A WIDE-ANGLE INFRARED RADIOMETER
FOR RADIOACTIVE WASTE MONITORING

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RADIOACTIVE WASTE MONITORING

by

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April 1968

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ABSTRACT

An infrared radiometer system which monitors the temperature of stored radioactive waste materials is described. The temperature monitoring system indicates an overtemperature condition when 1.8% or more of the area of the stored waste rises 150°C above the 100°C background temperature in the storage tank. The system will also yield an output indication if the entire bottom temperature varies $\pm 1^\circ\text{C}$ from its ambient temperature. Effects of water vapor absorption on the incoming infrared energy and effects of temperature on the infrared radiometer are discussed.

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INTRODUCTION

High level radioactive waste materials from the fuels reprocessing plants at Hanford are stored in underground steel-lined concrete tanks. These wastes consist of two phases, a liquid which contains primarily ^{137}Cs and a sludge which contains ^{90}Sr and most of the other heat producing isotopes. Heat is removed from these tanks by evaporation of the supernatant liquid and subsequent recycle of the condensate. Various phases of the Hanford Waste Management program, however, require removal of the supernatant solution for either limited periods as during the sluice mining of the tank sludges or permanently as when air-cooling bare sludge.

A reliable method of monitoring the tanks for overtemperature conditions is thus required. At the request of the Atlantic Richfield Hanford Co., a program was undertaken to develop an infrared instrument which would be capable of monitoring the tank temperatures and which would be operable within the tank environment.

Other methods of monitoring the tanks' behavior such as embedding thermocouples in the sludge and remote photography using various film types have also been proven effective. The wide angle infrared radiometer described in this report provides an additional approach to the temperature monitoring problem.

SUMMARY AND CONCLUSIONS

In order to reliably monitor the temperature of the sludge in underground waste storage tanks, a system is needed which is capable of operating under the

extreme conditions of high levels of radioactivity, temperature, and humidity. The successful design of such an instrument is presented in this report.

Laboratory tests and tests with the instrument actually installed in a waste storage tank demonstrate that it is capable of detecting a ten-foot diameter hot region in the tank 150°C above the 100°C ambient tank temperature. A region of this size represents about 1.8% of the total area of the tank bottom. Calculations of water vapor absorption of the infrared energy from the sludge material in the tank have yielded curves which allow the operator of the instrument to correct measurement results for water vapor absorption under varying concentrations of water vapor.

The instrument described here provides a useful temperature monitoring technique which operates reliably under the above conditions present in the storage tanks. Its usefulness is further enhanced, since it may easily be installed in any of the many storage tanks present in the Hanford complex.

THEORY

Operation of this instrument relies on the self-heating property of materials containing radioactive fission products. It follows that areas where relatively larger amounts of sludge are concentrated will tend to be hotter than areas where significantly smaller amounts of sludge are present. Likewise, if the sludge protrudes above the water level, the temperature can rise appreciably. It is desirable that a reliable temperature monitoring system be available to warn of high temperature conditions.

All substances emit increasing amounts of infrared radiation as their temperature is increased. The radiant emittance from a substance depends directly upon its temperature and its emissivity (a measure of the radiant emittance of an object at temperature T compared to the radiant emittance from a standard reference blackbody at the same temperature). The sludge temperature in the tanks was assumed to be in the range from room temperature

to 100°C or greater, depending upon whether or not the sludge was completely covered with water. The emissivity of the sludge was assumed to be close to unity; that is, its emission properties were assumed to closely approximate a standard blackbody.

Measurements (see Figures 8-13) indicate that the radiometer can detect a ten-foot diameter hot region in the tank 150°C above the 100°C ambient tank temperature. Since the tanks themselves are approximately 75 feet in diameter, a region of this size represents about 1.8% of the total area of the tank bottom. The system will also yield an output indication if the entire bottom temperature varies $\pm 1^\circ\text{C}$ from its ambient temperature.

INSTRUMENTATION

The infrared radiometer is composed of two major sections: the optical head containing the infrared detector and its associated optical chopper and filter, and the electronic system used to process the signal from the infrared detector. Figures 1 and 2 illustrate the general construction of the instrument. Figure 1 depicts the optical head portion which is actually installed in the tank access riser, while Figure 2 shows the electronics console. The optical head will be described first.

The key component in the optical head is the infrared detector element. A standard PEM type detector was chosen for this application since it was available in the laboratory, and offered several operational advantages. Such a detector requires no external bias supply, it is relatively resistant to ionizing radiation, and its detectivity is adequate for this application. Finally, no cryogenic cooling is required for operation of the detector element.

