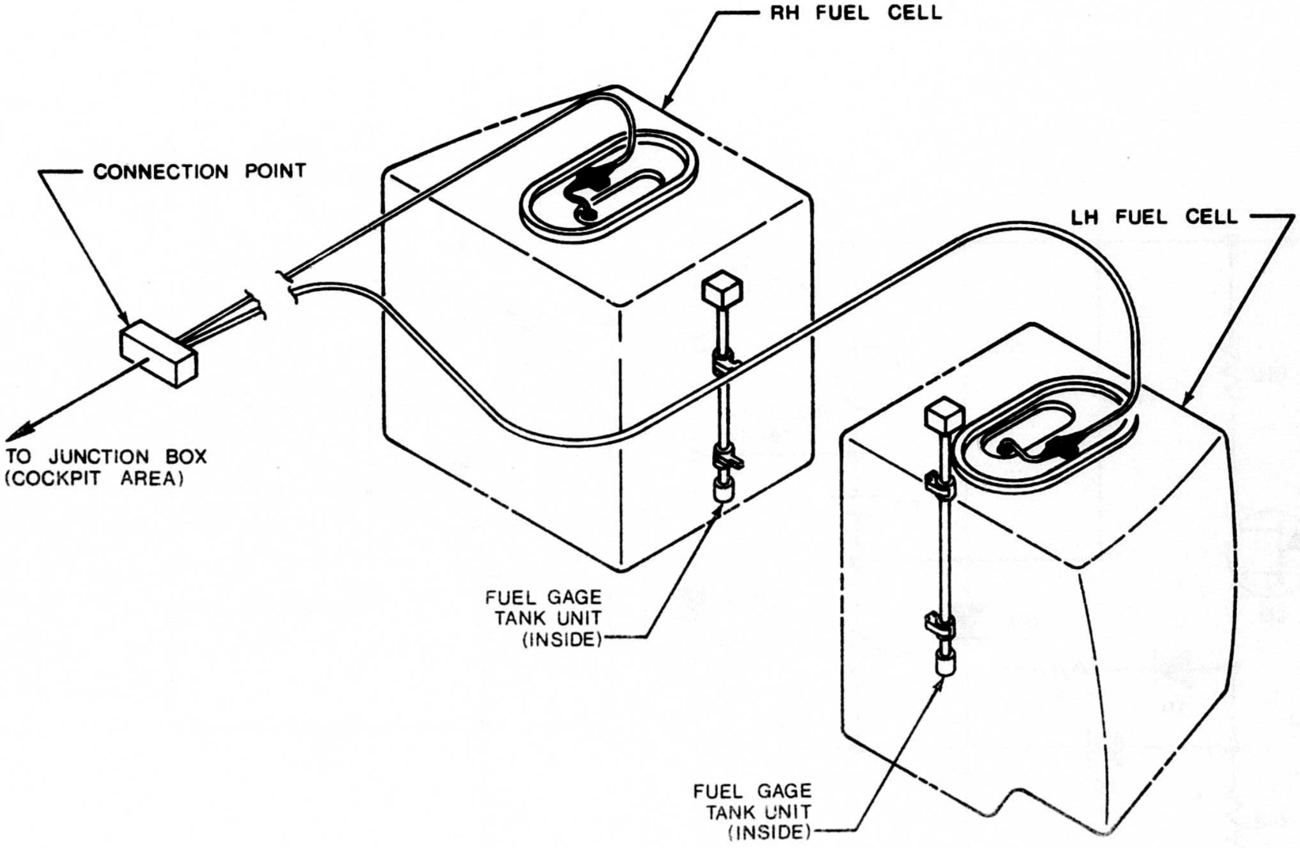


Figure 13. UH-1B Fuel Cells, Showing Location of Existing Capacitive Fuel Level Indicator Tank Units, Which Are Also To Be Used for the Hazardous Condition Indicator Sensors.

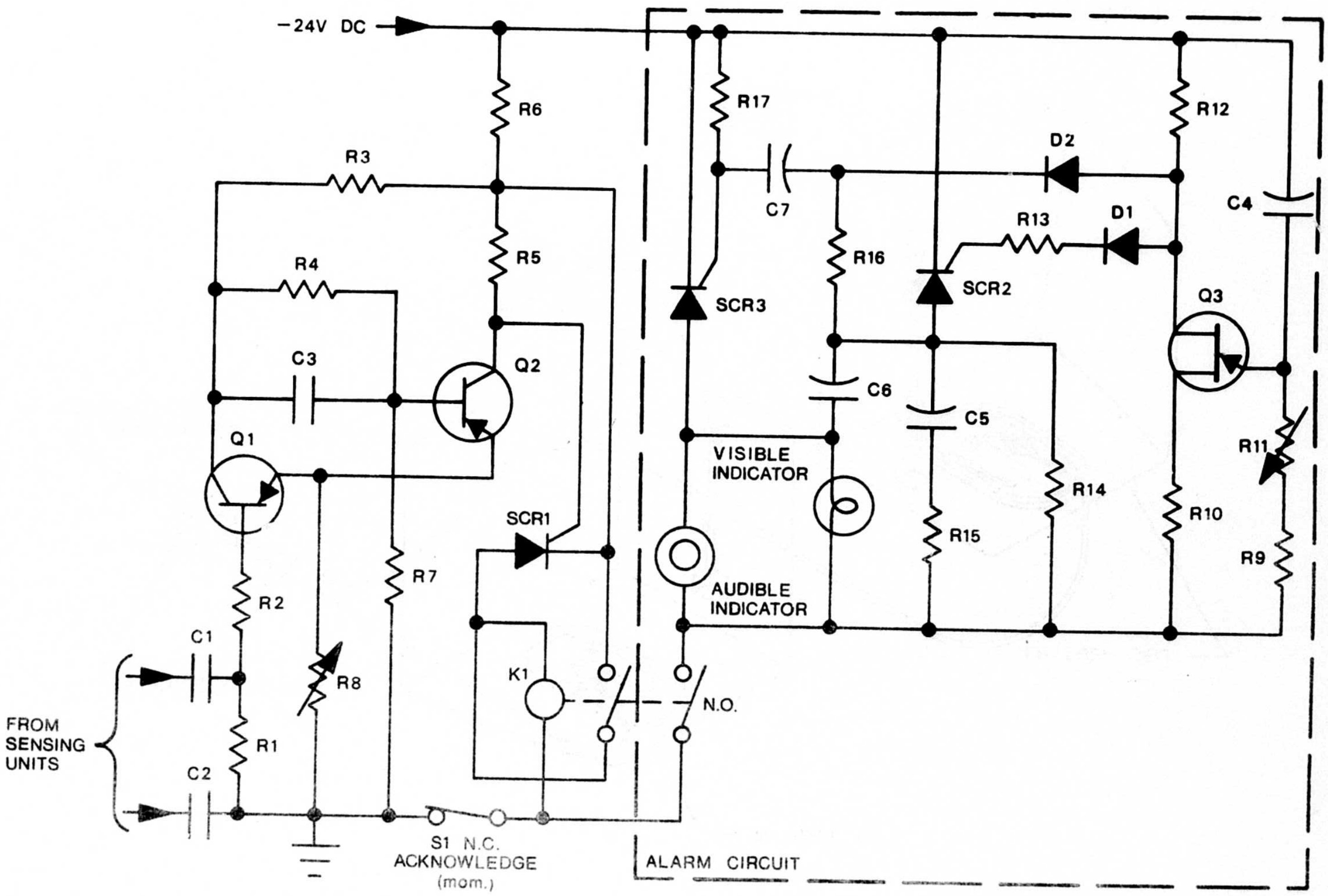


Figure 14. Hazardous Condition Indicator Signal Processing and Alarm Circuitry.

The alarm, when activated, will emit a slowly oscillating (1-2 cycles per second) audible and visible signal and remain in operation until an acknowledge switch is operated by the aircraft personnel. The acknowledge switch will return the alarm circuitry to the state where it is ready for reactivation by another signal to the alarm trigger.

Referring to Figure 15, the hazardous condition indicator power supply requires an input of 115V AC, 400 cycle, single phase at a current of approximately .5 ampere. For the fluid level monitoring system, the main power is supplied directly through the junction box, and the circuit breaker protecting the fuel quantity indicating circuit is increased from 1 ampere capacity to 2 amperes. The pressure sensing system requires power from the main AC buss with 1 ampere protection. The integrated circuit supply is required by the high input impedance amplifier of the sensing unit for either the level monitoring or pressure sensing approach, and the -24V DC supply is required by the signal processing and alarm circuitry. The isolated 12V DC supply is required for the bridge excitation voltage only by the pressure sensing system.

Figure 16 shows the general layout and approximate dimensions of the box containing the hazardous condition indicator circuitry and alarm which is to be located in the cockpit at a location visible to the pilot. This box has on its front face the hazardous condition indicator light and the audible indicator, which are the parts of the alarm circuitry used to alert the aircraft crew to a ballistic penetration of a fuel cell. The acknowledge switch allows the crew to turn off the alarm and reset the indicator for registration of possible subsequent ballistic penetrations. The other visible items on the box are a power-on indicator light, which is illuminated when power is supplied to the hazardous condition indicator circuitry, and a test switch, which simulates a ballistic penetration to test the indicator circuitry. Operation of the test switch would become part of the preflight check-out routine.

