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INNOVATIVE ELECTROMAGNETIC SENSORS FOR PIPELINE CRAWLERS

Design of a Rotating Permanent Magnet Inspection Exciter

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Abstract

Internal inspection of pipelines is an important tool for ensuring safe and reliable delivery of fossil energy products. Current inspection systems that are propelled through the pipeline by the product flow cannot be used to inspect all pipelines because of the various physical barriers they encounter. Recent development efforts include a new generation of powered inspection platforms that crawl slowly inside a pipeline and are able to maneuver past the physical barriers that can limit inspection. At Battelle, innovative electromagnetic sensors are being designed and tested for these new pipeline crawlers. The various sensor types can be used to assess a wide range of pipeline anomalies including corrosion, mechanical damage, and cracks.

Battelle is in the final year on a projected three-year development effort. In the first year, two innovative electromagnetic inspection technologies were designed and tested. Both were based on moving high-strength permanent magnets to generate inspection energy. One system involved translating permanent magnets towards the pipe. A pulse of electric current would be induced in the pipe to oppose the magnetization according to Lenz's Law. The decay of this pulse would indicate the presence of defects in the pipe wall. This inspection method is similar to pulsed eddy current inspection methods, with the fundamental difference being the manner in which the current is generated. Details of this development effort were reported in the first semiannual report on this project. The second inspection methodology is based on rotating permanent magnets. The rotating exciter unit produces strong eddy currents in the pipe wall. At distances of a pipe diameter or more from the rotating exciter, the currents flow circumferentially. These circumferential currents are deflected by pipeline defects such as corrosion and axially aligned cracks. Simple sensors are used to detect the change in current densities in the pipe wall. The second semiannual report on this project reported on experimental and modeling results. The results showed that the rotating system was more adaptable to pipeline inspection and therefore only this system will be carried into the second year of the sensor development. In the third reporting period, the rotating system inspection was further developed. Since this is a new inspection modality without published fundamentals to build upon, basic analytical and experimental investigations were performed. A closed form equation for designing rotating exciters and positioning sensors was derived from fundamental principles. Also signal processing methods were investigated for detection and assessment of pipeline anomalies. A lock in amplifier approach was chosen as the method for detecting the signals. Finally, mechanical implementations for passing tight restrictions such as plug valves were investigated. This inspection concept is new and unique; a United States patent application has been submitted.

In this reporting period, a general design of the rotating permanent magnet inspection system is presented. The rotating permanent magnet inspection system is feasible for pipes ranging in diameter from 8 to 18 inches using a two pole configuration. Experimental results and theoretical calculations provide the basis for selection of the critical design parameters. The parameters include a significant magnet to pipe separation that will facilitate the passage of pipeline features. With the basic values of critical components established, the next step is a detailed mechanical design of a pipeline ready inspection system.

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Design of a Rotating Permanent Magnet Inspection Exciter

Introduction

A new inspection methodology, called rotating permanent magnet inspection (RPMI), has been demonstrated to be useful for the inspection of pipeline materials [1-2]. This new inspection technology utilizes pairs of permanent magnets that rotate around a central axis to induce sufficient current densities in the pipeline material undergoing inspection. Pipeline anomalies and wall thickness variations cause local changes in the magnetic field produced by these induced currents which can be detected using Hall Effect sensors. One application of this electromagnetic technology is for unpiggable pipeline inspection. This inspection technology can be mounted on a robotic platform capable of crawling through pipelines. These devices can move down the pipeline independent of the product flow, and potentially stop for detailed defect assessment. This report will highlight key design aspects and show that the RPMI device is small and light as compared to other inspection modalities such as magnetic flux leakage (MFL) systems. The basic configuration has ample space to maneuver past physical barriers like plug valves or bore restrictions.

The RPMI system follows the fundamental laws of electrical induction. By rotating permanent magnet pairs inside a pipe along its longitudinal axis, an alternating electrical current in the pipe wall is established. Figure 1, a cutaway drawing showing the rotating permanent magnet exciter, illustrates this concept. This system has the potential to induce strong eddy currents in the pipe wall. The dashed lines in Figure 1 illustrate the current flow as the magnetizer rotates in the pipe. The current flows in an elliptical path around the magnets. When the magnetizer is vertical, strong currents flow axially at the top and the bottom of the pipe and circumferentially at the sides of the pipe. When the magnetizer is horizontal, strong currents flow axially along the sides of the pipe and circumferentially at the top and the bottom of the pipe.

In experimental tests of a prototype two-pole magnetizer, strong current densities were produced at distances well away from the magnetizer assembly. Although the current is complex at the magnet poles (where it is strongest), at a pipe diameter or more away from the magnetizer the current is uniform and sinusoidal. Defects are detected by sensing changes in the sinusoidal currents.

This report describes a potential implementation of the RPMI systems for pipes ranging in diameter from 8 to 18 inches. Experimental results are used to justify selection of the critical inspection parameters.

