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Fiber Optic Cure Verification (FCV) Ensures Quality, Longevity of CIPP Liner Installations.

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ABSTRACT: Fiber optic cure verification (FCV) is a new approach to monitoring cure temperature continuously along the full length of a CIPP (cured-in-place pipe) liner. During cure, the exothermic reaction of the resin in the liner can occur on a small scale, and non-uniformly with respect to time and distance. For this reason, monitoring temperature at a liner's endpoints (the traditional method) provides no assurance that curing has happened everywhere (or anywhere) between. FCV uses laser pulsed over fiber optics to measure temperature continuously, eliminating the blind spots inherent in point measurement technologies. The data FCV gathers helps ensure storm and sewer lines are rehabilitated to specification, and that they perform as intended.

1. INTRODUCTION

For forty years, deteriorating storm and sewer pipes have been rehabilitated using the cured-in-place pipe (CIPP) lining method. CIPP liners are flexible, resin-impregnated fabric tubes that are inserted into pipes through adjoining manholes, then are expanded within the pipe to form a tight fit, and then cured with heat to achieve structural rigidity. Monitoring heat is essential to ensuring the quality and longevity of a lining project. Yet, until now no tool has been available to measure temperature along the liner with sufficient accuracy and exact positioning. Fiber Optic Cure Verification (FCV) is a new, patent registered technology that monitors cure temperature continuously along the full reach of a pipe, yielding comprehensive real-time data. This caliber of data is necessary to control the curing process, and to document a successful cure and cool-down for the asset owner.

2. THE SHORTCOMINGS OF CURRENT CIPP TEMPERATURE MONITORING PROTOCOLS

CIPP liner curing is a dynamic process that involves complex chemistry and variable environmental conditions, not to mention a lot of heating fuel and crew time. The liner itself is a fabric tube (commonly felt) vacuum-impregnated with thermo-setting resin (polyester, vinyl ester, epoxy or silicate) that is polymerized by an initiator system, or catalyst. This catalyst starts working at a specific temperature threshold, which is attained by circulating steam or hot water through the liner. Once activated, the catalyst undergoes an exothermic chemical process that generates still more heat as resin molecules are cross-linked into a rigid lattice. Monitoring the heating process and observing the exothermic reaction are essential to a proper cure, yet impossible to do adequately with existing technology.

So how is the CIPP process monitored today? Typically, the temperature at the interface between the liner and the host pipe is measured at both manholes using a thermocouple probe or heat gun. Where possible, it is also measured at intermediate manholes (if they exist) and through service connections accessible via a cleanout. Indeed, the current ASTM standard for CIPP liner installation calls for nothing more:

> *The temperature of the resin being cured should be monitored by placing gages between the impregnated tube and the existing pipe at both ends ... Initial cure will occur during temperature heat-up and is completed when ... the remote temperature sensor indicates that the temperature is of a magnitude to realize an exothermic or cure in the resin."*
>
> *(ASTM F 1216-09, 7.6.2.1-2)*

The problem is, curing a liner must account for temperature phenomena that can vary dramatically over the length of a single pipe. For instance, groundwater infiltration through cracks and joints can create localized heat sinks. Sags in a pipe can collect pools of steam condensate that create a thermal barrier. Active service connections can introduce flows that have localized cooling effects. The interplay of ambient ground temperature and the isolative properties of the host pipe can create another layer of temperature variability. And the setup for hot-water recirculation (discharge intervals and heights, plus flow rates) or steam heating (throughput volume and turbulence) can also create localized temperature conditions. Even variations in the composition and handling of the resin itself will yield temperature inconsistencies. In other words, temperatures measured at two endpoints cannot possibly account for cure progress everywhere in between. And even with intermediate point measurements, large blind spots remain.

So when point measurements tell an operator to conclude curing too early, intermediate regions that haven't reached cure temperature will remain soft, and will manifest as lifts (protruding ridges or bubbles in the liner). These lifts inhibit flow, and can leach uncured resin into the environment. Small lifts can be cut out and patched with a point repair; more extensive failures may require excavation. In all cases, addressing these failures poses a significant and unanticipated expense to the contractor, and there has been no quality assurance tool to prevent them.

