TWO NEW ROOF MOISTURE SENSOR TECHNOLOGIES

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The authors have devised two prototype leak sensors for low-slope roofs that can both detect the presence of moisture in the roof material and identify the location of the wetted area. One uses flat, inexpensive cable and is ready for commercial development and the other uses inexpensive, autonomous passive sensors imbedded in the roof, which requires further development. Both are patent pending.

The cable-based roof moisture detection and location system has been tested in simulated conditions. The detection system can use a variety of principles to monitor the roof for the presence of moisture. The location system uses a metallic time-domain reflectometer (MTDR) to locate suspected moisture by sending an electromagnetic pulse or step signal down the wire and looking for reflections caused by a change in the dielectric constant surrounding the wire caused by the presence of moisture. Tests revealed the MTDR technique to be sensitive and able to locate the position of less than 1L (0.22 gal) of water within 0.3 m (one foot) over 30.5 m (100 ft.) of cable. Where multiple regions of wetting were present along the length of the cable, it was possible to locate each boundary between wet and dry.

A prototype autonomous passive sensor has been tested in the laboratory. This sensor, consisting of an inductor and a specially designed capacitor that requires neither batteries nor power connections will remain operational for the life of the roof and automatically resets after the roofing material returns to a dry state. The moisture state of the sensor can be detected by a simple electronic circuit that is passed within 300 mm (2 ft.) of the sensor. Preliminary tests have been performed that indicate a potential to remotely poll the sensor electromagnetically to determine moisture state. Further instrumentation to poll remotely the assemblage of sensors to detect the presence of some that are wet has been proposed and the principle tested; however, a practical implementation has not yet been developed.

KEYWORDS

Capacitance, detection, gate dip oscillator, insulation, leak, oscilloscope, pulse/function generator, roofing, roofs, sensor, time-domain reflectometry wet.

INTRODUCTION

Early detection of leaks in low-slope, compact roofing systems is recognized to be important. Such a roof costs approximately 76 to 108 \$/m^2 (7 to 10 \$/ft^2) to replace. When one considers that low-slope roofs often cover tens of thousands of square feet, the cost of allowing water to intrude too long can be significant.

A variety of techniques are available for detecting wet areas in such roofs. ASTM Standard Practice C 1153[1] describes both on-the-roof and aerial infrared thermography as effective survey techniques. Other survey techniques use nuclear moisture meters or dielectric meters. Such methods require that people go onto the roof, or above the roof, as in the case of aerial thermography. Tobiasson and Korhonen[2] and Tobiasson[3] compare various roof moisture survey techniques.

Bailey, et al.,[4] describe eight roof moisture detection schemes, one using autonomous sensors and the others using sensors that are connected by wire to a display. In summary, these are the:

- Water-activated battery with transmitter—Autonomous sensor by Bryan, Jr. and Seagrave,[6] discussed later.
- Resistance probe—Two prongs and a resistor, wired to a display, produce a voltage that is a function of moisture.
- Pin probe—Two parallel plates, attached to pins inserted into the insulation and wired to a display, produce a capacitance that changes with moisture.
- Wooden probe—A chip of wood between two metallic surfaces that form a capacitor, wired to a display.
- Moisture detection tape—Two wire electrodes attached to a tape that when wet closes an electrical circuit.
- Plywood disc sensor—Two wire electrodes read the electrical resistance of a plywood disk, which changes as a function of moisture.
- Twisted pair of wires—Twisted wires form a capacitor that monitors the dielectric of the surrounding medium, which changes with moisture content.
- Breather vent sensor—The breather vent provides a means of access and inspection for any of a variety of moisture sensors.

All but the first of these sensors require separate, dedicated cables to each sensor. The moisture detection tape requires a grid system of independent tapes to locate the moisture.

Various devices have been patented for detecting wet areas in roofs. The U.S. patent to Farris and Farris, Jr.[5] for example, discloses a system for detecting the presence of moisture. The detector of this system includes a grid of wires arranged on a fabric backing sheet that ordinarily exhibits a high impedance. When a leak occurs, it wets the backing sheet and bridges a space between the wires, thereby reducing the impedance of the grid. This reduced impedance indicates the presence of a wet area.

The U.S. patent to Bryan, Jr. and Seagrave[6] discloses a wireless leak detection system for roofs that uses water-activated batteries to operate moisture sensors placed at various locations on a roof.

Other patents describe the use a time-domain reflectometer (TDR) to detect leaks. The U.S. patent to Reddy, III and Berkman,[7] for example, discloses a complex leak detection system for detecting leaks from a storage tank and pipeline containing fuel oil. The U.S. patent to Bailey[8] discloses a method and apparatus for detecting and locating leaks and determining whether the leaking liquid is a nonconductive liquid, such as a hydrocarbon, or a conductive liquid, such as water. Neither of these patents discloses a system using metallic time-domain reflectometer for detecting the presence and location of a wet area in a roof.

The authors discuss the development of two roof-moisture detection systems, one a cable-based roof moisture detection and location system using capacitance sensing and MTDR measurements and the other an unpowered, passive moisture sensor that can potentially be remotely polled by radio transmissions.

MTDR ROOF MOISTURE SENSING TECHNOLOGY

MTDR techniques are widely used for measurement and monitoring applications in industry.[9,10] The authors tested the possibility of using MTDR with sensing cables to locate wet areas caused by roof moisture in a laboratory test rig that accommodated three different insulation conditions over a 30.5-m (100-ft.) length of cable. The authors tried a number of combinations of wettings of the simulated roof, as described.

