# Evaluation of the Use of Sensors to Detect Erosive Wear

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## Abstract

The possibility of the use of sensors to detect erosive wear of pipes was explored. The time to yielding for different particle velocities was calculated using the erosive wear equation in which the critical volume was determined using equations for a thick walled pressurized cylinder. This data was used to determine the effective range of pipe sizes and particle speeds in which sensors could be applied. A useable sensor was found, and a program was written to compute the changing radius from the sensors output. The number of sensors required for a section of pipe was determined. Several improvements on the analysis were presented.

## Introduction

The conveyance of materials in the form of gas, liquids or solids, by means of pipes is increasing steadily. In all parts of the world, hydraulically or pneumatically operated pipelines are in permanent service, providing industrial and private consumers with raw materials and disposing of rubbish, tailings and domestic wastes [Lehrke and Nonnen 1975]. Also pipelines usually comply with environmental requirements, because they operate free of noise and dust, which has made them even more attractive for conveighing materials such as natural gas and oil [Lehrke and Nonnen 1975].

When pipelines are designed special attention has to be paid to the protect against deformation. Failures in pipelines can be difficult to fix, especially when the failures occur in locations that are not easily accessible. Furthermore, repair work, apart from being costly in itself, can result in the complete shutdown of the pipeline. Thus, wear in long distance pipelines is of prime interest because of its effect on both the initial cost and the life of the pipeline [Lehrke and Nonnen 1975].

A wear process that can cause serious deformation resulting in failures is erosion. There are two basic types of erosion. The first kind is high speed erosion which occurs when metal surfaces are bombarded by particles at speeds of mach 1 or greater. The second kind is known as low speed erosion and takes places at speeds less than mach 1. It is more applicable to pipes and pressurized vessels and has been studied extensively because of its application to pipes carrying coal slurry, oil wells pumping crude containing sand and in coal-to-fluid conversion plants [Rabinowicz 1980]. Low speed erosion has also caused serious problems due to the amount of damage it causes to the surface of parts of machines and installations such as cyclones, pipe systems, boiler units, gas turbines and separators [Uuemois and Kleis 1975].

In pipelines, a section must be replaced when its wall thickness can no longer withstand the radial and tangential stresses [Faddick 19751. A picture of the stress distributions in a pressurized cylinder are shown in figure 1.

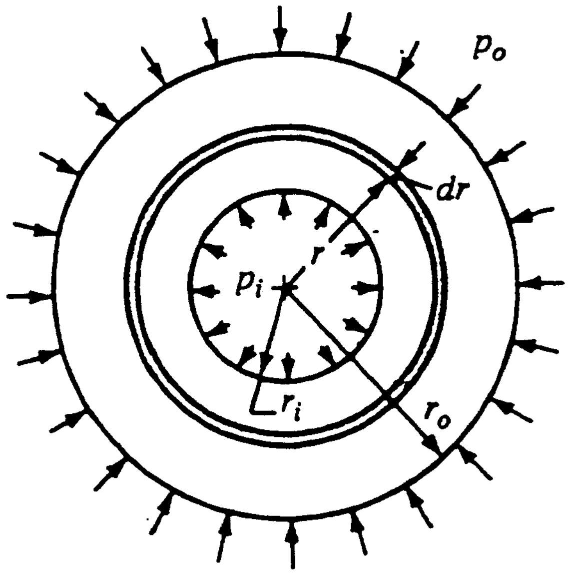



**Figure 1: Illustration of the distribution of stresses in a thick walled cylinder subjected to internal pressure [Reproduced from Shigley and Mischke 1989].**

Usually the pipelines designer provides adequate initial wall thickness to contain the stresses with a reasonable margin of safety, but it is difficult to predict the additional wall thickness required to account for wear. Often the designer has very little information with which to calculate the wear thickness allowance [Faddick 1975].

Currently there are a few measures to reduce wear. These include the use of highly wear resistant materials, improved designs of parts and units subject to erosion and the changing of operating conditions such as reducing the velocity of abrasive stream and filtration of solid dustlike particles from air and gas [Uuemois and Kleis 19751.

These are all viable solutions if it is possible to change operating conditions, but this is not always possible. For example, if we have a mile long section of pipe, it may be very difficult to filter the abrasive particles along the whole length of the pipe. In such cases, it would be of great assistance if realtime wear information could be obtained. Using such data, sections of pipeline subjected to erosion could be repaired well before a failure occurred.