To reduce the risk of a failure, most contractors will overcook a liner. Still, this precaution carries its own cost (significantly more boiler fuel and crew time), and without comprehensive temperature data from within the liner, the contractor is still unable to identify and address specific problems.

3. CAPTURING MORE COMPREHESIVE DATA WITH FIBER OPTIC CURE VERIFICATION

Fiber Optic Cure Verification (FCV) is a new, patent-registered approach to monitoring CIPP liner cure temperature. Using a linear fiber optic probe, the FCV system partitions a liner into zones of 1.5 feet, monitoring the average temperature of each zone to determine when cure temperature has been reached, and when post-cure and cool-down periods have each concluded. Measurements are taken every 30 seconds and are accurate to within ±2° Fahrenheit. FCV is capable of monitoring temperature over distances of several kilometers, and data is presented as a temperature waveform (temperature over distance), and as a 3D plot where temperature (represented by color) is mapped over axes of distance and time. The result is comprehensive data that delivers real-time, actionable intelligence, and which documents for both the contractor and asset owner that the liner was installed to specification.

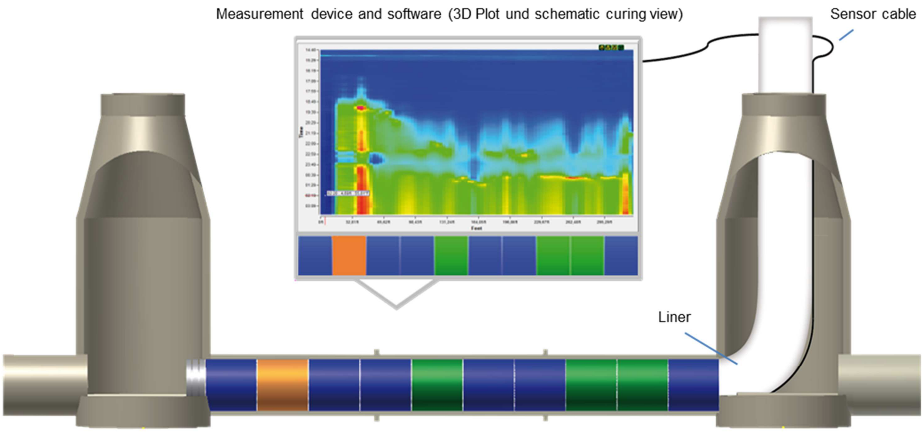

Figure 1: Typical setup for fiber optic cure verification.

So how does a single fiber optic probe deliver such robust temperature data? Molecules within the optical fiber oscillate at an intensity directly related to their temperature, and the intensity of this oscillation has a predictable effect on the backscatter (or reflectance) of laser light pulsed through the fiber. Specialized instrumentation analyzes this backscatter to decode temperature, and calculates temperature position by multiplying the laser pulse's time of flight by the speed of light - a process known as optical time-domain reflectometry, or OTDR. In this manner, temperature readings are taken every centimeter along the length of the probe, and then clustered and averaged into zones of approximately 1.5 feet.

The fiber optic probe is deployed in the host pipe prior to inversion or pulling of the liner. The probe measures just 3mm in diameter and most of that cross-section is jacketing designed to ensure performance in harsh environments. The probe lies at the bottom of the pipe, which is the slowest region to heat (since heat rises), and the region most prone to pooling of steam condensate. Upon completion of the cure, probe ends are cut and discarded along with the protruding liner ends; the remaining portion remains embedded in the installed liner.

Admittedly, linear sensing as a general concept is not new; it has been attempted previously using electronic temperature sensors. In a typical embodiment, these sensors would be placed in series along ribbon cable every 10 or 20 feet and sandwiched between a liner and its host pipe. By definition, a point-measurement solution disregards everything between the points. A zone measurement solution like FCV, on the other hand, provides an average measurement for each interval, so even phenomena smaller than the interval can influence the reported measurement. In short, FCV has no blind spots.

4. DISTILLING INTELLEGENCE FROM DENSER DATA

Comprehensive data is invaluable, but only when it can be comprehended and acted upon in real time. FCV development places a strong emphasis on the role of software in distilling critical intelligence from a mass of data. Typical software plots temperature over distance for both current temperature and peak temperature, and depicts cure and cool-down temperatures as horizontal reference lines on the same plot. To depict curing over time, a flat graph of time versus distance is colored according to temperature, allowing an operator to analyze an entire cure history in a single glance.