Figure 3 shows a sectional view of the optical head with the locations of the major components indicated on the diagram. The infrared detector is positioned in the center of the cylindrical enclosure. Immediately in front of the detector is an optical chopper disc which chops the incoming infrared beam to the detector

FIGURE 1
Wide-Angle Infrared Radiometer

BNWL-773

FIGURE 2
Radiometer Electronics Console

FIGURE 3
Optical Head Assembly

to produce an ac signal output from the detector. An optical bandpass filter is placed in front of the chopper. The filter is designed to pass wavelengths that the PEM detector is sensitive to while attenuating wavelengths associated with unwanted emissions from the atmosphere of the tank. An infrared-transmitting Irtran-II[©] window is placed in the end face of the optical head. The window serves to transmit the infrared energy to the detector while providing a gas- and water-tight seal in the end of the enclosure. Such a seal prevents the environmental gas and vapors in the storage tanks from entering the interior of the optical head.

A small shroud, visible in the foreground in Figure 1, is attached circumferentially about the Irtran-II[©] window. A gas line running to the shroud from the opposite end of the instrument carries helium gas to a manifold in the center of the shroud. The helium exits in the vicinity of the window and is trapped temporarily in the shroud. The presence of this helium "bubble" prevents condensation from occurring on the window surface. Water condensing there would prevent the passage of infrared energy through the window.

Cooling water lines travel from manifolds installed on the opposite end of the instrument down to cooling coils wound on the two faces and inside wall of the optical head. An additional line carries argon to the inside of the optical head. Argon pressure inside the head is maintained at approximately 5 psig in order to prevent any contaminants in the tank atmosphere from entering the apparatus itself should a small leak occur. The argon atmosphere also prevents water condensation from occurring inside the head.

The flange visible at the other end of the device (see Figure 1) is designed to bolt directly to a mating flange on the tank access riser (the reader is referred to Figure 4 for a sketch illustrating the installation of the optical

[©] The registered trademark of the Eastman Kodak Co.

FIGURE 4
Radiometer Installation in Underground Storage Tank

head in the waste storage tank). A gas-tight seal is necessary at the top of the riser in order to prevent airborne radioactive materials from escaping from the tank.

The electronic system is contained in a standard relay rack enclosure and is shown in Figure 2. A block diagram of the system appears in Figure 5. Two commercial amplifiers, a Tektronix type 122 and a Hewlett-Packard 450A, are used to boost the signal output from the PEM detector to a level of several volts, peak-to-peak. The signal is then filtered to remove noise and is passed into a simple diode detector. The diode detector output is a dc level, having an amplitude proportional to the amount of infrared energy being received by the PEM detector at any given time.

After detection, the signal is passed into one input of a dc differential amplifier. A reference signal is applied to the other input. The reference signal is obtained from a voltage divider consisting of a well-regulated supply and a ten-turn precision potentiometer. Since the differential amplifier output is the algebraic difference between the signals applied at its inputs, the reference level is used to provide a bucking voltage to cancel the signal due to the normal background infrared radiation in the tank. The increased signal due to a hot spot thus causes a non-zero output signal from the differential amplifier. This signal drives a linear current source which in turn drives a panel meter indicating relative radiometer output. Output of the radiometer is read by adjusting the reference voltage to give a zero meter reading, and reading the reference voltage potentiometer dial. The output is calibrated so that a pre-determined level corresponds to a known hot-spot temperature. An alarm relay is actuated when a preset point is reached. Circuit descriptions, and a schematic diagram of the electronics system appear in Appendices B and C.

FIGURE 5
Block Diagram of Radiometer Electronics System

EXPERIMENTAL

It proved necessary to perform extensive calibration tests in the laboratory due to the sensitivity of the radiometer to various external and internal temperature effects. In order to perform meaningful tests it was necessary to model the storage tank bottom on a small scale. Such a model was easily achieved by using a standard laboratory hot plate to represent the tank bottom and a small disc heater to represent a hot spot. That such a model is valid can readily be demonstrated on the basis of radiation theory. In particular, it can be shown that the infrared detector output signal will be constant provided that the radiation flux in the solid angle representing the acceptance angle of the detector remains constant. Thus, a small hot plate positioned close to the detector is equivalent to the very much larger tank bottom many feet from the detector in the actual installation in the tank.

