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Thermal Sensing for Characterizing the Contents of Waste Storage Drums

Temperature differences were found to be sufficient for discriminating among drums filled largely with aqueous solutions, organic solutions, and clay materials (or empty).

Abstract: *Field tests assessed the feasibility of using thermal remote sensing to discriminate among liquid storage drums on the basis of the thermal inertia of their contents. Radiometric and contact temperatures of eight 55-gallon steel drums were monitored from afternoon to late-night on two occasions. The drums were black and white and either empty, half-filled with water, or completely filled with water or acetone. Radiometric measurements were made with a radiometer (8 to 14 μm), hand-held above the drum top.*

Temperature differences were found to be sufficient for discriminating among drums filled largely with aqueous solutions, organic solutions, and clay materials (or empty). Temperature differences could also be used for distinguishing leaking drums from full drums containing the same liquid. In either case, temperature discrimination is best during overcast periods with rapidly changing air temperature (post-sunset).

Introduction

The ultimate objective of this study was to determine if and how remote sensing can be applied to characterize the contents of liquid chemical waste storage drums. The development of an operational remote sensing method for characterizing the types of chemicals that will be encountered in a particular drum storage area would provide the field investigation team with the means for collecting valuable beforehand information.

This effort began with the observation by image analysts at the Environmental Protection Agency's Environmental Photographic Interpretation Center that the tones of several drums in two drum storage areas appeared anomalous on airborne thermal imagery. These drums were subsequently found to contain quart jars of picric acid packed in vermiculite (F. Wolle, personal communication). Based on these findings, a theoretical analysis of thermal remote sensing for drum characterization was undertaken by Philipson *et al.* (1981). They found that, when the air temperature is changing rapidly, differences in the thermal inertia of the drum contents can lead to detectable differences in the skin temperature of the drums. Thus, post-sunset, airborne thermal remote sensing could potentially provide some level of discrimination among chemical storage drums. More precisely, discrimination should be possible among steel drums filled largely with (1) aqueous solvents, (2) organic solvents, or (3) clay packing materials. The response of a drum filled with clay packing materials should be similar to that of an empty drum.

The objective of the work described here was to verify the theoretical findings. This was accomplished through controlled ground-level testing with experimental drums and a hand-held infrared radiometer.

Research Approach

Theoretical Background

Observations of radiometric temperature differences among storage drums containing different chemicals suggested the hypothesis that the differ-

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ences were due to differences in the thermal inertia of the stored chemicals. This would imply that, under the appropriate conditions, discrimination among selected types of chemicals could be made remotely.

To test this hypothesis, a simple mathematical model was developed to predict the temperature response of the storage drums (Philipson *et al.*, 1981). The model was intended only to assess the feasibility of using the remotely sensed drum temperature as an indicator of the drum content. No attempt was made to describe the complete heat transfer problem; rather, several simplifying assumptions were made: (1) the drums would be full of liquid chemicals (not partially filled), (2) the temperature of the drum would be the same as that of the liquid chemicals and that the liquid would be well mixed (uniform temperature), (3) the primary heat transfer mechanisms would be radiation and conduction (windless conditions), and (4) the driving force would be a sinusoidally varying air temperature (radiative heating by the sun would be ignored).

These assumptions allow an analytical solution to the heat transfer equation (Krieth, 1965). At the same time, these assumptions should yield conservative estimates of the actual temperature differences that might be encountered.

The final form of the transfer equation is

$$T = T_a + T'' \sin(\omega t - \delta) \qquad (1)$$

where T = instantaneous drum temperature (°C),
T_a = mean air temperature (°C),
ω = frequency of the temperature variation (0.20/hr),
t = time (hours),
δ = phase difference (lag time) between the air temperature and the drum temperature, and
T'' = maximum drum temperature (°C).

Predictions of this model are illustrated in Figure 1. In general, the temperature of the drums always lags the air temperature. Further, the greater the thermal inertia of the stored liquid, the greater the lag and the smaller the deviation of the drum temperature from the mean air temperature. The predicted temperature difference between drums containing aqueous solutions and drums containing organic solutions arises because water has a greater thermal inertia than the organic solvent (Varagaftik, 1975) and, thus, responds more slowly to temperature changes. Although the predicted difference is rather small (0.5°C for the range of 5-15°C, Figure 1), it is within the detection range of existing remote thermal imaging systems.