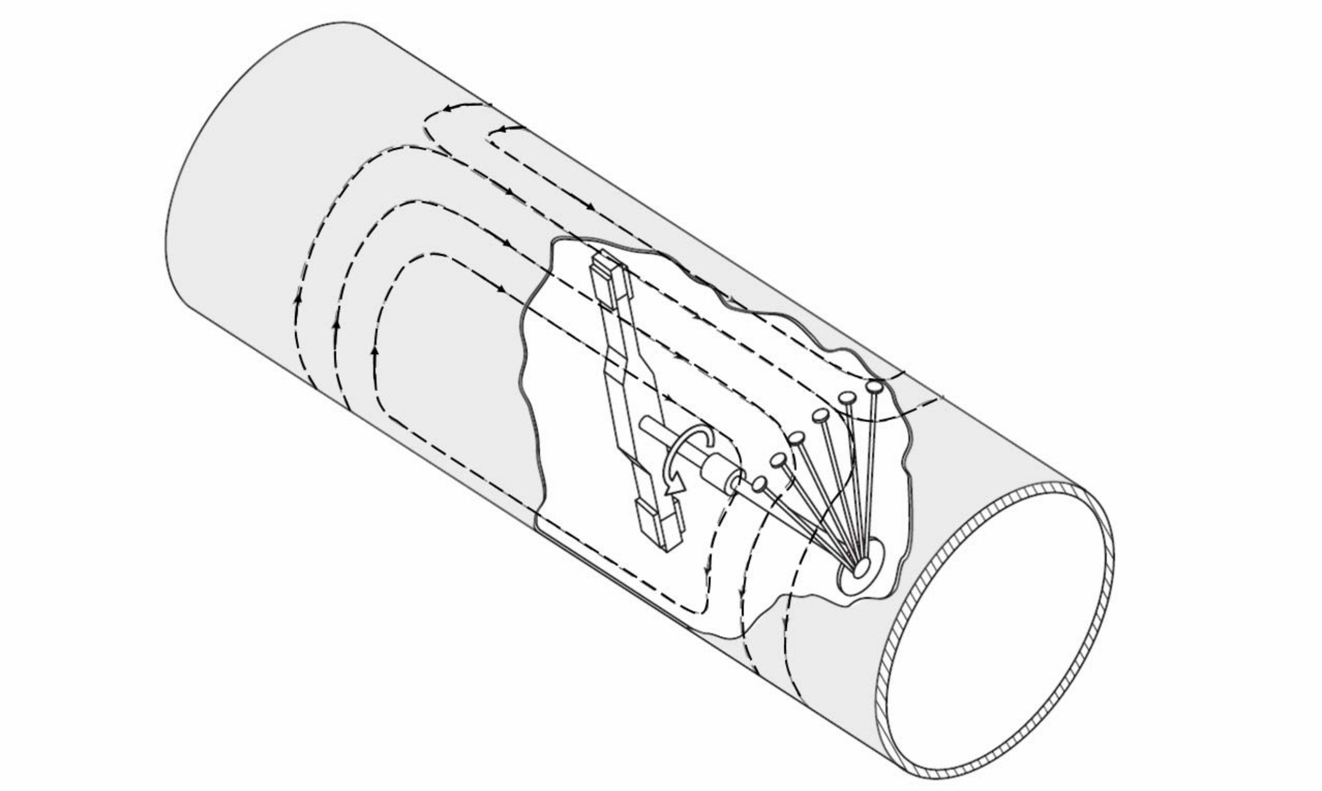

Figure 1. Rotating permanent magnet inspection system concept.

System Design

In its simplest form, the rotating permanent magnet inspection system is a bar magnet that spins on the shaft of a motor. Although the basic design principle is simple, there are a number of individual components that need to be optimized to obtain the best inspection capability while still maintaining design practicality. The design goals for the RPMI system are to:

- Maximize current away from the rotating magnets so that changes at anomalies produce larger signals.
- Minimize the motor power requirements to rotate the magnets, thus enabling longer inspection runs on a single battery charge.
- Minimize inspection system size so that it is capable of passing though openings much less than the nominal pipe diameter.

As with any engineering design, some of these goals cannot be met simultaneously. Specifically, first engineering principles would indicate that the largest, most powerful magnet will produce the strongest current in the pipe, which addresses the first design goal. However, large, strong magnets are in opposition to the second design goal, since power to spin the magnets is greater for large and powerful magnets. Furthermore, large strong magnets are in opposition to the third design goal since larger support components are needed for larger magnets.

The functionality of the entire system must be considered in a prudent design. For example, a significantly smaller inspection system may be possible while still maintaining reasonable inspection performance. The following sections discuss optimizing the size of the magnet bar, the design of the motor and rotating assembly, and the design of the collapsible components of the inspection system. The result is the conceptual design rotating permanent magnetic system for pipe form 8 to 18 inches in diameter

Number of poles

The first step in the design is to determine the number of magnets. In prior reports [3], a first order approximation of the field behavior in the rotating permanent magnet inspection system was derived through Ampere's Law and the Law of Charge Conservation. The peak amplitude of the magnetic field as a function of axial position is given by

$$B_{pk}(z) \propto \frac{\beta}{n}\left(\frac{r}{\delta}\right)^2 M_0 e^{-(\frac{n}{r})Z}$$

where:

- Z is the distance from the magnets along the pipe
- r is radius
- n is the number of pole pairs
- δ is the classical skin depth
- β is a coupling factor that includes liftoff (between 0 and 1)
- M_0 is magnetic energy in magnet pole piece

This equation indicates that the peak amplitude of the magnetic field is proportional to the magnetizing strength of the pole piece (and the coupling factor) and the square of the ratio of the pipe diameter to classical skin depth, and inversely proportional to the number of pole pieces. Also, the exponential decay constant, given by the ratio of pole pairs to pipe radius (n/r), will cause greater decay for smaller pipe diameters and a higher number of pole pieces. This first order approximation suggests that the decay rate is basically geometry dependent. The validity of this equation was demonstrated experimentally. The other term in the decay rate, distance from the magnets along the pipe Z is essentially a constant for all diameters.

The magnetic field in the pipe can be described as having two parts, each with distinct properties and effects. One part is the direct magnetic field from the strong permanent magnets. The second field is due to the current flowing in the pipe. Near the rotating magnets, the direct field from the magnet is dominant. Farther away from the rotating poles, the magnetic field caused by the currents flowing in the pipe dominates. Experiments on 6 inch, 8 inch, and 12 inch diameter pipe have shown that the direct coupling of the field from the magnets to the sensors is not significantly related to pipe diameter. Experiments have also shown that the direct coupling signal becomes large as compared to the signals generated by the current in the pipe when the sensor-to-magnet distance is less than 8 inches (20 cm). For the 12 inch diameter prototype, the experiments have not indicated a need for sensor-to-magnet distances to be greater than 12 inches (30 cm). For the straight magnet bar with a magnet at either end (1 pole pair), signals with no direct distortion were attained for 12 inch diameter pipe with sensor-to-magnet distances of 12 inches. At 8 inches of separation, the direct field distortion signal was nominally 20 percent of the current field. Table 1 shows the relative signal levels for a range of pipe diameters and pole configurations. Areas of marginal performance are in grey.

