APPLICATION OF AMORPHOUS METALS FOR PLASTIC PIPELINE DETECTION

Final Report

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ABSTRACT

The objective of this project was to evaluate the potential for using amorphous metal foil to enable the belowground detection of plastic pipelines. Amorphous metals have the highest known values for magnetic permeability, which makes them excellent conductors of magnetic field lines. These materials can create distortions in Earth's magnetic field that are comparable to more massive, crystalline, ferromagnetic objects, and these distortions can be detected with conventional magnetic gradiometers. The evaluation began with an experimental study of the characteristics of amorphous foil magnetic distortion, including effects of foil composition, geometry, and orientation to Earth's magnetic field. Based on this information, a potential candidate application was identified for the foil, and prototype locating tapes were designed and produced. The project concluded with in-ground locating measurements of one of the tape prototypes. Overall, the locating tape based on amorphous metal foil would have the functionality of existing aluminum-based detectable tape but with the added option of passive magnetic location. The preferred orientation of the foil is also compatible with plow installation of spoolable plastic pipe and conduit. Based on these results, the project's industrial partner, Metglas Inc. of Conway, South Carolina, plans to evaluate the commercialization of this technology.

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INTRODUCTION

The objective of this project was to evaluate the potential for using amorphous metal foil to enable the belowground detection of plastic pipelines. These pipelines are inherently nonconductive and nonmagnetic which make them difficult to locate once buried. Amorphous metals possess unique properties compared to more common crystalline counterparts, and it was believed that their combination of flexibility, toughness, and high magnetic permeability would make amorphous metal ribbon highly suited for tagging plastic pipe.

BACKGROUND

Polymer Pipelines

Plastic polymer pipelines are in use through the United States for water, petroleum, natural gas, brine water, and fiber optic/electrical conduits. For natural gas in particular, plastic piping is a key component of distribution networks, comprising 69% of the nation's 2.149 million miles of natural gas distribution piping [1]. Plastic piping can be easier to install than metal pipe, and it is less susceptible to time-dependent threats such as corrosion. However, these polymer materials generally have no intrinsic locating properties, making belowground detection and avoidance much more challenging. Because of this difficulty, excavation damage ranks as the single largest cause of incidents in gas distribution pipelines; see Figure 1. Over the last 20 years, excavation damage caused $219 million in reported damages and 109 fatalities [1].

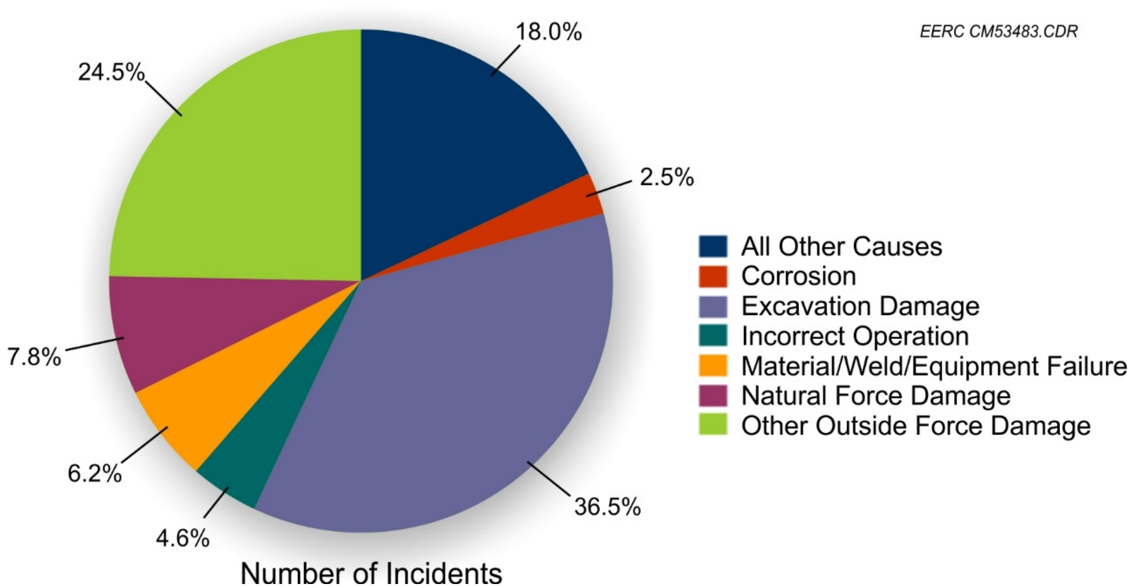

Figure 1. Breakdown of all reported incident causes for natural gas distribution systems, 1996 to 2015 [1].

With respect to regulation, there is no single overarching entity that enforces plastic pipeline construction, installation, monitoring, location, and emergency response. The federal government, through the Pipeline and Hazardous Material Safety Administration (PHMSA), regulates interstate and intrastate gas pipelines as well as interstate hazardous liquid pipelines and gathering pipelines for high-consequence areas [2]. The relevant federal code covering pipelines is CFR Title 49 "Transportation," Parts 190–199 [3]. In addition to federal regulation, each state, county, and municipality also has the authority to govern utilities within its boundaries. For pipelines outside of direct federal oversight, states or local governments determine whether to follow federal rules or abide by their own as they relate to pipeline construction and maintenance.

At the state level, many states have a commission or organization for monitoring pipelines in its territory. For example, in North Dakota, that responsibility falls on the North Dakota Industrial Commission and the North Dakota Pipeline Authority. Table 1 shows how hazardous liquids and natural gas oversight responsibilities are designated in the state. North Dakota has chosen to follow federal guidelines in some of these areas especially as they relate to safety and emergency response. Otherwise in North Dakota, federal oversight is generally limited to interstate natural gas and safety measures for hazardous liquids transmission pipelines.

Table 1. Hazardous Liquids and Natural Gas Pipeline Governance for the State of North Dakota

Hazardous Liquids				
		Construction	Safety	Emergency Response
Interstate	Gathering	State	State	Federal, state
	Transmission	State	Federal	Federal, state
Intrastate	Gathering	State	State	Federal, state
	Transmission	State	Federal	Federal, state
	Distribution	N/A	N/A	N/A
Natural Gas				
		Construction	Safety	Emergency Response
Interstate	Gathering	State	State	Federal, state
	Transmission	Federal	Federal	Federal, state
Intrastate	Gathering	State	State	Federal, state
	Transmission	State	State	Federal, state
	Distribution	State	State	Federal, state

North Dakota has separate laws in place regulating oil and gas gathering lines. Table 2 shows the applicable codes as they apply to construction, corrosion, spills, reporting, and materials in the state [4–7].

Table 2. North Dakota State Codes for Oil and Gas Pipelines

Topic	Code	Comments
Construction	38-08-26, 38-08-27, 43-02-03-29	Location of finished pipelines, limited construction language, GIS reporting, trenching and filling
Corrosion	None	No corrosion guidance in ND
Spills	43-02-03-30	Spills of any kind, reporting fires
Materials	None	No materials guidance in ND

Despite the negative consequences of pipeline incidents, very little guidance is provided or mandated relating to construction practices to aid in the location of underground utilities. In North Dakota, the only technique that is mentioned in code and regulation documents is that plastic pipelines must be buried with a tracer wire or some type of metal foil tape so they can be located through either induced current or magnetic search tools [8]. In addition to this, in North Dakota, new pipeline designs must also be submitted to the state for logging in a GIS (geographic information system) database [6]. Discussion with North Dakota's One Call coordinator generally confirmed this situation [9], stating that the only true regulatory backstop that pipeline operators must comply with are the timely locate requests through each state's 811 or similar call-before-you-dig programs. The actual means by which these locate requests are processed is largely left to the discretion of the operator. Noncompliance with locate requests can potentially expose the operator to liability for resulting pipeline damage or expenses associated with project delays.

Amorphous Metal Film

Amorphous metals are metallic solids that lack a crystalline atom structure. They have an analogous relationship to conventional crystalline metals as glass does to crystalline quartz. In fact, amorphous metals are described as metallic glasses. The absence of a crystalline structure and grain boundaries in amorphous metals results in almost transcendent material properties, including improved strength, hardness, and resistance to corrosion initiation compared to the same metal alloys with a crystalline microstructure.

The high-performance features of amorphous metals made them the subject of a Defense Advanced Research Projects Agency (DARPA) research effort to develop bulk materials for mission-critical components such as projectiles, air frames, and ship hulls. However, these efforts have largely not materialized because of the difficulty in making bulk amorphous metal parts. Current techniques for bulk parts are limited to casting specialized alloy compositions that prefer to solidify in an amorphous state [10].

In contrast to bulk materials, the material under evaluation in this project was amorphous metal foil, which is produced from a wide array of conventional metal alloys and reaches its amorphous state kinetically, by very rapid cooling (up to 1,000,000°C/s) of thin metal ribbons before crystalline grain structure can form. These materials retain the high-performance characteristics of amorphous metals and are mass-produced today for a variety of applications. Despite having increased strength and hardness compared to crystalline metals, these foils remain very flexible, given their thin 25 µm thickness.

The amorphous nature of these foils results in desirable physical properties, such as improved toughness and corrosion resistance so that thin foils of amorphous metals might be suited to being embedded within caution tape or pipe or adhered to the exterior of a buried pipe. However, the property of most significance to this project is the very high magnetic permeability of these materials, which is a measure of the magnetic flux density that can be concentrated in a material compared to a vacuum. In conventional crystalline metals, the individual crystalline grains and grain boundaries present resistance to a magnetic field, and the actual permeability of metals is less than the theoretical maximum for pure, single-crystal material. Amorphous metals, on the other hand, are without grains and grain boundaries and, therefore, excel as magnetic field conductors. In fact, amorphous metals have the highest known magnetic permeability values, even exceeding the permeability of specialized Mumetal alloys that have been developed specifically for magnetic shielding; see Table 3. In addition to having higher potential permeability, amorphous metals will generally be lower cost than these specialty alloys because of lower material costs (i.e., nickel-free) and, for this application in particular, being directly cast as a thin foil versus needing a secondary rolling step to achieve thin sections.

Table 3. Typical Relative Permeability Values for Several Materials

Material	Magnetic Relative Permeability
Vacuum	1
Air	~1
Water	~1
Concrete	~1
Copper	~1
Carbon Steel	~100
Iron	~5000
Mumetal (MuShield®)	50,000–200,000
Amorphous Metals	50,000–1,000,000

Several market applications have already been developed based on the magnetic properties of amorphous metal foil. A key use for these films is as the building block for high-efficiency power transformer cores where the foil’s decreased resistance to magnetic fields leads to a measurable reduction in the heat generated within the core from the alternating magnetic and electric fields. Another interesting application for these films is in antitheft tags, some of which use strips of amorphous foil to provide a unique magnetic signature for detection.

The hypothesis of this project is also based on the unique magnetic properties of amorphous metal film; namely, that the high magnetic permeability of the foil can be used to create a magnetic signature of similar magnitude to that of all-ferrous metal pipe but with very little added metal. Such a signature could be easily detected using conventional magnetic locating devices.

Magnetic Pipe Locating

Magnetic pipe detection is a mature technology, and the associated instrumentation is widely available to industry. The method is believed to offer practical advantages for pipe locating compared to other methods, but it has the obvious disadvantage of being limited to detecting ferromagnetic pipe materials. This project was aimed at overcoming this fundamental limitation by exploring the use of amorphous metal foil to add a magnetic signature to nonferrous materials, including plastic piping.

Magnetic locators rely on passively detecting distortions in Earth's magnetic field caused by nearby ferromagnetic objects. These instruments typically monitor the differential signal from two precisely spaced magnetometers. In undisturbed regions of Earth's magnetic field, both detectors receive the same flux reading which does not produce a differential signal. However, nearby ferromagnetic materials distort Earth's magnetic field such that the magnetometer readings differ and do produce a detectable signal. The magnitude of the field distortion is dependent on several factors, including the mass of the ferromagnetic object and its orientation to Earth's magnetic field. A skilled operator can sometimes interpret magnetic locator feedback to infer information about the type of underground object and its orientation.