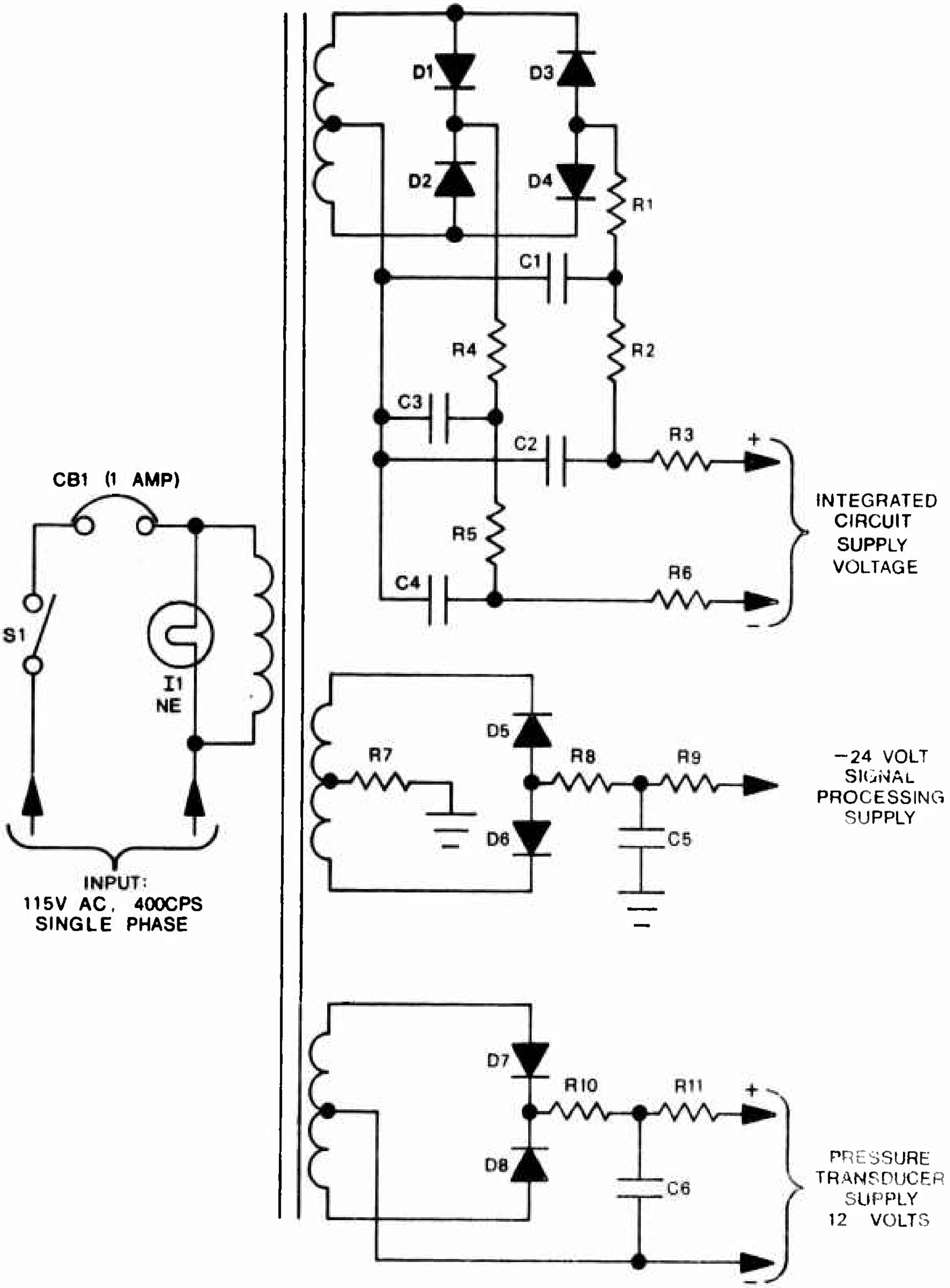


Figure 15. Hazardous Condition Indicator Power Supply.

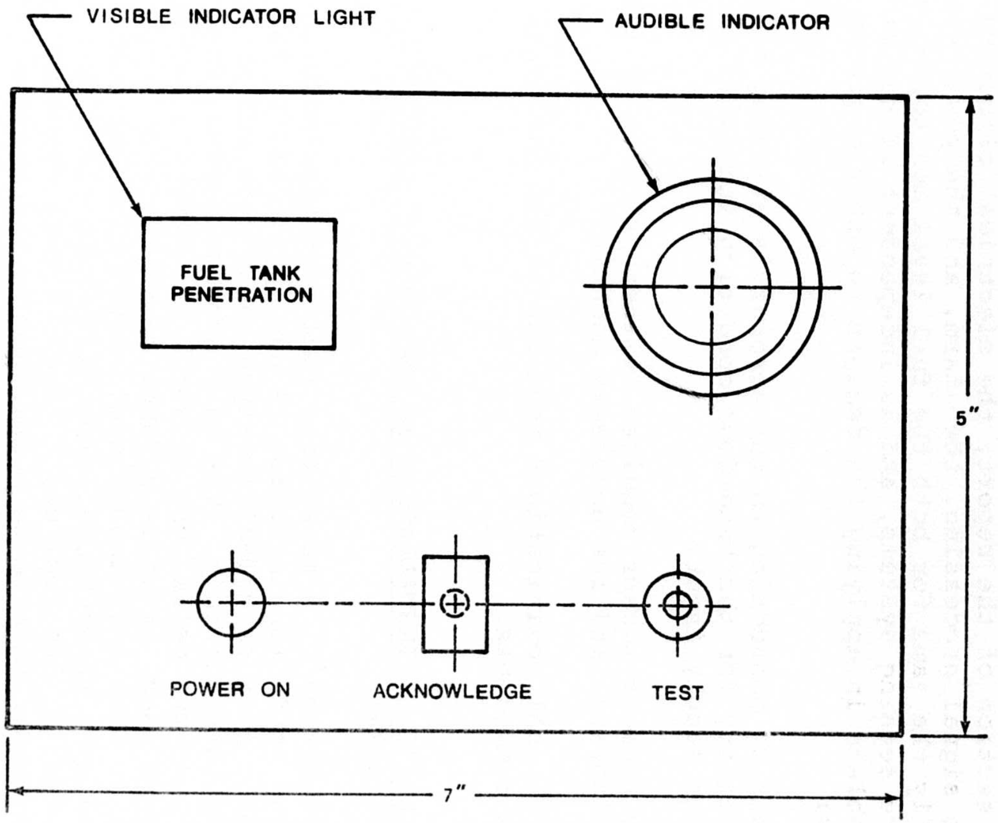


Figure 16. Panel Layout for Hazardous Condition Indicator Circuitry and Alarm. Approximate Container Dimensions Are 5 x 7 x 4 Inches.

V. APPLICABILITY OF RECOMMENDED SYSTEMS TO THE OH-6A AND CH-47 AIRCRAFT

This section deals briefly with the difficulties involved in applying the hazardous condition indicator designs previously presented to the OH-6A and CH-47 aircraft. As shown in the design section of the report, the electrical circuitry involving the signal processing, the alarm, and the power supply is basically the same for both the fuel level monitoring and the pressure sensing systems, and is independent of the aircraft. The problems in applying the designs to other aircraft are as follows:

1. Means of connecting to the aircraft's existing electrical circuitry for the hazardous condition indicator sensor and power supply input.
2. The type of sensor required (either pressure or level monitoring) and its necessary mounting.
3. Additional modifications required of the fuel cell and/or its components.

A. ANALYSIS OF INSTALLATION IN THE OH-6A: LIQUID LEVEL MONITORING

The utilization of a capacitive fuel quantity indicator for the hazardous condition indicator is not applicable to the OH-6A helicopter because capacitive-type tank units are not incorporated in this aircraft. The fuel storage system (Figure 2) consists of two cells, one of which has simply a variable resistance whose value is a function of the fuel level within the cells. The unit consists of a potentiometer mechanically actuated by a conventional float arm which rides on the surface of the fuel in the fuel cell. Thus, a fuel level monitoring approach would have to be redesigned to incorporate a variable resistance sensor instead of the variable capacitance sensor of the UH-1B helicopter. To use the variable capacitance approach, the OH-6A helicopter will require the installation of a separately excited capacitive-type sensor within each of the two fuel cells with additional modification to each fuel cell access door required for the electrical connectors.

B. ANALYSIS OF INSTALLATION IN THE OH-6A: PRESSURE SENSING

The pressure sensing system as previously described is directly applicable to the OH-6A helicopter with the exception of the pressure transducer mounting as shown in Figure 6. The placement of the fuel cells is such that a simple crossover fitting is required between them. Referring to Figure 6, the flange will be reconstructed to take the place of the crossover fitting, and an additional but oppositely directed pressure sensor mount and pressure sensor are added. Thus, when assembled, a pressure sensor mount will protrude through each fuel cell opening into each fuel cell from the flange. A modification for the electrical connector as shown in Figure 8 is required for each fuel cell access door. The electrical circuitry and power requirements remain as previously described.

C. ANALYSIS OF INSTALLATION IN THE CH-47: LIQUID LEVEL MONITORING

The fuel cells of the CH-47 helicopter (Figure 3) use a capacitive-type fuel gaging system which is equivalent to the UH-B system with the exception of the joining of the right- and left-hand tank units prior to connection to the fuel quantity indicator. The CH-47 has switching provisions available to the pilot to monitor each tank separately or in combination. The fluid level monitoring concept can be applied in this situation with a dual sensor input which allows for the monitoring of each fuel cell regardless of the position of the fuel quantity indicator switch. Tapping into the quantity indicator circuitry is possible using a junction box similar to the one of Figure 12, thus making the fuel level monitoring design of the UH-1B directly applicable to the CH-47.

D. ANALYSIS OF INSTALLATION IN THE CH-47: PRESSURE SENSING

The pressure sensing system is also directly applicable to the CH-47 helicopter. However, the means of mounting the pressure sensors and the number of pressure sensors required differ significantly from the UH-1B helicopter. Depending on the obstructions present within each fuel cell of the CH-47, two pressure sensors for each fuel cell may be required for reliable protection. The sensors are mounted using brackets similar to those described previously, but located at the access door at each end of each fuel cell. A single connector on one access door of each fuel cell is required for electrical connections to the pressure sensors within the fuel cells. The hazardous condition indicator circuitry remains the same with the exception of modifications to the transducer bridge to accommodate the additional sensors.

VI. DEMONSTRATION UNIT DEVELOPMENT

The liquid level monitoring approach to the hazardous condition indicator was recommended as being the most economical and practical. This recommendation was conditionally dependent upon the response time of the UH-1B fuel quantity indicator tank unit being sufficient for detection of the fuel level changes resulting from a ballistic penetration.