Table 1. Relative signal levels for a range of pipe diameters and pole configurations

Pipe Diameter		# of poles pairs	Signal level	
Inches	Meters		Sensor to Magnet Distance 8 in (20cm)	Sensor to Magnet Distance 12 in (30cm)
4	0.10	1	13.5%	5.0%
5	0.13	1	20%	9.1%
6	0.15	1	26%	13.5%
8	0.20	1	37%	22%
10	0.25	1	45%	30%
12	0.30	1	51%	37%
14	0.36	1	56%	42%
16	0.41	1	61%	47%
18	0.46	1	64%	51%
10	0.25	2	20%	9.1%
12	0.30	2	26%	13.5%
14	0.36	2	32%	18%
16	0.41	2	37%	22%
18	0.46	2	41%	26%
20	0.51	2	45%	30%
24	0.61	2	51%	37%

In general, a straight magnet bar with a magnet at either end (one pole pair) will work for diameters of 8 inches and greater. For diameters greater than 16 inches, a cross configuration with 4 magnets (2 pole pairs) should be considered. The cross configuration is advantageous because it would produce two cycles of alternating current per revolution. In other words, the rotation speed could be cut in half while maintaining the same inspection capability. This would reduce the motor power requirements and stress to the mechanical components. While there is no maximum theoretical diameter for a bar magnet with a pair of poles, there is a transition zone between 16 inches and 20 inches where the cross configuration becomes advantageous.

Magnetizer Design

An essential element in maximizing the current at the sensors and minimizing the system power requirements is in the design of the magnet bar. Referring to Figure 2, the key parameters of the magnet bar include the axial length, circumferential width and radial thickness of the magnets as well as the separation between the magnet and the pipe wall, further referred to as liftoff. As any electrical current generator that uses permanent magnets, the magnet composition and strength are also an important variable that affects the induced current densities and thus inspection capabilities. These design variables relate the design goals in the following way:

- Inspection current – Larger magnet area, thicker magnets, and smaller liftoff all increase current density for detection of anomalies
- Motor power – Two poles, smaller magnet area, thinner magnets, and greater liftoff all decrease motor power consumption
- System size - Two poles, smaller magnets and smaller pole pieces enable the passage of the tool though openings much less than the nominal pipe diameter.

A range of configurations were examined to establish the optimal system.

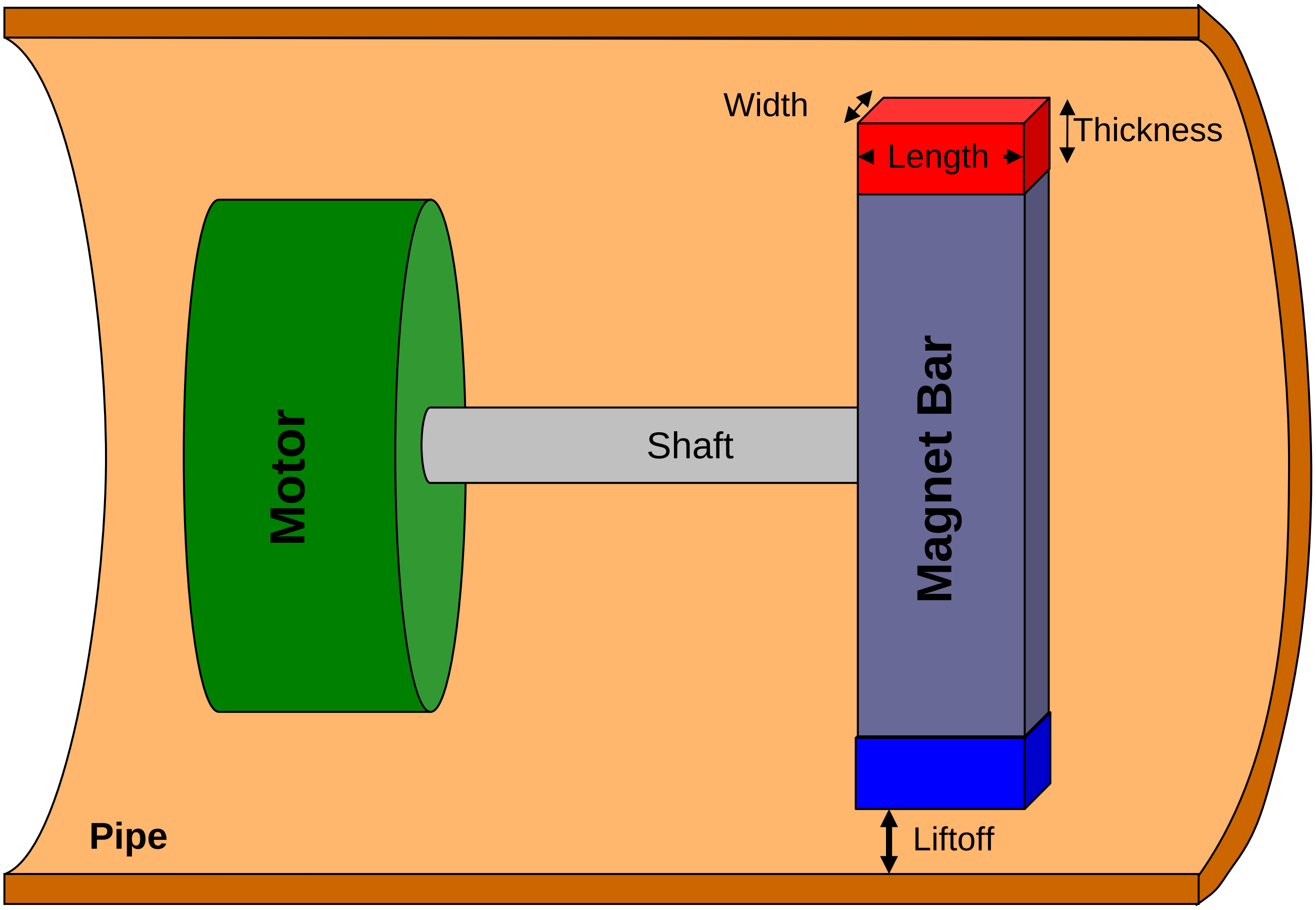

Figure 2. Fundamental components of the Rotating Permanent Magnet Inspection System

Initially, two prototypes were built to evaluate the inspection capability of this inspection method and optimize design parameters. The first had a nominal diameter of 12 inches and the second had a nominal diameter of 8 inches. Both were benchmarked in blind trails using pipe samples with machined metal loss anomalies and natural corrosion in 2004 [1] and 2006 [2]. Both prototypes used 2 inch long, 1 inch wide, and ½ inch thick bricks of neodymium iron boron (NdFeB) with an energy product of 35 megagauss oersted (MGOe). When specifying magnets, the orientation of the magnetic field is through the thickness.

