AEDC-TR-66-1

# INVESTIGATION OF MICROWAVE AND SONIC METHODS FOR MEASURING LIQUID LEVEL AND FLOW RATE

K. R. Carr and J. U. Clark
ARO, Inc.

March 1966

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# NOTICES

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## FOREWORD

The results of the work reported herein were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The Program Element was 65402234. The investigation was conducted under ARO Project No. TB3516, and the manuscript was released for publication on January 5, 1966.

The authors wish to express their appreciation to Mr. R. M. Williams, Managing Director, ARO, Inc., and Mr. G. H. Pope, Chief, Engineering Support Facility, for their suggestions and encouragement in performing their work. Also to Mr. S. G. Walker, Manager of the Engineering Support Facility Chemical and Metallurgical Branch, for the use of ultrasonic flaw detectors in accomplishing preliminary work before the project was begun. The loan of microwave components by the VKF and LORHO facilities made it possible to continue work at times when malfunctions occurred in equipment being used for this project.

This technical report has been reviewed and is approved.

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## ABSTRACT

Microwave and ultrasonic reflections from a liquid surface have been studied to determine the feasibility of their use in measuring liquid flow. Reflected ultrasonic pulses appear useful for measuring the change between static levels of large dimensions. However, for measuring small continuous changes the accuracy is not satisfactory. Microwave reflections provide an output that can be used for the measurement of total change in level or flow data.

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## ILLUSTRATIONS

# SECTION I
# INTRODUCTION

The turbine-type flowmeter has been widely accepted for use in rocket test facilities, but its use has been accompanied by difficulties brought about by requirements for cryogenic and chemical liquid flow data of high accuracy. Consequently, within the last few years much work has been done in constructing and evaluating the results of various flow calibrating facilities for use with different liquids (for example, see Refs. 1, 2, and 3.)

Prior to this time, turbine-type flowmeters were calibrated using a weigh or volume-type device used for the calibration of other flow measuring devices. The use of these systems requires extended periods of steady-state flow, large volumes of test fluid, large pumps or pressurized supply tanks, and large catch tanks for volume or weight measurement. This, in effect, has somewhat limited their use to the smaller size flowmeters, and they were suitable only for water or hydrocarbons that presented no handling problems. Calibration of a turbine-type flowmeter with either water or hydrocarbons and subsequent use with other liquids did not prove satisfactory. The variations in calibration constants for the same meters when used on water and cryogenic liquids are discussed in Refs. 1 and 2.

The economic factor associated with large capacity flow calibration systems plus the added handling difficulty associated with the particular physical and chemical properties of various liquids are almost prohibitive. Development of a simple, accurate method for determining flow by utilizing small volumes would be quite helpful.

Also, if it were possible to use some method to measure flow from a storage tank without resorting to flowmeter calibration, considerable savings would be realized.

Developments in the field of ultrasonics (Refs. 4 and 5) and the use of reflected microwaves for determining projectile motion in gun barrels (Ref. 6) suggest that these methods could be used to determine liquid flow from a tank. For this reason the present investigation was undertaken.

## SECTION II
## PROCEDURE

### 2.1 STORAGE TANK

The storage tank used for this work was a cylinder approximately 10 ft long with a nominal diameter of 30 in. A photograph of the storage tank with microwave equipment connected is shown in Fig. 1. A sight glass was mounted on the side of the tank so that the liquid levels could be observed visually over a distance of approximately 8 ft. A cathetometer, reading to 0.001 in. was used to measure changes in liquid level.

A calibration of the tank volume was required to convert changes in liquid level to volume units of liquid. The method used was that of filling an accurately known volume with water several times while observing the change in level in the tank. The accurately known volume was a glass container with a small neck. By filling the container to a well-defined mark on the neck and recording the weight and temperature of the water, the volume could be calculated. This was repeated several times to arrive at a mean value. Corrections were made for air buoyancy and density changes with temperature.

The procedure followed was to measure the change in water level in the tank occurring when the known volume was filled an integral number of times. This was repeated several times over the entire length of the sight glass. The results of the tank calibration gave a mean value of 3.05 gal/in. of tank height. There were variations of as much as ±0.5 percent in this volume per unit length over the entire length of the sight tube.

### 2.2 ULTRASONIC METHOD

The use of reflected sonic waves for the measurement of tank level has been widely used (Ref. 7). The method of utilizing sonic waves in this study is shown in Fig. 2.

Some difficulty was encountered in purchasing a packaged ultrasonic transmitter suitable for this investigation. Preliminary experiments with a borrowed ultrasonic flaw detector revealed that the pulse width and rise time would have to be accurately controlled to obtain meaningful results. The equipment finally purchased was a Dual Stream Monitor* used

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*Automation Industries, Inc., Boulder, Colorado for the measurement of stream depth. A functional block diagram of the instrument is shown in Fig. 3.

An extremely stable electronic clock is used to provide a time base. When a pulse from the clock fires a pulser, a similar clock pulse is fed to the computer. This results in two pulses arriving at the computer, the pulser firing pulse which passes through the receiver and arrives at the computer as a reset pulse and the set pulse from the clock. The time durations of each pulse are such that the computer responds only to the set pulse from the clock. The clock set pulse starts the timing cycle of the computer. When a reflected pulse is received it is amplified, detected, further amplified, and sent to the computer as a reset pulse which turns off the computer. An output voltage is obtained from the computer which is a direct measure of the time between the transmitted pulse and received echo. Assuming a constant ultrasonic velocity, the voltage output of the computer represents the distance between the transducer face and reflecting surface. This effectively measures the time for a pulse to travel twice the distance from the transducer to the reflecting surface. The output of the timer is then printed out by the printer. A timing diagram for the circuit is shown in Fig. 4.

At some level of liquid in the tank a time is determined for the pulse to traverse the liquid, reflect from the surface, and return to the transducer. If the level of the liquid is changed and the process repeated, the difference in time is a measure of the change in liquid level. From this, the time required for a unit change in length may be determined. The results of a series of measurements and calculated values (Ref. 8) are shown in Fig. 5 for various temperatures. From this, it can be seen that a change in temperature of 1°C will result in an error of about 0.16 percent.

The first attempt at measuring the change of liquid level in a tank was to calculate values and compare them with measured values. It was found that a determination of the temperature at one point in the tank is not sufficient. It is best to measure the time for a known distance through the liquid and then use this calibrated value for calculating other values. To make the calibrated value readily available, a hollow steel tube of accurately known length was mounted on the side of the tank. A second tube was mounted on the tank for determining the level of the liquid in the tank. The Dual Stream Monitor has two channels so that one channel can be used with each of the side tubes.