The purpose of the demonstration model is to show the feasibility of the recommended capacitive sensor approach to the hazardous condition indicator. This is accomplished by showing that a specific rate of change in the apparent surface level of the fluid can be used as the trigger for an alarm through the capacitive tank unit. Referring to Figure 17, the basis of the model is a tank which contains the capacitive fuel gage element and a fluid simulating aviation fuel (a commercial solvent Chlorothene NU), and to which is attached a CO_2 pistol. The basic concept of the model is to fire a burst of gas into the fluid, thus producing a bubble which simulates the cavitation of a ballistic penetration of the fluid. The burst of gas enters the tank near the bottom through a valve from the CO_2 pistol, which is fired manually and fires a single burst. The shutoff valve is to insure against leakage during transportation or to allow for removal of the pistol should the need arise. Refill CO_2 cartridges can be inserted with the pistol in place and the model completely assembled (complete operating instructions would accompany the model). The bubble within the fluid will cause the fluid level to increase within the tank at a specific rate which is dependent upon the volume and pressure of the air burst from the pistol. This level change is monitored by the capacitive fuel gage element (fuel quantity indicator tank unit), and the signal is sent to the hazardous condition indicator circuitry for processing. The circuitry for this model as shown in Figure 18 is selective and will respond only to the pulse produced by the burst from the pistol. The excitation for the capacitive element is a DC voltage, as the actual change in capacitance due to a level change is independent of the frequency of the voltage applied to the capacitor. Thus, only minor modifications of the hazardous condition indicator model circuitry are needed to adapt the indicator to the actual case of detection of ballistic penetration of the UH-1B fuel cells. These modifications are:

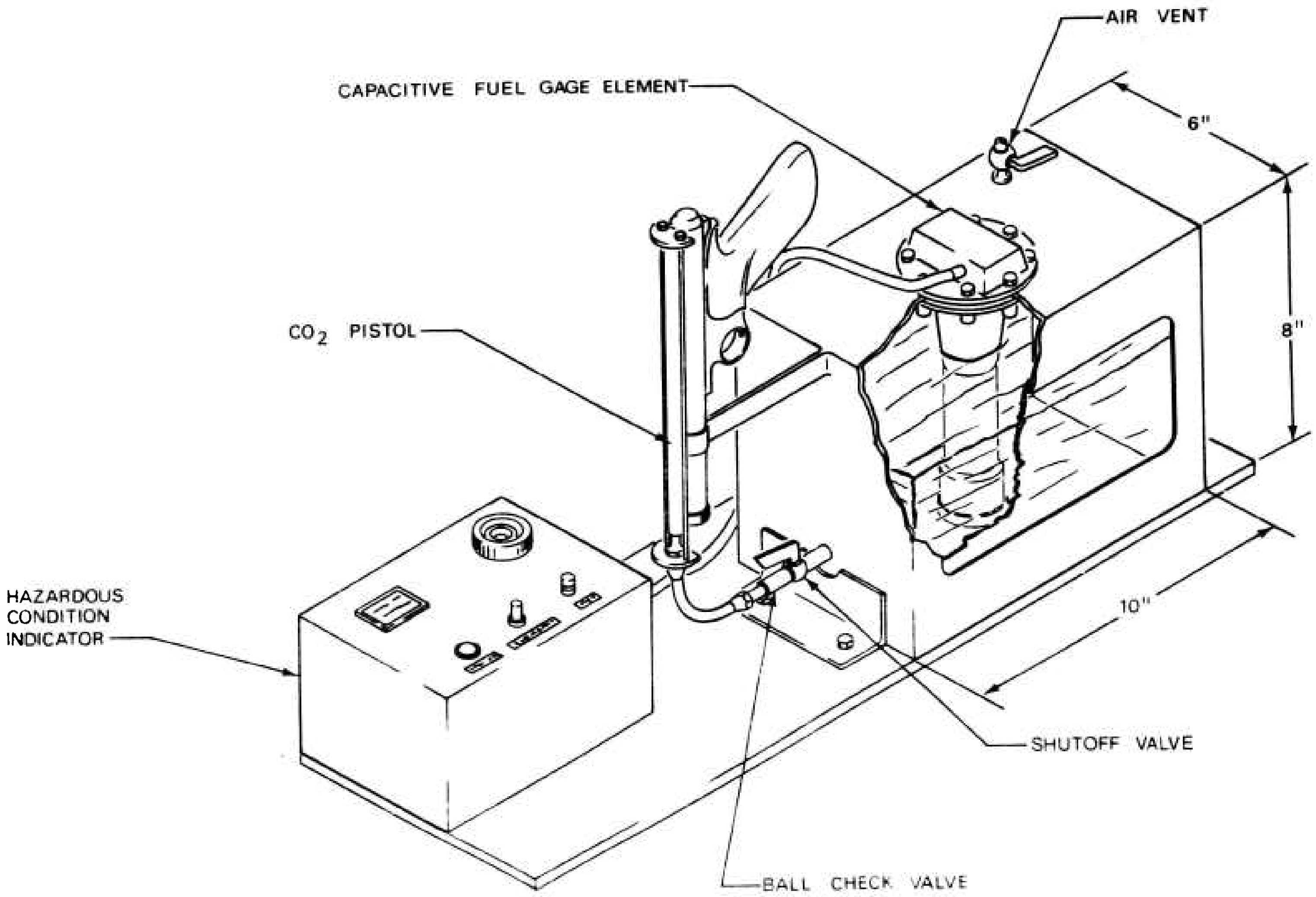


Figure 17. Hazardous Condition Indicator Model Utilizing the Capacitive Liquid Level Monitoring Approach.

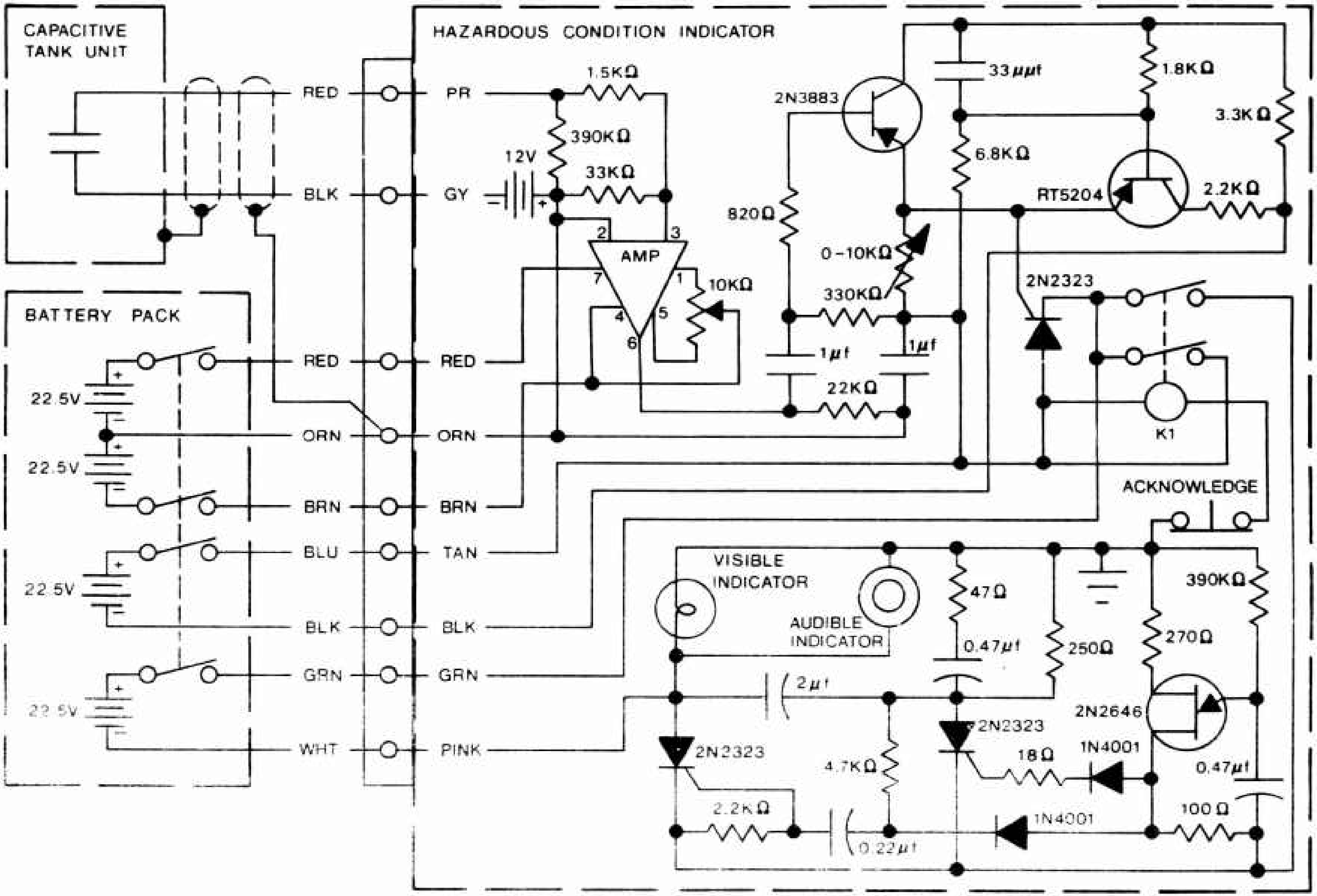


Figure 18. Hazardous Condition Indicator Model Circuitry.

1. Adjustment of the discriminating circuitry to respond to the fluid level rise time typical of an actual ballistic penetration.

2. Conversion of the circuitry to operate on 400-cycle power.

VII. BALLISTIC TESTING PROGRAM

A. TEST OBJECTIVES

The purpose of the ballistic test program was to provide data relative to the feasibility of the hazardous condition indicator design which utilizes the capacitive fuel gage tank unit as the sensor of a ballistic penetration.

The test program involved firing into a fuel cell and varying the conditions of fuel level, distance of the shot line through the cell from the sensor, bullet velocity, and degree of restriction of fuel flow to and from the sensor itself. The last of these variables will determine the response rate of the fuel gage tank unit, and whether or not it can respond rapidly enough to detect the disturbance in the fuel associated with a bullet penetrating the fuel cell.

B. TEST SETUP

Figure 19 shows a diagram of the experimental setup, which consists of five basic components: the gun, two photoelectric screens for measuring bullet velocity, the fuel cell, and the capacitive tank unit being tested. The longer capacitive tank unit of the UH-1B helicopter protrudes from the fuel cell through the modified fuel cell cover plate because the smaller but readily available 2-foot cube fuel cells were used. It is believed that this arrangement had no adverse effect in determining the response characteristics of the UH-1B capacitive tank unit. The tank unit mounting and fuel cell cover plate modifications are shown in Figure 20. The structure protecting the bottom of the tank unit was found during the preliminary ballistic testing to be a necessary item.