FIELD STUDY DESIGN

Having demonstrated the theoretical plausibility that the observed drum temperatures could be related to the drum contents, a field experiment was designed. The temperatures of several 55-gallon storage drums were monitored through the cooling period from late afternoon to late night to determine if the predicted temperature difference would occur, if it would be great enough to be detected remotely, and if it would be consistent enough to be used for distinguishing drums according to their contents.

Drum characteristics other than the drum content will also have an effect on the surface temperature of a storage drum. The most important of these are the surface characteristics (color, roughness, rust, and wetness). Because the color of the drums was the easiest factor to control and the most likely to affect the radiative heating and cooling of the drum surface, the drums were paired and painted* either black (B) or white (W): black to maximize and white to minimize the radiative heating during the day.

Eight 55-gallon drums were used: two drums (1B,

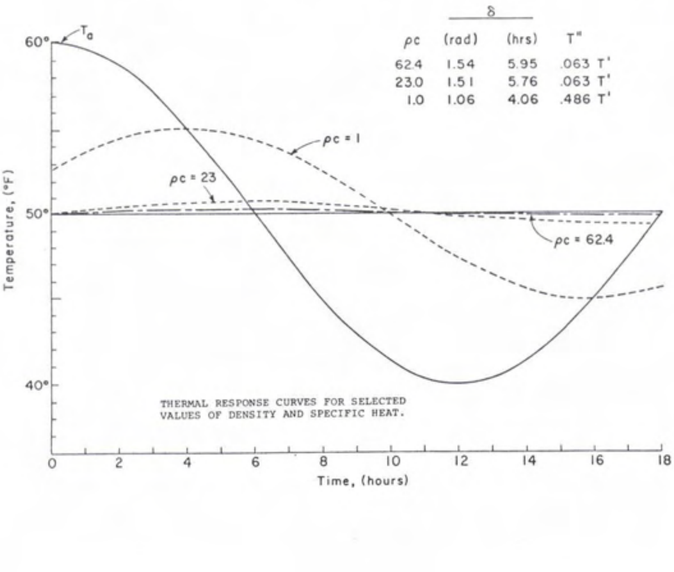

FIG. 1. Theoretical predictions of the thermal response of 55-gallon drums filled with fluids with different densities (ρ) and specific heats (c). T′ represents the amplitude of the air temperature variation (±5°C). The phase difference between the air temperature and the drum temperature is given in radians and hours. (after Philipson *et al.*, 1981.)

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* Glidden, latex paint.

TABLE 1. CONTACT TEMPERATURES OF WATER AND ACETONE FILLED WHITE AND BLACK STEEL DRUMS, 3-4 NOVEMBER 1982

		Contact Temperatures (°C)							
		White Drums				Black Drums			
			Water				Water		
Avg. Time	Avg. Air Temp (°C)	Acetone	Full	Half	Empty	Acetone	Full	Half	Empty
1518[1]	19.8	20.0	20.0	20.0	20.0	21.0	21.0	21.0	20.5
1530	19.6	19.0	19.5	19.1	19.1	21.5	21.4	21.1	20.2
1540	19.5	19.5	20.0	19.1	19.1	21.8	21.8	21.0	20.2
1614	18.1	17.6	18.0	17.5	16.9	19.9	20.0	19.1	18.3
1647	17.1	17.1	17.5	17.0	16.9	18.0	18.8	17.7	17.0
1715[2]	17.2	17.3	18.0	17.0	16.5	18.0	18.7	17.5	16.5
1748	16.8	17.1	17.8	16.9	16.0	18.0	19.0	17.4	15.9
1818	16.5	17.0	17.4	16.5	15.8	17.7	18.9	17.2	15.9
1850	16.1	16.8	17.5	16.4	15.8	17.5	18.5	17.0	15.8
1913	16.4	17.0	16.8	16.0	15.7	16.9	17.9	16.5	15.7
2058[3]	15.2	16.5	17.0	16.2	15.2	16.6	18.1	17.0	15.2
2118	15.2	16.2	16.8	16.0	15.2	17.0	18.0	16.5	15.2
2246	14.8	16.1	16.5	15.4	14.8	16.0	17.0	15.8	14.8
2308	15.0	15.9	16.7	15.8	15.1	16.0	17.4	16.0	15.0
2424[4]	14.0	15.1	15.7	14.8	14.6	15.1	16.1	15.2	14.5

Weather conditions (continue until reported change):
[1] cloudy, slight breeze
[2] cloudy, humid, little/no breeze
[3] foggy, humid, little/no breeze
[4] foggy, light precipitation

1W) were filled with a typical organic solvent, acetone; two drums (1B, 1W) were filled with water; two drums (1B, 1W) were half filled with water; and two drums (1B, 1W) were left empty. Because of cost considerations and the emphasis on feasibility, test drums were not replicated. Rather, the use of paired black and white drums was intended to give a representative range of temperatures for each case.