Illustrative magnetostatic finite element modeling results are shown in Figure 2. Figure 2a shows the calculated distortion in Earth's magnetic field lines from the presence of a 4-inch nominal cast iron pipe. Figure 2c compares the distortion caused by a thin layer of amorphous metal foil wrapped around a nonferromagnetic 4-inch pipe diameter, and it shows that the resulting field distortion is qualitatively comparable to that of the solid metal pipe. For contrast, Figure 2b shows the effect of the same thin shell dimensions as in 2c, but instead of using an amorphous metal permeability value, the cast iron material properties from 2a were used. Clearly, the cast iron shell is unable to conduct a significant fraction of the magnetic field lines because of its much lower magnetic permeability compared to the amorphous foil. As a result, the distortion of Figure 2b is much less pronounced and would be more difficult to detect with a magnetic locator.

The modeling of Figure 2 is only an illustrative comparison and is not necessarily representative of the best application pattern of the amorphous foil. However, it does show that very thin profiles of a highly permeable material do appear to conduct the magnetic field as efficiently as the modeled solid wall pipe section.

Locating Technology Comparison

In this section, the concept of applying a highly permeable amorphous metal to "tag" plastic piping is compared to other commercial technologies and applied research approaches. A summary of relevant technologies is presented in Table 4.

An analogous field-based approach in Table 4 is electric field detection, which relies on applying or inducing an excitation signal to a conductive pipe tracer so that the resulting electrical field can be detected aboveground. Application of the signal is either through direct electrical contact if an exposed terminal is available, or the signal can be induced from above ground using an induction coil. This process is in contrast with magnetic location, which passively detects distortions in Earth's magnetic field rather than depending on the generation of a field for detection.

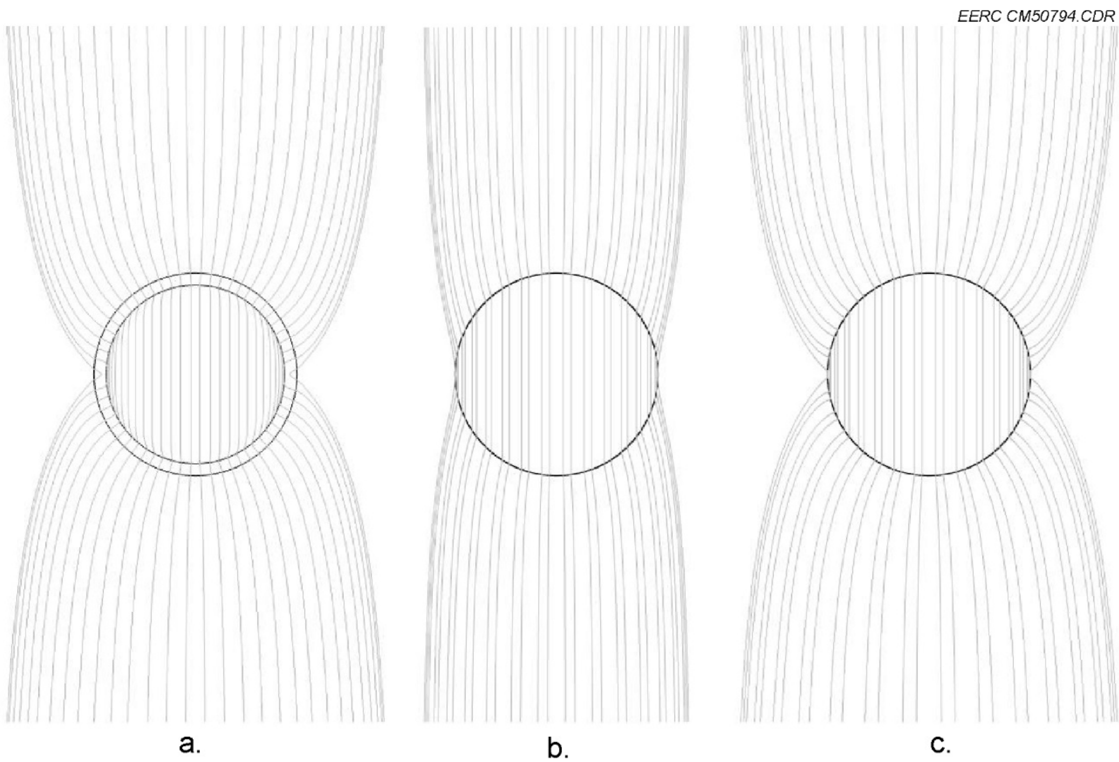

Figure 2. Magnetostatic modeling of the distortion caused by a pipe cross section in Earth's magnetic field: a) 4-inch Schedule 40 cast iron pipe, b) 50-µm shell of cast iron around a 4-inch pipe diameter, and c) 50-µm shell of high-permeability amorphous film around a 4-inch pipe diameter.

Electric field detection requires that a conductive tracer be added to plastic piping, which is not unlike the effort that is anticipated to be needed for adding an amorphous metal tag for magnetic location. However, to be fully functional, the conductive tracer should maintain its conductivity over its entire length for the useful life of the pipeline, whereas breaks in the amorphous foil would have little impact on its functionality for conducting magnetic field lines. Furthermore, the electric field itself can be limited by soil conditions since the constituents of soil and water attenuate electrical fields differently. Meanwhile, Earth's magnetic field is generally only attenuated by highly ferromagnetic soils or nearby steel objects. Common soil constituents, water, and air all present virtually the same attenuation factor to Earth's magnetic field, thus making magnetic detection practical in a number of situations.

The approach described in Table 4 of magnetizing plastic pipe itself is also worth comparing further. This technique embeds "hard" magnetic materials that retain a magnetic polarity like a permanent magnet into the resin used to make plastic pipe [11]. In comparison, amorphous metals are magnetically "soft" and do not retain a magnetic polarity in the absence of an external magnetic field. Instead of conducting and distorting Earth's magnetic field, the use of hard magnetic materials essentially turns the pipe into a weak permanent magnet with its own field that can be detected aboveground. During the evaluation of that concept, the permanent magnetic field did

Table 4. Summary of Existing and Potential Plastic Pipeline Detection Methods

Approach	Description/Status	Assessment
Amorphous Film-Based Magnetic Detection (this project)	Would use amorphous metal foil to add a magnetic signature to plastic pipe for passive magnetic detection (i.e., no pipe excitation).	Could allow conventional magnetic locators to be used with plastic pipe. Requires pipe modification similar to electric tracer technology. Applicable to a wide variety of soil conditions.
Conductive Tracer Wire/Tape with Electric Field Detection	An electric conductor mated to the pipe or buried nearby generates a detectable electric field signal when energized. Available technology with widespread industry experience.	Effective but can be limited by soil conditions and the excitation method. Requires an electrically conductive path to be maintained over the life of the pipe.
Radio Frequency Identification (RFID) Tagging	Commercially available technology based on rugged RFID tags and reader system.	Effective for unique identification of discrete point tags, not ideally suited for long pathway tracking. Radio frequency operation limits maximum effective depth.
Ground-Penetrating Radar and Other Reflected Signal Mapping	Maps underground structures using transmission and reflection of acoustic or radio frequency signals. Commercially available.	Can provide complete underground 3-D mapping for any pipe material. Complex technology and data processing; seemingly expensive for routine locating tasks.
Sonde-Based Location	Pipe excitation through a transmitter inserted into the pipe coupled with an aboveground detector. Commercially available.	Effective but generally not practical for transmission pipelines because of limited access points.
Magnetizable Plastic Pipe	Magnetic materials are mixed and extruded with plastic pipe resin, then magnetized to create a unique and permanent magnetic signature. Development work supported by PHMSA, not yet commercial.	Shown to be effective for detection, but unresolved issues remain concerning increased cost and material longevity.
Asset Mapping and Proactive Avoidance	Uses infrastructure location data to define virtual no-dig zones. Development work supported by PHMSA for an automated, location-based warning system.	Could be an effective tool to raise awareness before digging but probably will not displace the need for sensing technologies when nearby digging must occur.

generate a detectable and unique magnetic signature, but a substantial addition of magnetic filler was needed which impacted the projected costs and the practicality of the concept. Unlike the use of magnetically hard materials, the current project focuses on magnetically soft amorphous metals which simply conduct and distort Earth's background magnetic field to create a magnetic signature. Given the high permeability of amorphous metals, this effect will be achieved with far less added ferromagnetic material than was the case for the hard magnetic filler.

The final technology worth distinguishing in Table 4 is the use of adhered RFID tags for pipe and underground asset location. In this system, the tags consist of compact radio frequency antennae linked to a responder circuit that emits a return signal when activated. This approach offers several desirable features such as a unique identifier and minimal interferences from nearby conductors. It is highly suitable for fixed point or specific asset location but not ideal for the detection of pipeline pathway because of the discrete nature of the RFID antenna tags. On a pipe, the tags can be placed close enough to delineate its path, but this approach may become cumbersome and, possibly, cost-prohibitive over a long length. Tagging with amorphous metal ribbon, on the other hand, is intended to run the length of the installed pipe and be detectable anywhere along the continuous length.

METHODS

Magnetic Field Distortion Measurements

A test fixture was designed to allow repeated measurements of the magnetic field distortion caused by various utility pipe samples and the amorphous metal samples under investigation. The apparatus held the gradiometer used for the project, and it was constructed using nonferrous materials, primarily plastics and wood. A picture of the fixture is shown in Figure 3.

During the distortion measurements, pipe and amorphous metal samples were placed on the ground underneath the gradiometer. Since the magnetic field attenuation does not change whether passing through air or ground, it was not necessary to bury the samples during the field measurements. The gradiometer was held at various heights above the samples to simulate an average burial depth range for utility pipes.

The gradiometer used for the experiments was a Dunham & Morrow Inc. Mag Pro II model. Gradiometers use a passive detection method that sense distortions in Earth's magnetic field. The gradiometer generates a differential signal from two fluxgate magnetometers mounted in the instrument. The sensors in the Dunham & Morrow gradiometer were spaced 19.5 inches apart along the shaft of the instrument. As stated in the instrument's manual, "fluxgate magnetometers are vector magnetic field sensors that measure the average magnetic field component along their sensitive axis, i.e., the magnetic field component along the longitudinal axis of the sensor tube [12]." The magnitude of the instrument's output is proportional to the magnetic field distortion caused by ferromagnetic objects. The differential output from the gradiometer was displayed in milligauss (mG) units.

Figure 3. Pipe sample magnetic measurement apparatus.

Accurate and repeatable measurement of the magnetic field distortion required that extraneous magnetic interferences be removed from the test scenario. Examples of interference included nearby ferrous pipes and conduit or ferrous materials in the tester's clothing. Where magnetically clean conditions could not be achieved, such as when measurements were made indoors, data were postprocessed by subtracting the background magnetic readings.

A series of magnetic field distortion experiments were completed during the summer and fall of 2016. The test plan included comparisons of pipe size, amorphous metal foil composition, foil geometry, and orientation to Earth's magnetic field. Most data were single-point measurements of the field distortion taken with the sample centered underneath the gradiometer. These values were representative of the peak differential reading that could be expected at a given gradiometer height above the target. Profile measurements of the magnetic field distortion along the length of selected samples were also collected in order to better visualize the three-dimensional field surrounding the target and also to validate magnetostatic modeling of the amorphous foil's effect. To gather the profile data, each target was incrementally advanced in a straight line underneath the mounted gradiometer, and differential field readings were recorded at regular intervals, typically every 2 inches.

Initially, the experiments for this project were performed outdoors in a magnetically clean location with no nearby interferences. While the location was good for utmost sensitivity, the downside of the outdoor location was that wind gusts would cause the gradiometer probe to move which would slightly change the mG readout and introduce unwanted variability to the data. Since the peak gradiometer readings were sensitive to even small movements, the team chose to move the magnetic testing indoors. The indoor location did suffer from surrounding magnetic interference, but these effects were compensated for by subtracting the initial background reading of the location from the mG reading(s) of the test sample. Of course, the gradiometer will need to weather outdoor conditions for use as a locator; however, this situation differs from that of the sensitivity measurements. In the former, the gradiometer will constantly be in motion to find the approximate peak location, while in the latter, the goal is to record the peak value, which requires steady positioning.