During one of these tests with the conditions of standard bullet velocity, 70 percent full fuel level, minimum tank unit flow restriction, and a 6-inch miss distance between the bullet and tank unit, the tank unit itself was destroyed. Careful inspection of the tank unit pieces showed evidence that the bottom of the tank unit had received severe impacts from the bottom of the fuel cell as a result of the distortion of the self-sealing fuel cell with each ballistic penetration. Bullet energy is absorbed by the violent stirring of the fuel. This causes the tank to try to bulge in all directions. The net

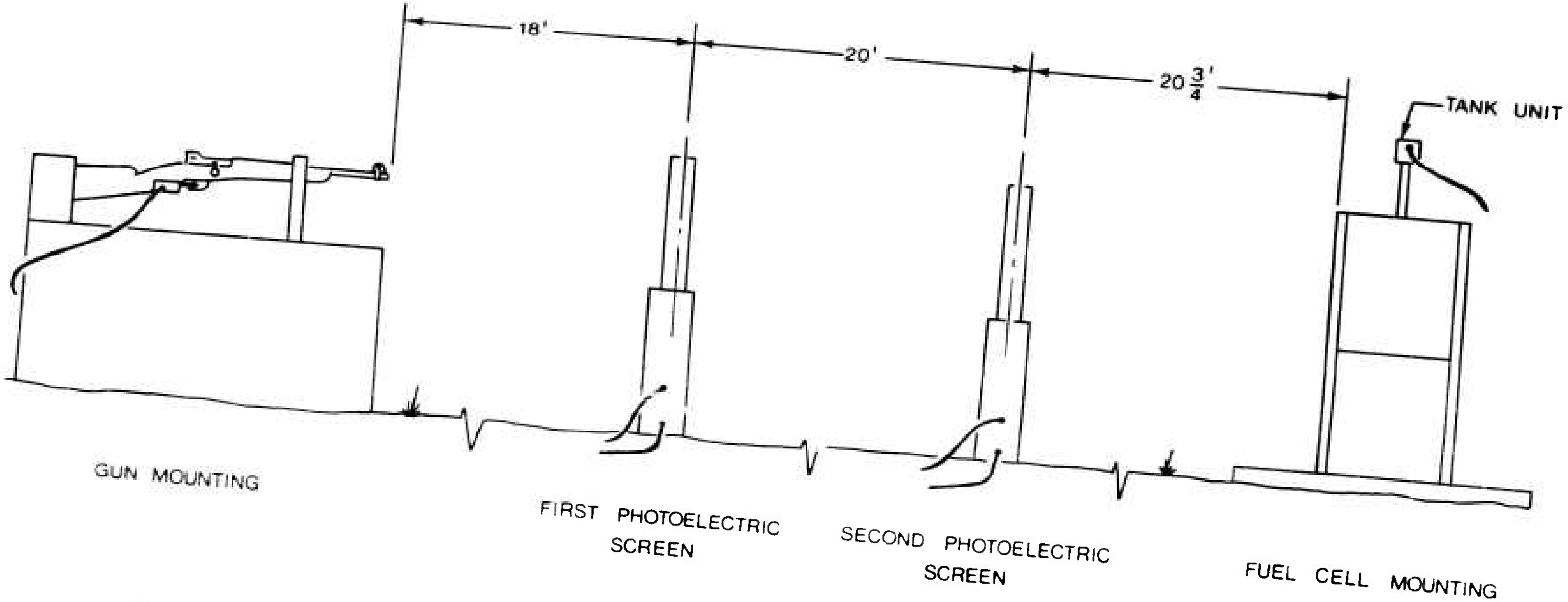
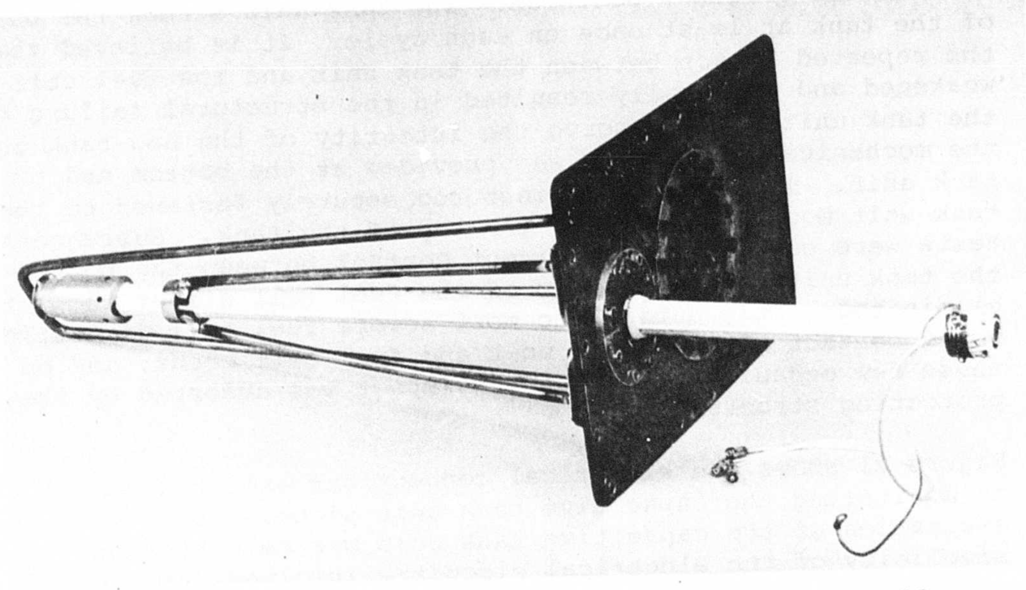
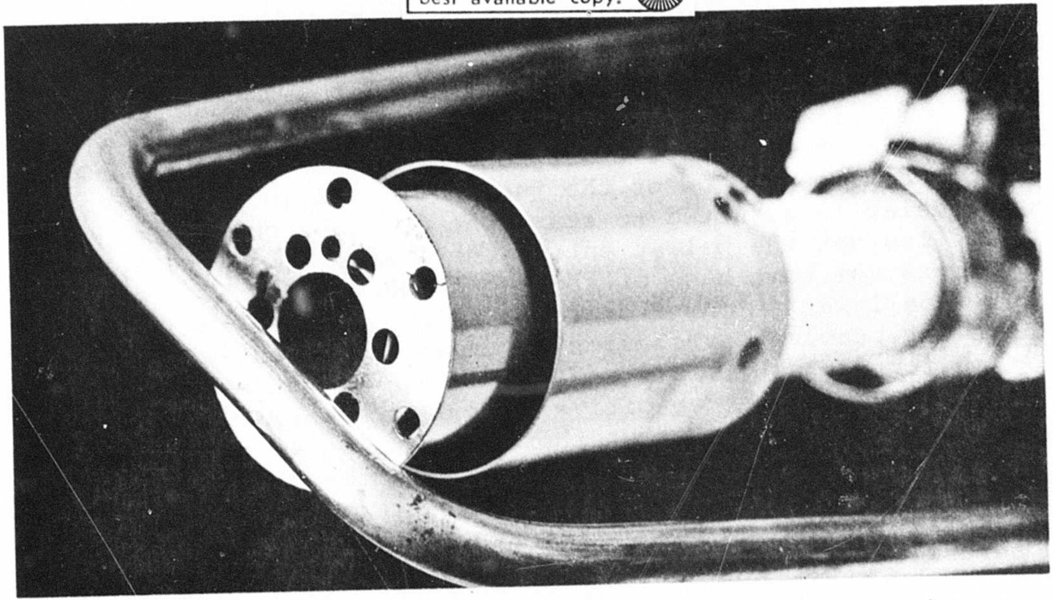


Figure 19. Equipment Layout Diagram for Ballistic Testing Program.



a. Capacitive Tank Unit Mounting on the Fuel Cell Cover Plate.



b. Protective Structure Which Prevents Direct Contact Between the Fuel Cell and the Bottom of the Tank Unit.

Figure 20. Capacitive Tank Unit Mounting for Ballistic Testing.

effect was for the tank to jump up several inches and then fall back to its original position. The tank unit struck the bottom of the tank at least once on each cycle. It is believed that the repeated impact between the tank unit and the fuel cell weakened and eventually resulted in the structural failure of the tank unit. To preserve the integrity of the new tank unit, the mechanical protection was provided at the bottom end of the tank unit. This was a 3/8-inch rod securely fastened to the tank unit mounting plate on the top of the tank. Subsequent tests were completed with direct contact between the bottom of the tank unit and the bottom of the fuel cell almost completely eliminated. Only during the most severe fuel cell distortions would contact between tank unit and fuel cell occur; and on these few occasions, most of the impact was absorbed by the protecting structure.

Figure 21 shows the electrical connections and arrangement used in monitoring the capacitive tank unit signal. Direct current excitation of the capacitive tank unit was used because of the simplicity of the electrical circuitry involved, and to minimize the introduction of noise signal to the signal resulting from a change in capacitance of the capacitive tank unit. The second photoelectric screen provides a signal, as the bullet passes through it, which serves both as a stop pulse for the interval counter and as a trigger pulse through the delay timer for the horizontal sweep of the oscilloscope. The amount of delay required for the sweep trigger signal is determined by the distance between the second photoelectric screen and the front or impact side of the fuel cell, and the bullet velocity. The delay is adjusted to start the oscilloscope sweep at the same instant the bullet enters the fuel cell in order to best utilize the time base of the oscilloscope's horizontal sweep. The small variations from round to round in bullet velocity prevent precise correlation of impact time and sweep trigger time for each shot, and small portions of either the beginning or the end of the capacitive tank unit signal variations may be lost depending upon whether the particular bullet was fast or slow respectively. However, as the actual firing tests have shown, a signal variation characteristic of all ballistic penetrations where the bullet passes through the fuel occurs several milliseconds after the initial bullet impact. Thus, no essential information is lost at the beginning of the oscilloscope trace due to minor variations of bullet velocity.