The eight drums were placed in a circle, spaced at intervals of approximately three metres. The arrangement and spacing of the drums was intended to keep the drums as close to one another as possible (i.e., within the same microclimate), while minimizing drum interactions.

An infrared radiometer sensitive in the 8 to 14 micrometre region (Barnes Precision Radiation Thermometer, PRT-5) was used to monitor the radiometric temperature of the different drums over two afternoon-post sunset periods. Measurements were made with the radiometer hand-held immediately above (approximately 0.1 metre), and aimed vertically down on, the drum top. The contact temperatures of the drums and the ambient temperature were also monitored with a "Tele-Thermometer" (Yellow Springs Instrument Co., Inc., model 42SC).

RESULTS AND DISCUSSION

Two field tests were run. In each, the contact temperature and radiometric temperature of the eight drums and the ambient air temperature were monitored from mid-afternoon to late night. These data along with the general weather conditions are reported in Tables 1 through 4 and Figures 2 through 4. A complete set of measurements (all eight drums and ancillary measurements) took from 10 to 20 minutes, with each drum being monitored sequentially; only the average time is reported.

TEST #1

During the first test, 3-4 November 1982, the air temperature dropped 5.6°C over the 9-hour monitoring period (Tables 1 and 2, Figures 2 and 3). There was little or no breeze during the study, and the weather was overcast or foggy—conditions which would suggest that radiative cooling would be the dominant mechanism behind any temperature differences (matching the model assumptions). Data collections was terminated shortly after midnight because of rainfall.

Figures 2 and 3 illustrate the range of temperatures of the white and black drums. The black drums were generally warmer than the white drums, presumably because of more efficient radiative heating during the day. The temperature difference was greatest at the beginning of the monitoring period and decreased with time. The large initial temperature difference between the different colored drums was probably due to radiative heating which, even under overcast skies, would be greatest during daylight hours. More significantly, the tem-

TABLE 2. RADIOMETRIC TEMPERATURES OF WATER AND ACETONE FILLED WHITE AND BLACK STEEL DRUMS, 3-4 NOVEMBER 1982

		Radiometric Temperatures (°C)							
		White Drums				Black Drums			
			Water				Water		
Avg. Time	Avg. Air Temp (°C)	Acetone	Full	Half	Empty	Acetone	Full	Half	Empty
1518[1]	19.8	19.7	18.9	18.7	18.9	21.4	21.7	21.0	20.2
1526	19.6	19.8	19.6	19.1	19.0	22.1	22.2	21.4	20.5
1536	19.2	19.5	19.4	18.9	18.8	21.9	21.8	21.3	20.2
1606	18.5	18.2	18.5	17.7	17.4	21.4	21.2	20.4	19.2
1638	17.4	18.0	18.3	17.1	16.5	19.1	19.6	18.4	17.1
1641	17.2	17.5	18.0	16.6	15.6	18.6	19.1	17.1	16.8
1707[2]	17.2	18.3	18.5	17.5	17.0	18.7	19.5	18.3	16.9
1740	17.0	17.5	18.0	17.0	16.4	18.0	19.2	17.9	16.1
1809	16.6	17.5	18.0	17.0	16.0	18.0	19.3	17.6	16.0
1840	16.4	17.4	18.0	16.9	16.0	18.0	19.0	17.5	16.0
1906	16.2	17.3	17.7	16.5	15.8	17.5	18.9	17.4	15.8
2049[3]	15.3	17.1	17.5	16.3	15.2	16.8	18.6	17.0	15.4
2109	15.3	16.9	17.5	16.6	15.5	17.2	18.7	17.4	15.8
2236	15.4	16.2	16.4	15.6	14.8	16.2	17.7	15.9	14.8
2257	14.8	16.7	17.0	16.3	15.2	16.5	18.1	16.7	15.3
2415[4]	14.2	15.8	16.5	15.5	14.8	15.6	17.4	16.3	15.0