In the laboratory tests, the radiometer was positioned in the horizontal plane and the hot plate was supported immediately in front of the optical window. A black-anodized aluminum disc was attached to the hot plate to provide a more uniformly heated surface. A small disc heater was moved to various positions on the surface of the aluminum disc in order to simulate the effect of a given-temperature hot spot appearing at various positions on the tank bottom. A sketch of the experimental setup appears in Figure 6.

The radiometer output was found to be a sensitive function of the internal temperature in the optical head. Furthermore, the PEM detector exhibited a different response to a given amount of infrared radiation arriving at the detector from different positions (with respect to a fixed detector position). Thus, it was of interest to generate curves which illustrated these effects to enable the operator of the device to properly interpret readings in the actual installation.

FIGURE 6
Laboratory Tank Bottom Modeling Setup

Figure 7 shows the effect of a given amount of infrared radiation arriving at the PEM detector from different orientations with respect to the detector. The data were obtained by holding the internal temperature of the optical head and the hot plate representing the tank bottom both at constant temperatures while moving a constant-temperature disc heater around the perimeter of the hot plate. The resulting curve exhibits two peaks approximately 180° apart and two valleys also 180° apart. The PEM detector was thus found to have a preferential axis yielding maximum detector sensitivity. Minimum sensitivity was noted along an axis perpendicular to the preferential axis. These data are significant since the access risers in the storage tanks are offset from the geometrical center of the tanks by approximately twelve feet. The response of the radiometer to heated regions in the tank at a maximum distance away from the device will be smaller than for regions closer to it. This effect can be overcome by orienting the radiometer in the riser such that the preferential axis of the PEM detector lies along a radius line in the tank passing through the most distant point from the radiometer. Thus, the direction of maximum device sensitivity is aligned with the most distant points in the tank.

In order to accurately determine the effects of internal optical head temperature on the radiometer output signal, it was necessary to devise a test in which the various conditions that would occur during operation in a hot vapor atmosphere (target, background, and internal optical head temperatures) could be accurately simulated. Data from these tests were compared with the more complete laboratory data to provide complete calibration curves for the instrument.

A 4000 gallon stainless steel tank at an outdoor location in PNL was selected to perform the simulation tests. The tank had an access port in the top through which the radiometer could be installed. Furthermore, steam lines present in the

FIGURE 7
Change in Radiometer Output Due to Hot Spot Versus Angle of
Hot Spot from Reference Position

tank made it possible to heat water in order to simulate operational conditions. The presence of water vapor in the tank under the test conditions further enhanced the usefulness of the tests, since in the actual waste storage tank installation the presence of various amounts of water vapor was anticipated. The tests would thus yield information on the absorption of infrared radiation by the water vapor.

A target hot plate was installed in the tank and was mounted in such a manner that it could be swung to various positions within the acceptance angle of the radiometer. In this manner, the sensitivity of the detector to hot spots located at various distances from the geometrical center of the radiometer could be determined for comparison with the laboratory data. The temperature of the hot plate was controlled by means of a Variac autotransformer, while the temperature of the water in the tank (background temperature) was controlled by varying the flow of steam through the pipelines in the tank. Internal optical head temperature was controlled during the tests by varying the rate of flow of cooling water through the optical head cooling coils.

Figures 8 and 9 show plots of the radiometer output versus internal optical head temperature for various constant values of background (water) temperature. Two plots were necessary in order to ascertain the effect of infrared energy emitted from the tank walls when they were hot. Figure 9 provides this information, while Figure 8 shows data obtained with cold tank walls.

It is readily observed that the output signal decreases rapidly for a given background temperature as the internal optical head temperature increases. This characteristic of the radiometer is due to the temperature sensitivity of the PEM detector; as the temperature of the detector increases above normal ambient temperature, the output signal is proportionally diminished.

It is thus necessary to know the internal optical head temperature at all times in order to correct the observed response for any internal temperature

FIGURE 8
Composite Calibration of Radiometer Output Versus Internal
Temperature and Tank Bottom Temperature (Tank Walls Cold)

FIGURE 9
Radiometer Output Versus Internal Temperature and Tank
Bottom Temperature (Tank Walls Hot)

variations which might occur. A thermocouple was positioned in the housing next to the PEM detector in order to provide a constant real-time monitor of the internal temperature.

It is, of course, more desirable to maintain the internal optical head temperature within limits so that the correction is as small as possible. The cooling coils on the surface of the optical head effectively accomplish this. As mentioned previously, the temperature can be held fairly constant by controlling the rate of flow through the coils and by holding the cooling water temperature constant. A $\frac{1}{2}$ -inch thick layer of General Electric RTV-90 silicone rubber cast around the outside of the optical head was necessary to provide insulation and reduce heat picked up from condensing water vapor. Although this material is embrittled by gamma radiation, it retains adequate strength for use as an insulating coating.