Magnetostatic Modeling

Finite element modeling of the magnetic field distortion caused by the amorphous metal in Earth's magnetic field was also performed to optimize the amorphous foil's configuration. This modeling was magnetostatic, meaning that there was no time-varying component included in the analysis. The software chosen was CST EM Studio®, an electromagnetic simulation tool specifically intended for static and low-frequency fields. Once general agreement was reached between the gradiometer measurements and the model results, the model was used to screen a variety of locating tape design parameters and develop a prototype locating tape design.

The basic model consisted of two elements: a target (e.g., a representation of an amorphous wrap or tape) and a surrounding bounding volume which contained the background magnetic field. Material properties, including the relative magnetic field permeability, were defined for these two model elements. The bounding volume was defined using the software's air material properties with a relative permeability value of 1, which actually represents most other nonferromagnetic materials like water, stone, wood, etc. The software did not have amorphous metal properties in its library; therefore, a user-defined material was created based on standard iron but with the relative permeability increased to 80,000.

The surrounding magnetic field was defined to approximate the field strength and orientation in Grand Forks, North Dakota. According to the National Centers for Environmental Information Magnetic Field Calculator [13], Grand Forks (coordinates of N 47° 53' 57", W 97° 3' 32") has a total field strength magnitude of 563.8 mG. The magnetic inclination at Grand Forks is 73.43°, meaning that the vertical and horizontal field components when oriented toward the Magnetic North Pole are 540.4 and 160.7 mG, respectively. Finally, Grand Forks has a magnetic declination (i.e., deviation from true North) of +3.18° which was used to compute field components for orientations other than facing magnetic North.

Each simulation resulted in a 3-dimensional set of field strength values for each node in the finite element model. The raw field data were postprocessed to produce results that were comparable to the gradiometer output, which is actually a differential signal between the two magnetometers in the instrument. In order to duplicate these readings, postprocessing of the raw results consisted of extracting the vertical field strength data for two planes spaced the same distance apart as the gradiometer sensors (19.5 inches) and then subtracting these data to get a differential value. Only the vertical axis field value data were used because the gradiometer only measures field strength along its longitudinal axis.

Prototype Evaluation

For evaluation of using amorphous-based ribbon as an underground locating marker, short production runs were produced of a locating tape based on the collected experimental data and modeling efforts. The tape was then evaluated by burying segments in the same manner as it would be installed in the field. Detectability of the tape was quantified by recording magnetic field distortions along transects across the buried tape layout.

RESULTS

Magnetic Field Characteristics

Detectability, or the distortion caused by the amorphous foil in Earth's magnetic field, degrades exponentially with distance away from the target such that the results produce a straight line when plotted on log-log coordinates. An example of the generalized response of different ferrous metal targets is shown in Figure 4, which is based on a more comprehensive figure found in Breiner [14]. Single-point, peak distortion values that were measured for the amorphous metal targets resulted in similar trends with respect to target distance and were also plotted on log-log coordinates.

Pipe Diameter

Covering the exterior circumference of a polymer pipe with an amorphous metal foil wrap was the initial configuration that was considered to add a magnetic signature to the pipe. As an example of this configuration, Figure 5 shows a 4-inch conventional steel pipe and a 4-inch polyvinyl chloride (PVC) pipe that was wrapped with amorphous metal foil (Metglas 2605HB1M). The 0.001-inch-thick amorphous alloy was wrapped around the circumference and along the entire length of the PVC pipe (48 inches).

The gradiometer test apparatus described previously was used to measure the magnetic signature of several pipe samples, including the 4-inch samples in Figure 5 and a series of 1-inch NPT (National Pipe Thread) pipes that were 8 inches long. The detection signal from each sample is shown in Figure 6 and shows the characteristic exponential degradation trend with increased distance from the target. The chart suggests that an amorphous alloy-wrapped PVC pipe has a magnetic signature reading that is comparable to its steel counterpart at close distances but has a higher gradient value as the distance is increased. Also included in Figure 6 is a comparison of amorphous foil to crystalline foil (i.e., steel shim) for the 1-inch pipe size. Both foil materials had the same thickness, 0.001 inch and were wrapped identically, yet the amorphous material clearly resulted in a larger, more detectable magnetic distortion. The results in Figure 6 generally substantiate the qualitative model results of Figure 2.

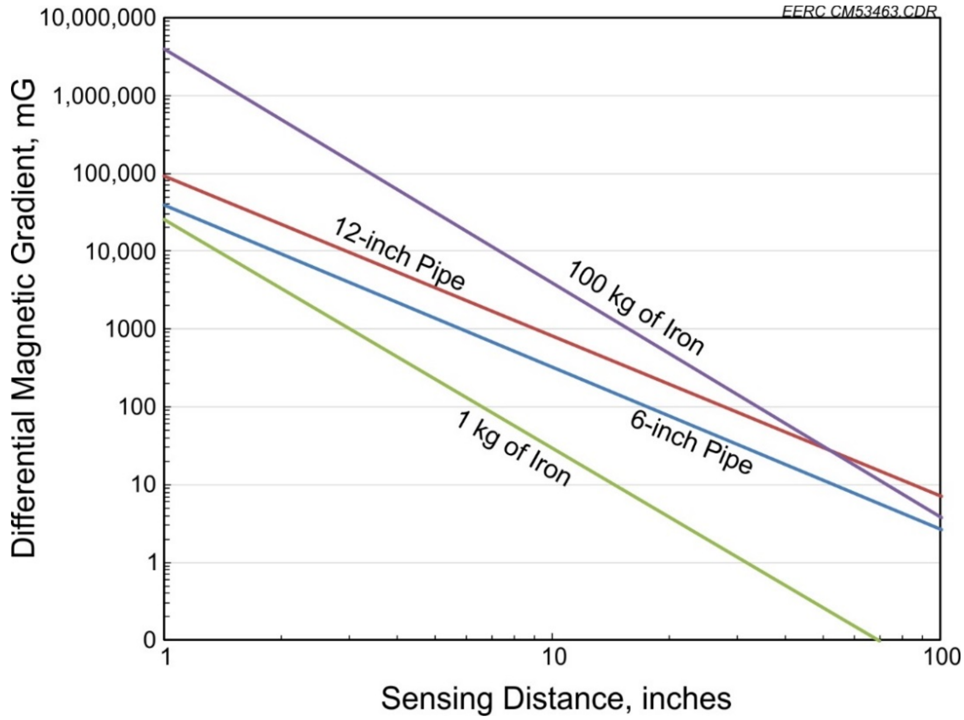

Figure 4. Generalized gradient values for estimating magnetic anomalies from various objects, adapted from Breiner [14].

Figure 5. Photograph of PVC pipe wrapped in amorphous foil (top) and standard iron pipe (bottom).

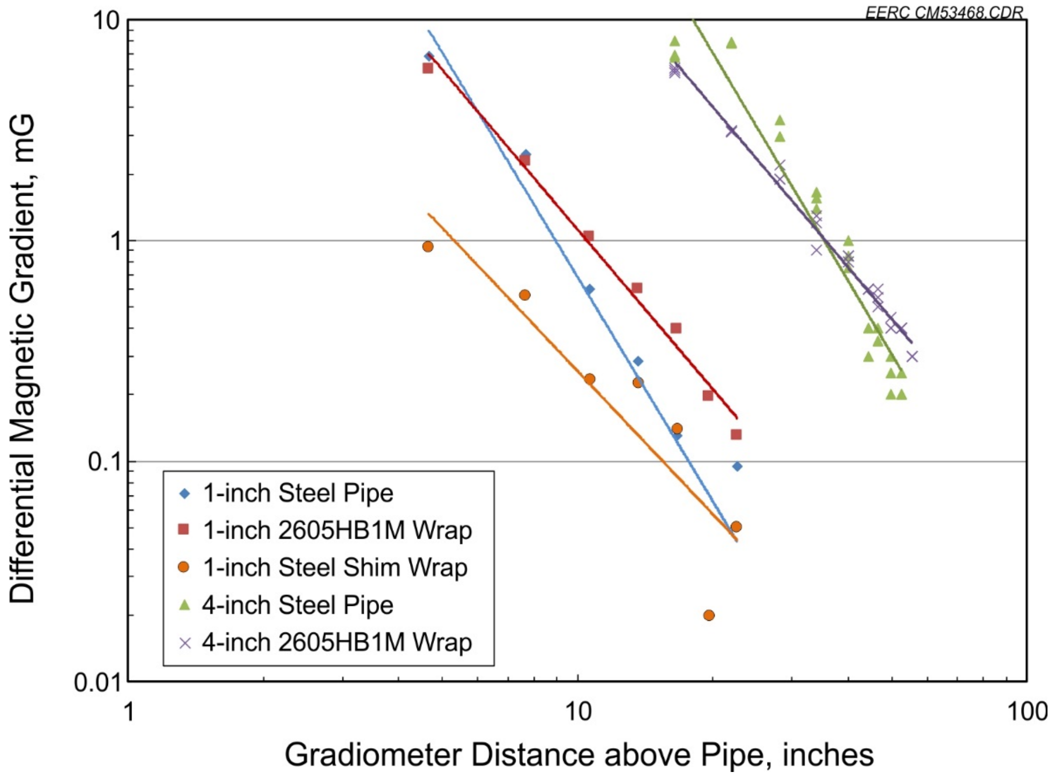

Figure 6. Trend comparisons for standard steel pipe and amorphous-wrapped PVC.

Amorphous Metal Comparison

Several amorphous foil alloys were screened in order to identify an optimum materials composition. The alloys were provided by the project's industrial partner, Metglas Inc., and details of the tested samples are summarized in Table 5. Differences included iron- and cobalt-based metallurgies, and the samples were picked to evaluate a range of magnetic permeability and saturation values. Values reported in Table 5 are for foils in the as-cast state without a secondary annealing cycle. Annealing enhances the magnetic properties of the foil but generally causes the ribbon to become mechanically brittle.

Table 5. Summary Magnetic Properties of Tested Amorphous Metal Alloys

Alloy	Induction, T at an Applied Field of 800 A/m	Relative Magnetic Permeability	Composition
2605CO	1.15	156,400	Fe-Co-B
2605HB1M	0.958	159,900	Fe-B-Si
2605SA1	0.829	67,890	Fe-B-Si
2705M	0.754	929,300	Co-B-Si
2714A	0.602	190,000	Co-B-Si

Results for the material screening are summarized in Figure 7 for the wrapped 1-inch NPT PVC pipe segments. As the figure shows, most of the materials fall within a narrow detection band that suggests the actual amorphous metal composition has minimal impact on detectability in Earth's static magnetic field. This observation is interpreted as each foil had the minimum threshold permeability necessary to cause the maximum gradient possible given Earth's magnetic field strength and the specific pipe geometry.