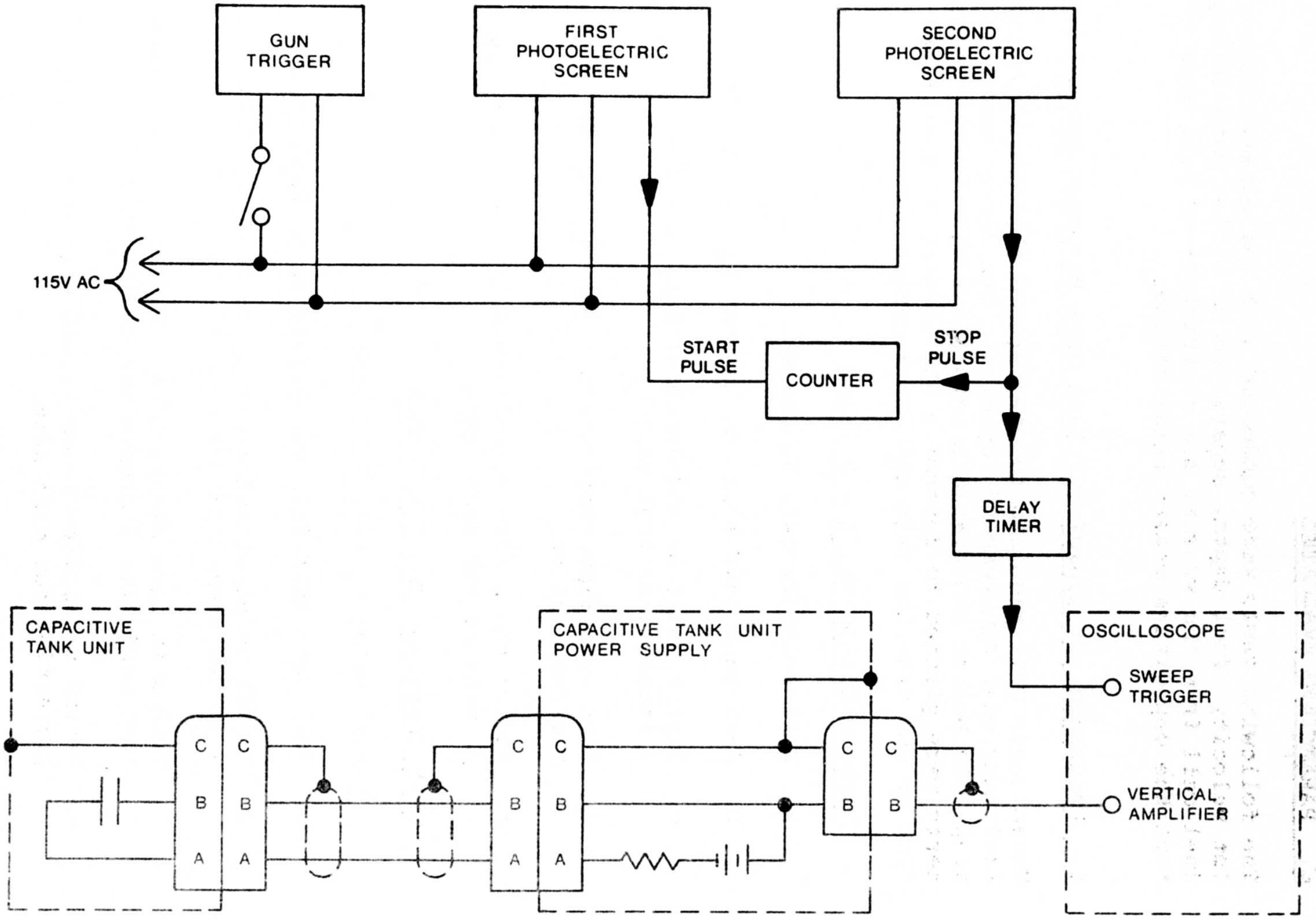


Figure 21. Equipment Electrical Connection Diagram for Ballistic Testing Program.

C. PARAMETERS EVALUATED

The following tests were conducted with the parameters of bullet velocity, fuel depth, separation of bullet path through the fuel cell from the sensor, and restriction of fuel flow to and from the capacitive sensor being varied.

1. Evaluation of Capacitive Tank Unit Response Rates

These tests were required to demonstrate that the capacitive fuel tank unit can respond rapidly to the disturbances associated with bullet penetrations into the fuel. Further, the tests were planned to determine the effects of restricted fuel flow to and from the tank unit upon response rates.

Test Condition No. 1 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full, or halfway up on tank unit.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - open at the bottom, minimum restriction.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 2 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full or halfway up on tank unit.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - half the open area of test condition 1 closed off to restrict flow.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 3 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full or halfway up on tank unit.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - three-fourths of open area closed off to limit fuel flow.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 4 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full or halfway up on tank unit.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - maximum restriction, all open area closed off except for two or three small (approximately 1/8 inch) holes for fuel flow.

e. Record the bullet velocity and the tank unit signal properties for each shot.

2. Evaluation of Fuel Level on Signal Properties

These tests were to establish the feasibility and potential reliability of the hazardous condition indicator under the full range of fuel quantity values that may be involved in combat exposure.

Test Condition No. 5 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank 90 percent full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 6 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank 70 percent full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 7 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank 50 percent full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 8 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank 30 percent full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 9 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank 10 percent full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

3. Evaluation of Shot Line Offset Distance on Signal Properties

These tests were to establish the feasibility and potential reliability of the hazardous condition indicator at a range of separation distances between the shot line of the bullet and the location of the tank unit.

Test Condition No. 10 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 12 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 11 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 9 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 12 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 13 - 5 shots

a. Full velocity cal. 30 rounds.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 3 inches from tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

4. Evaluation of Bullet Velocity on Signal Properties

These tests were to establish the feasibility and potential reliability of the hazardous condition indicator at varying ranges from the threat. Since range is an inverse function of bullet velocity, it can be evaluated by tests employing reduced velocity rounds.

Test Condition No. 14 - 5 shots

a. Cal. 30 rounds at 1000 ft/sec.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from the tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 15 - 5 shots

a. Cal. 30 rounds at 1500 ft/sec.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from the tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 16 - 5 shots

a. Cal. 30 rounds at 2000 ft/sec.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from the tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 17 - 5 shots

a. Cal. 30 rounds at 2500 ft/sec.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from the tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

Test Condition No. 18 - 5 shots

a. Cal. 30 rounds at 3000 ft/sec.

b. Fuel tank half full.

c. Impact point at mid-depth of fuel and shot line offset 6 inches from the tank unit.

d. Tank unit flow restriction - minimum.

e. Record the bullet velocity and the tank unit signal properties for each shot.

D. RESULTS OF BALLISTIC TESTING

The results of the ballistic testing are presented in this section as oscilloscope traces, each of which represents one of the test conditions previously described. The fluctuations in the oscilloscope traces correspond to the changes in capacitance of the capacitive fuel gage tank unit due to the fuel agitation resulting from a ballistic penetration of the fuel.

Figure 22 shows the effect of varying the capacitive tank unit restriction from a completely open condition to an approximately 95 percent closed condition. The cal. 30 bullet was fired at standard velocity into the mid-depth of the fuel with the shot line at a distance of 6 inches from the tank unit for each condition of restriction. The fuel level was maintained at 50 percent full.

Figure 23 shows the effect of varying the fuel depth from a 10 percent filled to a 90 percent filled fuel cell. The cal 30 bullet was fired at standard velocity into the mid-depth of the fuel with the shot line at a distance of 6 inches from

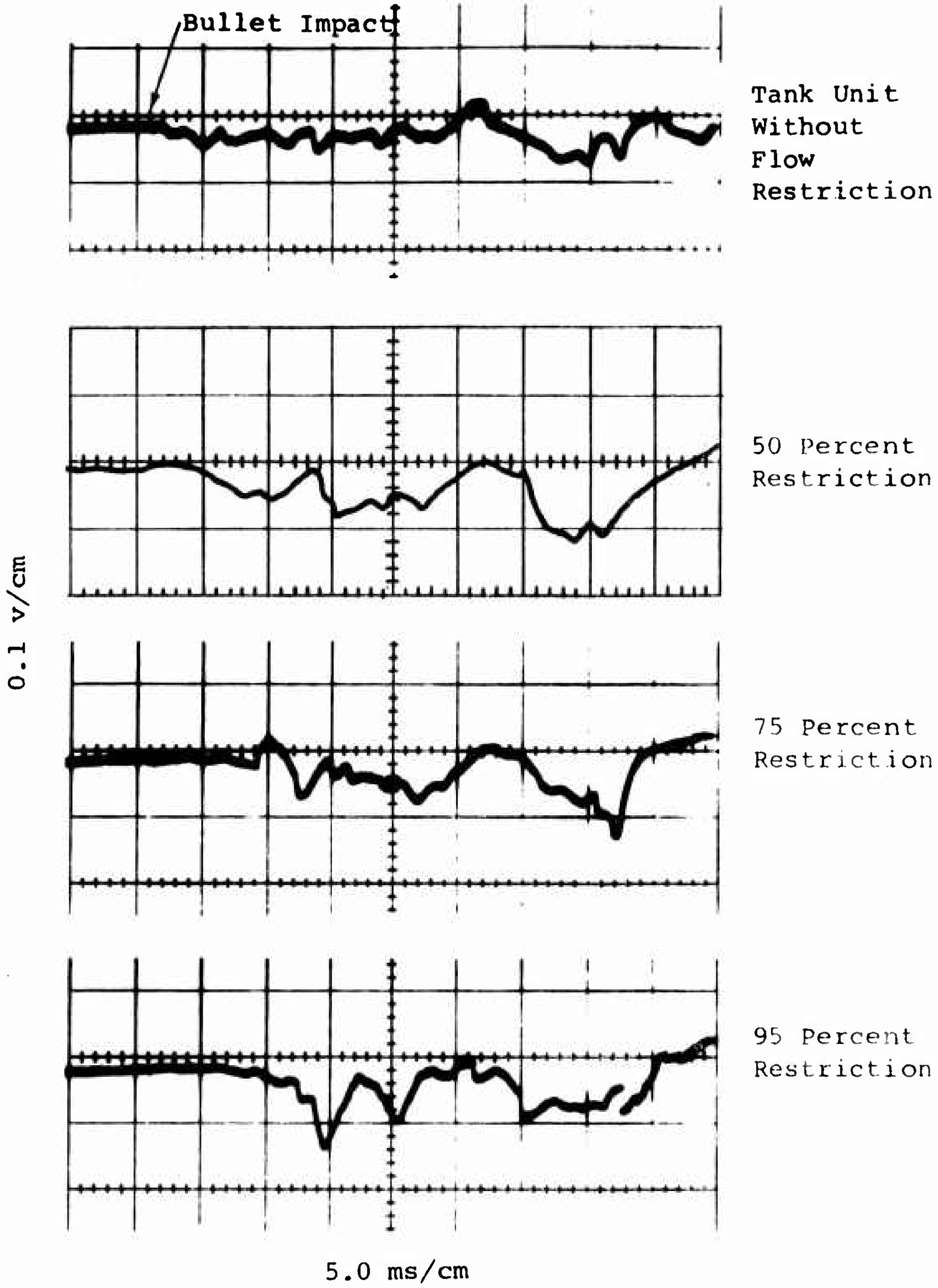


Figure 22. Effect of Tank Unit Flow Restriction on UH-1B Tank Unit Signals. Cal. 30 Standard Velocity Bullets Fired Into Mid-Depth of the Fuel, 6 Inches From Tank Unit, Fuel Level at 50 Percent.