In order to determine the change in the radiometer output due to a given temperature hot spot, as a function of the distance from the axis of the radiometer to the center of the hot spot, further use was made of the experimental installation in the 4000 gallon tank. For this experiment, the hot plate installed in the tank was used to simulate a hot spot. By moving the hot plate radially out from the center of the radiometer, it was possible to obtain quantitative data indicating the sensitivity of the device to remotely-located hot spots.

Figure 10 illustrates the sensitivity of the instrument to hot spots of three given temperatures as the distance between the radiometer axis and the hot spot center is increased. It can readily be observed that the sensitivity of the instrument drops off rapidly as the distance between the hot spot and the radiometer axis is increased. Thus it is desirable that the most sensitive (preferential) axis of the PEM detector be lined up with the most distant points in the storage tank installation.

FIGURE 10
Increase in Radiometer Output Above Background as a Function
of Distance Between Radiometer Axis and Center of 8 ft. Hot
Spot in Tank

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REFERENCES

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APPENDICES

APPENDIX A

Calibration for Hot Spot Detection

A general tank bottom temperature between 80°C and 100°C gives a radiometer output voltage that depends upon whether the tank walls are hot or cold as shown in Figures 8 and 9. This voltage is called the "background" in the curves that follow. Figures 11, 12 and 13 show the increase in radiometer output voltage when an 8.2 foot diameter hot spot is produced on a tank bottom that is at any temperature between 80°C and 100°C. Hot spot temperatures are shown as the independent variable (abscissa) in the curves. The distance from the radiometer axis to the hot spot center, radially outward along the tank bottom, is shown as a parameter for each curve. This distance was measured in a direction that corresponds to the zero degree direction in Figure 7. As mentioned earlier, the zero direction was aligned with the most distant point on the tank bottom in the final installation in the 108-SX tank. Using Figure 7 and Figures 11 and 12 we see that the sensitivity to a hot spot in any direction, except the 270 degree direction, is adequate for detection of a 250°C hot spot 8.2 feet in diameter that is located near the outer edge of the tank bottom (the 270° direction is masked by a 24 inch riser in the tank and is, therefore, not important). Sensitivity to hot spots closer to the radiometer is, of course, greater as shown in Figures 10, 11, and 12. Hence, an 8.2 foot diameter hot spot at any location in the tank that is visible to the radiometer is detectable when it reaches a temperature no greater than 250°C (assuming a low water vapor concentration in the tank atmosphere).

The curves in Figures 11 through 13 are for a tank atmosphere which is free of water vapor. If water vapor is present, a correction must be made to account for attenuation of the infrared energy reaching the radiometer. This correction

FIGURE 11
Increase in Radiometer Output Above Background as a Function
of Hot Spot Temperature and Position

FIGURE 12
Increase in Radiometer Output Above Background as a Function
of Hot Spot Temperature and Position

FIGURE 13
Increase in Radiometer Output Above Background as a Function
of Hot Spot Temperature and Position

can be made as an increase in hot spot temperature that would be required to obtain the same radiometer output as would be obtained for the same hot spot without water vapor attenuation. Although the minimum detectable hot spot temperatures are somewhat higher when water vapor effects are considered, they are still low enough to be within the worst case design goal (detection of a 600°F (315°C) hot spot 10 feet in diameter). The method for making water vapor corrections is described below in the section entitled "Correction for Water Vapor Absorption".

Figures 11 through 13 show the importance of operating the radiometer at internal temperatures no higher than 25°C; a severe decrease in sensitivity occurs at higher temperatures. The time at a given temperature is also important; the internal operating temperature of the radiometer should be as nearly constant as possible for 12 hours prior to a measurement to allow equilibrium to be established.

Calibration Using Built-In Calibration Source

The radiometer output voltage is shown in Figure 14 as a function of internal radiometer temperature. The calibration source temperature is shown as a parameter on each curve. It is necessary to position the calibration source under the radiometer so that a maximum signal is obtained during calibration. At infrared levels that give signals greater than 9.25 volts, it is necessary to reduce the gain of the Hewlett-Packard Model 450A amplifier from 40 db to 20 db to prevent saturation. As shown in Figure 14, this occurs when the calibration source reaches a temperature of 200°C.