The software VISCOM (Visualization and Communication) is a high-performance tool for the measurement and analysis of the curing process. The software contains a liner information view, a schematic curing view and a 3D plot view (see figure 2).

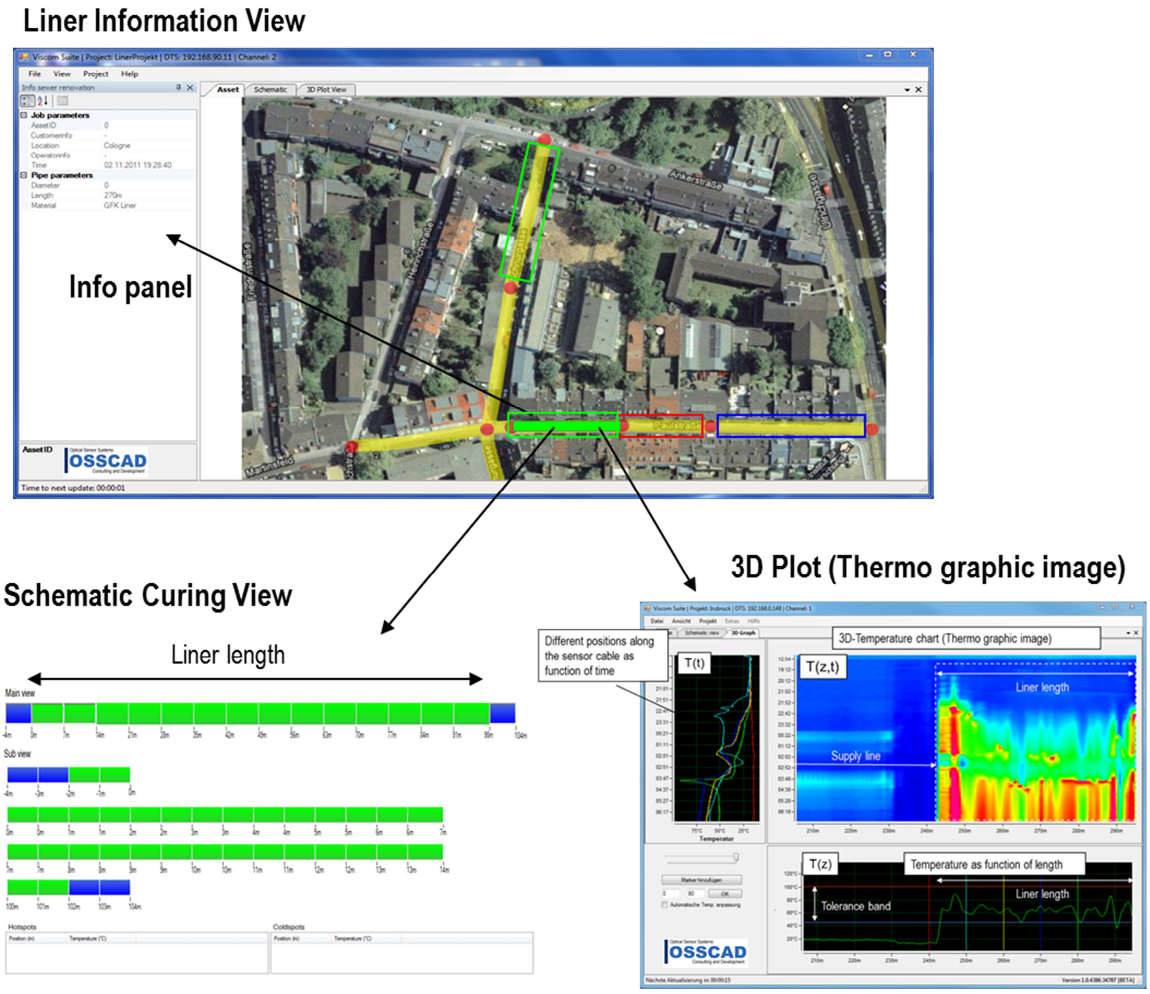

Figure 2: Software tools of the FCV monitoring system.