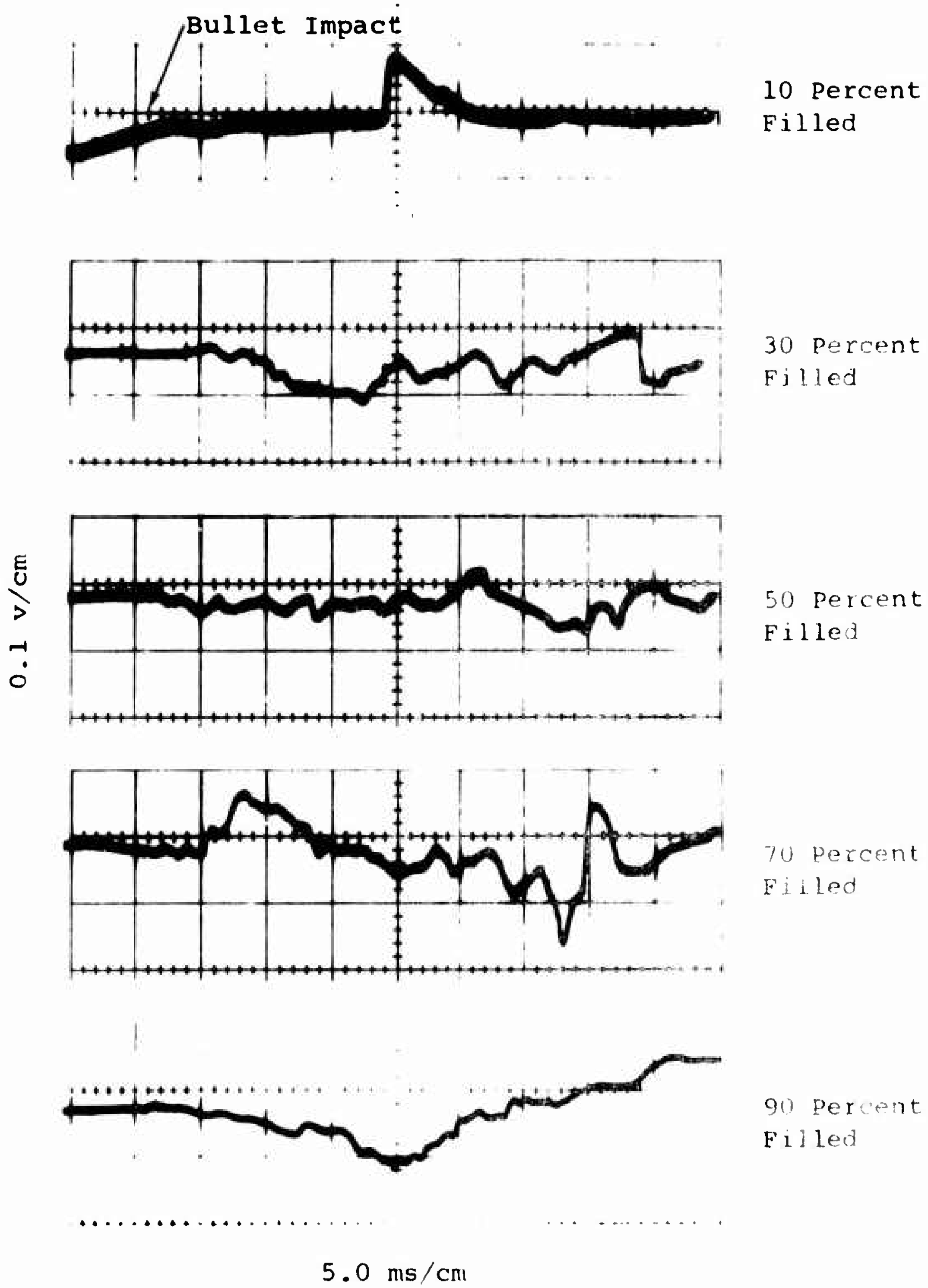


Figure 23. Effect of Fuel Depth on UH-1B Tank Unit Signals Cal. 30 Standard Velocity Bullets Fired Into Mid Depth of the Fuel, 6 Inches From Tank Unit. Tank Unit Restriction at Minimum.

the tank unit for each condition of fuel level. The tank unit restriction was maintained at a minimum.

Figure 24 shows the effect of varying the bullet shot line offset distance from the tank unit. The range from a 3-inch miss distance to a 12-inch miss distance is covered. The cal. 30 bullet was fired at standard velocity into the mid-depth of the fuel with the fuel level at 50 percent for each miss distance. The tank unit restriction was minimum.

Figure 25 shows the effect of varying the bullet velocity from 1000 ft/sec to 3000 ft/sec. The cal. 30 bullet was fired into the mid-depth of the fuel at a 6-inch shot line offset with the fuel level at 50 percent for each velocity. The tank unit restriction was maintained at a minimum.

E. DISCUSSION OF RESULTS

The oscilloscope traces which have been selected for presentation in Figures 22 through 25 are representative of the results obtained for each test condition. In each instance, the trace sweeps across the figure from left to right at a rate of 5 milliseconds per centimeter. Generally, the bullet strikes the tank between 5 and 10 milliseconds from the start of the trace. The vertical scale for Figures 22 through 24 is 0.1 volt per centimeter, and the vertical scale for Figure 25 is 0.05 volt per centimeter.

The cal. 30 ball projectiles generally reached the back wall of the 2-foot-cube tanks in a tumbled orientation and with some residual velocity. In most cases, however, the residual velocity was insufficient to penetrate the back wall completely, and the bullet remained inside the tank. The time from bullet impact on the front surface to impact on the back surface is not precisely known and would be expected to vary somewhat depending on the way the bullet tumbles in the fuel. Generally, the time for bullet passage should be less than 5 or at most 10 milliseconds. Thus, in Figures 22 through 25, the exchange of energy between bullet and fuel takes place very early in the trace. For the full-velocity bullets, total energy exchange should be completed within the first 3 centimeter divisions. Thus, the remaining 70 percent of the trace covers the bubble expansion and collapse and various reverberations following the cavity collapse.

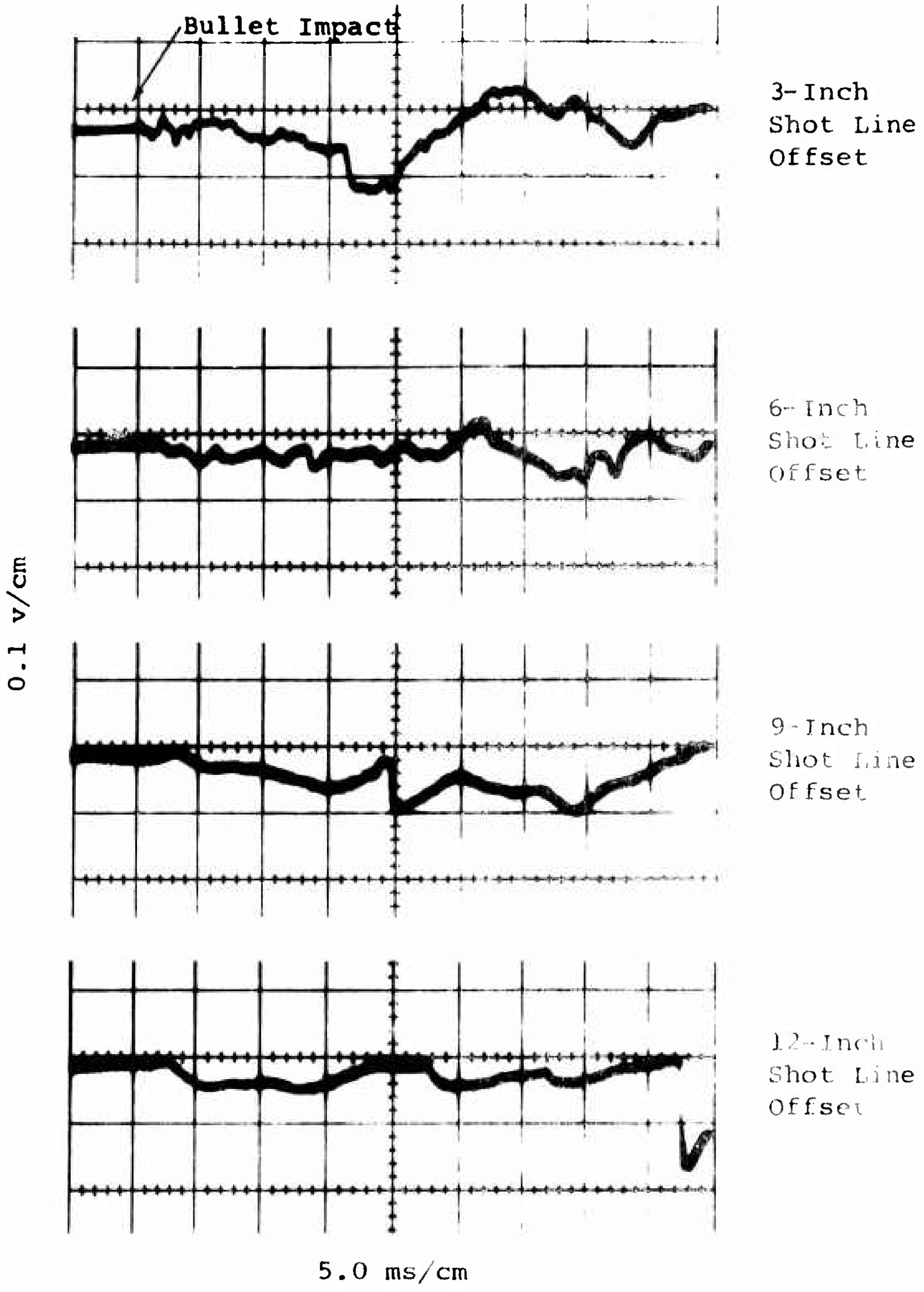


Figure 24. Effect of Shot Line Offset Distance on UH-1B Tank Unit Signals. Cal. 30 Standard Velocity Bullets Fired Into Mid-Depth of the Fuel, Fuel Level at 50 Percent, Tank Unit Restriction at Minimum.