To check the operation of the radiometer, the calibration source is heated to a temperature of approximately 180°C, and swung into the position giving a maximum signal. Readings of the calibration source temperature, radiometer internal

FIGURE 14
 Radiometer Output as a Function of Internal Radiometer
 Temperature and Built-in Calibration Source Temperature

temperature, and output voltage are then made and compared to the values in Figure 14. The output voltage should be within ± 0.05 volts of the correct value. The source should be held at temperature for an hour or so prior to calibration to ensure that equilibrium is reached. As mentioned in the section on hot spot detection, it is essential that the radiometer internal temperature be constant for 12 hours prior to any measurements.

The calibration source must be swung out of the field of view of the radiometer after the calibration check is completed, since radiation coming from the tank bottom would be blocked otherwise.

Calibration for Overall Tank Bottom Temperatures Higher Than 100°C

The infrared radiation input to the radiometer from the overall tank bottom and walls at a given temperature is approximately the same as the infrared input from the built-in radiation source at the same temperature. Hence, Figure 14 can also be considered as a calibration for the approximate overall tank bottom temperature, provided the walls are at about the same temperature.

Correction for Water Vapor Absorption

Water vapor in the atmosphere through which infrared is transmitted causes attenuation of the infrared signal due to absorption. This absorption is an extremely complicated function of the infrared wavelength. For this reason, theoretical methods for predicting the absorption under various conditions give an approximation that is only accurate to within a few percent. Empirical measurements duplicating the in-tank conditions would give precise results, but these were too costly to make within the available funding levels. A literature search showed that empirical data were available for mixtures of CO_2 and H_2O vapor, pure H_2O vapor in certain specified wavelength bands, and for ordinary

atmospheric transmission over long pathlengths. However, none of the conditions under which these data were taken were the same as those that will prevail during in-tank temperature monitoring with the wide-angle radiometer. The empirical data available in the literature were therefore not applicable, and instead, the best available theoretical model was used to compute the correction curves for water vapor absorption. This model is called the Quasi-Random Model of Band Absorption⁽¹⁾. Since the theoretically predicted absorption is approximate, and since a small hot spot in the most remote location in the tank gives a change of only about 5% in the radiometer output voltage, the presence of a large amount of water vapor in the tank atmosphere would mean that the background voltage should be established by measurement prior to the occurrence of a hot spot to assure a high enough accuracy for detection of the most remote hot spots. However, once the background voltage is established for a given water vapor content and overall tank bottom temperature, the changes in background voltage resulting from a moderate change in either of these two parameters can be predicted theoretically with enough accuracy for practical applications.

Unlike the tank bottom background signal level, hot spot signals can be theoretically predicted with high enough accuracy at any water vapor concentration. A few percent error in the small contribution a hot spot makes to the total signal does not seriously influence the final result. The correction for water vapor absorption can be made by directly determining the increase in target temperature required to increase the infrared emission enough so that it compensates for absorption of the infrared signal as it passes through the tank atmosphere. The final information desired is the value of target temperature that would be required to give a predetermined output voltage from the radiometer when the tank atmosphere contains any known amount of water vapor. In using the quasi-random model to

determine the effects of absorption, it is necessary to include the effect of the spectral distribution of the target radiant emittance, and the bandpass of the infrared filter in the radiometer. The spectral response of the detector should also be included for best accuracy. However, the photoelectromagnetic detector response is not strongly dependent on wavelength in the interval of interest in the present application. In addition, ordinary off-the-shelf detectors rarely have precisely the spectral response furnished for typical units by the manufacturers. For this reason, the spectral response of the detector was assumed constant. Since the photoelectromagnetic detector is a quantum detector, its output signal is a function of the photon flux falling on the detector and computation of absorption effects must thus be in terms of photon flux.

Table I shows the product of the spectral radiant photon emittance, $N(\lambda)$, of the target, the spectral transmittance factor, $G(\lambda)$, for the infrared bandpass filter, the spectral transmittance of the water vapor, $F(\lambda)$, in the tank atmosphere, and the narrow incremental bandwidth $\Delta\lambda$. This product is tabulated according to the wavelength, λ , the water vapor content of the infrared pathlength in centimeters of precipitable water, and the target temperature (the number of centimeters of precipitable water, cm. pr. H_2O , are found by considering all of the water vapor in the infrared path between the target and radiometer to be liquified at one end of the path; the height of the water column in centimeters thus produced is defined as the value of cm. pr. H_2O). It can be shown that the product given in the table is the radiant photon emittance of the target adjusted for the absorption of the filter and water vapor. Multiplying these values by a geometry factor, ϕ_g , gives the values of spectral photon irradiance, $N_{D\lambda}$, within the increment $\Delta\lambda$ at the detector (the geometry factor takes into account the size and location of the target area). Summation of all values within a given column of the table thus gives the value of photon irradiance, N_D , at the detector,