The length and width of the magnet bar should be the exact same dimensions as the magnets. The main goal is to channel as much magnetic flux into the pipe wall as possible; any size variation would establish alternate paths for the magnetic flux which would reduce current generation. The magnets hold themselves to the magnet bar with a force of attraction often 50 pounds or greater. Even with the large attractive force, the magnets can still slide on the magnet bar causing a misalignment which would establish an alternate path for the flux. For this reason, caps made of a non-ferromagnetic material, such as brass sheet metal, are placed over the magnets and attached to the magnet bar to maintain the magnet alignment. The thickness of these caps is not critical for system performance; brass sheet metal with a thickness of 0.040 inches was used for the two prototypes.

High strength magnets made from NdFeB are readily available in a number of standard shapes. In recent years, the magnetic energy of these specialized magnets has increased while at the same time the cost to purchase these magnets has decreased. These factors have enabled the practical experimentation of a range of magnet configurations to identify optimal inspection parameters. While the magnets themselves are less than $20 per brick, a unique magnet bar had to be machined for each configuration which became the dominate cost of the optimization tests of components.

To establish the optimum magnetizer geometry, a range of magnet lengths, widths, thicknesses and liftoffs were examined. The magnet configurations tested are given in Table 2.

Table 2. Optimization of magnet length, width, thickness and liftoff variables

Length	Width	Thickness	Liftoff
(inches)			
2.0	1.0	0.5	0.5
1.0	1.0	1.5	0.5
1.0	1.0	1.5	1.0
1.0	1.0	0.5	0.5
1.0	1.0	0.5	1.0
1.0	0.5	0.5	0.5
1.0	0.5	0.5	1.0

An 8 inch test sample was built to quantify the anomaly detection capability of each magnetizer configuration. The sample had seven metal loss anomalies:

- N1: 1 inch long 3 inch wide 30% deep
- N2: 1 inch long 3 inch wide 70% deep
- N3: 1 inch long 3 inch wide 50% deep
- N4: 1 inch long 2 inch wide 50% deep
- N5: 2 inch long 2 inch wide 50% deep
- N6: 1 inch long 1 inch wide 50% deep
- N7: 3 inch long 1 inch wide 50% deep

The first three anomalies are used to examine the effect of depth. Anomalies N3 and N7 were used to examine the effect of orientation. Anomalies N4, N5 and N6 were used to examine the effect of area.

Successive inspections of the pipe sample were conducted while varying the magnet rotational frequency between 3 and 20 hertz and measuring the electrical power supplied to the motor at each frequency. Figure 3 shows the signal amplitude for the first three metal loss anomalies (30%, 50%, and 70% of wall thickness) for the seven different magnet configurations at a rotational speed of 5 Hz. The motor power requirement for each configuration is provided along with a depiction of the magnet shape and liftoff. The following observations can be drawn form the results:

- The 1-inch x 1-inch x 1.5-inch magnet (thickest) at 1-inch liftoff produced the largest signal.
- Magnets at a 1-inch lift-off produce better signals than magnets at a ½-inch liftoff. Similar results were attained in a 12-inch pipe sample previously inspected where the gap was adjusted in 0.1 inch increments [3].
- Motor power required to maintain rotational speed was larger for magnets at ½-inch liftoff than magnets at 1-inch liftoff.
- At both the ½ inch and 1 inch liftoffs, the signal strength for the smallest magnets (1 x ½ x ½ inch) were significantly weaker than the 1 x 1 x ½ inch magnets, while the power requirements were only slightly less.

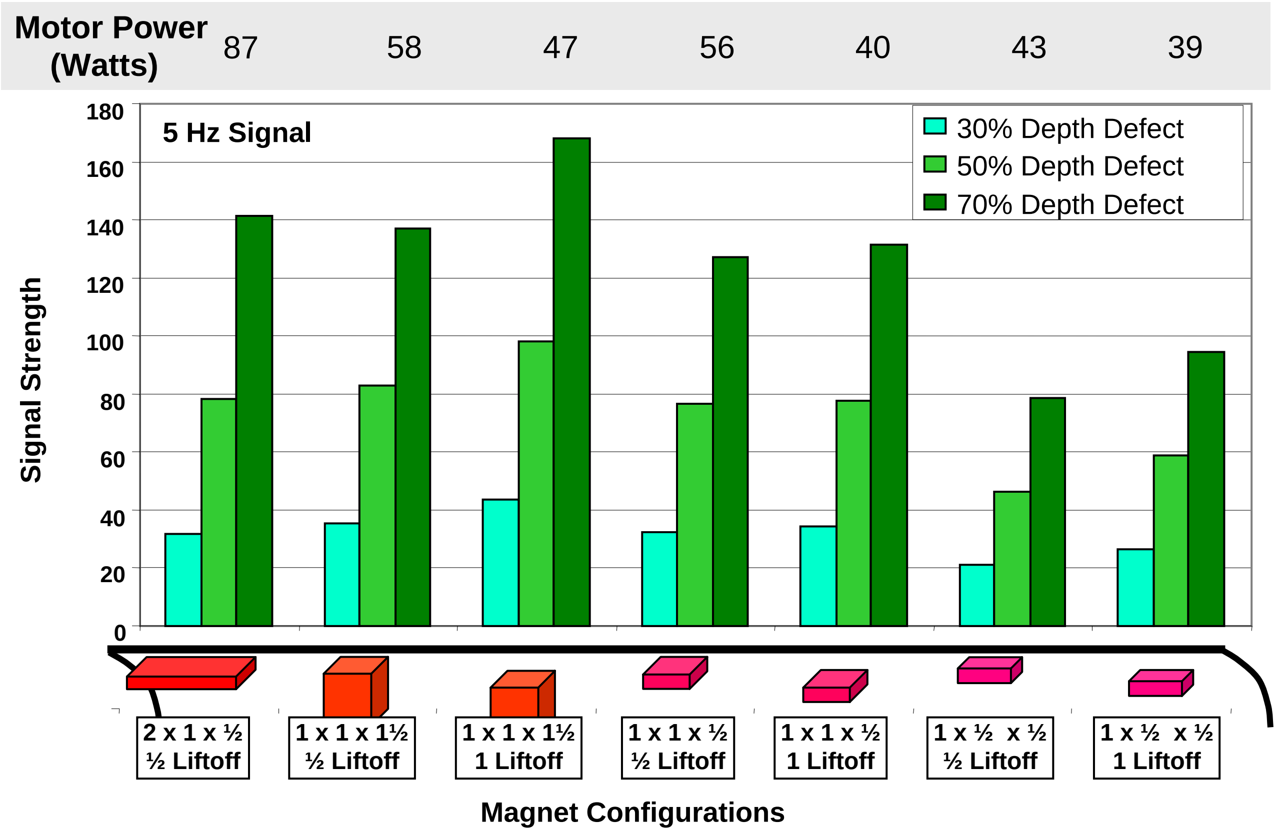

Figure 3. Signal level from corrosion anomalies for seven magnet configurations at 5 hertz rotation frequency

Similar results, presented in Figure 4, are achieved for a test frequency of 10 Hertz. Overall, the signal levels are smaller at the higher frequency; however the general trends are similar.