The liner information view gives the operator / customer an easy overview about the local mapping and about the different operating states of the liner renovation projects. The frame of the asset zones can be configured freely. For example: The liner project is finished successful the colour of the frame is green, if they are failures during the liner renovation the frame colour is red and for projects which aren't finished yet, the frame colour is blue (see figure 2). The info panel contains all important information about the liner production (liner type, dimension, material, etc.), the project planning (flow direction, chamber number, etc.), the transport & installation of the liner, the parameter of the optical temperature set up, the heat input during the liner curing, the results of the temperature measuring, and the final inspection and the quality approval. By a mouse click the user can open the corresponding schematic curing view or the 3D plot view.

The schematic curing view contains main and sub views (zone view) which represents the temperature value of the curing and the heat input per position along the liner. The threshold for the visualisation of the temperature values and of the heat inputs, the length of the main and sub view and the colour of the zones can be freely configured.

The 3D plot view converts the temperature data into a RGB (red-green-blue) scale. This thermo graphic 3D image shows the thermal curing process as a function of the length of the reach and the time of the heat supply over the total period of the rehabilitation process in real time. The operator can select chronologically the most important points and temperature changes. The latest local temperature graph (temperature reading as a function of the length of the measuring cable) is also displayed. An analysis tool allows to record the measurement data and display it as described. This analysis tool has an animation function which enables the data from the local temperature graphs to run through in a chronological way.

Furthermore, FCV software allows an operator to enter key parameters like cure temperature, cure dwell time, cool-down rate and cool down temperatures. The performance of each zone is then tracked according to those parameters, and the software aggregates that data to determine when curing has begun, when it is complete, and when cool down has concluded (see figure 2: Schematic Curing View).

Most importantly, FCV data and metrics are easily integrated with pipe inspection and asset management applications, making it easy to cross-reference temperature data with visual data and map locations.

5. RESULTS FROM FCV FIELD TRIALS

Figure 3 shows a hot-water cure. The first exothermic reactions take place at the end of the liner, and are initially concentrated in a very small area of the liner. After a time, other exothermic reactions occur sporadically along the length of the liner. At the beginning of the curing process, exothermic reactions yield a steep rise in temperature (approximately 70°F/min), with peak temperatures up to 480°F. Several minutes after the start of the first exothermic reaction, temperature declines at a much slower rate (approximately 3°F/min), leveling off around 140°F.

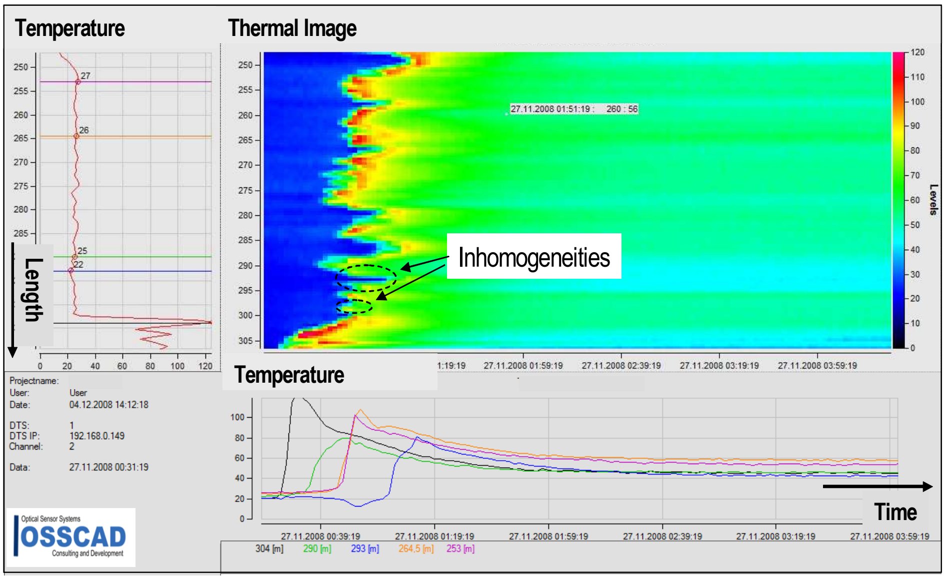

Figure 3: Data plots for a hot-water cure.