RATIO OF TRANSMITTED PHOTONS TO GEOMETRY FACTOR BETWEEN 3.08 AND 5.72 MICRONS FOR VARIOUS
ATMOSPHERIC WATER VAPOR CONTENTS AND TARGET TEMPERATURES

$$\left(\text{BODY OF TABLE SHOWS } \frac{N_D \lambda}{\Phi_g} \times 10^{-18} = F(\lambda) G(\lambda) N(\lambda) \Delta \lambda \times 10^{-18} \right)$$

$$\left(\text{BOTTOM LINE OF TABLE SHOWS } \frac{N_D}{\Phi_g} \times 10^{-18} = \sum_{\lambda=3.08}^{\lambda=5.72} \frac{N_D \lambda}{\Phi_g} \times 10^{-18} \right)$$

λ	250° Target				300° Target				350° Target			
	1.0 cm Pr H ₂ O	0.5 cm Pr H ₂ O	0.2 cm Pr H ₂ O	0.1 cm Pr H ₂ O	1.0 cm Pr H ₂ O	0.5 cm Pr H ₂ O	0.2 cm Pr H ₂ O	0.1 cm Pr H ₂ O	1.0 cm Pr H ₂ O	0.5 cm Pr H ₂ O	0.2 cm Pr H ₂ O	0.1 cm Pr H ₂ O
5.72	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
5.55	0.000	0.000	0.004	0.009	0.000	0.001	0.006	0.014	0.000	0.001	0.008	0.020
5.40	0.000	0.004	0.014	0.027	0.001	0.006	0.022	0.042	0.002	0.008	0.032	0.061
5.25	0.000	0.016	0.030	0.047	0.005	0.018	0.048	0.075	0.008	0.027	0.071	0.111
5.13	0.014	0.028	0.049	0.063	0.022	0.045	0.078	0.100	0.033	0.067	0.116	0.149
5.00	0.025	0.041	0.060	0.072	0.041	0.066	0.097	0.116	0.061	0.098	0.145	0.174
4.87	0.039	0.052	0.066	0.074	0.063	0.085	0.108	0.121	0.095	0.128	0.163	0.184
4.76	0.050	0.063	0.076	0.083	0.082	0.104	0.125	0.136	0.125	0.158	0.190	0.207
4.65	0.052	0.062	0.071	0.076	0.088	0.104	0.120	0.128	0.135	0.160	0.184	0.197
4.55	0.066	0.071	0.076	0.078	0.112	0.121	0.129	0.133	0.174	0.188	0.200	0.206
4.45	0.071	0.074	0.076	0.077	0.121	0.126	0.130	0.131	0.190	0.198	0.203	0.206
4.35	0.074	0.075	0.076	0.076	0.127	0.129	0.131	0.131	0.201	0.205	0.207	0.207
4.25	0.063	0.064	0.065	0.065	0.112	0.113	0.114	0.115	0.179	0.181	0.183	0.183
4.16	0.056	0.056	0.056	0.056	0.099	0.100	0.100	0.100	0.161	0.162	0.162	0.162
4.08	0.054	0.054	0.054	0.055	0.096	0.096	0.097	0.098	0.157	0.158	0.159	0.160
4.00	0.053	0.052	0.053	0.053	0.093	0.094	0.094	0.094	0.156	0.156	0.157	0.157
3.92	0.049	0.050	0.050	0.050	0.091	0.091	0.092	0.092	0.151	0.152	0.152	0.152
3.84	0.040	0.041	0.041	0.041	0.076	0.076	0.077	0.077	0.126	0.127	0.128	0.128
3.77	0.038	0.038	0.039	0.039	0.072	0.073	0.073	0.074	0.119	0.121	0.122	0.122
3.70	0.034	0.035	0.036	0.037	0.065	0.068	0.070	0.070	0.108	0.113	0.116	0.118
3.63	0.029	0.029	0.030	0.030	0.055	0.056	0.057	0.057	0.094	0.096	0.098	0.098
3.57	0.026	0.027	0.028	0.028	0.050	0.052	0.053	0.054	0.087	0.091	0.093	0.094
3.51	0.025	0.026	0.026	0.027	0.048	0.050	0.051	0.052	0.085	0.089	0.091	0.092
3.45	0.020	0.021	0.023	0.023	0.041	0.044	0.047	0.048	0.073	0.079	0.084	0.087
3.39	0.015	0.017	0.019	0.021	0.031	0.036	0.041	0.043	0.056	0.064	0.073	0.077
3.33	0.011	0.013	0.014	0.015	0.022	0.026	0.029	0.031	0.039	0.046	0.052	0.056
3.27	0.003	0.003	0.004	0.005	0.006	0.007	0.009	0.010	0.010	0.013	0.017	0.019
3.22	0.001	0.001	0.002	0.003	0.002	0.003	0.005	0.006	0.004	0.006	0.009	0.011
3.18	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.003	0.003	0.004	0.005	0.006
3.13	0.000	0.000	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.003
3.08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001
$\frac{N_D}{\Phi_g} \times 10^{-18}$	0.909	1.014	1.140	1.232	1.624	1.792	2.007	2.152	2.633	2.898	3.223	3.449