Metallic time-domain reflectometry

MTDR apparatus—An MTDR generates an electromagnetic pulse (or a fast rise-time step function) into a sensing cable, consisting of two parallel conductors. The pulse travels down the transmission line at a fixed and calculable velocity, a function of the speed of light in the cable and other electrical and physical characteristics of the cable.[11] The pulse propagates down the transmission line until the end and then reflects back to the source. The time *t* in seconds that the pulse propagates the length of the cable and reflects back to the source is called the "round-trip travel time." The time that the pulse propagates a given length of the cable is called the "propagation travel time."

The boundary between two media with different dielectric constants, as between dry and wet material surrounding the transmission line, causes a pulse propagating down the transmission line from the MTDR source to reflect a portion of the pulse energy back to the source from the boundary. A portion of the energy continues to propagate through the boundary until another boundary or the end of the cable causes all or part of the remaining pulse energy to return along the transmission line to the source. Knowing the nature of the dielectric media through which the pulse is propagating and measuring the travel time of the pulse permits calculation of the physical distance from the MTDR source to each of the dielectric interface boundaries encountered.

Signal behavior—The MTDR apparatus displays an oscilloscope-like trace, representing reflections of an electromagnetic pulse propagating in a cable. Where the impedance of the cable is constant, the trace signal is a constant, baseline value. At an impedance discontinuity within the cable, occurring at the interface of materials of different dielectric constants surrounding the cable, the signal changes from the baseline value in response to the change in dielectric constants.

Signal interpretation—The presence of water around the cable can significantly change the dielectric constant and the consequent propagation travel time from that of dry insulation or other roofing materials. The distance between features shown on the MTDR display represent the propagation travel time rather than the linear physical distance. The literature often refers to the distance displayed on the MTDR as "electrical length" in contrast to the linear physical distance that is called "physical length." The dielectric constant of the material surrounding the cable governs the relationship between electrical length due to signal propagation travel time and physical length along the cable.

Calculation of physical length from electrical length requires interpretation, as discussed in the section on analysis of MTDR signals.

Roof moisture sensing cable placement

For a cable-based roof moisture detection system to be effective, it must be placed within the roof near features that are likely to leak and at a position within the thickness of the roof system where water is likely to accumulate.

Placement within roofs—Flashings, penetrations, and seams in the membrane are vulnerable to leakage on low-sloped roofs. Therefore, any roof moisture detection cable should pass near such features and downslope from them.

Placement within roofing layers—There is a large variety of possible material combinations within the cross section of low-slope roofs. Most types of low-slope roofs have a membrane on top of layers of insulation. In some, the membrane rests on the roof deck. Prediction of which layer or interface between layers within the cross section will be the most likely to accumulate water from leaks into the roofing requires judgment. Water is likely to be retained over continuous, impermeable surfaces. Water is not likely to travel horizontally along adhered interfaces or over cracks to lower levels of the roof system.

Placing the sensing cable within the roofing matrix so that there is little impact on the propagation of the electromagnetic pulse may require locating the cable at least 50 mm (2 in.) from metal roof decking or standing water on the roof surface.

Roof moisture alert methods

There are several ways in which the sensing cable can be continuously monitored for the occurrence of moisture. The authors recommend techniques that measure capacitance or power at only one end of the cables. Either technique could alert a building operator to a change from dry to wet along a portion of the cable, as small as a meter. Neither technique would provide information for locating the position of the wet area along the cable. Finding the location of a wet area would be accomplished by MTDR or other technique, like infrared thermography.

Capacitance measurement—The electrical capacitance of a sensing cable is a function of the dielectric constant of the medium surrounding the cable. The dielectric constant changes when a sensing cable becomes wet, as follows. An economical real-time capacitance measurement system could use existing capacitive meters on the market or be a special-purpose instrument consisting of an AC capacitive bridge and small microcontroller. Immediately following the installation of an MTDR roof moisture sensing cable, a measurement of the cable capacitance is made and recorded. The capacitive meter then continually monitors the cable for changes in the capacitance and alarms when a preset threshold has been exceeded.

Power measurement—A single-ended version of the power-measurement circuit can be implemented where the level of the reflected signal is monitored. Here, the cable is terminated with an impedance matching that of the cable so that no signal would be reflected from the far end. If any reflected power, due to dielectric discontinuities occurring along the cable's length, was measured at the source, then the cable has presumably been wetted and an alert can be triggered.

Roof moisture detection test procedure

Laboratory tests were performed using the MTDR apparatus on wetted insulation in a test apparatus that was designed to simulate extreme examples of roof insulation types that might be encountered.

Test apparatus—An apparatus was designed that comprised five 2.4 x 1.2 m (8 x 4 ft.) trays, each divided in half to accommodate the length of cable. Each tray was lined with polyethylene film and either fitted with one of two types of insulation (with no membrane on top) or left empty. The sensing cable was laid along the bottom of each tray beneath the insulation, when present, and in a puddle of water, when present.

Insulation treatments—Boards of extruded polystyrene foam and glass fiber insulation boards were chosen to be extreme examples of a material that absorbed relatively little moisture and one that readily absorbed moisture. In addition, open trays used as containers for water without the influence of insulation.

Water application—Water was poured into the insulation in amounts ranging from 1 to 5 L (0.22 to 1.1 gal.). Water was placed, in some cases, both near the beginning and near the end of the cable to determine whether both areas of moisture would be identifiable. Up to four wetted areas along the cable length were tried. In all cases, most of the water migrated to the polyethylene film at the bottom of the trays where the cable was.

In one test, the cable was placed between two layers of glass fiber insulation and 2 L (0.44 gal.) of water was added to the top of each layer at the 15-m (49-ft.) mark on the cable. The authors then monitored the change in signal from the MTDR over a week with the insulation wrapped all the way around with polyethylene film.

Cable characteristics—The transmission line cable used in these experiments is a readily available, commonly used and relatively inexpensive product that is typically used for radio communications, called "ladder line." Two varieties of ladder line were tried (shown in Figure 1) with characteristic impedances of 300 Ω and 600 Ω. The wires at the ends of the two cables were unconnected to each other or any other component.