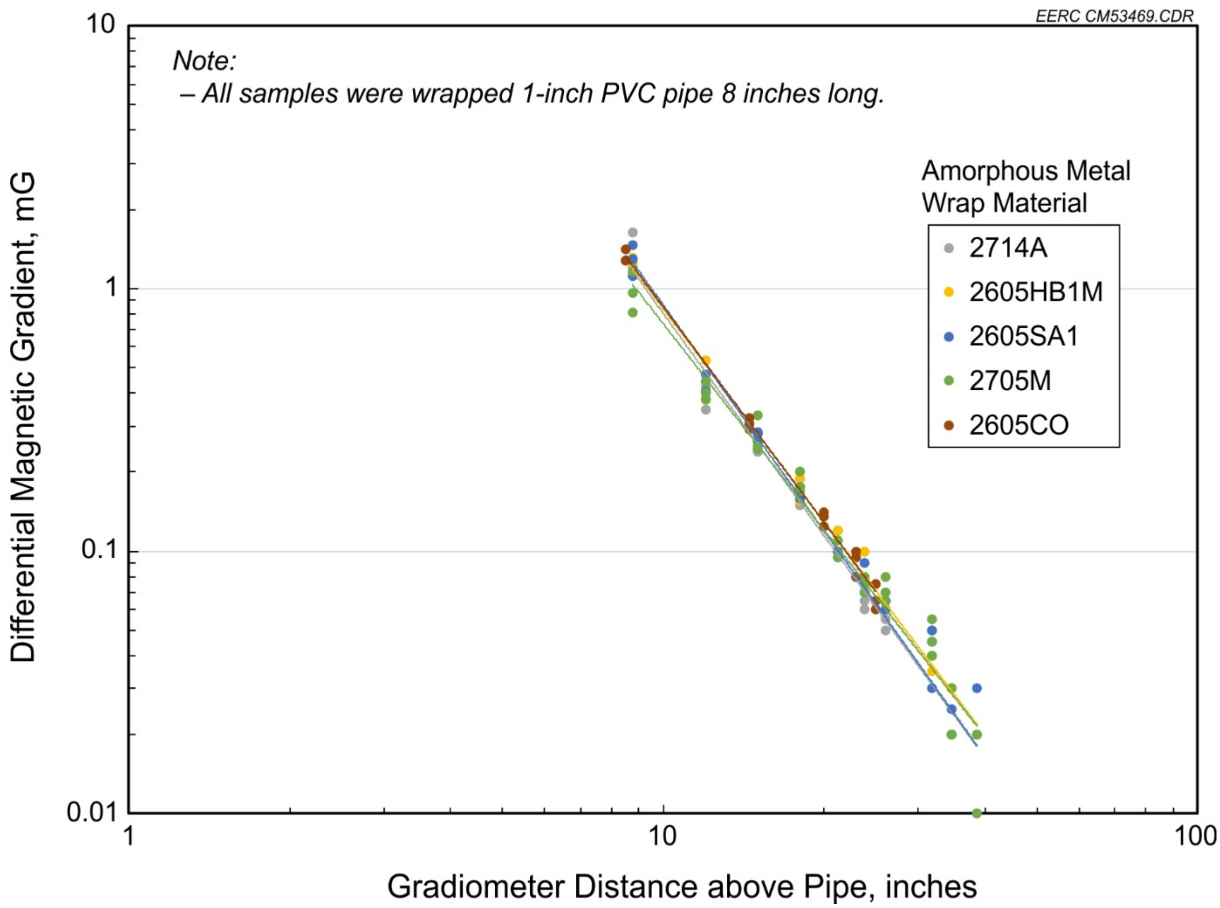

Figure 7. Comparison of amorphous metal composition results.

Higher-resolution measurements comparing two of the amorphous metal alloys were also made with larger 4-inch NPT pipe samples. These larger-diameter pipes resulted in larger magnitude distortion values which were thought to be helpful for comparing subtle differences between the alloys. The results for these measurements are shown in Figure 8. However, even with the roughly 10 times increase in signal magnitude, both the 2605HB1M and 2705M foils were only minimally distinguishable, despite the significantly higher permeability of 2705M (see Table 5). Of the two materials in Figure 8, the as-cast form of 2605HB1M was marginally more detectable than the 2705M. Alloy 2605HB1M comprises Fe, B, and Si. In its annealed state, this alloy is the preferred composition for power transformer cores and is commonly produced.

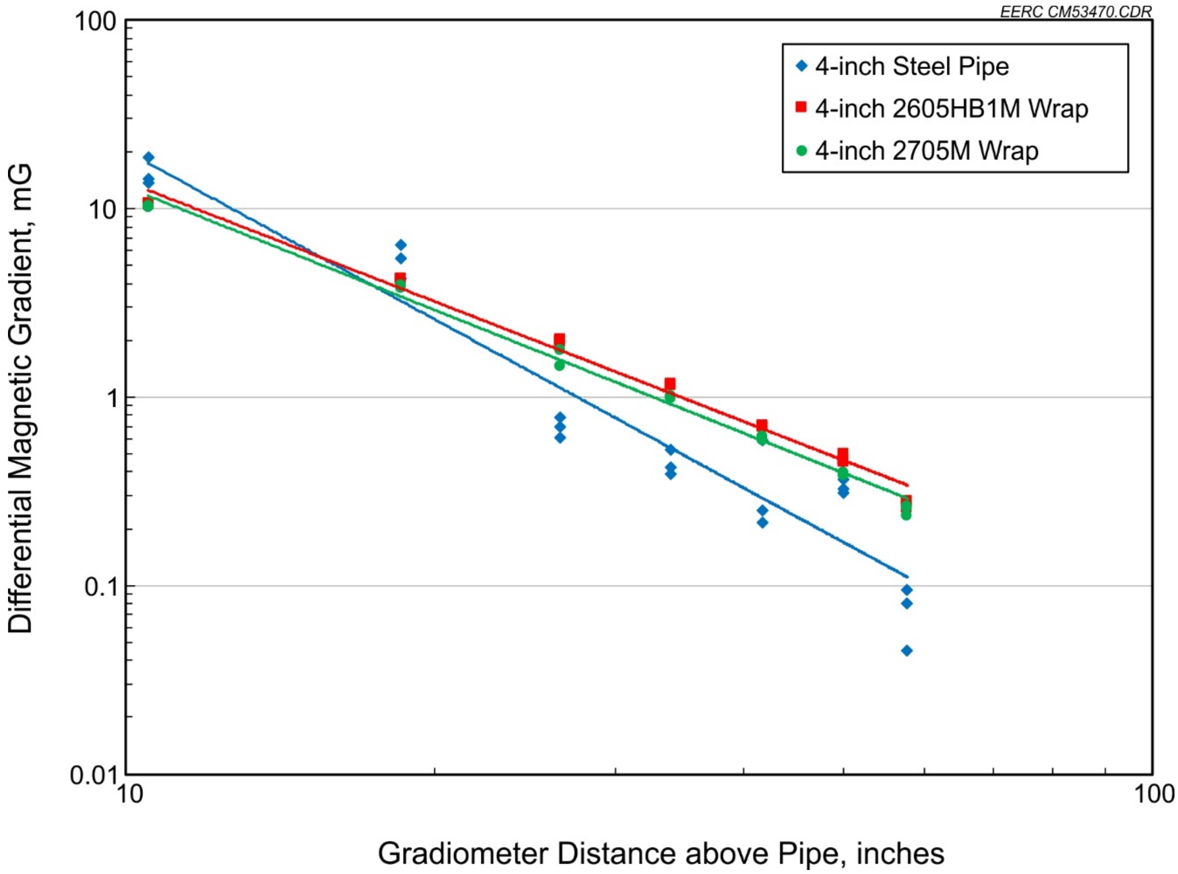

Figure 8. Higher-resolution comparison between two amorphous metal candidates and steel pipe.

Flat Ribbon Orientation

Wrapping pipes with amorphous metal foil appears to result in distortions that are roughly equivalent to conventional steel pipes, but in practice, this arrangement would require extensive manipulation of the pipe before installation to apply the wrap. Single strips of amorphous foil might be more feasible to attach to a pipe or simply bury above the pipe as is done with existing excavation caution tape. Figure 9 shows how caution tape can be installed horizontally above a buried utility, with the expectation that it would be encountered first if excavation were started above the pipe. Some conventional tapes are made with a thin layer of aluminum so that they can be detected using electrical field methods. An amorphous metal-based tape would have the same physical and electrical functions as conventional caution tape but would also be magnetically locatable.

As with previous measurements, the test fixture was used to measure the peak distortion value for various samples and orientations of flat amorphous foil. Figure 10 is a picture of 6-inch-wide flat ribbon samples, and Figure 11 is a plot of the peak magnetic distortion for these samples in both a horizontal and vertical orientation. Generally, the longer foil samples produce a larger

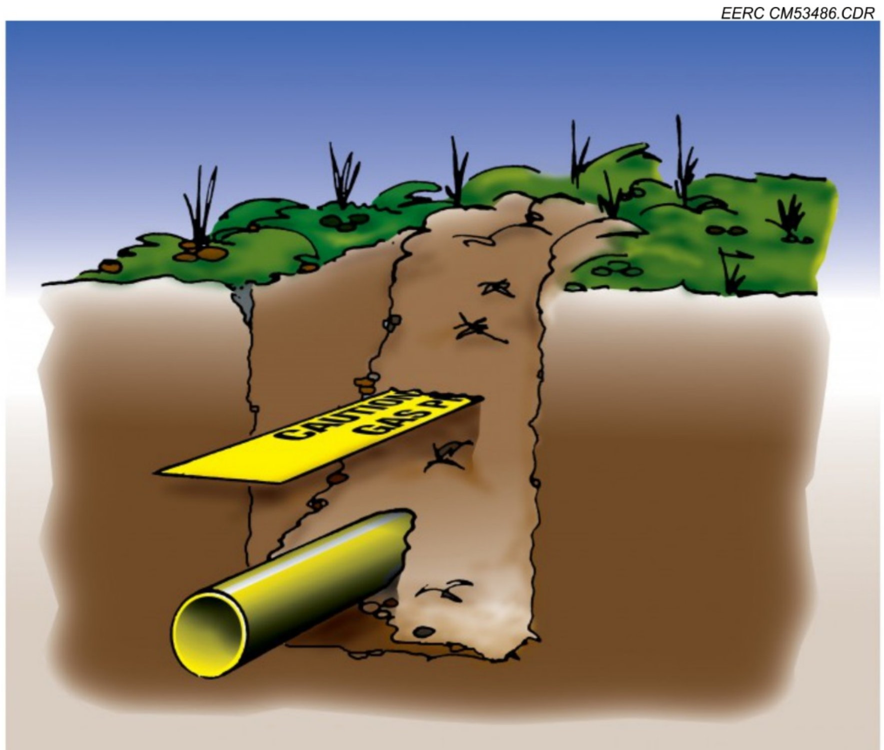

Figure 9. Caution tape buried above an underground pipeline [15].

distortion, especially as the target distance increases. Also, the strips are significantly more detectable when oriented vertically than when they are placed horizontally. This second observation is key since it affects how the foil can be practically used as a magnetic locating tape.

Earth's Magnetic Field Orientation

All of the gradiometer measurements presented thus far have been single-point peak values with the samples oriented along a true (not magnetic) north-south axis. However, as indicated by the difference between the vertical and horizontal orientations in Figure 11, the orientation of the amorphous foil to Earth's magnetic field is a key parameter. In order to visualize this effect, profile measurements were made with vertically oriented samples of the flat ribbon in both N-S and E-W orientations. Figure 12 presents these results for 8-inch- and 10-inch-wide ribbon samples. Overall, the wider (or taller) ribbon sample resulted in larger distortion peaks, and the N-S orientation resulted in higher peak values than the corresponding E-W measurements. However, the N-S profiles show a reversal in distortion polarity from end to end and a resulting zero crossing for these measurements.

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Figure 10. Photograph of flat amorphous foil tape samples.

INDUSTRY INTEGRATION

The magnetic field distortion measurements highlighted the key sensitivities associated with detecting amorphous foils. During the synthesis phase of the project, industry information was collected regarding pipeline installation to determine what characteristics of amorphous foil might prove useful to industry for marking and locating plastic pipelines. With a potential application identified, modeling was used to develop prototype product designs, which were then produced and evaluated with further field distortion measurements.