The experimental results in these examples are for eight inch diameter pipe; optimal values for each magnet configuration may vary for different pipe diameters. When designing a RPMI system, the following guidelines can be drawn from the experimental results:

- Positioning the magnets further away from the pipe wall is better for both signal strength and power considerations.
- A larger magnet area (length x width) is not necessarily better. A 1-inch x 1-inch inch magnet area performed better than both the 2-inch x 1-inch and a 1-inch by ½-inch magnet configurations.
- Thicker magnets tend to give better signals, but other practical design requirements will limit thickness. Thickness limitations are discussed later.

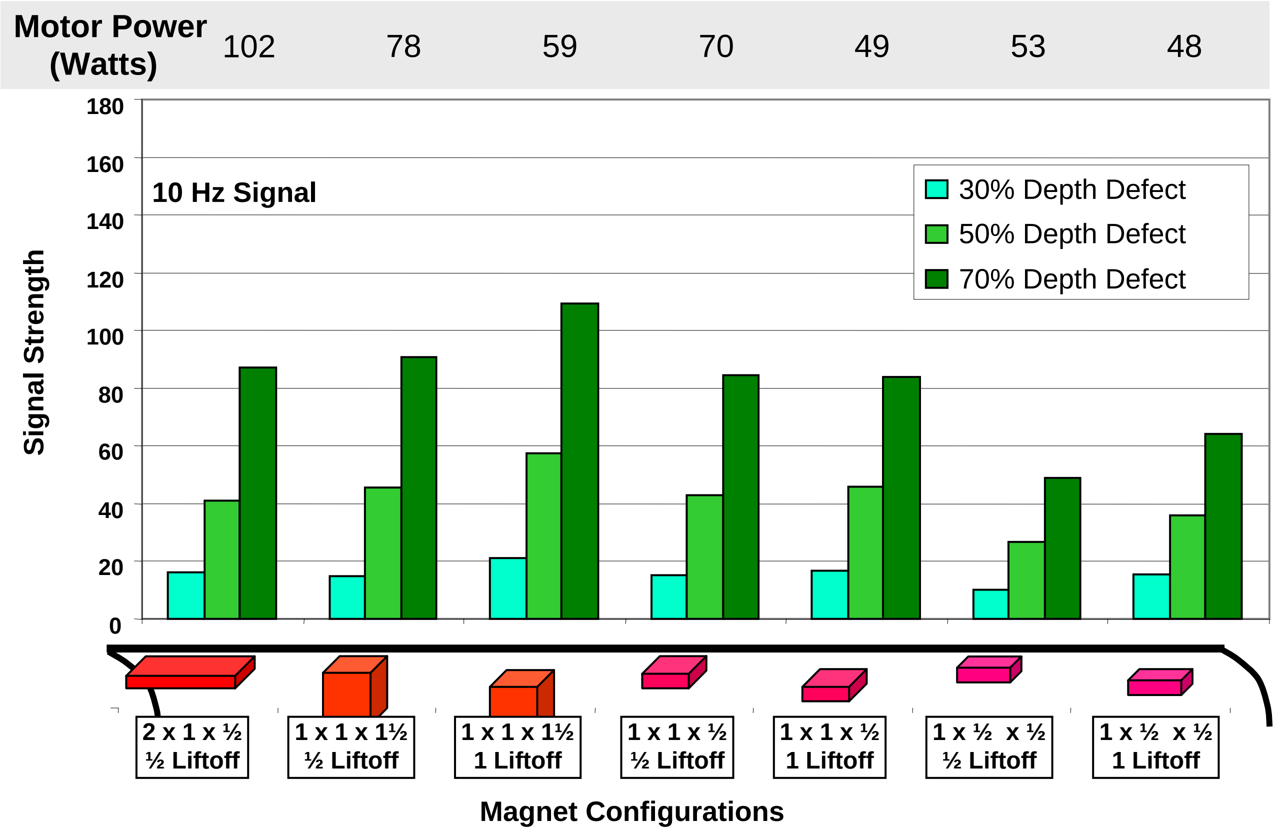

Figure 4. Signal level from corrosion anomalies for seven magnet configurations at 10 hertz rotation frequency.

While first principles indicate that bigger magnets close to the surface would increase current generation, the first two guidelines establish limits on these values. With these guidelines for the magnet configuration, implementation details for the rotational assembly can be considered.

Motor and Rotating Assembly

A wheeled carriage system, illustrated in Figure 5, is used to center and support the motor and magnet in the pipe. In the first two prototype designs, the motor shaft used to rotate the magnets also transferred the forces from the drive and sensor modules. This dual load caused the bearings at the motor and the carriage closest to the magnet to misalign and prematurely fail.

The bearing problems can be reduced by having the magnets rotate around a fixed tube or shaft, as illustrated in Figure 6. A bearing pair is inserted into the magnet bar with the inner race connected to the fixed tube. At the end of the motor shaft is a gear that meshes with a second gear directly coupled to the magnet bar. The axial pulling loads applied from either end are transferred through the fixed shaft to the other side rather than to the bearings. An added benefit of this design is that the fixed tube can be hollow, enabling the passage of power cables, signals and data from one end of the system to the other. Figure 6 shows the motor in an offset position. A centered motor configuration could be easily implemented with the addition of a second gear pair which would facilitate the use of a larger motor or enable the passage of tighter bends with a smaller motor.