The thermo graphic image shows that the cure temperature target of 140°F given by the liner manufacturer is not reached at every point along the liner. These irregularities appear light blue (less than 120°F) in the thermo graphic ploy. Extending the curing time to 24 hours to boost heat input allowed the liner to ultimately achieve the required mechanical strength.

Figure 4 shows steam cure of an oval pipe. During cure, pooling of condensation kept the liner from reaching the necessary minimum temperature toward the far end. The operator was able to identify these irregularities using the 3D data plot and react accordingly. With steam input time extended, the liner ultimately reached full cure.

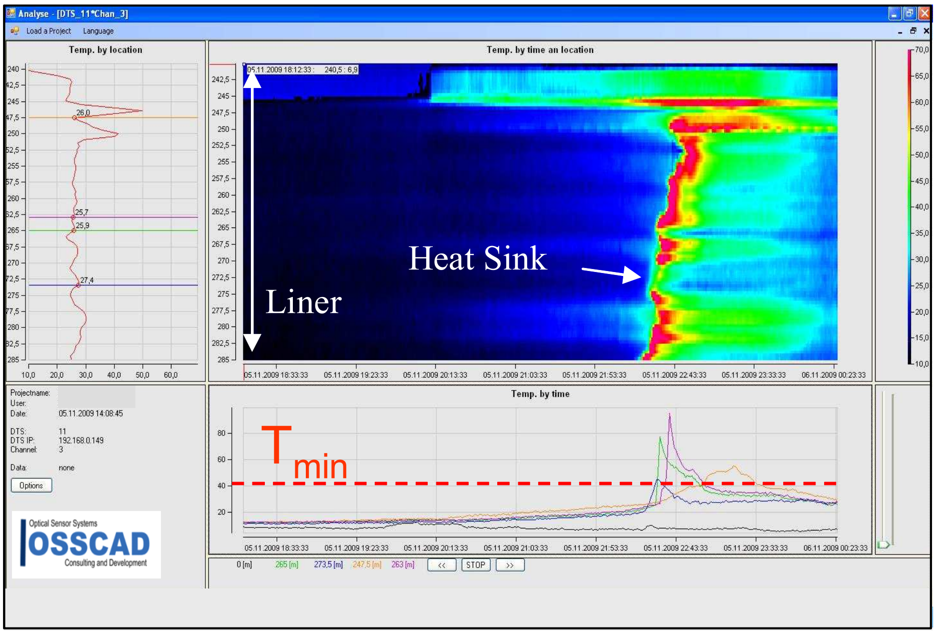

Figure 4: Data plots for a steam cure.

6. RESEARCH EFFORTS SEEK ADDITIONAL INTELLIGENCE, EASE-OF-USE FOR FCV

Understanding and controlling a process like CIPP lining requires proper metrics based on comprehensive data. Continued development of FCV technology is focused on further simplifying data collection, and automating how the collected data is utilized:

- *Cloud data:* Real-time upload of temperature data to an off-site server, allowing cure progress to be monitored and reviewed remotely.
- *Closed-loop control:* Integrating software logic with process control mechanisms so that temperature and recirculation can be throttled automatically for optimum cure.
- *Embedded probes:* Integrating the fiber optic probe into the liner itself for easy, one-step installation.
- *Sensor Reuse:* Maintaining and reusing embedded fiber for additional temperature monitoring, flow sensing or data transmission.

7. CONCLUSION

The FSV means that the thermal properties along the liner can be measured without gaps in real time during the sewer rehabilitation process. The VISCOM software with the thermo graphic view (3D plot view) and with the schematic curing view allows thermal irregularities to be easily identified and countermeasures can be taken in relation to the heat input during the liner rehabilitation process.

CIPP liner failure is always a source of anxiety for contractors, primarily because it has been impossible to verify a comprehensive cure using available technology, and because the cost of correcting failures is so great. Likewise, public agencies want assurance that CIPP liners have been installed to specification, and will perform as intended for their stated design life. Fortunately, the data collected using FCV can be summarized graphically for real-time control of the cure process, and delivered as a concise report documenting proper liner cure.

8. REFERENCES

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