To determine the accuracy to be expected in measuring a change in level, several runs were made with known changes of level and the results compared with calculated values.

The equipment is shown in Fig. 6. A series of nine determinations was made over a 50-in. interval with a mean error of 0.038 in. The data corresponded to a velocity calibration factor of about 33.75 µsec/in. of depth. Use of the tank calibration results in a volume calibration factor of approximately 11 µsec/gal of water.

Using a velocity calibration run and the tank calibration data, a series of runs was made to cross-check the accuracy to be expected. This was done using a previously calibrated flowmeter for comparison. Two sets of data consisting of five runs each were taken on different 30-in. intervals. The flow rate was 10.5 gal/min, which corresponded to the linear portion of the flowmeter response curve. The deviation between runs was 0.35 percent on one interval and 0.39 percent on the other interval. The mean calibration factors were 4867 cycles/gal and 4837 cycles/gal, respectively. The factor obtained for this flow rate with the Cox flow calibrator was 4861 cycles/gal. The difference in the mean calibration factors is 0.62 percent of the largest mean calibration factor. This large a difference could not be explained except that it must be characteristic of the sonic system. The results of the ultrasonic system were not of sufficient accuracy to warrant further pursuit. Attention was then directed to the use of microwaves as described below.

### 2.3 MICROWAVE METHOD

Two factors must be considered in the choice of a microwave system for measurement of liquid level or flow rate. First, electromagnetic waves travel in air at a velocity very nearly equal to that of light in free space, or approximately 300 m/µsec (Ref. 9). For this reason it would not be practical to use a radar-type measurement of elapsed time between transmission of a pulse of energy and reception of the reflected pulse similar to that used for ultrasonic waves.

At a distance of 15 m, the total elapsed (round-trip) time between transmission of a pulse and reception of the reflected pulse would be only about 100 nsec. For an overall system accuracy of ±0.5 percent, it would be necessary to make an elapsed time determination nearly an order of magnitude better than 0.5 nsec for a liquid level differential of 15 m. For measurement of shorter intervals, the tolerances decrease proportionately, resulting in extreme tolerances on pulse rise time, pulse width, and circuitry for the measurement of elapsed time.

Second, free-space radiation from an antenna would not be practical. It is not difficult to focus electromagnetic waves into a narrow beam for transmission at great distances, but it is impossible to eliminate scattering of the waves at short distances from the antenna. Scattering of the waves would deteriorate the phase coherence of the reflected energy because of variations in round-trip path length of the reflected waves.

From the above considerations, it appears that the most practical approach is to use a vertical, metallic wave guide for a completely guided transmission of a continuous wave to and from the surface of the liquid.

Electromagnetic waves experience a continuous phase lag or retardation of 360 deg for each wavelength in the direction of propagation (Ref. 9). Since the transmitted and reflected waves are propagated in opposite directions, there is a unique phase relationship established between the transmitted and reflected waves at any fixed distance above the surface of the liquid.

At some given distance above the surface of the liquid, the transmitted and reflected waves will be 180 deg out of phase. Total field strength will be a minimum at this point. At a distance of one quarter-wavelength in either direction, the transmitted and reflected waves will have experienced relative phase shifts of 90 deg in opposite senses and will therefore be in-phase. Total field strength will be a maximum at this point.

The points of minimum and maximum total field strength are repeated at intervals of half-wavelengths throughout the entire section of wave guide which is above the surface of the liquid. The result is a train of standing waves which is displaced upward and downward in the wave guide as the surface of the liquid rises or falls.

To utilize the standing waves, a detector is placed at a fixed location in the wave guide above the highest liquid level to be used. The detector samples the total field strength at that point in the wave guide and provides a d-c output voltage proportional to the instantaneous, stored energy at that point in the standing wave.

If the surface of the liquid is displaced a distance equal to one half-wavelength, the detector is subjected to one complete cycle of field strength variation corresponding to one cycle of the standing wave. Correspondingly, the output voltage of the detector will have experienced one cycle of variation in magnitude. Figure 7 shows a block diagram of the components used. A recording of the detector output is shown in Fig. 8.

In a tank of known cross-section, each section one half-wavelength in height will correspond to a known volume. Therefore each cycle of detector output voltage variation will correspond to a known volume of liquid flow.

Two limitations of the microwave system should be noted.

1. It is not possible to measure the absolute height of the liquid in the tank since the standing wave pattern is identically repeated at half-wavelength intervals. The measurement must therefore be made in terms of units of volume flow over a given time interval.

2. The direction of flow is not known since the standing wave pattern is exactly symmetrical. The direction of flow must be established independently.

Two factors that affect the accuracy of the wave guide wavelength are:

1. Frequency stability. A microwave source of 10 gc with a stability of better than ±1 mc/s or < ±0.01 percent has been used in the experimental setup.

2. Wave guide dimensional tolerance. A wave guide was fabricated with internal dimensions of 1.122 by 0.497 in. to a tolerance of ±0.002 in. It may be shown that the corresponding tolerance on the wave guide wavelength is ±0.05 percent at 10 gc (Ref. 10).

Two methods may be conveniently utilized for the direct measurement of flow rate.

1. If the detector output is applied to a recorder with known accurate time base, a continuous display of flow versus time is obtained. Each cycle on the trace corresponds to the known unit volume of flow previously determined. A static trace represents a stationary standing wave pattern corresponding to a period of zero flow.

2. If the detector output is applied to a counter in the "Period" mode of operation, the counter will display elapsed time for one cycle of output voltage, or one unit volume of flow.

A cross-check of the method using a turbine-type flowmeter may be achieved by applying the outputs of the flowmeter pickup and the microwave detector to the two inputs of a counter designed to count frequency ratio. The resultant count of flowmeter pulses per detector output cycle (or half-wavelength) may be divided by the known system calibration factor of volume per half-wavelength to obtain the flowmeter constant in pulses per unit volume.

$$K = \frac{N}{V}$$

where

N = flowmeter pulses per half-wavelength (output of counter)

V = volume per half-wavelength

K = flowmeter constant, pulses per unit volume

Each of the above methods has been demonstrated experimentally. Figure 9 is a photograph of the microwave equipment used.