## Discussion

In order to obtain wear data in realtime it is necessary to first understand the erosive wear process. Erosive wear occurs when particles impinge on a surface. The factors that contribute to the amount of wear are, impact velocity, angle of attack, particle size, particle concentration and hardness of the surface. The volume eroded from a surface is given by the formula:

$$V = k_e'(Wv^2)(\alpha\beta\gamma\delta)/(gH)$$

The terms $\alpha,\beta,\gamma,\delta$ correspond to the effects of impact velocity, angle of attack, hardness of the surface and the size of the erosive particles, respectively. W is the total weight of the erosive particles, and is found from the volumetric flow rate.

$$W = (\rho_{erosive})gXQt$$

The terms in this equation correspond to the density of the erosive particles, the gravitational constant, the composition of the flow, the volumetric flow rate and the time of flow, respectively. since Q is equal to the velocity of the flow multiplied by the area over which it is acting, the rate of volume removed is given by:

$$V/t = k_e'((\rho_{erosive})XAv^3)(\alpha\beta\gamma\delta)/(H)$$

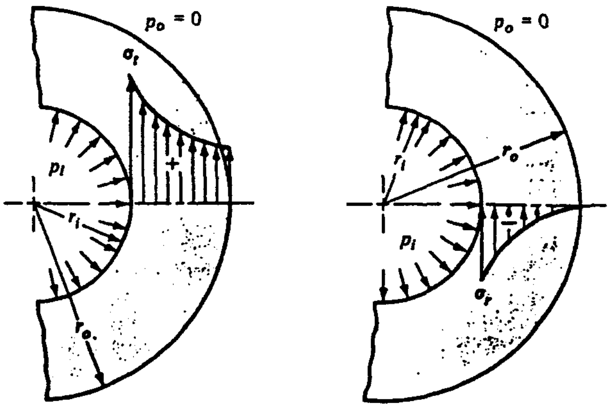
For common natural abrasives and surfaces the values of H, $k_e'$ and $\rho_{erosive}$ can be found using tables like those in the Material Science CRC Handbook. The values of X and v must be obtained via measurement to properly calculate the rate of volume removal. Once this rate is calculated the rate of change of the stress can be calculated because cylindrical pressure vessels, hydraulic cylinders and pipes carrying fluids at high pressures develop radial and tangential stresses.

In the general case for a cylinder subjected to an internal pressure, pi, and an external pressure, $p_o$, with inner radius $r_i$ and outer radius $r_o$, the magnitudes of the tangential and radial stresses are given by the equations at a position $r_i \le r \le r_o$:

$$\sigma_T = (p_i r_i^2 - p_o r_o^2 - r_i^2 r_o^2 (p_o - p_i)/r^2)/(r_o^2 - r_i^2)$$

$$\sigma_R = (p_i r_i^2 - p_o r_o^2 + r_i^2 r_o^2 (p_o - p_i)/r^2)/(r_o^2 - r_i^2)$$

An illustration of this is shown in figure 2.




(a) Tangential stress distribution

(b) Radial stress distribution

**Figure 2: Illustration** of **a cylinder subjected** to **both internal and external pressure [Reproduced from Shigley and Mischke 19891.**

In the case of a pipe in air there is no hydrostatic pressure, so $p_o = 0$. This simplifies the two expressions:

$$\sigma_T = (p_i r_i^2)(1 + r_o^2/r^2)/(r_o^2 - r_i^2)$$

$$\sigma_R = (p_i r_i^2)(1 - r_o^2/r^2)/(r_o^2 - r_i^2)$$

The from these expression it is obvious that the max/min values of the stress occur at the inner radius $r_i$. This is illustrated in fig 1. At $r_i$ the two stresses will have magnitudes given by the equations:

$$\sigma_T = p_i(r_i^2 + r_o^2)/(r_o^2 - r_i^2)$$

$$\sigma_R = p_i(r_i^2 - r_o^2)/(r_o^2 - r_i^2)$$

The critical value of this stress depends on whether or not plastic deformation can be tolerated. Plastic deformation is usually an unwanted situation so, the critical value of the stresses would be the yield strength, $\sigma_y$.

In order to determine if sensors could be employed in the detection of wear in a pressurized cylinder, the case of oil pipelines was considered. In gas and oil pipelines the radii of the pipes vary between 14 to 30 inches, but there is a trend toward lines with 20 to 36 inch radii [Considine 1976]. The pipes are usually made from pipes of high strength steel ($\sigma_Y$ = 200,000 psi) of thicknesses from 3/8 to 1 inch and usually come in 40, 60 or 80 feet sections [Considine 1976]. The internal pressures, pi, range from 500 to 5000 psi, with 1000 psi being the most common [Considine 1976].