Weather conditions (continue until reported change):

[1] cloudy, slight breeze

[2] cloudy, humid, little/no breeze

[3] foggy, humid, little/no breeze

[4] foggy, light precipitation

TABLE 3. CONTACT TEMPERATURES OF WATER AND ACETONE FILLED WHITE AND BLACK STEEL DRUMS, 8-9 NOVEMBER 1982

		Contact Temperatures (°C)							
		White Drums				Black Drums			
			Water				Water		
Avg. Time	Avg. Air Temp (°C)	Acetone	Full	Half	Empty	Acetone	Full	Half	Empty
1626[1]	14.1	14.1	13.5	13.5	12.8	14.6	14.1	14.0	13.8
1704	13.8	13.9	13.2	13.0	12.9	13.9	13.5	13.2	13.1
1746	13.3	13.6	13.2	12.9	13.0	13.6	13.7	13.1	13.0
1857[2]	12.0	11.0	10.0	8.9	8.8	10.0	10.0	9.3	9.0
2024[3]	11.2	11.5	11.0	10.9	10.9	11.1	11.2	11.0	11.5
2044	10.7	10.9	10.5	10.6	10.3	11.0	10.9	10.7	10.3
2126[4]	8.5	8.0	8.0	7.2	8.1	8.0	8.0	7.6	7.6
2148	7.7	7.5	7.7	6.7	6.9	7.2	7.2	6.9	6.5
2314[5]	6.4	5.4	5.3	4.5	4.3	4.9	5.6	4.8	4.0
2337	6.1	5.1	5.2	4.1	4.4	4.8	5.1	4.5	3.5
2451[6]	4.8	4.0	4.0	2.1	2.0	2.8	4.1	2.7	1.3
0116[7]	4.2	3.2	3.9	2.1	2.0	2.5	4.0	2.4	1.4
0214	5.0	4.9	5.2	4.4	4.0	4.0	5.2	5.1	4.0

Weather conditions (continue until reported change):

[1] overcast, breezy

[2] clearing, breezy

[3] cloudy, windy

[4] clearing, windy

[5] clear, breezy

[6] clear, little/no breeze

[7] increasing clouds, little/no breeze

TABLE 4. RADIOMETRIC TEMPERATURES OF WATER AND ACETONE FILLED WHITE AND BLACK STEEL DRUMS, 8-9 NOVEMBER 1982

		Radiometric Temperatures (°C)							
		White Drums				Black Drums			
			Water				Water		
Avg. Time	Avg. Air Temp (°C)	Acetone	Full	Half	Empty	Acetone	Full	Half	Empty
1606[1]	—	15.0	13.9	14.0	11.5	15.0	15.0	15.0	14.6
1614	—	14.5	14.0	14.0	12.3	15.0	14.8	14.9	14.8
1638	13.9	14.3	13.9	14.0	13.0	14.7	14.5	14.4	14.0
1716	13.6	14.1	13.5	13.4	13.0	14.4	14.1	13.5	13.2
1755	13.2	13.8	13.5	13.4	13.2	14.1	13.9	13.6	13.1
1805	13.1	13.7	12.0	11.6	11.0	13.2	12.4	11.9	11.0
1842[2]	12.2	12.2	11.0	10.0	10.3	11.1	11.0	10.0	9.5
1912	11.2	12.3	10.4	7.3	6.3	10.1	9.8	6.4	8.3
2014[3]	11.3	12.8	11.3	11.0	10.7	11.3	12.0	11.6	11.5
2036	11.1	12.1	11.9	11.4	11.4	11.8	11.9	11.9	11.7
2116[4]	9.2	8.0	8.7	7.5	5.3	6.7	7.5	6.2	6.8
2138	8.1	7.1	6.7	4.9	3.7	6.6	6.2	5.2	4.4
2303[5]	6.9	1.5	3.6	−2.2	−4.3	−0.5	−0.7	−2.7	−3.2
2328	6.1	2.5	2.3	−1.7	−3.1	−2.2	−0.7	−2.2	−3.1
2441[6]	5.0	−0.3	0.6	−4.4	−5.6	−2.7	−1.6	−2.8	−6.5
0106[7]	4.5	−1.7	−0.4	−4.7	−7.9	−4.1	−2.5	−5.4	−7.3
0204	4.9	1.5	3.7	1.0	−4.7	−1.4	2.8	−0.1	−3.6