MTDR apparatus—The MTDR apparatus that was used principally generated a pulse signal that propagated down the sensing cable. A Tektronix* 1503C metallic time-domain reflectometer was used (Figure 2) to generate the signal and display the reflected response. The signal was recorded on a personal computer, using specialized software that records the trace, as displayed on the screen of the MTDR, digitized into 251 discrete bin locations that are evenly distributed along the apparent signal path.

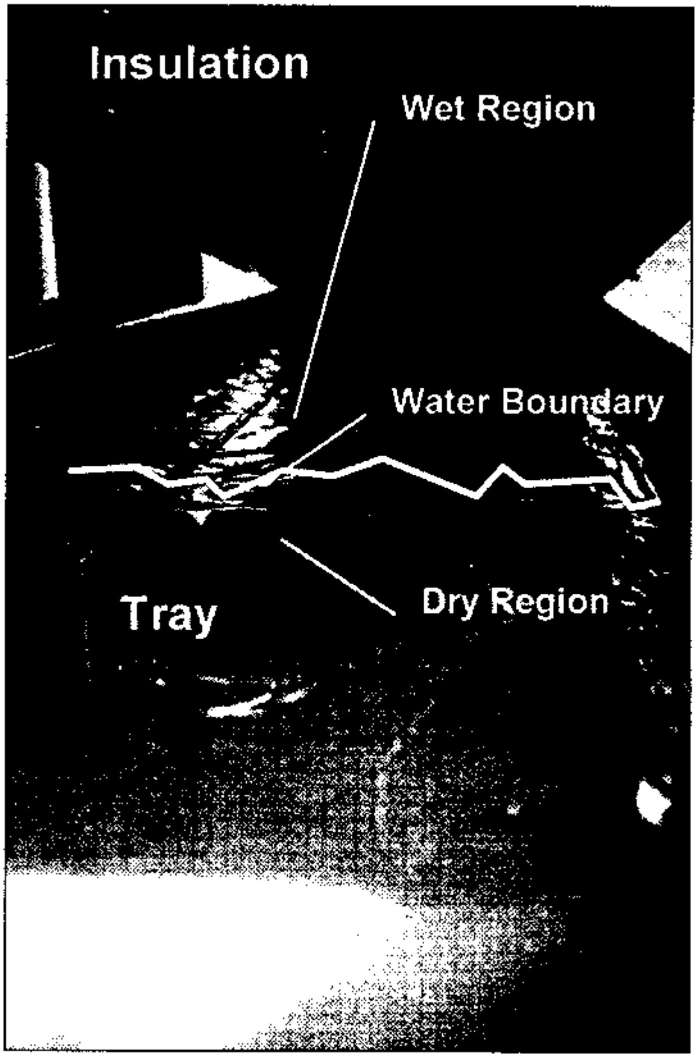

Figure 1. Water placed in test apparatus tray with insulation lifted up. The 300-Ω cable is visible to the left and the 600-Ω cable is visible to the right.

Roof moisture detection test results

The apparent locations of moisture were compared, as detected by the MTDR apparatus, with the known locations of moisture in the test apparatus.

Analysis of MTDR signals—Because the primary objective of using the MTDR was not just to detect the presence of water, but to locate it, the authors developed an algorithm[12] for locating the beginning and end points of water along the sensing cable. MTDR signals from cables with wetted portions have a different electrical length than their actual physical length. Calculation of physical length from electrical length requires interpretation, as discussed below. It involves comparing two cases; the baseline without water and that with wetted insulation.

A typical baseline case signal return for a dry cable is shown by the light line in Figure 3 that overlaps the case where the cable was wetted along 2 m (6 ft.), starting 6 m (18 ft.) from the end of a 30.5-m (100-ft.) sensing cable. In Figure 3, one can see the reflected signals from the cable connection to the MTDR (a spike on the left) and from the end

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*Brand names are given for complete identification and do not imply endorsement of the product.

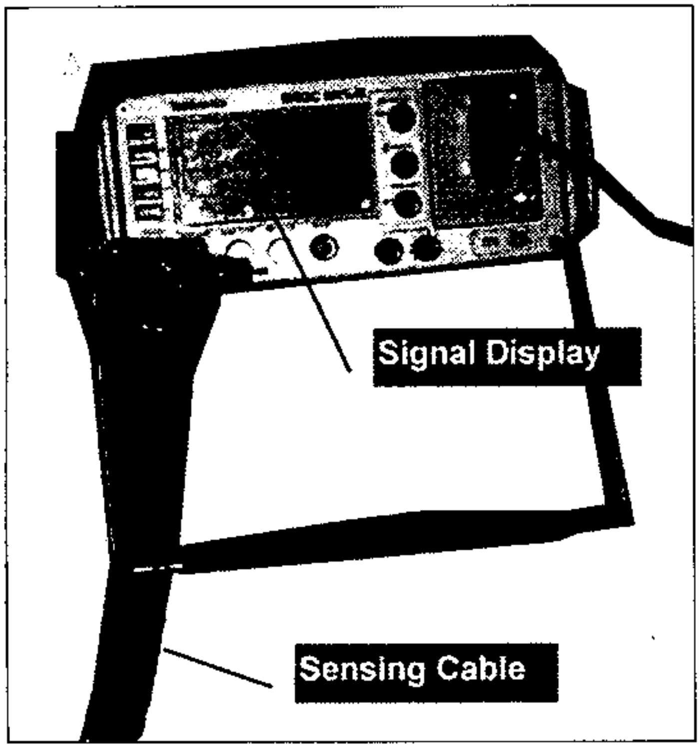

Figure 2. Metallic time-domain reflectometer and sensing cable used in these tests.

of the cable (a spike on the right) for both cases. The signals in both cases superimpose on each other until the point where the cable is wet. Note that the horizontal axis on the MTDR is represented by "bins," rather than units of length to avoid the confusion between physical and electrical length.