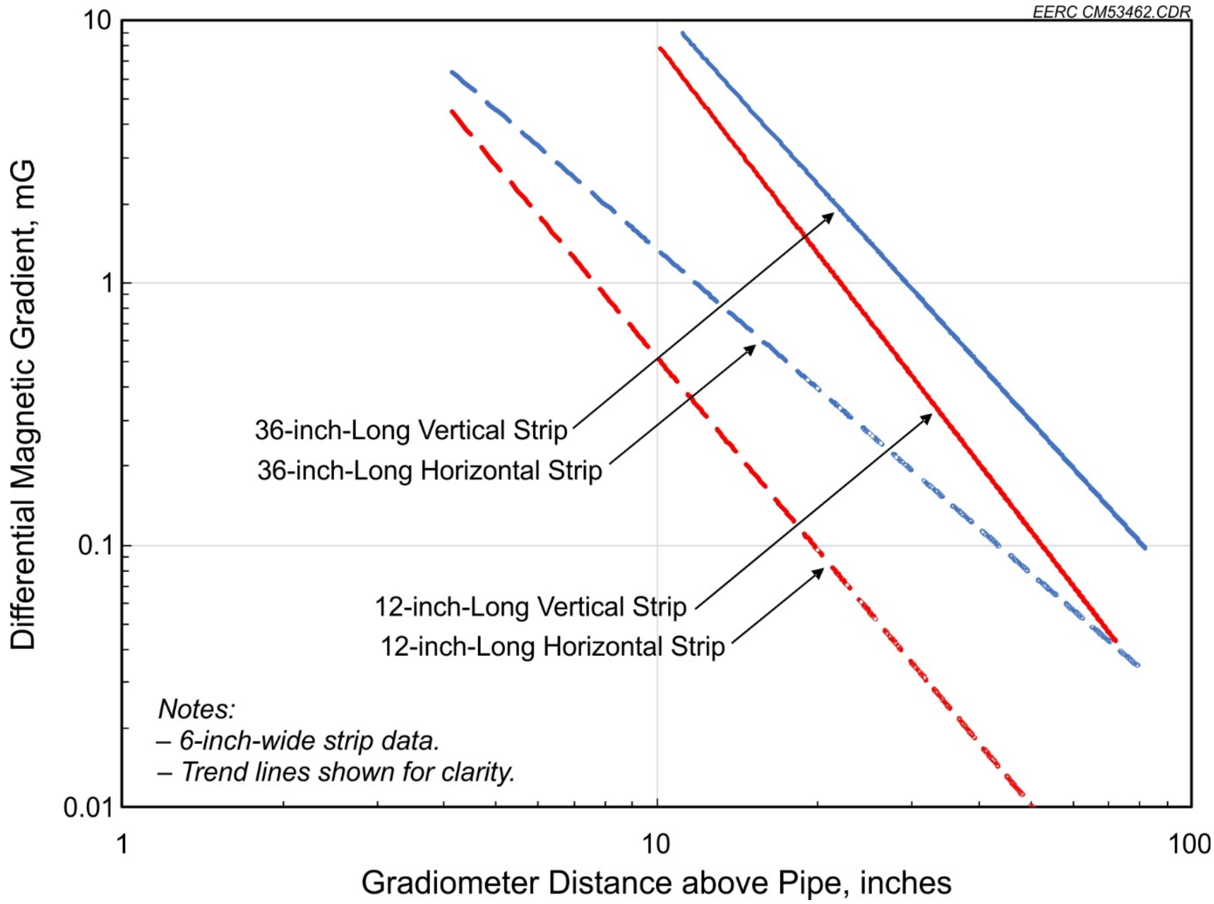

Figure 11. Comparison of detectability from amorphous foil orientation (trend lines shown, actual data points omitted for clarity).

Pipeline Installation

Plastic pipelines are installed using three different techniques. The first technique is excavation, or trenching. This technique requires digging a ditch, preparing a bed for the pipeline to rest on, and then burying the pipe with the fill that was excavated. This is the most common and basic type of pipeline installation method for plastic pipelines. An example of a trenched pipeline is shown in Figure 13.

The depth and width of a pipeline burial trench are determined by local conditions and by state and federal regulations. For northern locations, the frost layer is the most important factor in burying a pipeline. Tracer wire is shown in Figure 13, which is often included in plastic pipeline burial. Physical warnings such as caution tape buried above the pipeline can also be installed for trenched pipes. Trenched pipeline installation techniques are used for all pipe sizes but most often for larger-diameter plastic pipes.

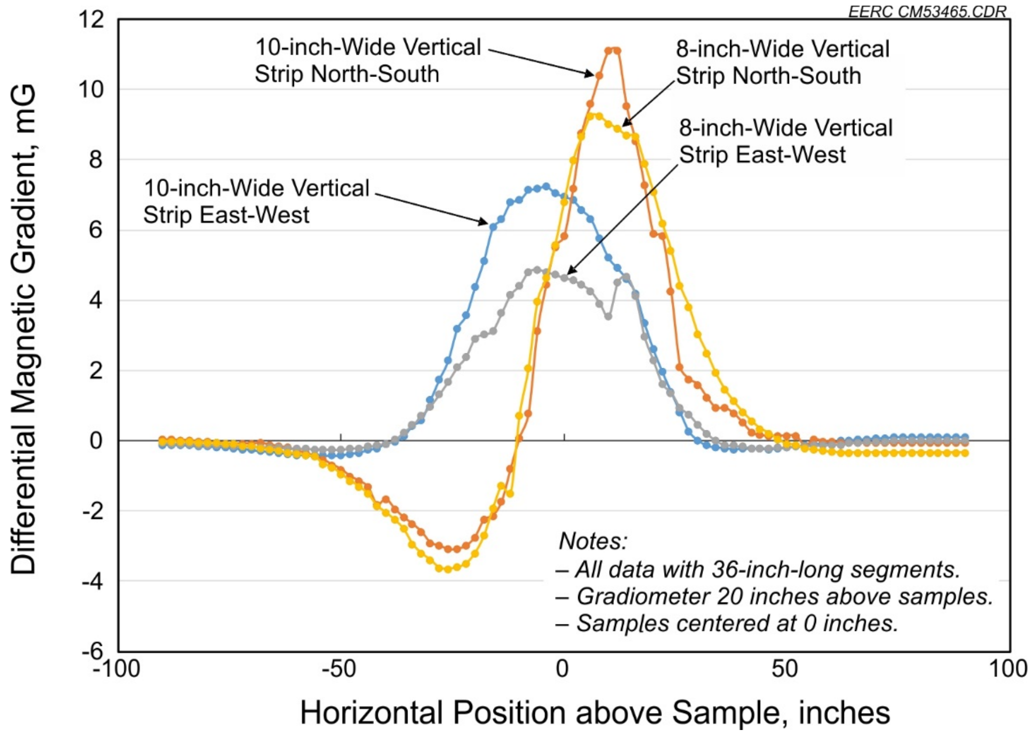

Figure 12. Experimental comparisons of N-S versus E-W orientations.

Figure 13. A trenched PVC pipeline [16].

Smaller-diameter plastic pipelines are often installed using either plowing or horizontal drilling techniques. Figure 14 shows a plow burying a plastic pipe. The plow has a large claw that vibrates and rips down into the earth creating a narrow trench. The vibratory plow has a slot along the back of the claw through which spoolable plastic pipe passes. Spoolable is an industry term for any type of plastic pipe that can be wound onto large spools and unwound during the installation and burial process. As the plow moves forward the plastic pipe is pulled out of the claw and left at the bottom of the trench. Vibratory plows bury pipe at 12–42-inch depths and can handle pipe up to 6 inches in diameter. Plows can bury pipelines quickly since the burial and excavation steps both happen at once.

EERC CM53479.CDR

Figure 14. Vibratory plow pipeline installation [17].

The final method for underground pipe burial is directional drilling. A directional drill can bore a hole under the ground through which a plastic pipe or conduit is then passed. Directional drills are frequently used to bury pipe under obstructions such as a roadway or body of water. A directional drilling crew is pictured in Figure 15.

Polymer Pipe Industry Applications

Plastic piping is used for a variety of services, including water, natural gas, and petroleum products and as conduit for electric and communication utilities. Table 6 shows information relating to underground pipe applications, including typical diameters and installation depths. Because each state has its own burial rules, the information in Table 6 is a general estimate for pipeline and utility burial based on a survey of various installation guidelines across the country [2, 8, 19–21].

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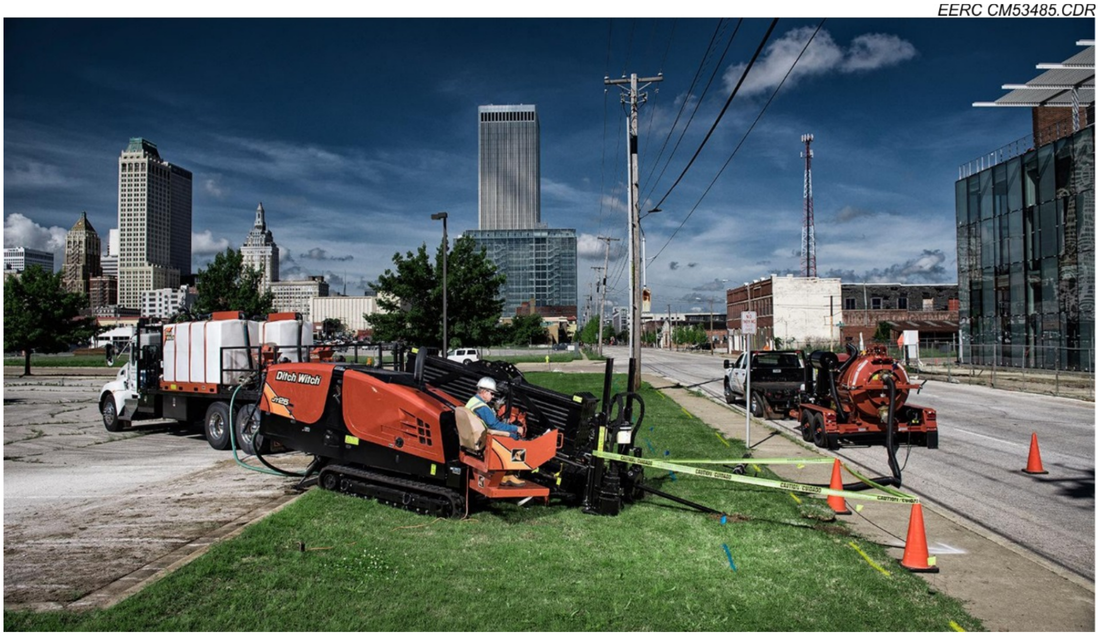

Figure 15. Directional drilling [18].

Table 6. Underground Pipeline Information

Utility Type	Diameter, in.	Depth, in.	PE	PVC	Metal	Plastic/Metal Hybrid	Plastic Conduit
Natural Gas	1–36	>48	X		X	X	
Petroleum Liquids	3–12	>48					
Produced Water	4–8	>48	X			X	
Fiber Optic	1–2	48					X
Communications Cable	1–2	36					X
Water Supply	0.75–48	36	X	X	X	X	
Sewage, Wastewater	3–24	>24	X	X	X	X	
Power	1–3	60					X
Cable TV/Copper Communication	0.5–2	24					X

Polyethylene (PE) and PVC are the two most common types of material used for water transport. Polyethylene plastic pipe is used for water supply lines which operate at higher pressure. These pipes range from small-diameter spoolable pipe for home service up to 12 inches and greater for water mains. PE also finds service for smaller-diameter natural gas distribution and petroleum gathering networks. Utilities are also often encased in spoolable plastic conduit and then buried. These conduits can carry fiber optic, copper communication, cable television, and electrical distribution lines. Polyethylene and PVC are common conduit materials.

Product Synthesis

This section describes the coalescence of the separate data collection activities that included experimental measurements of magnetic field distortion, magnetic field modeling, and industry application research. Based on this synthesis of information, promising opportunities for amorphous metal-based pipe locating would appear to have the following characteristics:

- Long-distance right of way marking where passive magnetic field distortion can be a great benefit, e.g., as in situations where a starting point is not available to apply an electric excitation signal.

- Installation geometries where the foil can be installed vertically, or perpendicular to the ground's surface.

- Limited burial depth for maximum sensitivity.

Based on the above criteria, a potential opportunity for amorphous foil-based locating technology would be as a detectable locating tape to be used with plow installation of spoolable pipe and conduit. The installation layout for this application is contrasted with conventional trenching and horizontal tape installation in Figure 16.

To assess this application, a design exercise was undertaken to determine what features are needed and what the film prototype might look like. These features were evaluated based on the criteria of detectability and compatibility with plow installation.

Detectability consists of two components. The first is to achieve a signal of sufficient magnitude so that it can be distinguished from any background disturbances. With a vertical tape installation orientation, it was shown that the determining factor for signal strength was the width of the tape (or the height of the vertical section) which can be tailored to provide the desired level of signal strength.

The second component of detectability relates to the spatial pattern of the signal that will be present at ground level. As Figure 12 shows, the magnetic signal can vary significantly along the length of the target and as a function of its orientation to Earth's magnetic field. With that variation, it is clear that a continuous strip of amorphous foil would not result in a uniform detection signal all along a pipe's pathway. This fact is demonstrated with magnetic locating of conventional metal pipe, where the field distortion is concentrated at the ends of the pipe run or at fittings where there are breaks in its continuity [22]. These breaks in the magnetic circuit actually result in a significant portion of the detectable signal, and this observation was employed in the design of an amorphous foil locating tape by including a pattern of breaks or segments to provide a relatively consistent signal along its entire length.