Weather conditions (continue until reported change):
[1] overcast, breezy
[2] clearing, breezy
[3] cloudy, windy
[4] clearing, windy
[5] clear, breezy
[6] clear, little/no breeze
[7] increasing clouds, little/no breeze

peratures of the black water-filled and black acetone-filled drums are most similar at the beginning of the monitoring period, as are the temperatures of the corresponding white drums. This implies that the color of the drums is more significant than the drum content during the daylight hours. It is probable that the initial temperatures are due to radiative heating and are representative of only the drum surface. This would be consistent with the rapid drop in temperature experienced by all drums between 1515 and 1650 hrs (i.e., heat loss from the warmer skin layer).

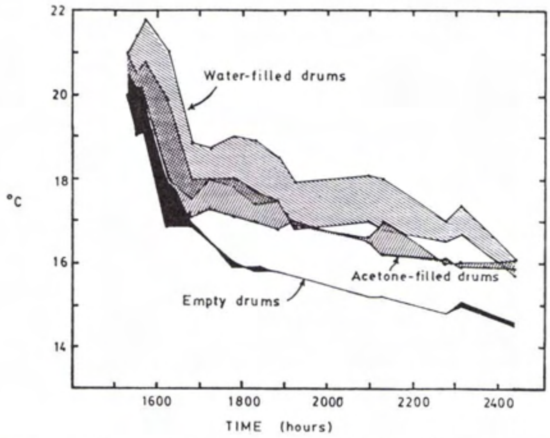

FIG. 2. Contact temperatures of 55-gallon storage drums, 3-4 November 1982. The range of values for each category is defined by the contact temperature of the black and white drums. The black drums are usually warmer than the white drums.

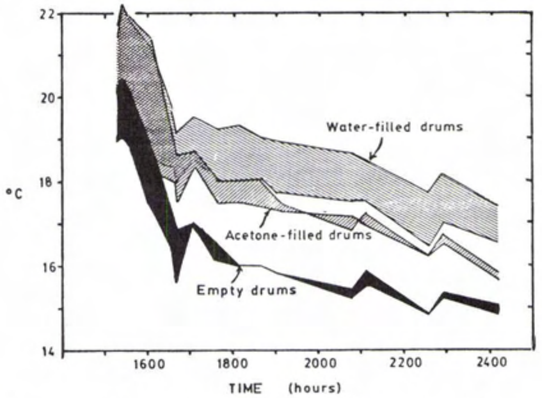

FIG. 3. Radiometric temperatures of 55-gallon drums, 3-4 November 1982.

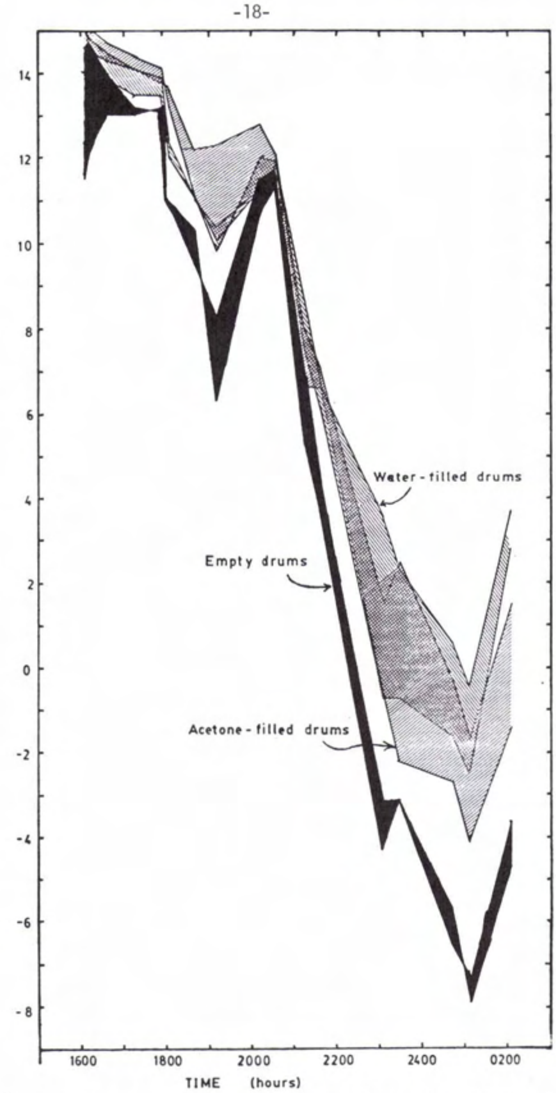

FIG. 4. Radiometric temperatures of 55-gallon drums, 8-9 November 1982.