In Figure 3, starting at the wetted portion of the cable, the signal plots for wet and dry are not collocated because the wet portion of the cable has extended its electrical length, compared with the dry. Note that the dry-to-wet boundary on the cable is characterized by a downward spike, whereas the wet-to-dry boundary is characterized by an upward spike. The signal strength of a segment between the two spikes equals that for the dry cable.

Figure 4 illustrates the anatomy of a typical MTDR plot that has the electrical length corrected for physical length by the appropriate algorithm, with a region of water near the beginning and end of the cable. In general, one expects to see a dip in signal strength at the beginning of a wet area, a return to the baseline value in the middle of the wet area, and a rise in signal strength at the end of the wet area, as one can see at the wetted area near the cable connection to the MTDR in Figure 4. In Figure 4, the rise that one might expect at the end of the cable is overshadowed by the reflected signal from the cable end.

The authors compared the location of the water in the test section along the cable with the apparent location, as determined by the MTDR signal, adjusted as described previously. The median difference between the actual wet and dry boundaries and those detected by means of the MTDR was 0.8 m (2.6 ft.) for dry-to-wet boundaries and 2.6 m (8.3 ft.) for wet-to-dry boundaries, 2 percent and 5 percent respectively of the length of the cable. The maximum and minimum differences were 3.7 m (12 ft.) and 0.0 m (0 ft.) for dry-to-wet boundaries and 3.2 m (11 ft.) and 0.0 m (0 ft.) for wet-to-dry boundaries.

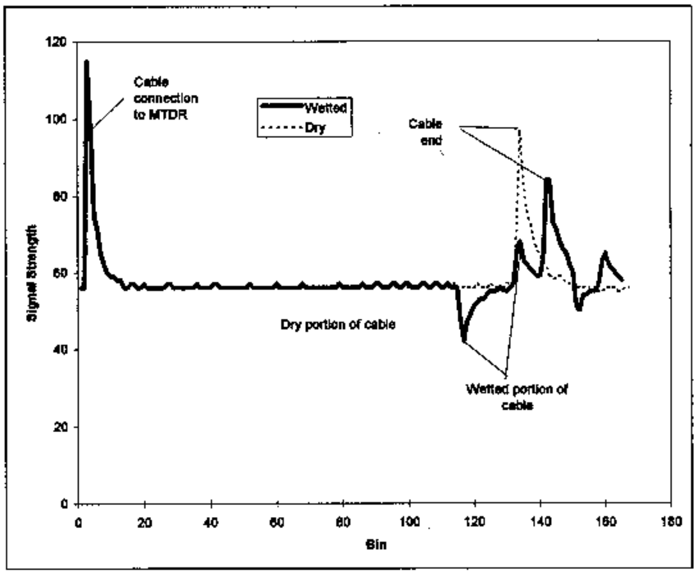

Figure 3. Typical MTDR signals for a dry cable and the same cable wetted near the end.

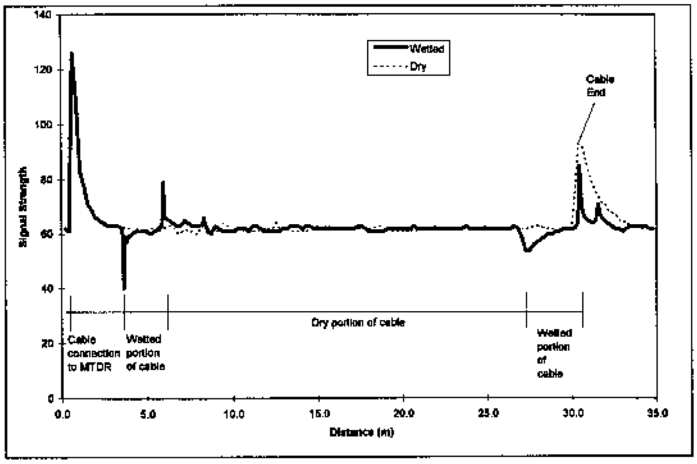

Figure 4. Typical MTDR signals for a dry cable and the same cable wetted near both ends with electrical length corrected to actual length.

The authors tested the ability of a cable positioned at mid-height in a 100-mm (4-in.) thickness of fibrous glass insulation to detect, over a period of 26 days, moisture that was introduced from on top of the insulation in the amount of 1 L and then covered with polyethylene film. Figure 5 shows the distribution of the moisture at the end of the period, based on a specimen obtained by coring the insulation at each position shown on the axis labeled "Position of Sample." Each core specimen was sliced into equal segments, shown on the axis labeled "Depth." The segments were weighed, dried and reweighed. The ratio between the first and second weight gave "Moisture Content" in Figure 5.

Figure 5 shows that, at most locations, the water had migrated towards the bottom, except at the 300-mm (-12-in.) location. Nevertheless, the MTDR detected water with the cable positioned at a depth of 2 in. (50 mm) in the 100-mm (4-in.) thick insulation. Figure 6 shows that the signal changed little over the entire period.