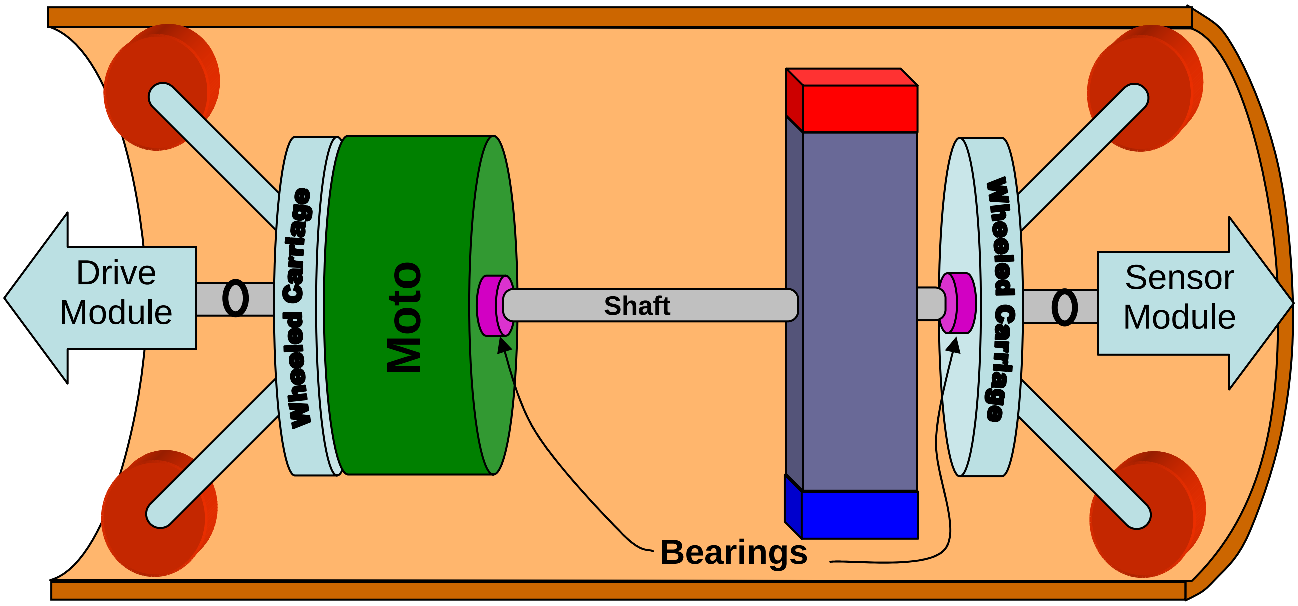

Figure 5. Illustration of carriage system used on prototype designs.

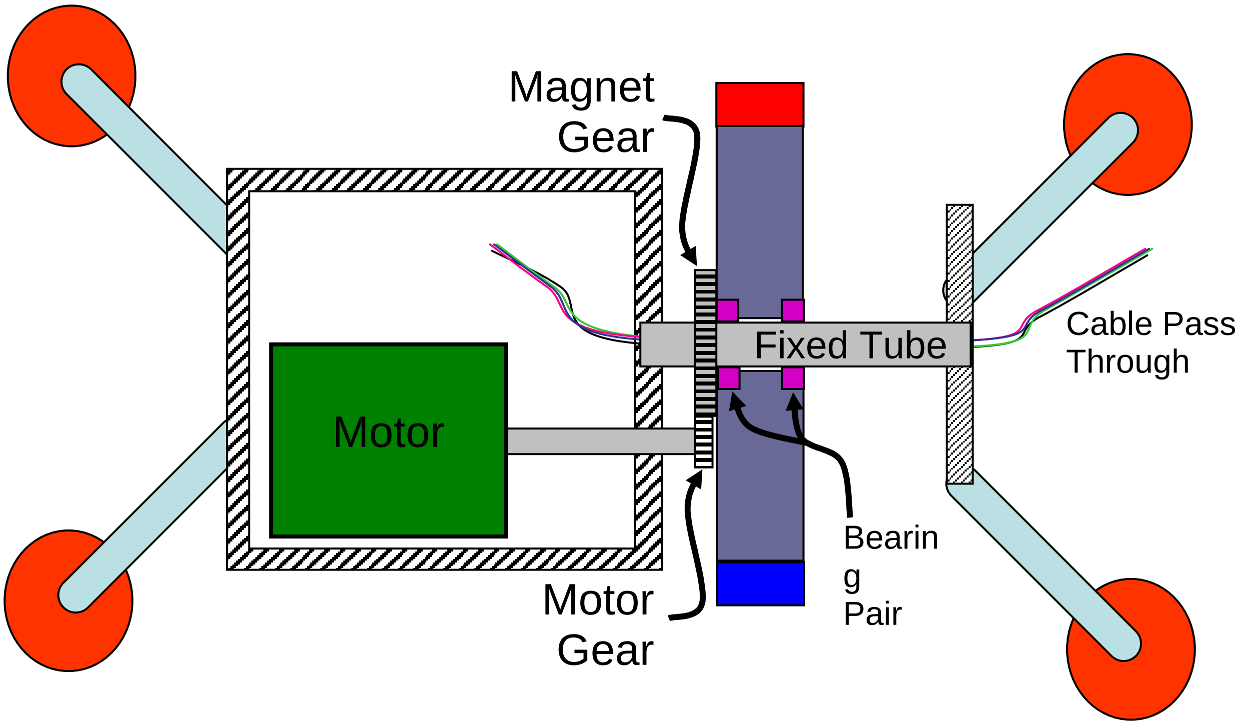

Figure 6. Fixed tube design for improved performance of the RPMI System

Retracting Magnet Bar

While one inch separation between the magnets and pipe is sufficient to pass significant obstructions, additional reduction may be desired. Since it would not be practical to expect an inspection system to perform in severe restrictions like plug valves, the rotation of the magnets would be stopped. To pass oblong obstructions, the magnet bar could be aligned with the largest opening. To further reduce the cross-section, the magnet bars can be designed to retract without degradation to the magnetic performance. The magnet system design has three basic guidelines:

- There must be a continuous path of magnetic material between the two magnets
- The path should not have any abrupt changes in cross-section.
- The cross-sectional area of the magnetic material perpendicular to the magnetic flux path must be greater than or equal to the cross-sectional area of the magnets (length x width)

Pole Piece and Sleeve. Following these guidelines, a magnet system can be designed to pass obstructions. As illustrated in the front and side view in Figure 7, each magnet is attached to a pole piece that is roughly a quarter of the extent of the entire magnet bar. Each pole piece fits snuggly into a sleeve that has low friction guides and pins to keep the pole piece from leaving the sleeve. The wall thickness of the sleeve is defined by the area of the magnet and the pole piece. For example, for a 1-inch x 1-inch magnet, the wall thickness must be at least 0.207 inches. A good design would include 10 to 25 percent more material; therefore a wall thickness of 0.25 inches will be appropriate[1]. A spring is useful in maintaining the magnet in full extension

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[1] The other dimension of the sleeve is 1.5 inches. The base area is 2.25 square inches. The area of the pole piece is 1 square inch. Therefore 1.25 square inches of material is available to carry flux to the 1 square inch pole piece.

position; however the attraction force between the pipe and magnet keeps the spring force requirement low.