At dusk, after the rapid cooling period, the temperature ranges are smaller for each pair (B and W) of drums. Moreover, the temperature ranges for each of the three pairs shown in Figure 3 are distinct: The water-filled drums are the warmest (slowest to cool), the acetone-filled drums are distinctly cooler, and the empty drums are both the coldest and the most similar to the air temperature. As expected, the half-filled water drums (not shown) had temperatures midway between the water-filled and the empty drums. This is precisely what one would predict if the liquid in the drum is indeed moderating the drum temperature; however, it is also indicative of the difficulties that will arise in discriminating among the storage drums if they are not all filled to the same level (or completely empty). Alternatively, if one were not concerned about the specific contents of the drums but knew that the drums should be full or nearly full with the same liquid chemical, one might rely on temperature difference to detect the presence of leaking drums.

Two positive results are apparent in Figures 2 and 3 that were not apparent from the theoretical development: (1) the optimal temperature difference for drums differing only in their contents was often greater than 1°C—substantially greater than the conservative prediction, and (2) this temperature difference was maintained for several hours. Discrimination among the drums according to their contents would have been possible on this night for a rather long period of time.

TEST #2

The second test, conducted on 8-9 November 1982, provides a striking contrast to the first. The drop in the air temperature (approximately 10°C in 10 hrs.) is nearly double that during the first tests (Tables 3 and 4, Figure 4). Had conditions been otherwise similar to the first test, the large change in temperature would probably have enhanced the discrimination among these drums; however, cloud cover varied widely over the study period. Conditions ranged from completely overcast at the beginning of the experiment to very clear for about four hours and returning to very cloudy at the end of the experiment. Because the emissivity of the air can range from about 0.7 under clear skies to almost 1.0 for overcast skies, one would expect a net radiative loss from painted drums (emissivity ~ 0.9) under clear skies and a net gain with overcast conditions. Notably, it is during the period of clear skies that the drums were cooled and their surface temperatures dropped well *below* the air temperature for most of the evening. As a result, not only were the water-filled and acetone-filled drums difficult to discriminate, but the acetone-filled drums were slightly warmer than the water-filled drums for almost half of the test period.

It is probable that the observed drum temperatures were largely due to radiative cooling. This would account for the similar temperatures during most of the study period. It would also be consistent with the relatively sudden increase in drum temperatures and the distinct difference in temperatures between the acetone-filled and water-filled drums when the clouds returned after midnight. When the emissivity of the air became more similar to that of the painted drum surface (under clouds), radiative loss from the drum was reduced, and the surface temperatures of the drums began to approach the ambient air temperature, driven by the internal temperatures of their contents.

The temperature response of the empty drums was greater than the response of any of the other drums for the entire test period. This is reasonable because there was nothing to moderate the temperature change. As with the earlier test, the temperatures of the half-filled drums usually fell midway between the water-filled and the empty drums.

SUMMARY

Based on the results of a theoretical study and two field tests, the feasibility of using thermal remote sensing to discriminate liquid chemical storage drums on the basis of their contents has been demonstrated. Under the proper conditions—post-sunset observations, rapid change in air temperature, and overcast skies—the temperature differences among drums filled largely with (1) aqueous solutions, (2) organic solutions, and (3) clay materials (or empty) will be significant and consistent. The thermal response of a drum partially filled with an aqueous solution can be expected to be similar to a drum filled with an organic solution. Alternatively, if one were not concerned about the specific contents of the drums but knew that the drums should be full or nearly full with the same liquid chemical, one could rely on temperature differences to detect the presence of leaking drums.

Factors other than drum contents contribute to the temperature response of the drum: drum orientation (upright, tilted, lying down), surface condition (roughness, rust, color, wetness), and factors affecting drum interactions (isolated, close-packed, or stacked drums). Only one factor, color, was taken into account in these field tests. The results indicated that, under the conditions cited above, the temperature differences due to the drum contents were generally greater than the differences due to the drum color.

ACKNOWLEDGMENTS

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