TABLE 1

within the 3.08 to 5.72 micron wavelength band, divided by the geometry factor. The summation for each column is shown at the bottom of the column. For compactness, the $N_{D\lambda}/\phi_g$ values shown in the table were multiplied by 10^{-18} . It is thus necessary to multiply the tabulated values by 10^{+18} to obtain the true values.

The target temperature increase required to give a constant photon irradiance at the detector can be determined from a plot of the irradiance at the detector as a function of moisture concentration with the target temperature as a parameter. Figure 15 shows such a plot. This plot was constructed from values given in Table I. To use the plot to determine, for example, the minimum detectable hot spot temperature the procedure is as follows: The minimum detectable hot spot temperature with no absorption is determined from the curves in Figures 10 and 11 or 12 (recall that operation at temperatures greater than 25°C as in Figure 13 is not recommended). The point corresponding to that temperature value is located along the 0.00 cm. pr. H_2O axis in Figure 15. This point gives the N_D/ϕ_g value required for detection of the hot spot. The value of target temperature required to give this N_D/ϕ_g value, when there is moisture content in the tank atmosphere, is found by locating the intercept of the N_D/ϕ_g value and the moisture concentration value in Figure 15. The temperature that corresponds to the constant temperature curve passing through this point is determined by interpolating between the curves shown in Figure 15.

As a further example of determining the minimum detectable target temperature when moisture is present in the tank atmosphere, let us consider a numerical example: Assume that the hot spot is 8.2 feet in diameter, and that it is located in the most remote region of the tank bottom. Assume that the remainder of the tank bottom is covered with water at 100°C , and that the radiometer internal temperature is 25°C . The atmosphere in the tank, as well as the tank walls, would be at approximately 100°C . A 63 foot long slant path of approximately 100% water vapor saturated atmosphere would exist between the detector and hot spot. At a density

FIGURE 15
 Approximate Photon Flux of Target as seen Through the Filter
 and Various Amounts of Water Vapor (No Fog in Tank)

of 0.598 Kg/m^3 , there would be approximately 1.15 pr. cm. H_2O in the path. Consulting Figure 12 we find that the minimum detectable hot spot temperature with no absorption is 250°C , since this temperature gives a signal change just equal to the long term instrument error of ± 0.05 volt. From Figure 15 we find that the N_D/ϕ_g value corresponding to the given target temperature is 1.6×10^{18} photons/cm² micron sec., assuming no absorption from water vapor. To account for the 1.15 pr. cm. H_2O in the infrared path, we merely find the (1.15, 1.6×10^{18}) coordinate in Figure 15 and interpolate to determine the target temperature required. This is found to be about 297°C which is the target temperature required to produce an N_D/ϕ_g value of 1.6×10^{18} photons/cm² micron sec. at the detector when the infrared path contains 1.15 pr. cm. H_2O .

The geometry factor, ϕ_g , and irradiance, N_D , will not ordinarily need to be known separately since the geometry with water vapor in the atmosphere is nearly the same as that without water vapor (neglecting refraction effects). This saves a great deal of labor, since it eliminates the need for establishing a view factor for each hot spot size and location. Figure 15 is thus universally applicable to all hot spots regardless of their size and location.

APPENDIX BCircuit Description of the Radiometer Electronics System

The electronics system incorporated in the radiometer is composed of three sections: the infrared detector and its associated amplifiers and filters; the differential amplifier and linear current source which provide front-panel meter indications of the radiometer output; and circuitry used to drive an alarm relay. There is also a separate circuit intended to provide real-time meter output corresponding to the thermocouple output from the couple located inside the optical head. This section has not been used in the present instrument as it is insufficiently sensitive to respond to the very small temperature changes which occur in the optical head. A brief description of it will be presented at the end of this section, however.