The wave guide half-wavelength was measured by direct comparison to a cathetometer measurement of relative water levels in the sight glass. A number of runs were made in the following sequence:

1. A cathetometer sighting was made and the relative height reading recorded with a static water level near the bottom of the tank.
2. Water was added to the tank to raise the water level by 70 half-wavelengths as indicated by 70 cycles on the strip chart recorder.
3. A second cathetometer sighting was made on the new water level and the relative height recorded.
4. Water was drained from the tank to lower the water level by 70 half-wavelengths as indicated by the strip chart recorder.
5. A final cathetometer sighting was made and the relative height recorded.
6. The half-wavelength in inches was calculated by

$$h = \frac{\sum_{n=1}^{n=T} (H_2 - H_1)_n}{70T}$$

where

$H_2$ = cathetometer reading at highest level

$H_1$ = cathetometer reading at lowest level

n = calibration run number

T = total number of runs

7. The mean measured value of the half-wavelength for 18 runs was h = 0.6957 in. with a standard deviation of 0.0004 in. or 0.056 percent.

8. Using the tank calibration factor of 3.050 gal/in., the resultant microwave calibration factor was 2.122 gal/half-wavelength.

9. A number of calibration runs were performed on a turbine flowmeter to determine the precision of the method. The calibrations were performed at a flow rate of 6.5 gal/min as determined by observation on a strip chart and a period measurement on the counter.

10. A number of comparative calibrations were performed on the same flowmeter at 6.5 gal/min using the standard Cox flow calibrator.

11. At a flow rate of 6.5 gal/min, the mean measured value of flowmeter pulses per half-wavelength for an accumulated run of 671 half-wavelengths was N = 10,365 with a standard deviation of 0.16 percent attributable to all factors, including tank nonuniformity. The flowmeter constant was calculated to be 4885 pulses/gal.

12. A series of 26 calibration runs at a rate of 6.5 gal/min in one 7-in. interval yielded a mean value of N = 10,362 flowmeter pulses per half-wavelength with a standard deviation of 0.05 percent. The corresponding flowmeter constant was 4883 pulses/gal.

13. A series of 15 runs at 6.5 gal/min performed on the Cox flow calibrator yielded a mean flowmeter constant of 4887 pulses/gal with a standard deviation of 0.15 percent.

## SECTION III
## DISCUSSION AND RESULTS

The results of this investigation verified that both reflected ultrasonic and microwave energy have possible uses in measuring liquid flow. Also it affirms the well-known problem that regardless of the method used, either volumetric or weighing, the data must be very accurate to be satisfactory.

Although not pursued as far as the microwave method, the ultrasonic method does have some advantages that may have application in other areas. Some of the advantages are listed below.

1. It is not necessary that any of the equipment be in contact with the liquid being used. The placement of the ultrasonic transducer on the bottom of a side tube is shown in Fig. 10.
2. The equipment is quite portable and can be easily moved from one location to another. With the exception of the small transducers and lead wire, the remaining equipment can be located remotely from the storage tank.
3. The data obtained are direct measurements of time required for an ultrasonic wave to travel to the liquid interface and return. These numbers are readily converted to absolute distances, not relative values. The direction of depth change is clearly indicated.

The disadvantages of using this equipment for flow measurements are summarized below.

1. Since a sampling technique is used, providing a record of step changes, it is necessary to measure time between samples to determine flow rate.
2. The time measurements are quite sensitive to turbulence at the interface and vortices in the storage tank caused by large discharge rates. It is also quite sensitive to suspended material in the liquid. For example, two Alka Seltzer® tablets were placed in a small container of water. The equipment was quite erratic until the entrapped air bubbles drifted to the surface. A calm surface is required because of the small area of the surface sampled by the sound waves and is discussed in Ref. 5.

3. The velocity of sound in a liquid is a function of the temperature. An error of $1^{\circ}C$ would contribute an error of ±0.16 percent to the overall error. This would become appreciable when a small temperature gradient existed over a long tank. This gradient is typical of a liquid that has been stored in an exposed tank for a period of time.

4. It was found that time measurements to the nearest microsecond were the shortest that could be used with optimum repeatability. One characteristic of electronic counters is the plus-or-minus one count error in any time displayed. The velocity of sound in water and the timer accuracy require at least a 30-in. change in level between readings to reduce this error to a nominal ±0.1 percent. Sampling intervals of 1 sec were tried as liquid was flowing from the tank. The plus-or-minus one count error in time for the resulting small distances was quite large percentage wise.

In summary, it may be said that the ultrasonic method could be used quite successfully as a tank level indicator for vessels containing corrosive or flammable liquids. It would be possible to use the method for measuring average flow rate over a period of time by measuring static levels at two points sufficiently distant apart. It could also be used in conjunction with a microwave system to sense direction of flow and tank levels.

The results obtained with the microwave method indicate that flow rates can be obtained that are well within a tolerance of ±0.25 percent. This is attainable over short intervals of time or short increments of tank depth. This accuracy can be improved somewhat by using the averaging effects of a 10 period count that is available on most counters.

Turbulence or vortexing will have the same effect on level measurements with the microwave system as experienced with the ultrasonic method. However, two factors are present to reduce this effect. First, the small cross section of the wave guide channel provides a still pipe effect which reduces the disturbance at the reflecting surface. Also, the 10 period averaging noted above should give a value representative of the mean period.

As noted previously, a precision section of wave guide was fabricated to maintain wavelength tolerances within ±0.05 percent. Commercially available wave guide has a standard wavelength tolerance of ±0.1 percent. The tolerance of ±0.05 percent can be obtained on special order provided very large quantities are purchased.

Although satisfactory results were obtained with the microwave methods, some difficulties will have to be overcome to have a practical working system on a large scale for all liquids. The materials used for standard wave guides are not compatible with the fluids commonly used in rocket testing. It would be necessary to fabricate any wave guides used from a material found to be compatible with the particular fluid to be used.

An additional problem arises in regard to pressurization of the storage tank. Microwave tubes and crystal detectors will not withstand pressures of very large magnitude and must be protected by means of a wave guide pressure window. Commercially available windows are for pressure differentials of approximately 50 psi. It appears practical to fabricate a high pressure window from a thick block of dielectric material. If this is not possible, an outside contract for development of such a window would be required.

An estimation of the absolute accuracy of the microwave method is limited by the comparison devices used. The turbine-type flowmeter was used as a means of comparing a standard flow calibration bench with the microwave method. Also, variations in the cross-sectional area of the cylindrical tank used limited the accuracy of flow and volume data.