Capacitance alert test—A capacitance meter was placed on the end of the MTDR cable to test how much wetted cable it

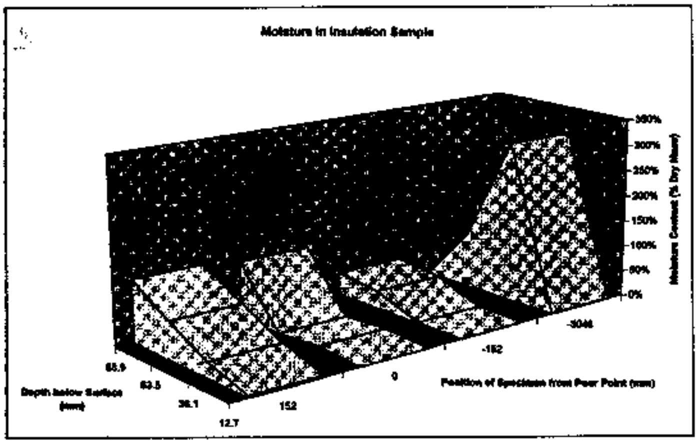

Figure 5. Distribution of moisture within core samples of 100-mm- (4-in-) thick insulation taken at the site where moisture was introduced 26 days earlier.

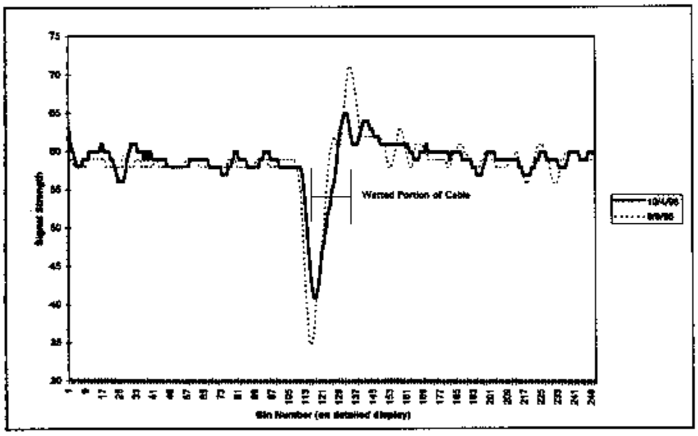

Figure 6. Change of MTDR signal over 26 days (detail at moisture location).

took to discriminate between a dry cable and one with wetted portions. This was done for both the 600-Ω and 300-Ω cables. When wetted over 1 m (3.3 ft.) in preliminary tests, the cables showed approximately a 10 percent increase in capacitance, a sufficient change to indicate a change in condition from dry to wet. The capacitance meter is a reasonably inexpensive instrument that could be adapted as part of an alert system for incipient roof leakage.

PASSIVE RESONANCE ROOF MOISTURE DETECTOR

The development of a simple, passive moisture sensor that does not require continuous attention or replacement of parts. The authors conducted a series of experiments with prototypes in situations that simulate moist conditions within low-slope roofing. Initial prototype configurations of the sensor and associated instrumentation still would require personnel to perform surveys from on the roof. However, results from preliminary tests indicate that the sensor can potentially be polled remotely.

Theory—The sensor comprises two passive electronic components: a capacitor (C) and inductor (L), forming a parallel LC circuit (Figure 7). Briefly, energy is stored in a charged capacitor in the form of an electrical field due to the electron charge (q) on the capacitor plates. Energy is stored in an inductor in the form of a magnetic field due to an electrical current (i) flowing through the inductor.

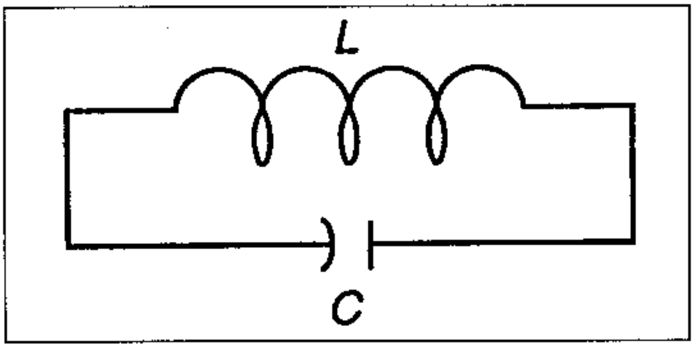

Figure 7. Schematic of a parallel LC circuit.

If in the parallel LC circuit, the capacitor is initially fully charged and the inductor is storing no energy, the capacitor will discharge, decreasing its electrical field, causing a current to flow through the inductor and thereby building up a magnetic field around the inductor. Once the capacitor is fully discharged, transferring all energy from its electric field to the magnetic field of the inductor, the process reverses and the inductor fully discharges all stored energy, which is again stored by the capacitor. In an ideal circuit, the process would continue indefinitely; however, in a practical circuit, some energy is dissipated in the form of heat due to finite electrical resistance present in the circuit. The process is periodic, oscillating from one energy storage state to the other at a resonant frequency.

Two practical configurations of capacitor are the flat-plate and the cylindrical version illustrated in Figure 8. Two different inductance coil geometries were used in the experiment, helical and flat spiral. The helical coils are cylindrical whereas the spiral coils are flat; both are illustrated in Figure 8.

Passive Sensor Prototypes

Test prototypes—Several types of flat plate capacitors were constructed and tested to develop a capacitor with optimum characteristics. Figure 9 shows a collection of these designs, coupled with inductors. The capacitor configurations include smooth flat plate, perforated plate, wire screen, and screen-faced plate, which are described below. In addition, an immersible design was conceived, but not constructed.

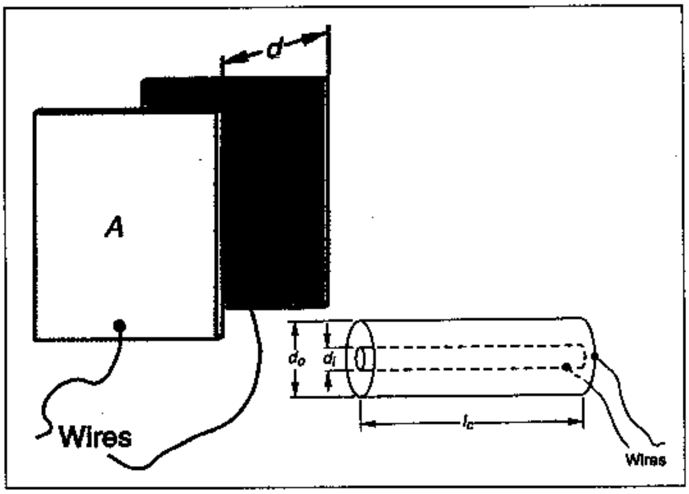

Figure 8. Schematic drawing of a flat-plate and a cylindrical capacitor. A, d, and l denote dimensions that define the characteristics of each.