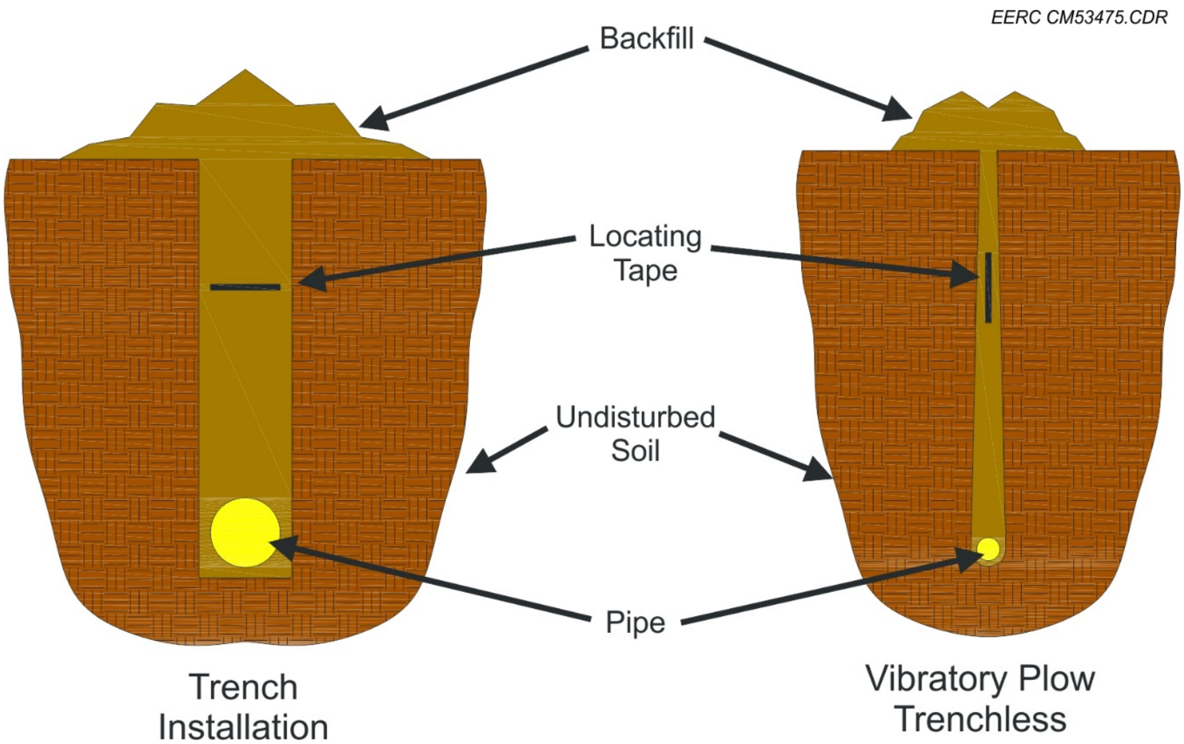

Figure 16. Amorphous foil burial orientations.

Magnetostatic modeling was used to evaluate the design parameters of the segmented locating tape and identify a pattern for prototyping. Figure 17 shows examples of the patterned tape in relation to its modeled field distortion and the distortion actually measured from mock-ups of the tape. Agreement between the model and the two tape patterns is generally good, keeping in mind that the gradiometer most likely measures a slightly averaged value compared to the discrete peaks calculated by the model. The more important trend in Figure 17 is the fact that the significant variation in signal strength and polarity observed with the north-south results of Figure 12 has been eliminated with the segmented design.

The results of Figure 17 only include three segments of the prototype pattern. However, it is intended to be extended by repeating the pattern as long as needed as depicted by the modeling results of Figure 18.

Prototype Evaluation

Based on the configuration highlighted from experimental data collection and modeling, the project's industrial partner, Metglas Inc., sourced a manufacturer capable of producing short runs of laminated amorphous metal foil. Two widths of tape were produced, 5.7 and 8 inches, along with two patterns, solid and 1 ft segmented. The prototype locating tape segments were laminated between layers of polymer film to protect the foil from abrasion during installation and corrosion during its service life. These design concepts were based on conventional detectable marking tapes produced from thin aluminum foil. A photograph of the 5.7-inch tape prototypes is shown in Figure 19.

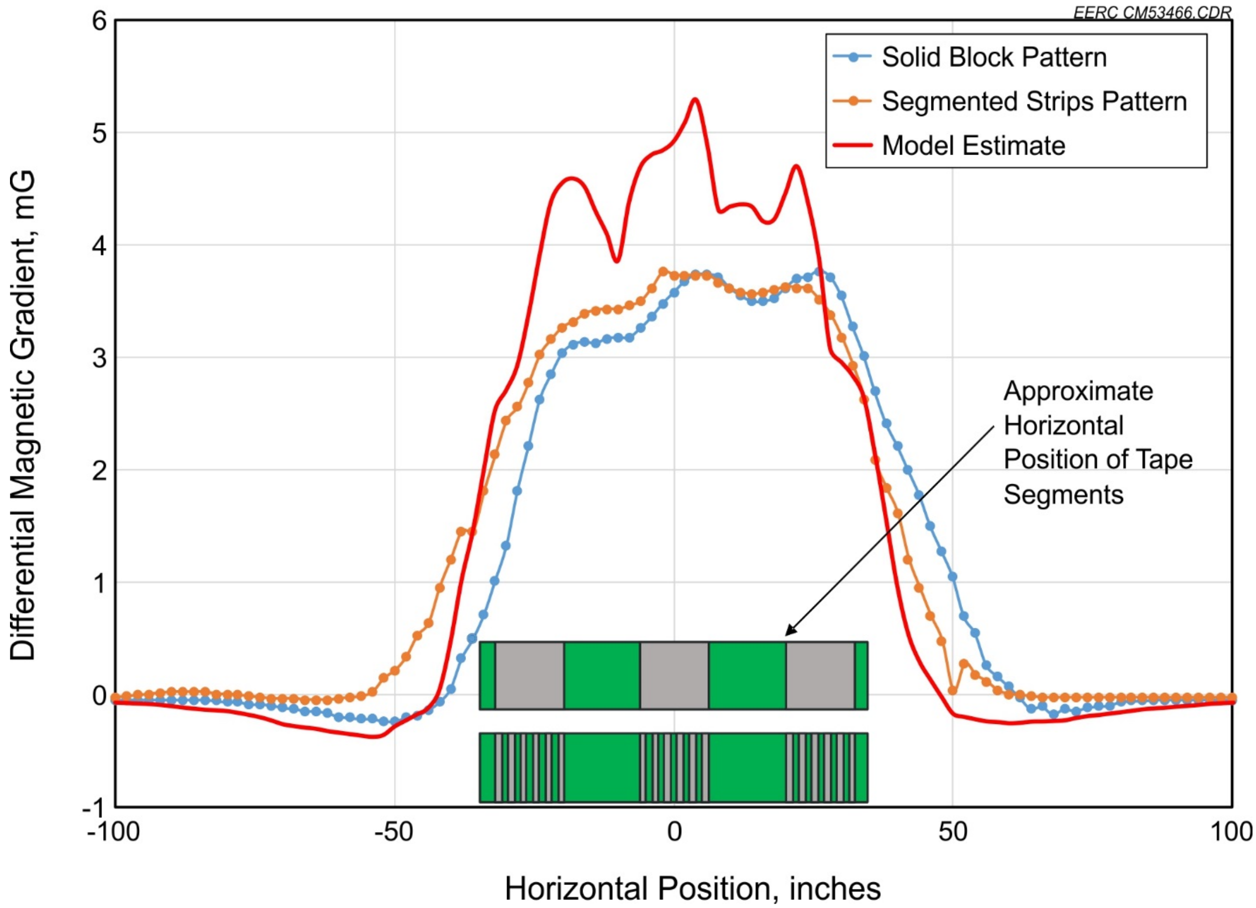

Figure 17. Profile measurements and model results for a three-segment amorphous foil tape concept in a north-south orientation.

Profile measurements of segments of the prototype tapes were made with the gradiometer using the same technique as with the nonlaminated foil samples. Results for the four prototypes are shown in Figure 20. Overall, profile measurements of the segmented samples were in line with expectations based on previous modeling, albeit the magnitude of the distortion was noticeably lower. Differences with the solid segments were more pronounced as shown by the comparison data presented in Figure 21. In these cases, the magnitude, but more significantly the overall profile distortion, appears to have been stunted in the laminated samples. Potential reasons for the changes with lamination were hypothesized to include heat-induced changes to the foil's static magnetic field properties during the lamination process or stress-induced changes from mechanical bonding of the foil to the polymer layers. Unfortunately, the root cause was not determined, although the resulting material changes did make the solid design preferred for the in-ground test since its altered profile in Figure 21 was relatively uniform (an outcome that the segmented design was intended to achieve). Furthermore, the solid design was more easily manufactured compared to the segmented version, and despite using more amorphous metal foil, it was estimated to be more cost-competitive because of the extra costs of chopping and placing amorphous foil segments in the segmented design.

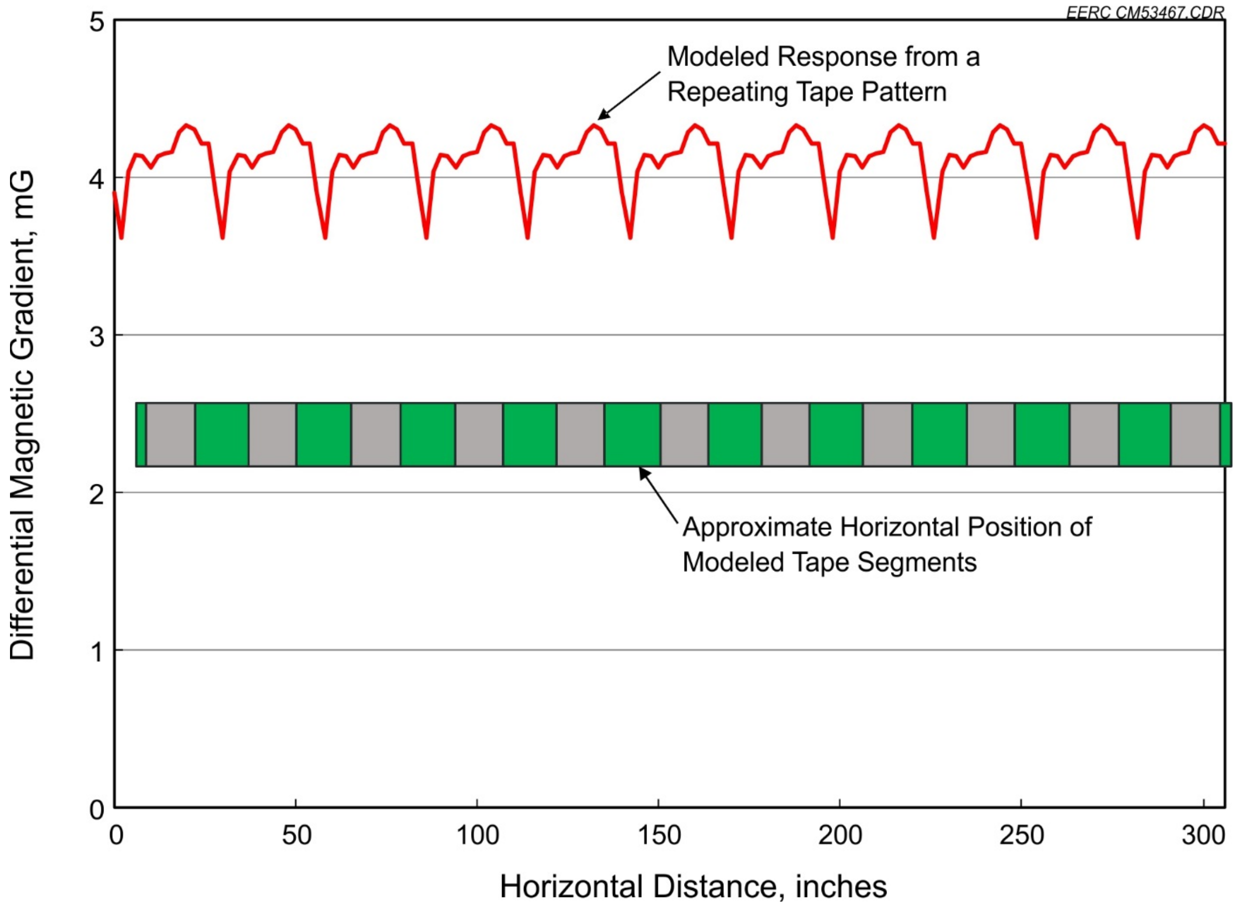

Figure 18. Modeling results for a continuous pattern length of the amorphous foil tape concept.