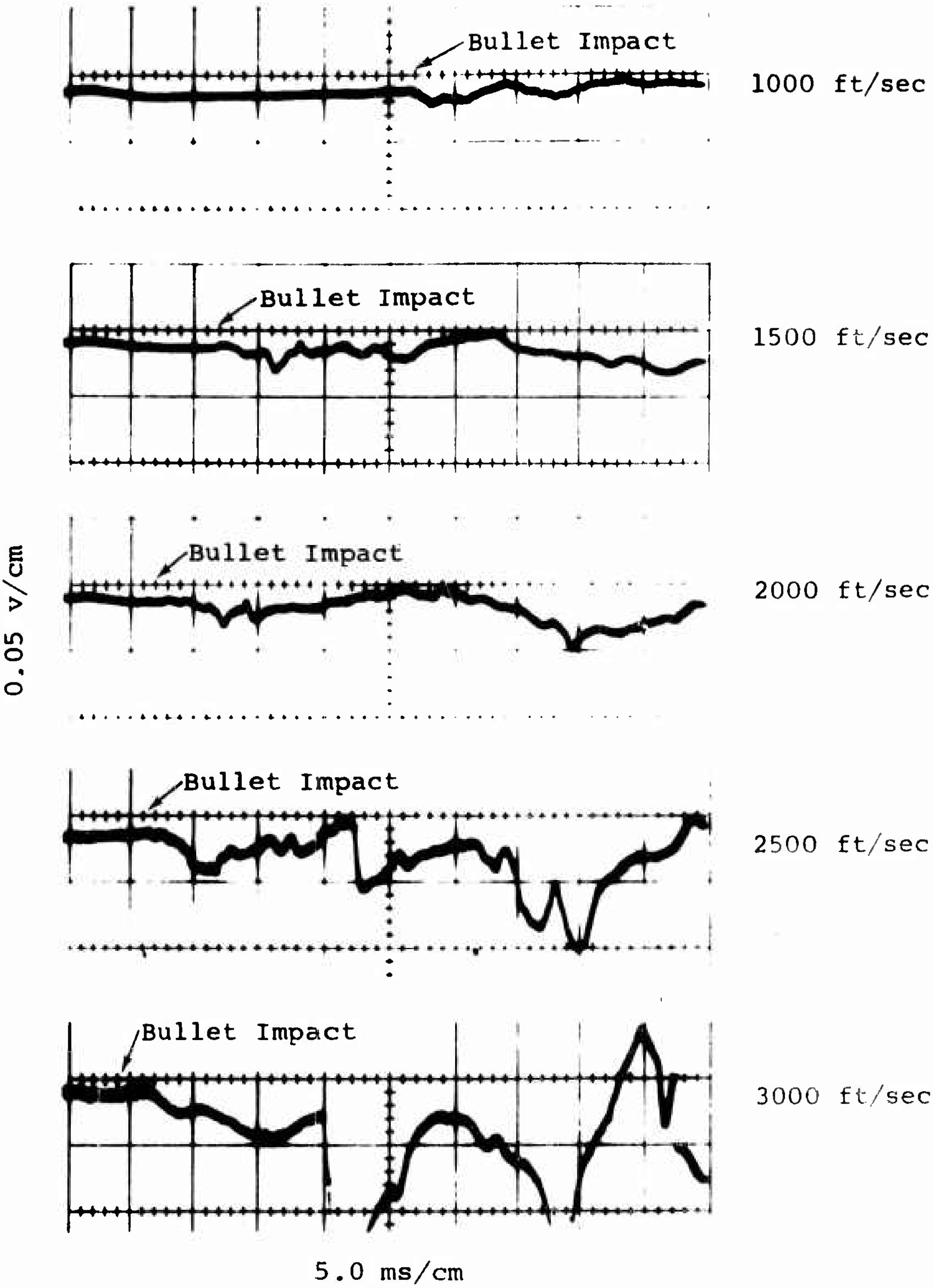


Figure 25. Effect of Bullet Velocity on UH-1B Tank Unit Signals. Cal. 30 Bullets Fired Into Mid-Depth of the Fuel, 6 Inches From Tank Unit, Fuel Level at 50 Percent, Tank Unit Restriction at Minimum.

Repetitive patterns in these signals are clearly present even when there are parametric variations in the test conditions. Some random variations which keep any of the traces from being identical also seem to be present. Such variations were expected and do not represent inaccuracies but real changes in the events within the fuel tank following bullet penetration.

The data presented in Figure 21 show that fuel flow restrictions to the capacitive tank unit do not interfere with the production of a useful signal by the fuel agitation following a bullet penetration. The patterns for all of the degrees of tank unit restriction are clearly similar, with only minor variations in amplitude. A signal variation with frequency characteristics in the range of 500 hertz occurs one or more times in each of these tests. There are higher frequency patterns which occur occasionally, but 500 hertz seems to be the highest frequency signal which is produced with high reliability under these test conditions.

The data of Figure 23 show that fuel level has a definite effect on the signal characteristics but that potentially useful signals are produced for all fuel levels.

The data for the 10 percent filled tank was taken early in the test program before the failure of the first tank unit due to interaction with the tank bottom. Thus no protective rod below the tank unit was involved in this test, and it must be assumed that the sharp voltage rise corresponds to the time of tank unit impact on the bottom of the tank. All other data included in Figure 23 were taken with the protective rod in place as shown in Figure 20.

While there are a variety of similarities in the signal patterns for the various fuel levels between 30 and 90 percent, there are some distinct differences as well. These differences are believed to be related to fuel level but they do not prevent the generation of a useful signal. It is believed that the full range of fuel levels can be handled by this type of hazardous condition indicator approach so long as the bullet passes through the fuel.

The data presented in Figure 23 show the effect of shot line offset distance on the signal produced at the tank unit. The general effect seems quite clear. The closer the shot line is to the tank unit, the stronger the signal. Also, more detail in the signal trace is provided by the closer shot lines. Note particularly the first 5 milliseconds after bullet impact, where the bullet is actually passing through the fuel. The 3-inch miss distance shows 6 or 7 significant cycles during this period. The 6-inch offset shows a similar number of cycles but with greatly reduced amplitude. At the greater miss distances, the individual cycles become virtually indistinguishable, with only the general shape of the signal showing a similarity. There are portions of each of these signals which show frequency characteristics of about 500 hertz, and thus at least shot lines which come within a foot of the tank unit should provide adequate signals.

Figure 26 provides information on the effect of bullet velocity on tank unit signal. The effect of increased velocity is very clear. Increased velocity provides increased signal strength. The patterns for these five velocities are generally very similar, with increasing amplitude for higher velocity. Even the lower velocities seem to provide sufficient signal strength for consideration as a trigger basis.

The scope trace was triggered by the bullet's passage through a photoelectric screen 20 feet ahead of the tank (see Figure 20). Thus the slower bullets took longer to arrive at the tank face than the fast bullets. The 100-ft/sec test shows the bullet arrival halfway across the trace. Succeeding faster bullets show earlier arrivals as noted on these figures. Signal components with at least a 500-hertz frequency characteristic are consistently produced in these data.

It should be noted that all of the testing reported in these preliminary results employed cal. 30 ball rounds. These are the smallest and least energetic bullets which may be considered to constitute a significant threat to Army aircraft fuel. Larger rounds such as the cal. 50 or 14.5 mm projectiles would provide much more energy for disturbing the fuel even at the lowest velocities. Thus, if a suitable signal can be produced with cal. 30 impacts, there should be no doubt about the adequacy of the signal from larger bullets.

VIII. CONCLUSIONS

The information which has been gathered or developed provides a basis for a number of conclusions which are summarized in the following statements.

1. There are a number of technical approaches to a hazardous condition indicator which might prove successful. The approaches which were found to be most promising as a result of the engineering analysis of potential systems were:

    a. Use the fuel tank capacitive gage unit to sense disturbances in the fuel caused by hits on the tank.

    b. Use a small pressure sensor within the tank to sense pressure increases due to ballistic impacts.

2. The use of the capacitive tank unit was selected for further development because it requires no modifications to the tank or its internal components.

3. The pressure measurement approach appears to be very desirable except for the requirement to install a sensor in the tank and bring the leads out through the tank wall. The difference between ballistically caused pressure pulses and normal pressure variations in the fuel tank is substantial. A system based on pressure levels within the fuel should be very reliable.

4. The limited firing program conducted with a UH-1B capacitive tank unit mounted in a 2-foot-cube tank showed that cal. 30 bullet impacts on the tank do produce characteristic changes in the signal from the tank unit.

5. Significant signals were achieved for a full range of fuel depths, projectile velocities, shot line miss distances, and flow restrictions to the capacitive tank unit. Larger projectiles would provide even stronger signals.

6. The present UH-1B capacitive fuel tank unit possesses marginal strength for the survival of ballistic impacts on the fuel. The first test unit failed after about 30 tests when it was allowed to strike the bottom of the tank following

a ballistic impact. The UH-1B tank unit survived more than 100 shots when protection was provided to prevent direct impacts of the tank unit on the bottom of the tank.

7. The investigation and limited testing which has been performed has indicated the feasibility of using the capacitive fuel level unit as a sensor for the hazardous condition indicator. A full feasibility demonstration was beyond the scope of the project.

IX. RECOMMENDATIONS

It is recommended that consideration be given to the development of a hazardous condition indicator for use on UH-1B/D Army aircraft fuel tanks.

APPENDIX

LITERATURE AND PATENT SURVEYS

The purpose of the comprehensive literature and patent surveys was to complete the study of the phenomena occurring during the ballistic penetration of a fuel cell, and to determine what devices are available to respond to these phenomena.

Many documents are available in the library at Falcon Research which were helpful to this program, particularly in the area of magnetic influence. Additional data was sought through the Defense Documentation Center (DDC), the U. S. Patent Office, and the following Government laboratories and commercial organizations: Ballistic Research Laboratories, Aberdeen Proving Ground, Harry Diamond Laboratories, and the Fenwal Corporation.

The field of interest register requesting separate report bibliographies and work unit summaries in four subject areas was submitted to DDC. The four subject areas covered were as follows:

1. Shock waves and associated pressure rises in a fluid which has been penetrated by a particle such as a bullet or shell fragment.
2. Magnetic influences of a small, high-velocity particle.
3. Fuel quantity indicating system construction and circuitry of the UH-1B, CH-47, and OH-6A helicopters.
4. Accelerometer and strain gage systems compatible with aircraft fuel cells.

As a result of the request, work unit summaries and report bibliographies covering the following areas of interest were obtained.

Work Unit Summaries	DDC Report No.
High-Velocity Particles	CT3175
Fuel Indicators	CT3176
Shock Waves in Fluids	CU3174

Report Bibliography	Search Control No.
Accelerometers and Strain Gages	043786
Accelerometers	045003
Strain Gages	045009
Fuel Gages	043889
Fuel Gages (Capacitive) for Aircraft	045007
Shock Waves in Fluid	043799
Shock Wave Sensors	045001
Capacitive Sensors	045002
Pressure Sensors	A45006
Pressure Sensors, Fluidics	845006
Magnetic Influence Sensing	045008

A review of the work unit summaries shows that few contractors or Government agencies are doing work in these fields which is directly applicable to the hazardous condition indicator. North American Rockwell Corporation, Los Angeles Division, however, under contract with the U. S. Army Air Mobility Research and Development Laboratory and Air Force Flight Dynamics Laboratory, has significant work in progress which is related to this study. The document covering their earlier work, entitled "Survivable Fuel Tank Systems Selection Technique, R. & D. Design Handbook Report" (U), Vol. I., contains valuable data pertaining to the internal pressure rise versus time characteristics of various fuel tanks which have been penetrated by high-velocity projectiles (20 mm and cal. 50 ammunition). The data includes graphs showing the rate of pressure rise and the peak pressures obtained for different size tanks with and without fuel.