Some measure of the precision of the microwave method is shown by the small deviations obtained when the same quantity was determined several times - for example, the measurement of half-wavelength intervals. The precision of the microwave method was shown to be much better than that obtained with the flow bench when using the flowmeter as a comparison device.

## SECTION IV

## SUMMARY OF RESULTS AND CONCLUSIONS

The results of this study indicate that the microwave method is an accurate and repeatable method for measuring flow rate and changes in liquid level from a storage tank. As previously mentioned, some auxiliary method must be used to determine the level of the liquid at the start of flow. The use of the ultrasonic method with side tubes on the tank was found satisfactory.

A combination of the two methods would be usable with any shape tank provided the volume per unit level change is known at all levels. The ultrasonic method could be used to determine the level at which flow was started. The microwave method can be used to determine time rate of change of level.

Although the methods described should be applicable to other fluids, no experiments were performed on any fluid other than water. It is therefore not possible to state definite conclusions except in regard to measurements with water.

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Fig. 1 Photograph of Storage Tonk

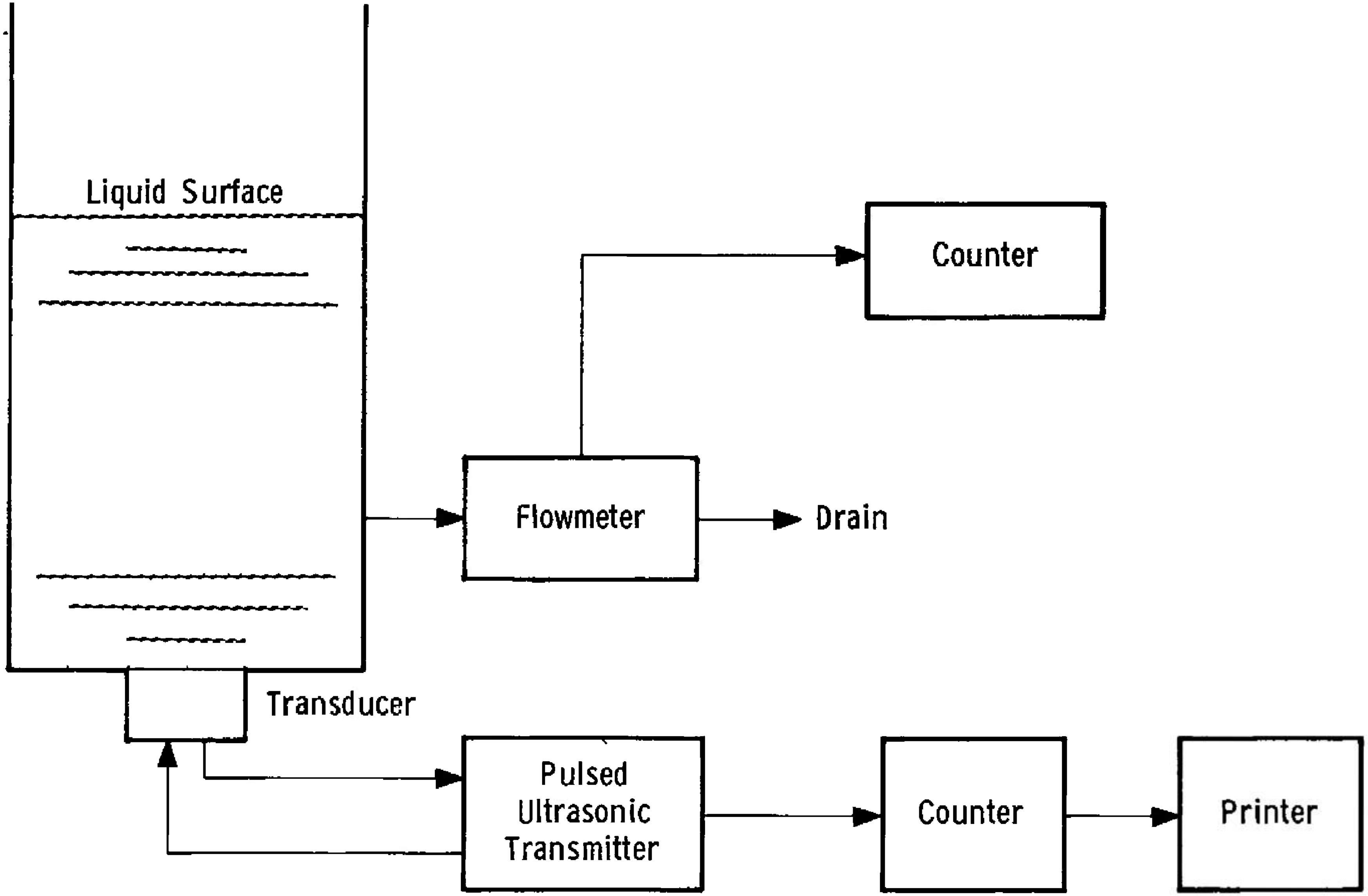

Fig. 2 Block Diagram of Ultrasonic Method

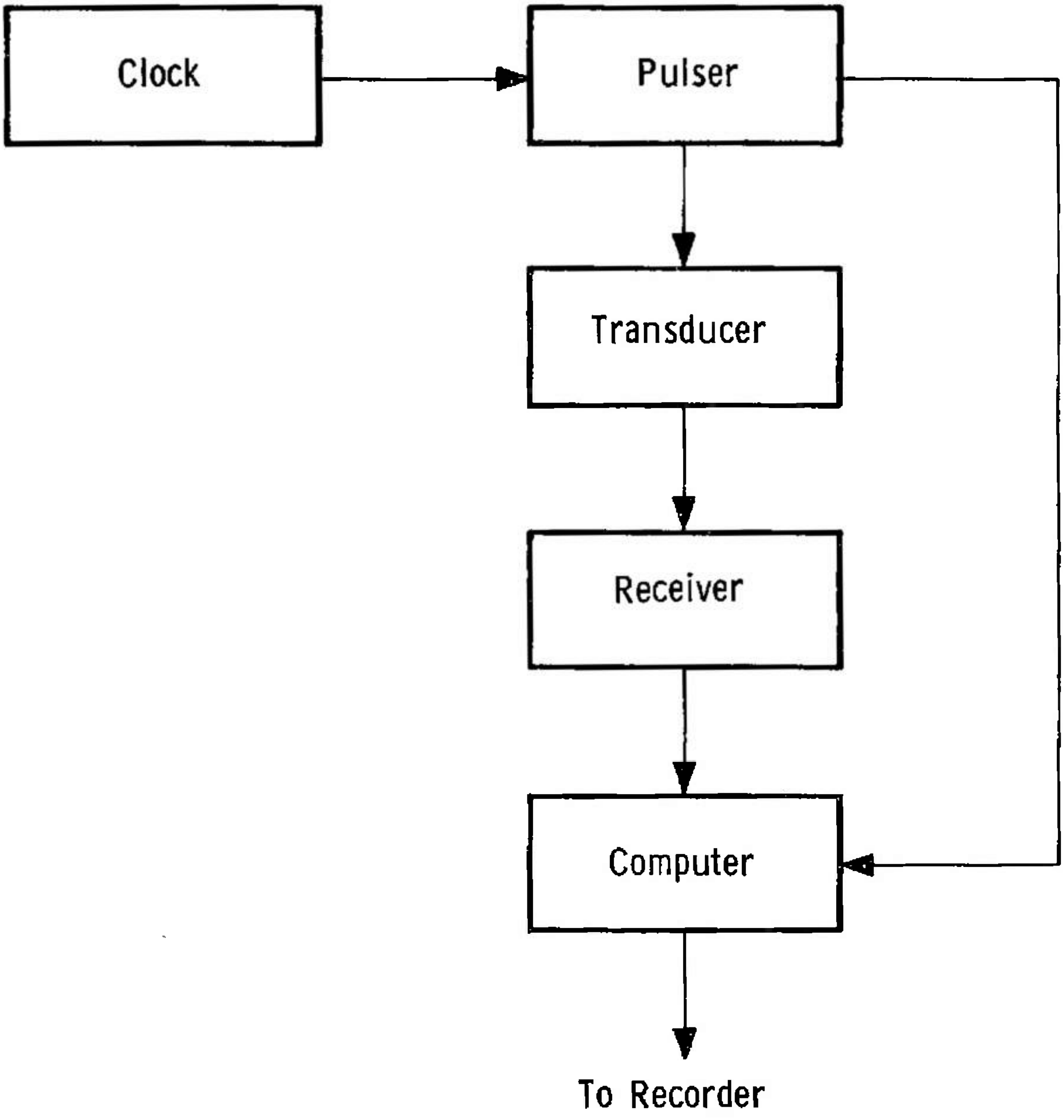

Fig. 3 Functional Block Diagram of Dual Stream Monitor

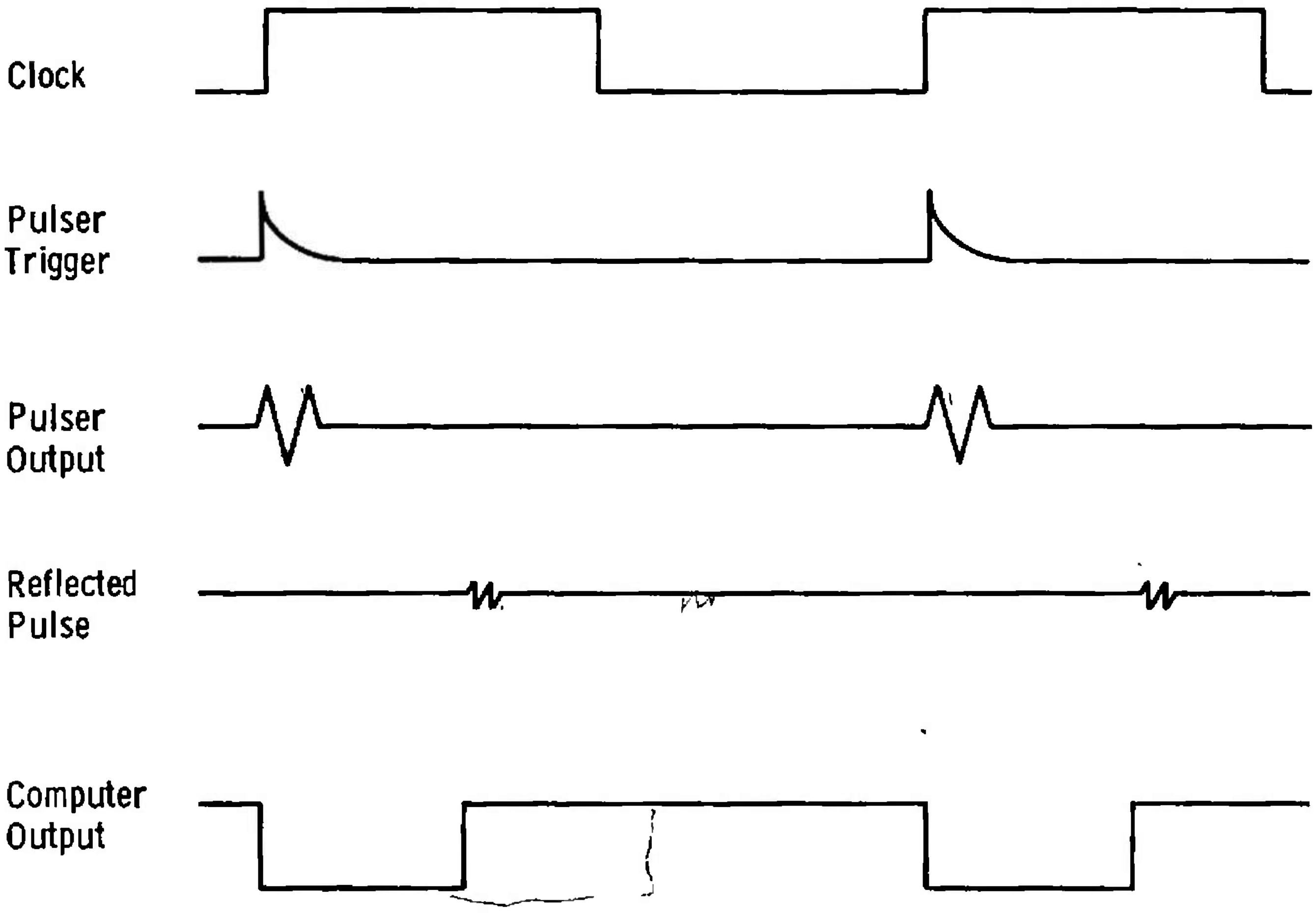

Fig. 4 Timing Diagram

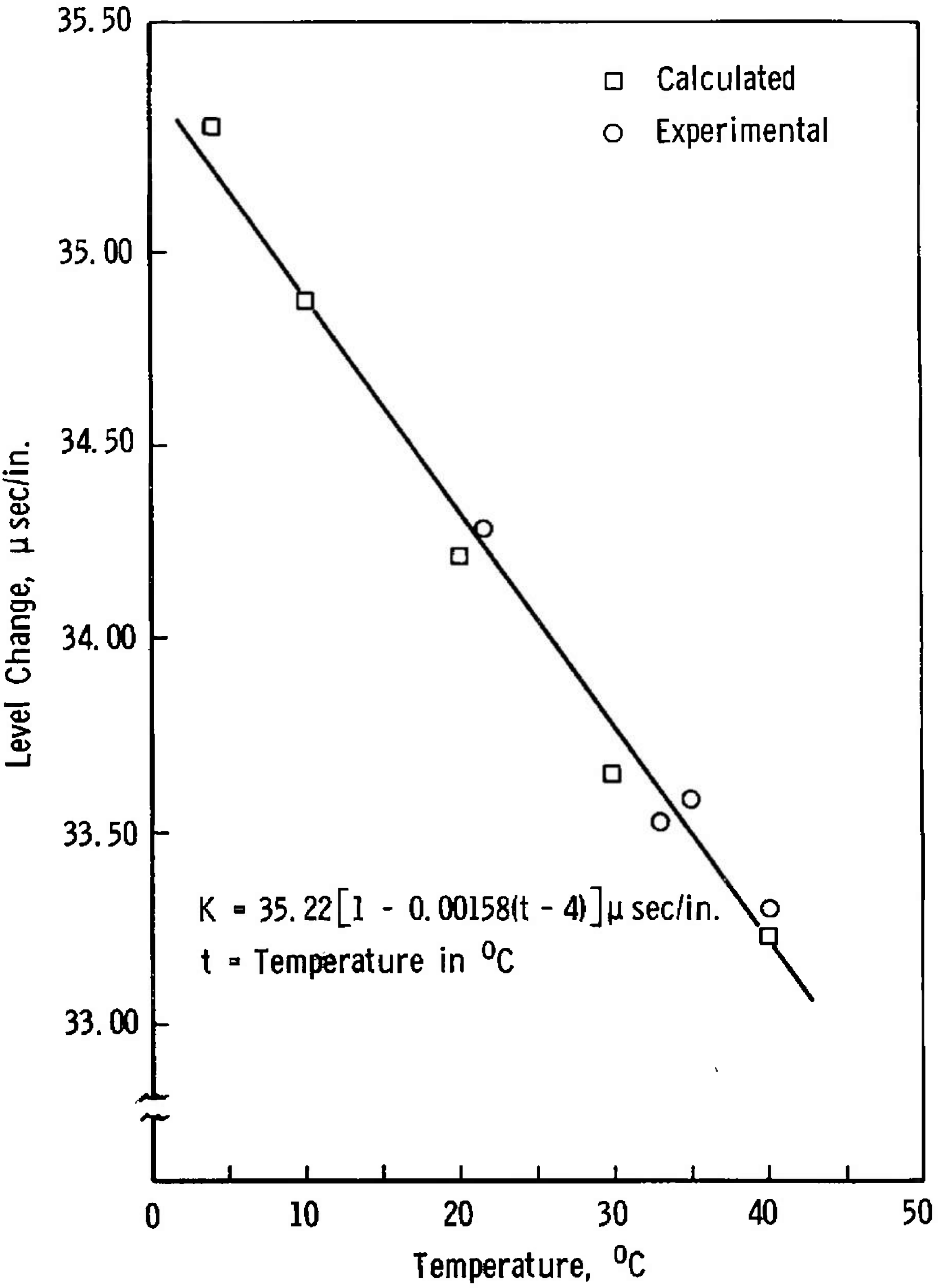

Fig. 5 Velocity of Sound versus Temperature

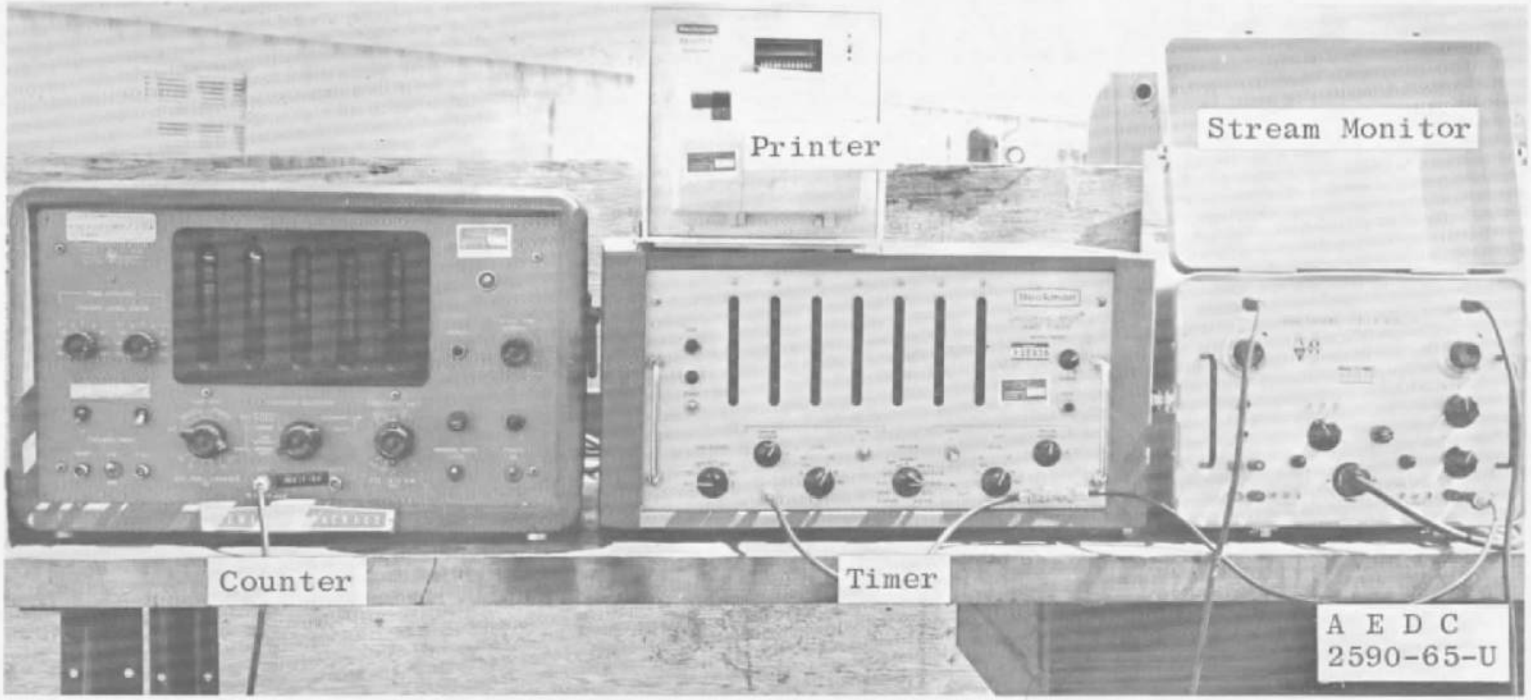

Fig. 6 Photograph of Ultrasonic Equipment