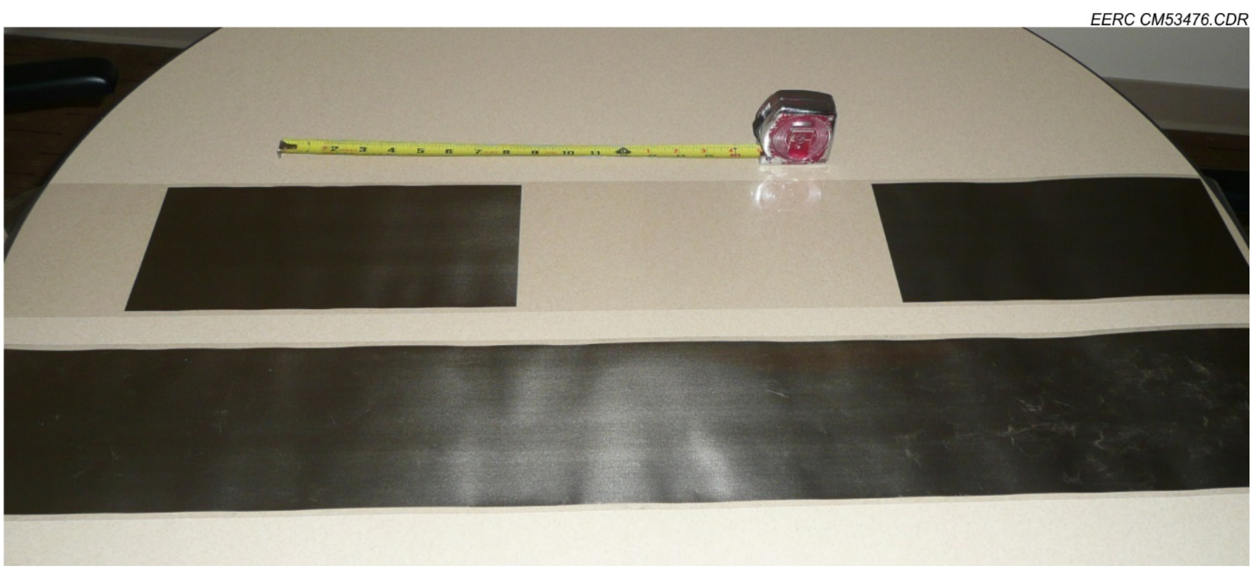

Figure 19. Laminated locating tape prototypes, 5.7-inch width.

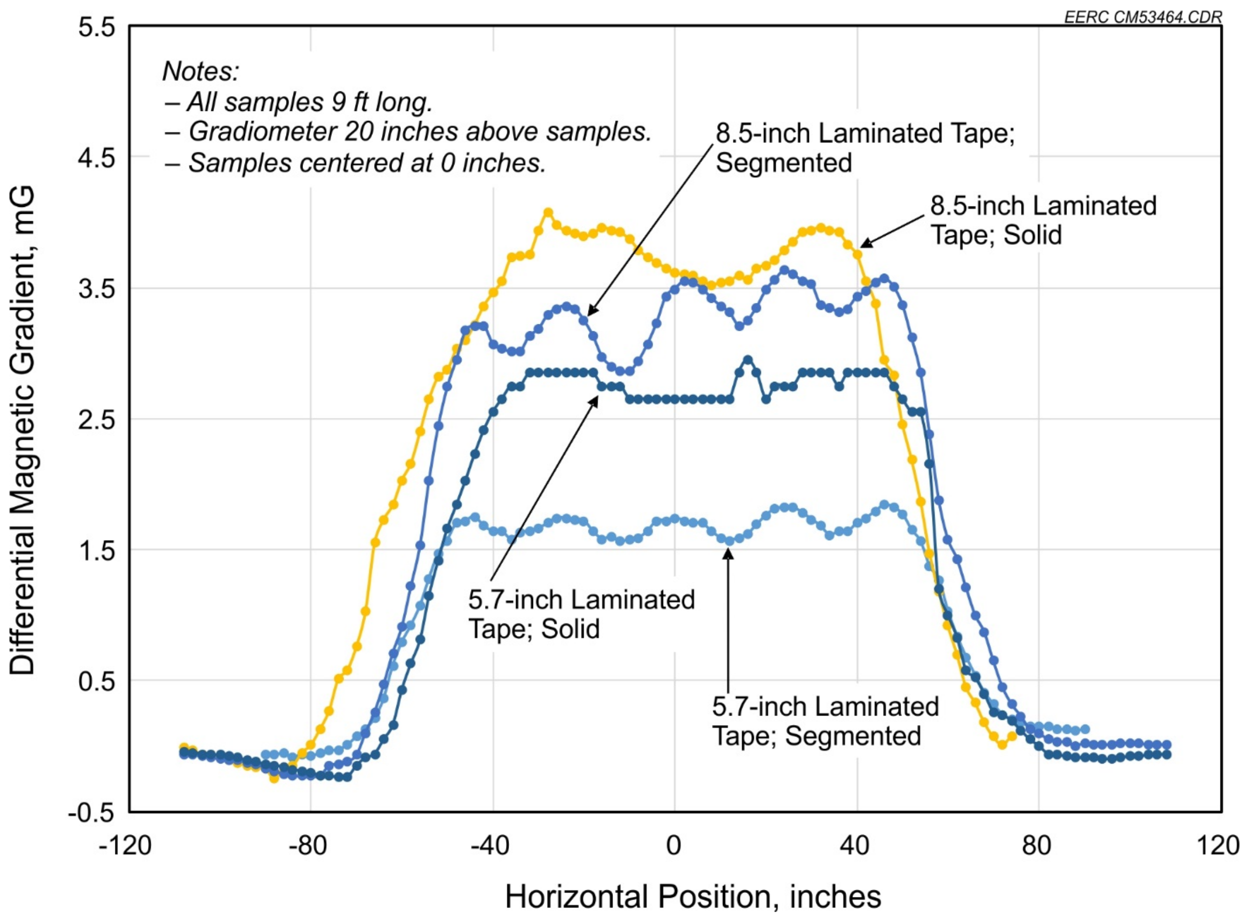

Figure 20. Comparison of the profile measurements for the four prototype locating tapes.

In-ground evaluation of the prototype locating tape was conducted with the 5.7-inch solid version and was installed 10 inches below grade according to the diagram of Figure 22. Vertical orientation was chosen to highlight the application where amorphous tape appears to have significant advantage, i.e., the vertical plowed installation of spoolable pipe and conduit. However, for this proof-of-concept evaluation a conventional trencher was used to dig a narrow cut in the ground, and the tape was positioned and backfilled manually as shown in Figure 23.

The plan view for the tape installation is shown in Figure 24 and consisted of a right triangle, with legs of the triangle oriented in true north-south and east-west directions. The triangle's hypotenuse ran nominally in a northwest to southeast orientation. Figure 24 also indicates the east-west gradiometer transects that were made to quantify the detectability of the buried tape. These results are shown in the waterfall diagram of Figure 25.

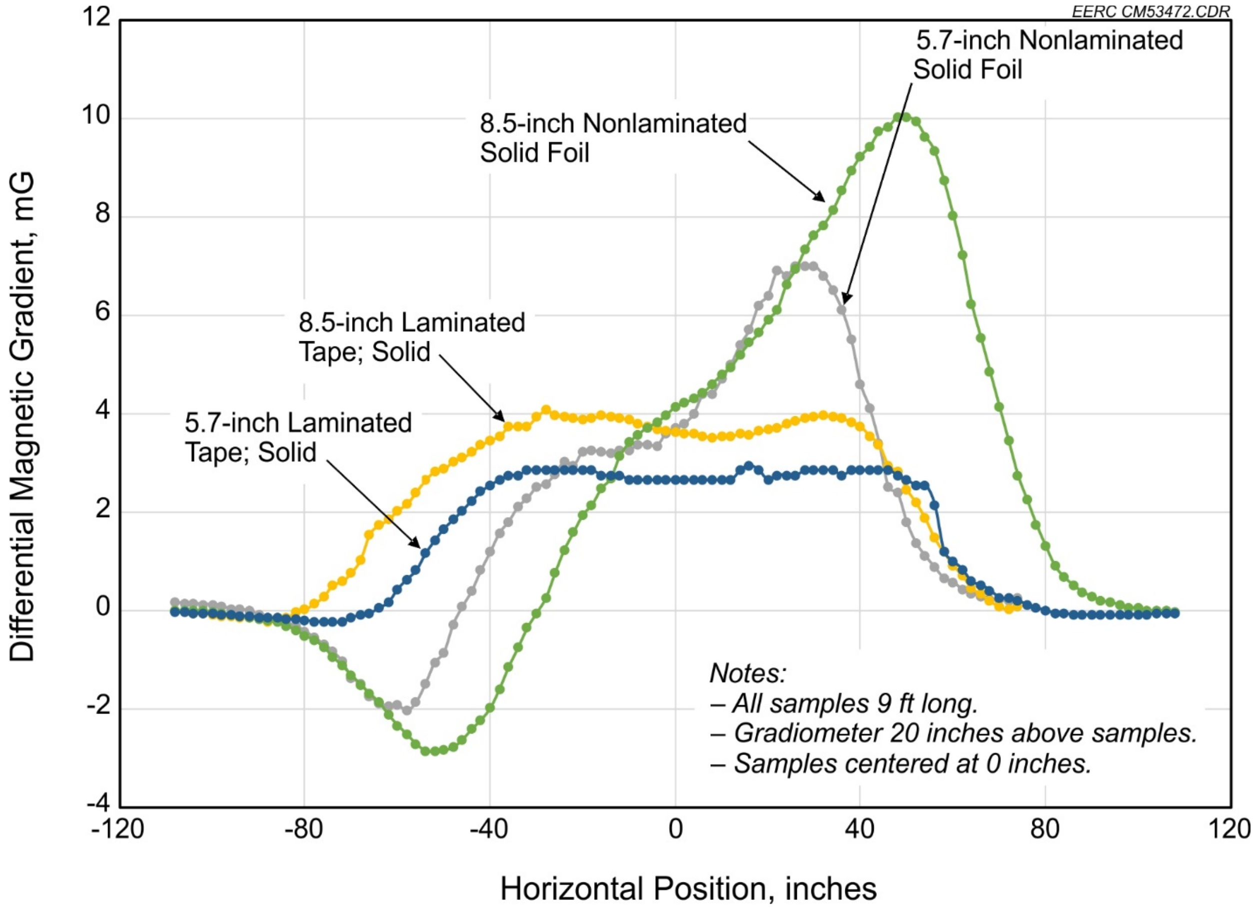

Figure 21. Comparison of the profile measurements for the laminated prototypes and the nonlaminated starting foil.

The transect results of Figure 25 show that the buried tape peaks consistently 2–4 mG above the surrounding background magnetic distortion. The highlighted peaks in Figure 25 appear to have a width of approximately 20–30 inches, but in practice, the peak value could be pinpointed within a few inches by sweeping the gradiometer perpendicular to the path of the tape.

The exception in Figure 25 was a segment of the east-west triangle leg which was difficult to locate. A partial reason was due to simple misalignment of the transect relative to the actual path of the tape, but more significant was a strong field disturbance located just north of the triangle layout. In hindsight, it would have been better to locate the east-west segment elsewhere, but this experience highlights a key limitation of the amorphous metal-based locating tape which is that the material will not be ideal for congested rights-of-way where other ferrous metal pipes or other infrastructure are installed.