A review of the report bibliographies resulted in the following list of documents which were pertinent to the various aspects of this project:

1. AD 868626 Lockheed-Georgia Co., Marietta Lockheed Georgia Nuclear Laboratory, "Trade Study Aircraft Fuel Quantity Systems Capacitance - Nucleonic."

2. AD 3406 North American Aviation Inc., Los Angeles, "Calibration of Capacitance Type, Non-Characterize +T Density Compensated, Minneapolis-Honeywell Fuel Quantity G+G5 P5R AAF Specification 21100-B, Model F-86D Airplane."

3. AD 834719 Bendix Corporation, Southfield, Michigan, Bendix Research Labs, "Fluid State Pressure Sensor."

4. AD 808683 Naval Ordnance Test Station, China Lake, California, "Fluerics Terminology, Nomenclature, and Schematics."

5. AD 706189 Wright-Patterson Air Force Base, Foreign Technology Division, "Semiconductor Pressure Sensor for Measuring Strong Shock Waves in a Liquid."

6. AD 703117 Harry Diamond Laboratories, Washington, D.C., "Fluerics .28. State of the Art."

7. AD 674222 Honeywell, Inc., Minneapolis Aerospace Division, "Fluidic Reliability."

8. AD 402217 Stanford Research Institute, Menlo Park, California, "Pressure Transducer for Measuring Shock Wave Profiles."

9. AD 694263 Royal Military Coll. of Canada, Kingston (Ontario), "Technique for Measuring Small Capacitance Changes."

10. AD 356328 Aerojet-General Corporation, Sacramento, California, "Propellant-Utilization Tank-Sensing Systems."

11. AD 86-831 Navy Underwater Sound Laboratory, New London, Conn., "Characteristics of the Hydrodynamic Shock Simulator Developed by the Navy Underwater Sound Laboratory."

12. AD 625946 Harry Diamond Laboratories, Washington, D.C., "Research In Transducers, Summary Report."

13. AD 357539 Thiokol Chemical Corporation, Bristol, Pa., "Airborne Bullet Alarm System."

14. AD 806482 Battelle Memorial Institute, Columbus, Ohio, "Transducer Information Center, "Quarterly Accession List 15."

15. AD 613711 Harry Diamond Laboratories, Washington, D.C., "Instrumentation."

16. AD 457635 North American Aviation Inc., Downey, California, "Strain Gage Pressure Transducer."

17. AD 475760 Battelle Memorial Institute, Columbus, Ohio, Remote Area Conflict Information Center, "A Digest of Literature Related to Detecting Buried Ferrous Objects and Earth Voids by Magnetic Methods."

18. AD 105573 Polytechnic Institute of Brooklyn, New York, Microwave Research Institute, "Antenna Field Shaping Research for Application to Mine Detecting."

19. AD 842599 General Dynamics/Astronautics, San Diego, California, "Evaluation Test Accelerometer Switch, CVA Part No. 27-04099-1."

20. AD 226868 Raymond Engineering Lab., Inc., Middletown, Conn., "Manufacture and Evaluation of 50 Integrating Accelerometers."

21. AD 393058 Conrac Corporation, Fairfield, New Jersey Division, "Fluerics and a Device."

22. AD 615802 Harry Diamond Laboratories, Washington, D.C., "Notes on the Use of Semiconductor Strain Gauges."

23. AD 71274 Picatinny Arsenal, Dover, New Jersey, Feltman Research Labs, "Diaphragm-Type Strain Gage to Record Pressure-Time Traces."

24. AD 812777L North American Aviation Inc., Downey, California, Space and Information Systems Division, "Strain Gage Pressure Transducer."

25. AD 463844L Barringer Research Ltd., Rexdale (Ontario) "Airborne Concealed Munitions Detector."

26. AD 811453L Douglas Aircraft Co., Inc., Missile and Space Systems Division, Santa Monica, California, "Qualification Test of Potentiometer Type Pressure Transducers DAC SCN 1A72013-561."

27. AD 811450L Douglas Aircraft Co., Inc., Missile and Space Systems Division, Santa Monica, California, "Qualification Test of Potentiometer Type Pressure Transducers DAC SCN 1A72913-543."

28. AD 859781L Naval Air Development Center, Johnsville, Pa., Aero Mechanics Department, "Evaluation of Glassco Instrumentation Co. Remote Pressure Indicating System Range 0-100 psi."

29. AD 848882L Naval Air Development Center, Johnsville, Pa., "Reliability Investigation and Failure Analysis of Honeywell Inc., Fuel Quantity Indicators Manufacturer's Part No. JG132B6."

30. AD 70128L General Dynamics/Fort Worth, Texas, "Gaging System, Fuel Quantity, Capacitor Type, Compensated, Aircraft Modification of Spec. MIL-G-7818)."

31. "Transducers: List of Current State-of-the Art Projects," J. Pearlstein, DOFL Report No. TR-968, 10 August 1961.

32. "Searching the Literature for Transducer Information - Part II: A Survey of the Field," J. Pearlstein, DOFL Report No. TR-898, 1 December 1960.

33. "Searching the Literature for Transducer Information: A Survey of the Field, Supplement No. 1 to Part II," J. Pearlstein, DOFL Report No. TR-996, 10 November 1961.

34. "A Survey of Transducer Research at DOFL," V. A. Johnson, DOFL Report No. TR-1036, 30 July 1962.

The following list of pertinent documents was compiled from the library at Falcon Research:

35. "History of the Development of Mine Fuses at DOFL," AD325620.

36. "Research and Development on Mine Fuses and Related Items," DOFL Report #PR-58-21.

37. "Design and Development Study of a Localizer Sensor for an Area Fuse," Design Summary Report Maxson Electric Corporation AD327474.

38. "Final Project Report, Fuse, Influence, Mine Anti-Tank, T1223x6," AD66450.

39. "Engineering Report, Fuse, Mine T1223x6," Frankford Arsenal, AD95284.

At the U. S. Patent Office, the following categories were reviewed for devices or concepts which may in one form or another be applicable for the detection of a ballistic penetration of an aircraft fuel cell and/or oil tank.

a. Fire Extinguishing. This was an extremely broad category which included many types of fire extinguishing and preventing devices and systems. Of particular interest to this project were the devices used for detecting a fire and/or explosion which depended upon a rise, or an unusual rate of rise, in the pressure of the surrounding medium. A few devices were found in this category which may be applicable to the project objectives.

b. Inductive Devices. This category covered a large number of variable reluctance devices, or those devices in which some part of a magnetic circuit was physically moved. For instance, there were many electromagnetic type devices whose air gap was varied through the action of a force such as fluid pressure. Many of the devices in this category could be applicable for the detection of the sharp pressure rise in the fuel of the fuel cell which has been penetrated.

c. Variable Resistances. The devices of this category which were specifically pressure sensors operated similarly to the inductance devices, except that a resistance was varied instead of a parameter of an inductive circuit. There were many devices of the strain-gage type in this category which were considered relevant.

d. Liquid-Level Gages. Most devices of this category were variations of the float type variable resistance. These are not very practical for use in aircraft fuel cells because of the in-flight agitations encountered.

e. Variable Capacitance Systems. This category was concerned mainly with the construction of capacitors and variable capacitors such as those used for radio and oscillator tuning. However, there was a class of pressure sensors which operated very similarly to the inductive pressure sensors. In most devices the force of a fluid or gas pressure rise would vary the separation of the plates of a capacitor.

f. Metal Locators. This category consisted mainly of devices used to detect large-mass, stationary metallic objects through the use of a magnetic influence. There were a few devices which would detect smaller metallic objects but at close proximity and low velocity (i.e., counting on a conveyor belt). No devices were found in this category which seemed to be applicable.

g. Instrumentation. This was an extremely broad and generalized category covering instrumentation of all kinds. A few relevant devices were found which may be useful in detecting pressure rises.

The following is a list of relevant patents in the above categories, of which copies were obtained.

Patent Number	Date
2,736,386	28 Feb 56
3,315,748	25 Apr 67
2,338,440	
2,413,087	
1,718,698	25 Jun 29
3,001,586	24 Feb 60
3,021,903	2 Apr 59
2,144,535	17 Jan 39
2,269,760	13 Jan 42
2,510,073	6 Jun 50
2,807,167	24 Sep 57
2,563,899	14 Aug 51
2,544,567	6 Mar 51
2,623,386	30 Dec 52
3,455,165	15 Jul 69
2,661,460	1 Dec 53
2,870,630	27 Jan 59
2,485,515	18 Oct 49
2,621,518	16 Dec 52
3,042,858	3 Jul 62
3,473,110	14 Oct 69
2,696,105	7 Dec 54
2,957,337	25 Oct 60
2,667,786	2 Feb 54

Of these devices, the most promising as applicable to the hazardous condition indicator sensor have been discussed in previous sections.

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13. ABSTRACT

The work covered by this report investigated the ways in which bullet perforations of fuel tanks might be sensed and indicated to the crew. The work included a literature survey, engineering analysis, and preliminary ballistic testing.

Pressure effects and fluid agitation were selected as being the most promising approaches which were worthy of further study. A preliminary design for the hazardous condition indicator was developed employing each approach for the UH-1B aircraft.

The final project task was to select the most advantageous system and construct a portable demonstration model showing the significant features and technical feasibility of the approach. The approach selected utilized the apparent fuel level fluctuations caused by fuel agitation during a ballistic penetration. The method of sensing the fuel level variations employed a standard capacitive fuel tank unit and discrimination circuitry sensitive to the pulse characteristics produced by a ballistic penetration.

Testing was conducted to investigate the signal produced on a UH-1B fluid level sensor during a ballistic penetration. Parameters investigated included the fuel depth, the bullet velocity, the shot line offset distance, and the fuel flow restriction to and from the tank unit. The results achieved were consistent and show promise for this approach to the development of a hazardous condition indicator.

Security Classification

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Capacitive Sensors						
Pressure Sensors						
Fuel Leakage						
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Fuel Fire Prevention						
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