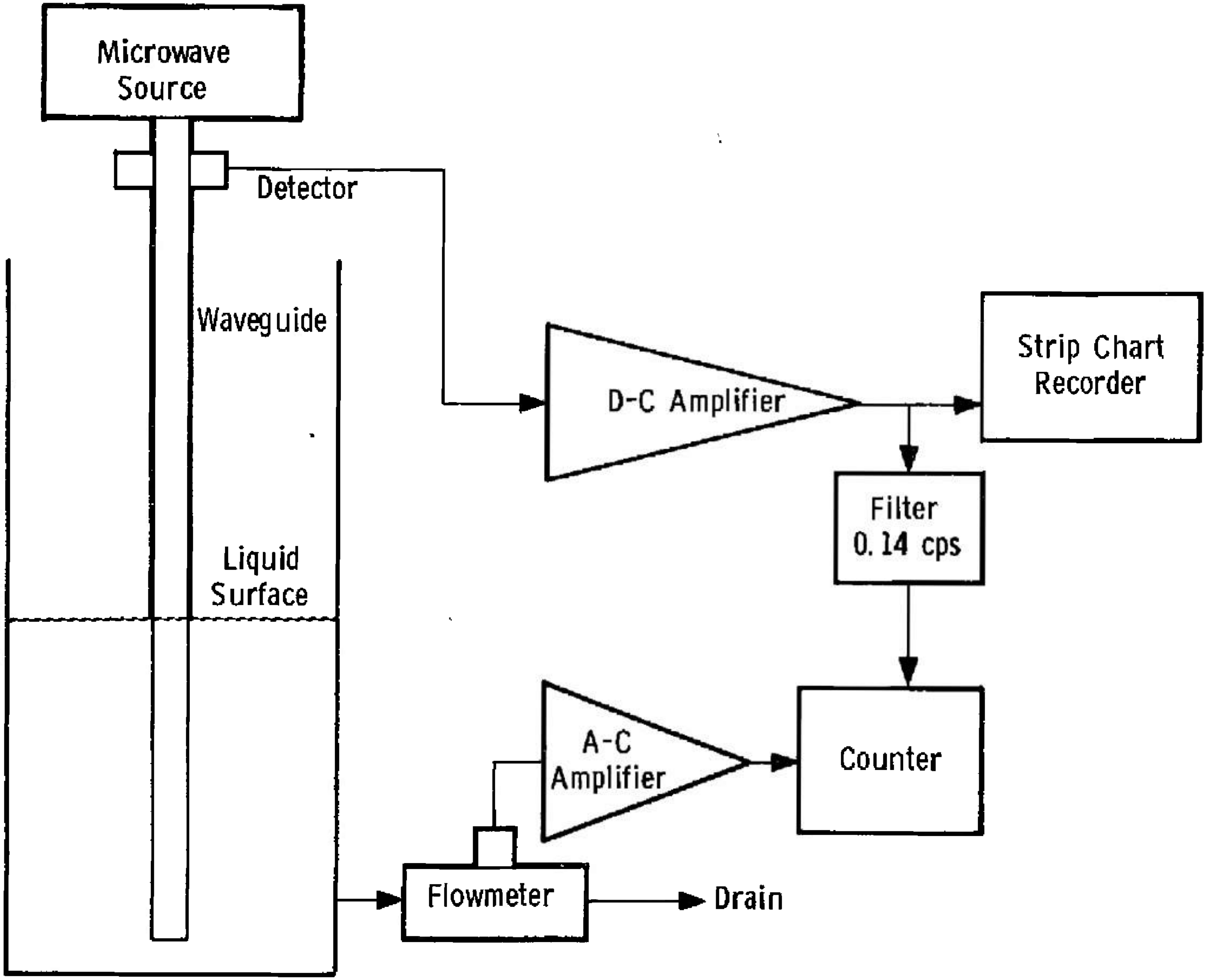

Fig. 7 Block Diagram of Microwave Method

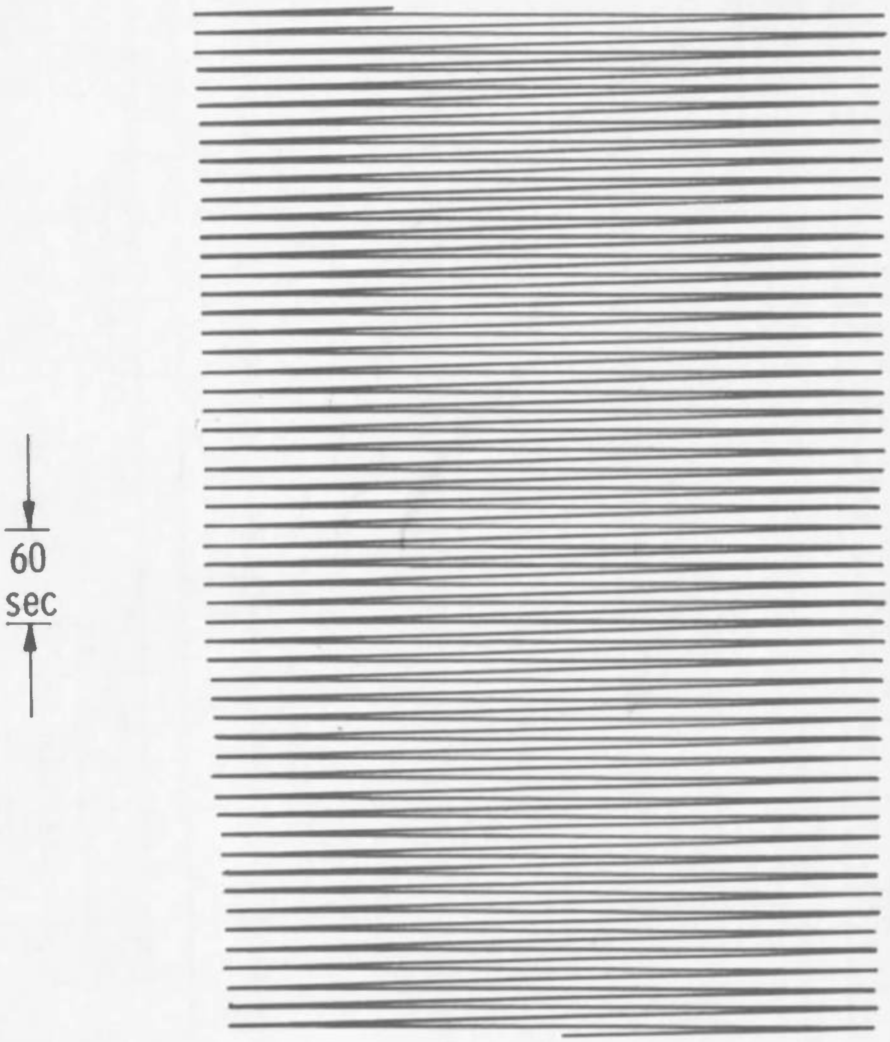

Fig. 8 Detector Output

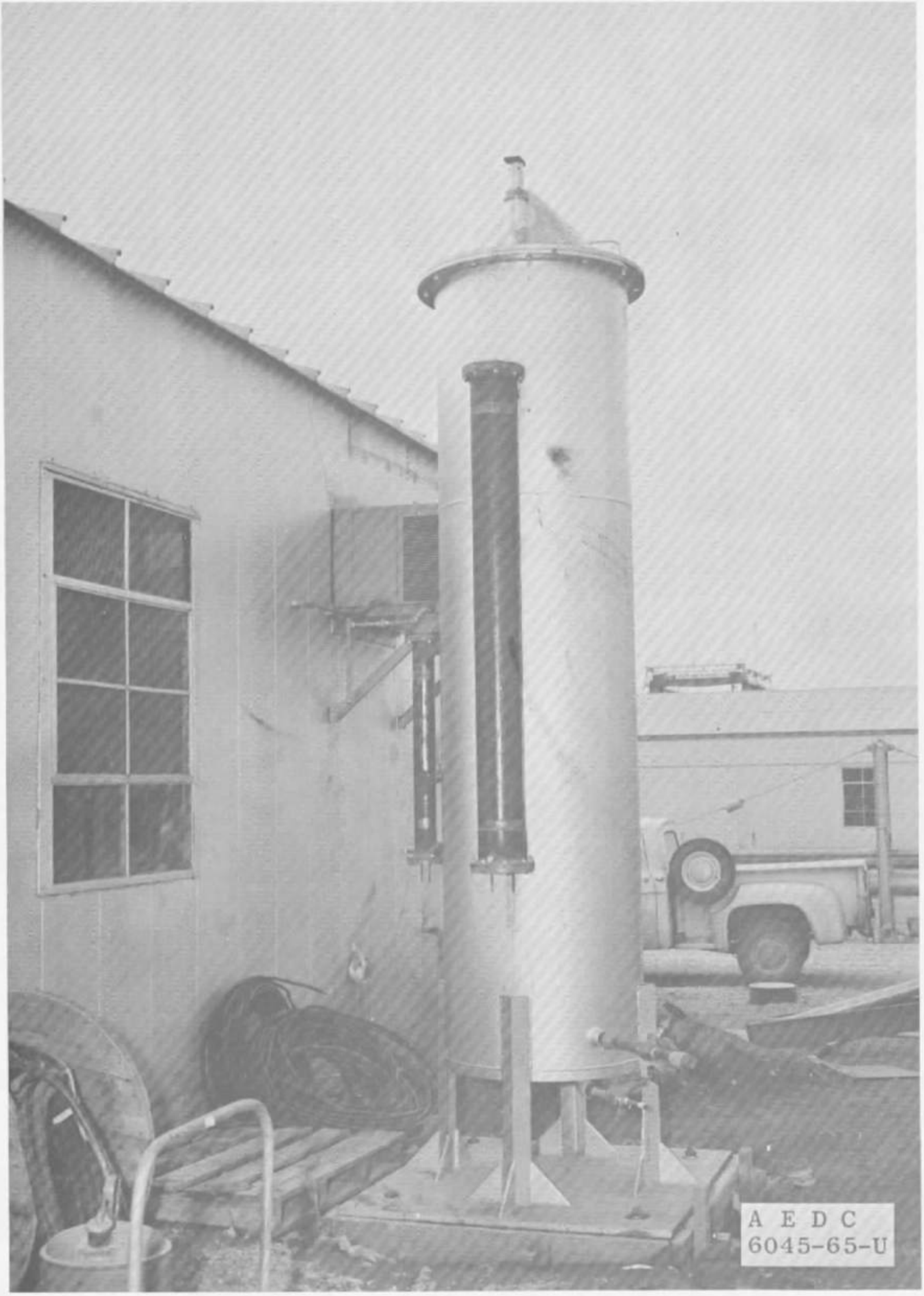

Fig. 11 Tank with Side Tubes

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| | | |
|---|---|---|
| 1. ORIGINATING ACTIVITY *(Corporate author)*<br>Arnold Engineering Development Center<br>ARO, Inc., Operating Contractor<br>Arnold Air Force Station, Tennessee | | 2a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED<br>2b GROUP<br>N/A |
| 3 REPORT TITLE<br>INVESTIGATION OF MICROWAVE AND SONIC METHODS FOR MEASURING LIQUID LEVEL AND FLOW RATE | | |
| 4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*<br>N/A | | |
| 5. AUTHOR(S) *(Last name, first name, initial)*<br>K. R. Carr and J. U. Clark, ARO, Inc. | | |
| 6. REPORT DATE<br>March 1966 | 7a TOTAL NO. OF PAGES<br>30 | 7b. NO. OF REFS<br>10 |
| 8a. CONTRACT OR GRANT NO.<br>AF40(600)-1200<br>b. Program Element 65402234<br>c.<br>d | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>AEDC-TR-66-1<br>9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*<br>N/A | |
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13 ABSTRACT

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