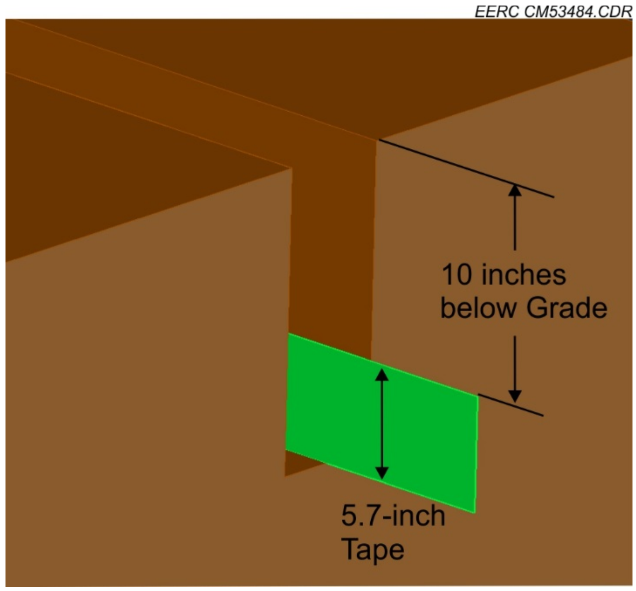

Figure 22. Orientation and nominal installation depth for buried tape.

Figure 23. Installation of solid, 5.7-inch laminated tape prototype.

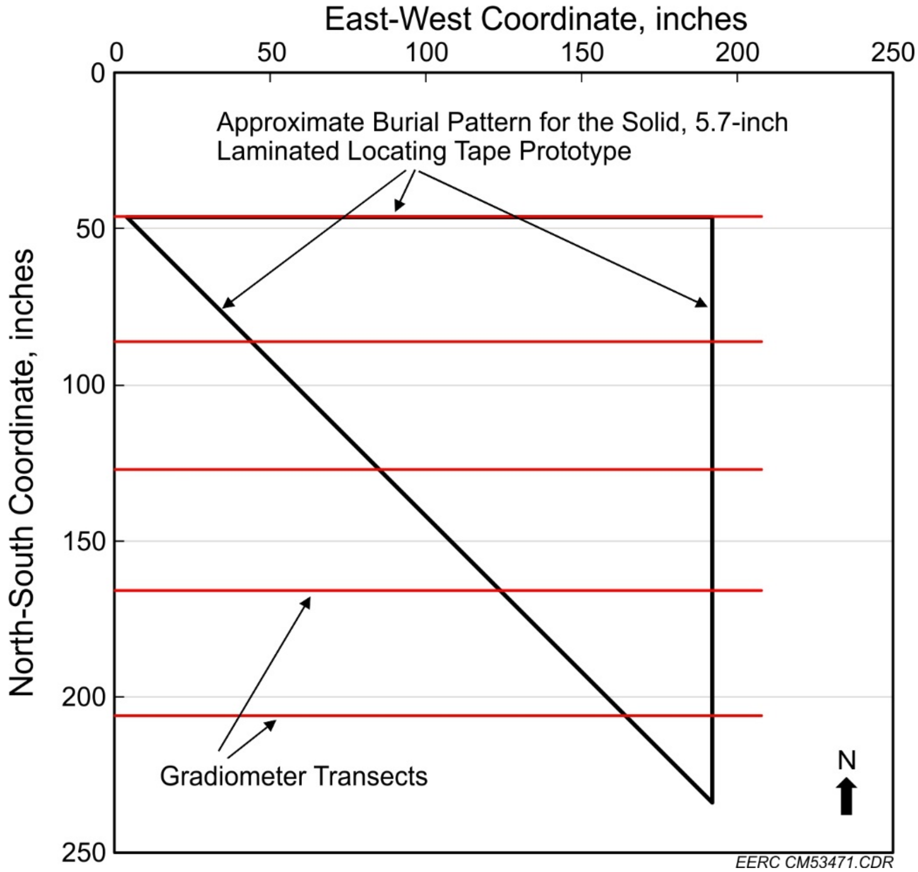

Figure 24. Plan view of buried locating tape prototype and sampling transects.

Compatibility with trenchless installation methods requires that the film have minimum toughness and flexibility to be installed with a vibratory plow. Conventional systems that install tracer wire or belowground caution tape funnel the material through a conduit or chute that turns it from a vertical to horizontal axis where the wire/tape is left in the cut seam. A photograph of typical installation equipment is shown in Figure 26. In addition to inserting the tape at the proper depth, an amorphous-based locating tape will have the added requirement of needing to be placed unfurled so that it is roughly parallel to the sides of the plow cut.

The vertical-to-horizontal turn could be accomplished several ways. One possibility is diagrammed in Figure 27, where the turn is made in a custom tape feed chute using an angled exit roller. In this concept, flat foil is fed down vertically into the chute and is folded over the angled roller to prevent crumpling of the tape. Similar chute designs are employed for other purposes, e.g., silt fence installation, but a chute specific to locating tape installation would need to be fabricated and tested.

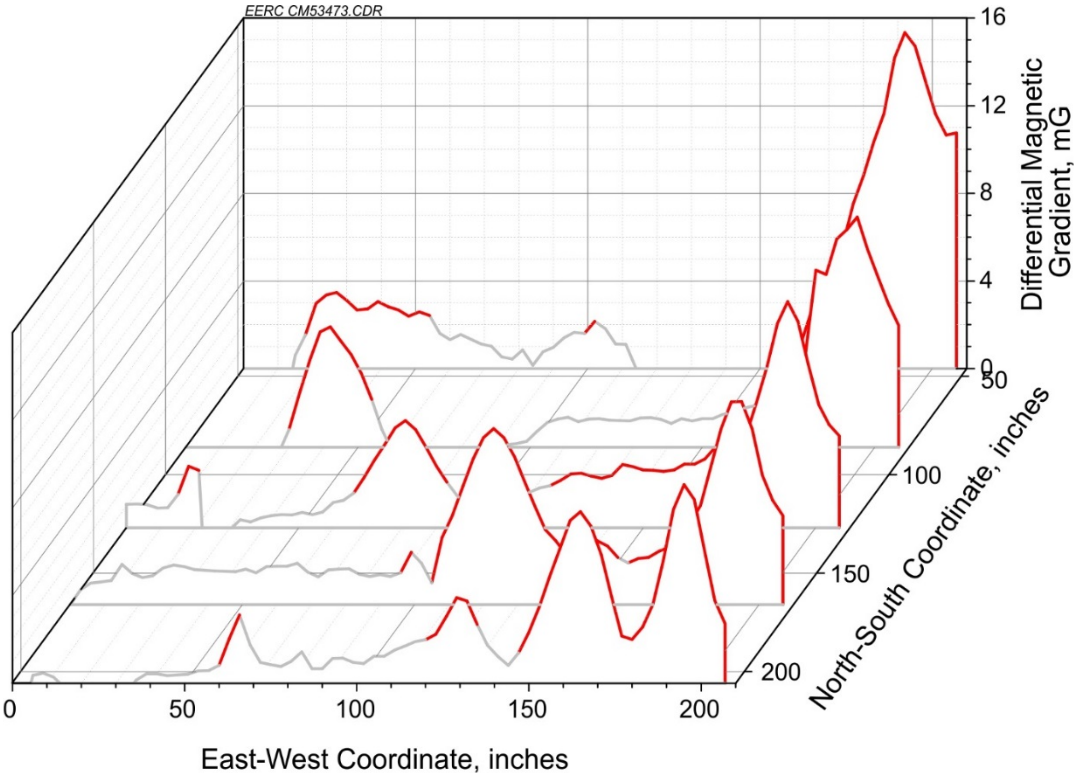

Figure 25. Gradiometer transect results over the buried laminated amorphous tape.

Figure 26. Combined pipe and caution tape trenchless installation (courtesy Sea Ranch Connect).

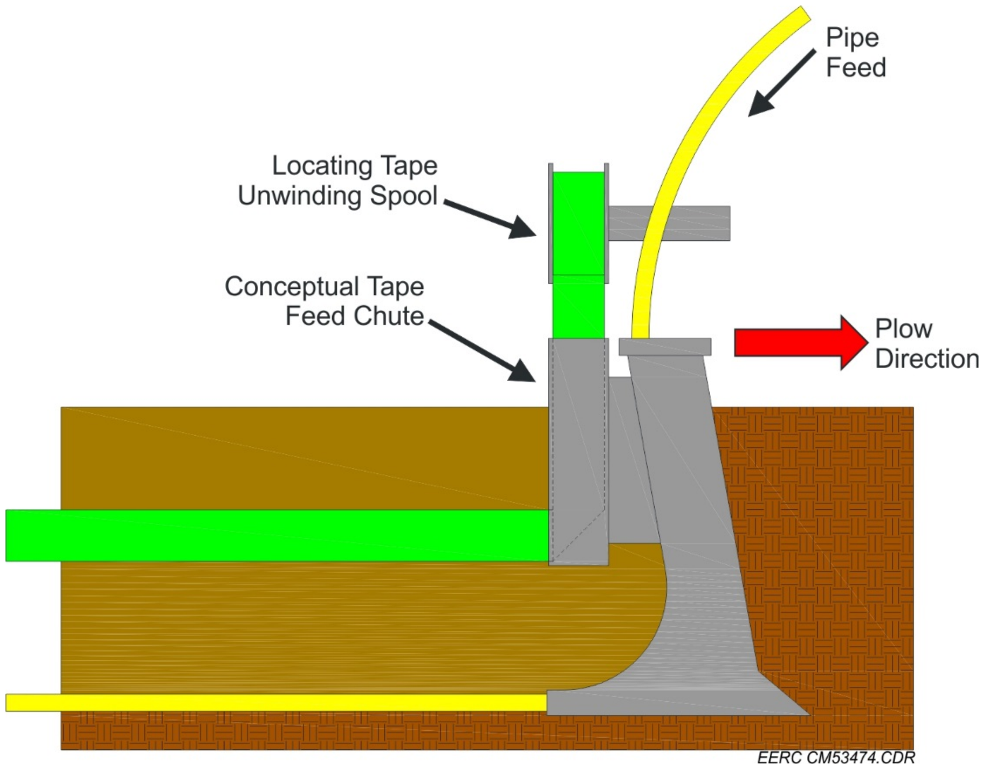

Figure 27. Custom locating tape feed chute concept.

CONCLUSIONS

Amorphous foil-wrapped plastic pipe can be as magnetically detectable as all metal pipe of the same diameter. This property appears to be directly due to the unique nature of amorphous metals since equivalent performance was not observed for a crystalline steel foil wrap. Additionally, the specific composition of the amorphous foil alloy did not have a significant effect on its detectability, suggesting that the increase in magnetic permeability between crystalline and amorphous metals is much more significant than even the large variations in permeability among amorphous metals themselves.

However, in terms of practical application, a complete wrap of a plastic pipe's exterior with amorphous metal would add significant effort during either the pipe's manufacture or its installation, which would effectively be a barrier to industry use. Placing a stripe of amorphous film along a pipe's length might be more feasible, but the field distortion measurements showed that the size and the orientation of the stripe both impact its detectability. Unfortunately, the maximum size would be limited by the pipe's diameter, meaning that small pipes would only be detectable at shallow depths. Also, detectability is at a minimum when the stripe is placed horizontally, or parallel to the ground's surface. The added stripe would ideally need to have its orientation maintained vertically along its entire length, which is another requirement that might make market acceptance difficult.

These findings suggest that decoupling the foil from the pipe, as with a detectable underground marking tape, might be the most attractive way to use amorphous foil for pipe locating. In this application, the amorphous foil tape would offer all of the functionality of existing detectable tapes based on aluminum, except that it also has the added capability of being magnetically locatable. Preliminary tests with a prototype tape show great promise for the tape as a simple, passive locating method. The characteristics that result in good detection appear compatible with plow installation of spoolable pipe, but some amount of follow-on work will be needed to demonstrate combined pipe and tape installation.

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