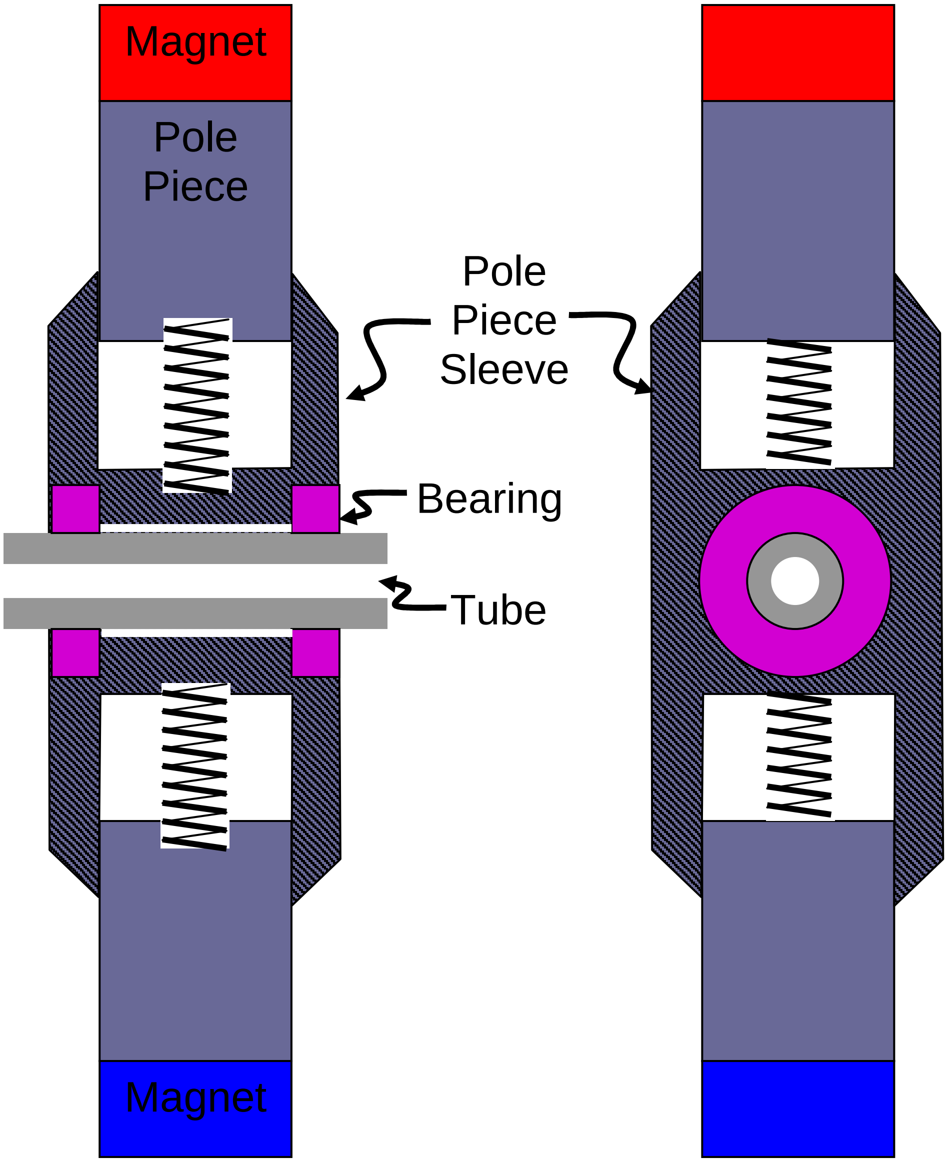

Figure 7. Retractable pole piece

A Protective Boot. Direct contact between the magnet and the pipe should be avoided. A method that isolates the rotating magnet from the pipe using a boot attached to the stationary parts of the system is illustrated in Figure 8. The magnetizer is free to spin within the boot; however to pass a severe obstruction, the rotation needs to be stopped. In this design, there are two ways to control the rotation and stop as necessary. First, if the deflection of the wheeled support arm on the carriage exceeds a threshold, power to the motor can be interrupted. If the obstruction is more localized and not detected by the carriage arms, the boot will be forced into the spinning magnetizer causing it to stop. Since the rotational speed is continuously monitored, a sudden drop in speed would indicate an obstruction and the system controller would interrupt power to the motor. To pass large obstructions, with the magnet rotation stopped, the boot can force the magnet pole piece into the sleeve. The cup material can be made from polyurethane, a material commonly used on current pipeline inspection tools. Note that in Figure 8, a second gear was added to center the motor, as discussed in a previously in the motor and rotating assembly section of this report.