Sensor detection equipment—The authors foresee the use of two types of instrumentation to monitor the presence of moisture within roofing, one for detecting leaks over a wide area of the roof by determining the presence of wet sensors there and the other for locating the exact spot of the moisture problem by determining which sensors are wet.

The wide-area technique for detecting wet sensors, discussed later as broadcast-induced resonance (BIR), has not yet been developed. Two methods were tested for querying sensors imbedded in a roof at problem locations that determine whether individual sensors are dry or not, the gate dip oscillator (GDO) and the swept frequency analyzer (SFA), as described in Yankielun and Flanders.[13]

The GDO was found to be an impractical method for querying individual sensors; the SFA, however, showed good potential.

Swept frequency analyzer—The SFA (Figure 10) generates a radio signal that changes frequency about the range of the resonant frequency of the roof sensor. This approach gives an instant and clear graphical indication of the moisture sensor's wet/dry state.

In operation, the swept frequency RF signal is transmitted in proximity (nominally 300 mm [1 ft.] or less) to the sensor under test. At frequencies above and below resonance of the sensor, little or no energy is inductively coupled into the sensor. At the resonant frequency, a measurable amount of energy is absorbed by the sensor. This change in energy absorption versus frequency is evident on the oscilloscope.

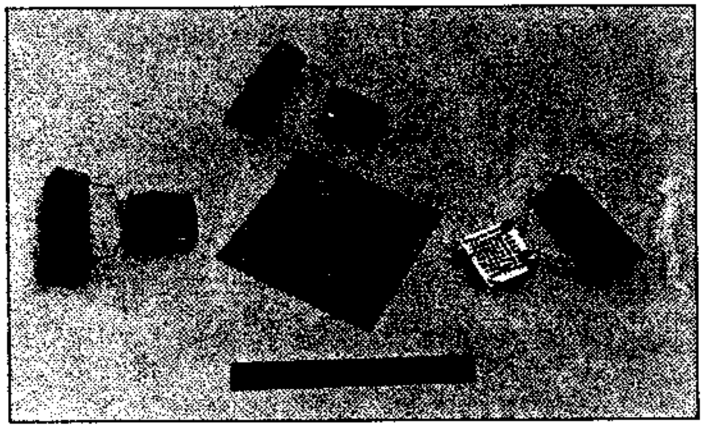

Figure 9. Capacitor designs tested as sensor components, together with their inductors that form the passive moisture sensor. Clockwise from left: wire screen, screen-faced plate, perforated plate (all with helical inductors), and smooth, flat plate (with flat spiral coil).

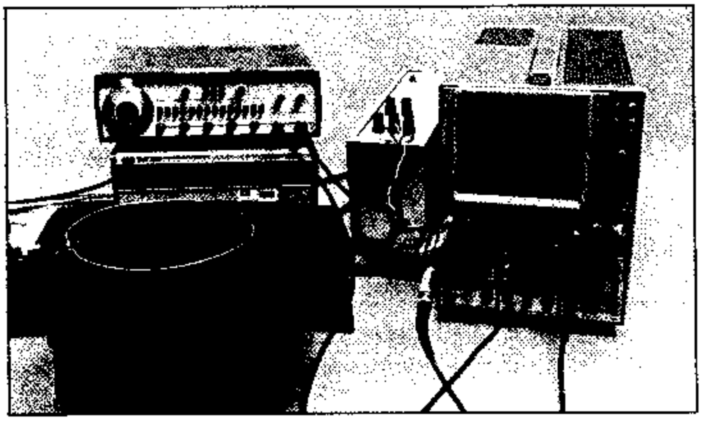

Figure 10. Swept frequency analyzer, as tested.

Broadcast-induced resonance—The wide-area technique for detecting wet sensors, discussed here as broadcast-induced resonance (BIR), has not yet been developed. It represents the next, most important step to create a roof-moisture detection system that is based on passive sensors. BIR measures the resonant frequency of the transducer as it rings after being energized by an electromagnetic impulse, instead of relying on detecting the absorption of electromagnetic energy as employed in the GDO and SFA techniques.

In concept, a roof-mounted directional antenna would, on occasion, launch a high-powered electromagnetic impulse, on the order of 10 to 100 ns duration, toward a field of roof sensors buried in a nearby section of roof. This wide-band pulse would energize the LC circuit roof sensors and cause them to oscillate (to "ring" electromagnetically) at their natural resonant frequency for numerous cycles, until circuit losses would cause the oscillation or ringing amplitude to exponentially decay to zero. This brief period of oscillation would be electromagnetically re-radiated and be detected by a radio receiver.

An RF spectrum analyzer would be used as a radio receiver to graphically display and measure the parameters of the spectrum of the received signals. Sensors in dry regions of the roof would resonate at a different frequency from those in regions where the roof is wet.

Passive sensor tests

Immersion tests—The authors demonstrated that immersing the capacitor of a helical-coil passive sensor attached to a flat-plate capacitor prevented it from resonating. In a second immersion test, each plate of the capacitor was laminated between layers of plastic electrical tape, providing a waterproof barrier, eliminating the plate to plate DC conduction path through the water. This permitted the sensor to retain a resonant frequency that was about 60 percent of its dry value.