Signal processing begins at the infrared detector. The detector output signal is carried through RG-58A/U coaxial cable to the instrument console. The low output impedance level of the detector allows direct processing of the output signal through a substantial run of cable before degradation of the signal due to cable noise and losses in the cable becomes of any consequence. A Triad G4 geoformer located on the instrument console provides an impedance transformation from the relatively low cable impedance to the considerably higher input impedance of the Tektronix RM122 preamplifier. A voltage step-up is also realized through the geoformer.

The Tektronix RM122 preamplifier provides a differential input which is used to reject common-mode noise voltage (mainly 60 Hz power line noise) entering the system through the input cable. It features, in addition, means of adjusting the preamplifier bandwidth. The upper and lower 3db frequencies are set to pass the 450 Hz signal frequency while simultaneously providing a degree of rejection of random noise signals that are also present in the signal at this point.

The output from the RM122 is applied to the input of a Hewlett-Packard 450A main amplifier. The combination of the two amplifiers provides the required overall system gain of 10,000 (the RM122 provides a gain of 100 as does the 450A). It is well to mention at this point that such a preamplifier-amplifier combination is indeed necessary since the RM122 is incapable of providing output voltage swings much in excess of 1 volt peak-to-peak. The 450A provides a 30 volt peak-to-peak swing which is considered adequate for this application.

Additional passive filtering is provided at the output of the 450A by an RLC filter section. The filter is designed to pass the 450 Hz sinusoidal voltage.

The IN914 diode detector rectifies this sinusoidal signal voltage and provides a dc level which is proportional to the peak-to-peak amplitude of the ac signal input. The magnitude of the dc level is thus proportional to the varying ac level present at the infrared detector output. As the amount of infrared energy arriving at the infrared detector increases (due to hot spots in the tank) the dc level at the diode detector output increases accordingly. That is, hot spots giving rise to increased excitation of the infrared detector yield progressively increasing dc levels at the diode detector output.

At this point, then, there is available a varying dc signal, proportional to the infrared detector output, which can now be utilized to provide deflection of a panel meter or other suitable indicating devices in order to supply an output indication from the instrument.

Since the instrument is intended to respond to signals originating from over-temperature conditions in the tank in which it is installed, some means must be provided to supply an output indication only when such over-temperature conditions do exist. A dc differential amplifier provides a solution to this problem in that it yields an output which is the algebraic difference between its two input levels. By providing a dc reference level at one input and the varying dc level from the

processed infrared detector output at the other input, one has a means by which any or all of the signal from the infrared detector can be cancelled out. Thus, when the instrument is looking at a tank bottom which exhibits no hot spots, the instrument output can be made identically zero by proper adjustment of the reference level applied to the dc differential amplifier. If and when a hot spot should occur in the tank, the dc level from the infrared detector output will increase and unbalance the dc differential amplifier. The resulting output can then be utilized for output indication purposes.

The dc differential amplifier drives a linear current source whose output is a current flowing through its load which is directly proportional to a small voltage change at its input. The load on the linear current source consists of a 0-1 ma dc meter with three switch-selectable resistors arranged in series with the meter movement. The three ranges available correspond to one, two and four millivolts per minor scale division on the output meter. The most sensitive scale is the one millivolt per division scale, and provides usable meter deflections for small over-temperature conditions in the tank; coarser indications (corresponding to larger over-temperature cases) are provided by the other two ranges.

An alarm actuator is provided by amplifying the dc differential amplifier output and applying the amplified signal to a level detector. The ALARM LEVEL SET control adjusts the gain of the third dc amplifier in the driver amplifier section and thus provides a means of adjusting the output level at which the level detector actuates the SPDT relay (Potter & Brumfield SS5D). The relay contacts are brought out to the front panel and can be used to control any suitable audible or visible alarm.

The radiometer housing temperature monitor consists of a linear current source driven by a dc differential amplifier. The current source drives a front-panel meter which provides an indication of the radiometer housing temperature. The differential

amplifier is driven by a chromel-alumel thermocouple cold-junction compensator. The thermocouple located in the housing is connected to the input of the compensator.

Due to the rather insensitive response to small temperature changes in the instrument housing, the use of this circuit was discontinued in favor of a more sensitive dc millivolt meter. A Fluke dc differential voltmeter was used throughout the testing of the instrument, as it was available in the laboratory. Any comparable instrument would prove satisfactory for this application, however.

APPENDIX C

Radiometer Electronics System

APPENDIX C (cont.)
Housing Temperature Monitor

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