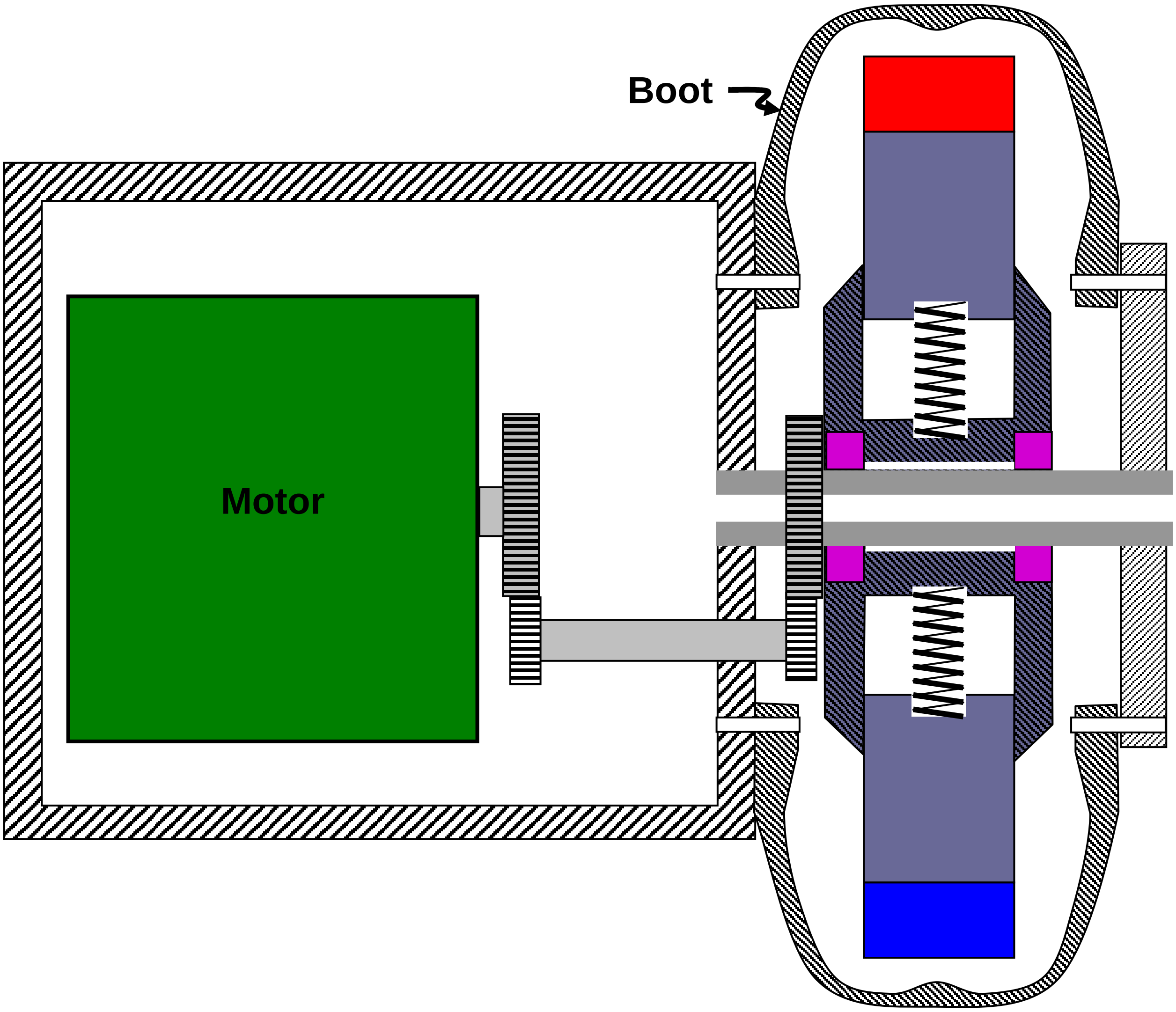

Figure 8. Stationary protective boot surrounding the magnet.

Range of Collapse. The amount the magnet bar can collapse is a function of the diameter of the pipe and the thickness of the magnets. The key design constraint is that the magnet cannot enter the sleeve. Using a 12-inch inside pipe diameter configuration as an example, as illustrated in Figure 9, the inspection diameter would be 10 inches with the optimum 1 inch lift-off. Each magnet bar can retract another 1.5 inches so that in the stationary position, the minimum size would be 7 inches.

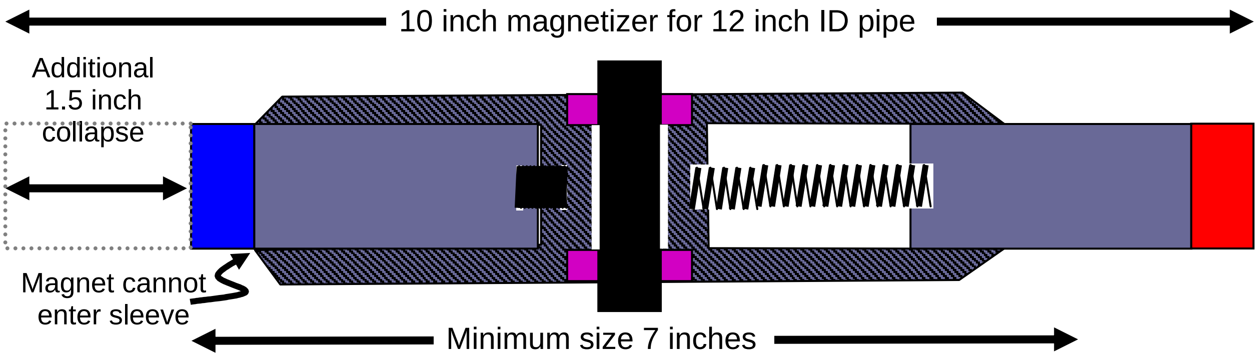

Figure 9. Retraction potential for a 12 inch diameter pipe

Table 3 shows the potential collapsible magnet bar configurations for pipe diameters ranging from 8 to 18 inches. Two values are given for inspection diameter and minimum diameter. The inspection dimension in inches assumes a 1 inch liftoff. The percentage value is the percentage obstruction that a tool could negotiate. It should be noted that the pipe inner diameter is controlled for pipe 12 inches or less and outside diameter is controlled for pipe greater than 12-inches in diameter.

Table 3. Collapsible magnet bar configurations for pipe diameters ranging from 8 to 18 inches

Pipe Diameter	**Magnet Thickness**	**Inspection Diameter (1 inch liftoff)**		**Minimum Diameter (Full Collapse)**	
Inches	Inches	Inches	Percent	Inches	Percent
8	0.5	6	25%	5	38%
10	0.5	8	20%	6	40%
12	0.5	10	17%	7	42%
14	0.5	12	14%	8	43%
16	0.5	14	13%	9	44%
18	0.5	16	11%	10	44%
12	1.0	10	17%	8	33%
14	1.5	12	14%	9	36%
16	1.5	14	13%	10	38%
18	1.5	16	11%	11	39%

Summary

The rotating permanent magnet inspection system is feasible for pipes ranging in diameter from 8 to 18 inches using a two pole configuration. Experimental results and theoretical calculations provide the basis for selection of the critical design parameters. The parameters include a significant magnet to pipe separation that will facilitate the passage of pipeline features. With the basic values of critical components established, the next step is a detailed mechanical design of a pipeline ready inspection system.

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