Simulated roofing materials—To simulate sensor placement in a roofing environment, we placed the benchmark passive sensor on a 50-mm- (2-in.-) thick block of extruded polystyrene foam insulation with the sensor capacitor extending down into a hole cut into the foam. Another 50-mm (2-in.) of extruded polystyrene foam insulation was placed over the sensor, along with three layers of asphalt roofing shingles (Figure 11). The SFA test successfully located the sensor and determined the resonant frequency from a range of up to 300 mm (1 ft.). To further validate the sensor function in a roofing environment, a 300-mm x 300-mm (1-ft. x 1-ft.) plastic bladder filled with water to a depth of 15 mm (0.6 in.) was placed over the asphalt roofing material (Figure 12) to simulate standing water on a roof. Again the SFA located the sensor and measured the unchanged resonant frequency at a range of up to 300 mm(1 ft.).

BIR preliminary test—A small-scale test was devised to evaluate the BIR concept.

A roof moisture sensor was modified to allow adjustment to simulated wet and dry frequencies. The BIR pickup loop was placed 38 mm (1.5 in.) from the sensor and the output on the oscilloscope was observed. Figure 13 (top) represents the signal produced by the pulse/function generator. Figure 13 (middle) represents the oscilloscope trace showing the generated pulse and the sensor response to the pulse, an exponentially decaying resonant ringing. Figure 13 (bottom)

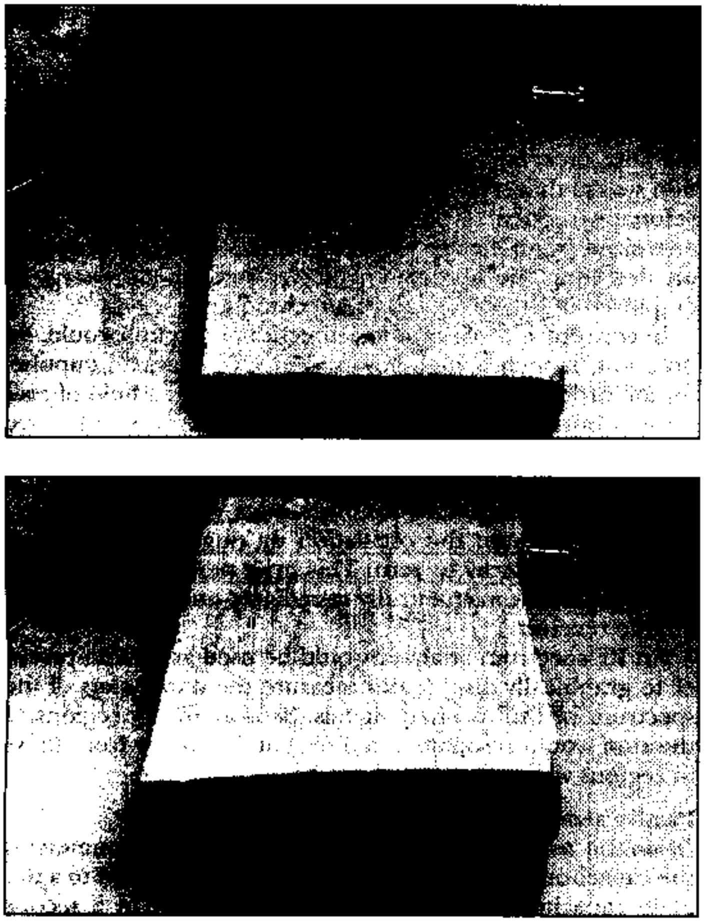

Figure 11. Sequence showing a passive sensor placed in a simulated roof construction.

is a detail of the trace, indicating how the resonant frequency was determined from the period of the resonant ringing.

Results—Two tests were performed, one with the variable capacitor at minimum setting to simulate a dry sensor condition, and another with the variable capacitor adjusted to the maximum value to simulate a wetted sensor. The difference in resonant frequency between the two conditions was readily distinguishable; they were 27 MHz for the dry condition and 20 MHz for the wet.

CONCLUSIONS

MTDR is ready for refinement—The authors believe that they have demonstrated a capability for a cable-based sensing system to detect and locate wet areas in low-slope roofing. The possibility exists for one of a number of inexpensive methods that would alert the building owner to the presence of water in the roof system. The use of an MTDR (metallic time-domain reflectometer) can pinpoint the location of the boundary between dry and wet insulation to within 1 m (3.3 ft.) over 30.5 m (100 ft.). This is possible for up to four separate portions of wetted cable. The authors believe that the technology is ready for refinement in test-bed applications within actual roofs.

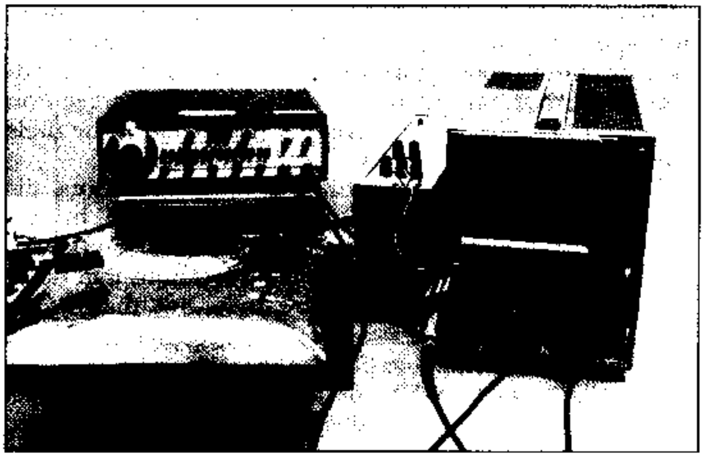

Figure 12. Detection of the passive sensor through standing water on the simulated roof.

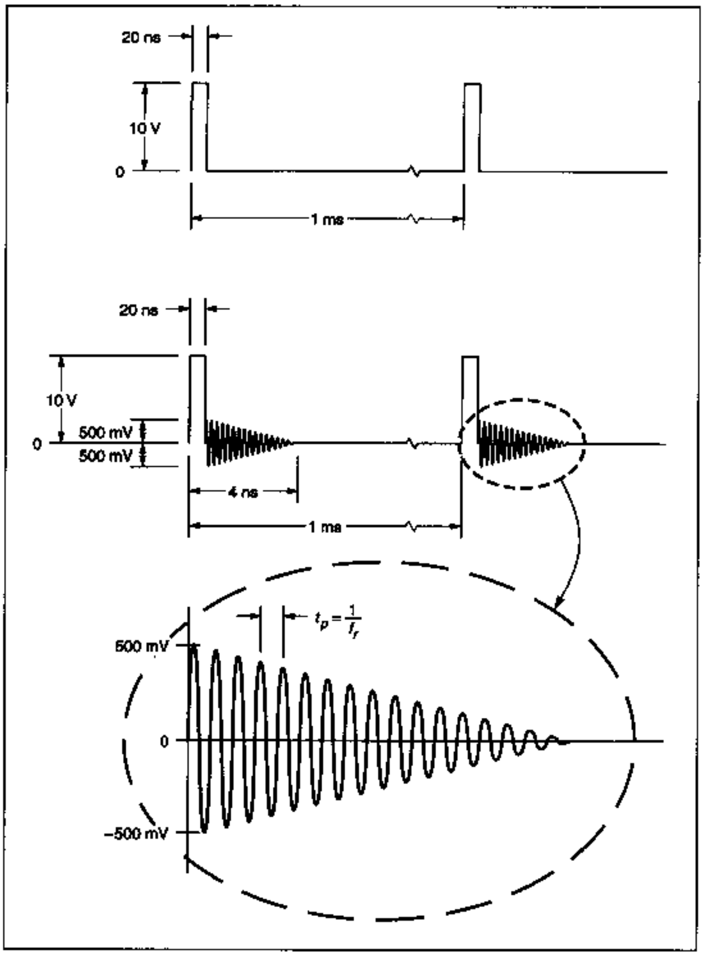

Figure 13. Typical BIR wave forms (not to scale). Top: Generated signal. Middle: Signal and sensor response. Bottom: Detail of sensor response.

Passive sensors require further development—The wet or dry status of a sensor can be detected at a range of up to 300 mm (1 ft.) using a portable, simple, and inexpensive SFA (swept frequency analyzer) test instrument. The GDO (gate dip oscillator) has more limited possibilities, since its detection limits were less than 50 mm (2 in.). Additional exploratory development must be done to increase the range at which the sensor can be remotely read and to determine whether it is possible to calibrate the degree of wetting within the roof with the resonant response of the sensor.

Practical development of the BIR (broadcast-induced resonance) technique, which is central to the passive sensor concept, requires the following:

- directed-beam, high-gain antenna
- higher transmitted pulse power
- greater receiver sensitivity

The next step will be to incorporate these features into a working, automated, BIR system.

The BIR system would detect the presence of both wet and dry passive sensors on the roof. When wet sensors were present, it would alert the building owner, who then could use BIR techniques to narrow the possible areas with wet sensors and use an SFA to query individual sensors.

A manufactured passive sensor might be a printed circuit on a flexible sheet of plastic with a capacitor attached to a tail that would be inserted into the roofing layer where water might be expected in case of a leak or other moisture problem.

REFERENCES

1. ASTM Standard Practice C 1153, Standard practice for the location of wet insulation in roofing systems using infrared imaging, *1991 Annual Book of ASTM Standards*, Section 4 Construction, Volume 04.06: "Thermal insulation; environmental acoustics," American Society for Testing and Materials, Philadelphia, Pennsylvania, 1990, 657-662.
2. Tobiasson, W. and C. Korhonen. "Roof moisture surveys: Yesterday, today and tomorrow," CRREL Miscellaneous Paper 2040, U.S. Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, September 1985.
3. Tobiasson, W. General considerations for roofs, *Manual on Moisture Control in Buildings*, ASTM MNL 18, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1994, 291-320.
4. Bailey, D., J. Ditman, R. Dupuis, and A. Budkner. "Survey of passive leak detection technologies for membrane roofing," CERL-fm-94/04, Construction Engineering Research Laboratories, Champaign, Illinois, 1994.
5. Farris, J. and J. Farris, Jr. Patent no. 4,502,044, Moisture alarm system, 1985.
6. Bryan, B.O, Jr. and E. Seagrave. Patent no. 4,598,273, Leak detection system for roofs, 1986.
7. Reddy, W.J. III and S. Berkman. Patent no. 5,134,377, TDR system and method for detecting leakage of a liquid, 1992.
8. Bailey, D.S. Patent no. 5,410,255, Method and apparatus for detecting and distinguishing leaks using reflectometry and conductivity tests, 1995.
9. Miller, E.K. (ed.), Time-Domain Measurements in Electromagnetics, Van Nostrand Reinhold, New York, 1986.
10. Hewlett-Packard, TDR fundamentals—For use with HP 54120T digitizing oscilloscope and TDR, Application Note 62, Hewlett-Packard, Palo Alto, California, 1988.
11. Hayt, W.H. Engineering Electromagnetics, McGraw-Hill, New York, 1967.
12. Flanders, S. and N. Yankielun. Laboratory tests of a cable-based roof moisture detection and location system, in preparation, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1996.
13. Yankielun N. and S. Flanders. "Passive resonance roof moisture detector," U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1996.