For calculation purposes 40 feet sections with $p_i$ = 1000 psi were assume. Calculations were performed for pipes with external radii ranging from 20 to 36 in. using the relationships for tangential and radial stress, the radii at which the stresses equaled the yield strength were found. Using these critical radii the volume lost to erosion to cause yielding was determined from the equation:

$$V_{eroded} = \pi(r_o^2 - r_c^2)l$$

By dividing this volume from the rate of volume reduction, the time required to cause this erosion was calculated for particle speeds of 10 to 150 m/s. It was assumed that $H_{steel}$ was between 10 and 300kg/mm$^2$; the abrasive particles were sand and were larger than 30 um; the angle of attack of the particles was between 10$^0$ and 60$^0$; and that the composition of the air was 0.1% sand. These assumptions were made to simplify the calculations. A summary results appears in table 1.

As the results in table 1 indicate, for wind velocities between 10 and 50 m/s a erosive wear sensor would be plausible, because the times required to erode the surface are on the scale of several hours. A sensor would be useful in determining the time remaining to failure and thus preventive measures could be taken. Another trend in the data indicates that sensors would have greater effectiveness in larger thicker pipes.

The main criteria in choosing a sensor was that the sensor would have to operate in an extremely high force regime. Many sensors could not detected forces corresponding to yield stresses, but an extremely versatile sensor known as an integrated force array was found.

IFA;s are flexible metallized membranes which produce motion on a macroscopic scale by adding together the responses of many microscopic elements acting under an electrostatic force [Bobbio 1993]. The force array technology is based on electrically deformable flexible membranes. The membranes are composed of microscopic force elements arranged in arrays containing $10^5$ to $10^{10}$ elements. When a high enough voltage (~100 V) is applied to the IFA, it contracts about 30% [Bobbio 1993]. See figure 3 for an illustration of the IFA before and after application of the voltage.

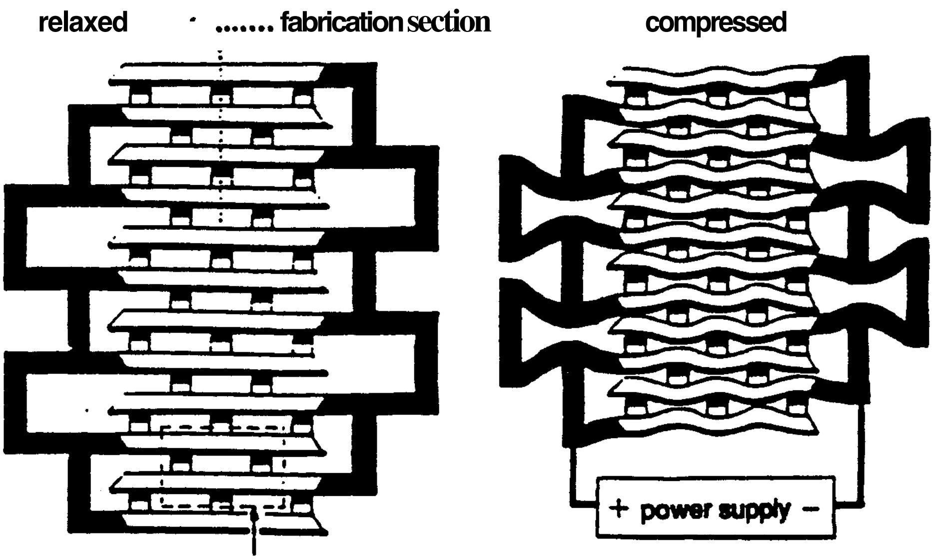



**Figure 3: A schematic of the Integrated Force Array. When a voltage is applied it compresses. Likewise, when a force is applied it compresses producing a voltage [Reproduced from Bobbio 1993].**

If the maximum compression is calibrated to correspond to the maximum stress, then when the voltage output reaches 100 V, the maximum operating voltage IBobbio 1993], yielding occurs. By continuously obtaining voltage reading from the sensor state of stress in the pipe can be calculated. A program which takes in the voltage readings and computes the current radius was written.

Once a feasible sensor was found, the next step was to determine the placement of the sensor. The IFA is made of 22 planar arrays of 1 cm x 3 cm [Bobbio 1993], which gives a sensing area of 0.465 inches. In order to cover a forty foot section of pipe with an internal radius of 19 inches, about 123 thousand sensors are required. When the next generation of IFA's, which are 10 times larger, are constructed, the number of sensors required will be about 370. The next generation of IFA's will be constructed in 1994 [Bobbio 1993], so these should be readily available now.

Once the number of sensors required was calculated a method of mounting of the sensors need to be found. There were two obvious techniques. The first would be two place the sensors at the critical radius. This would provide force and wear data along with the failure of the sensor when the critical radius had been reached. This method requires that holes would be drilled into the section of pipe, the sensors would be placed in, then the holes would be filled in. The processes of drilling creates residual stresses in the material which may cause failure earlier than expected near a hole. If many holes were required the residual stress would have a significant impact on the life of the pipe. For the current generation of sensors more than 123 thousand holes would be required, this would not be feasible. For the next generation only 370 holes are required, which would acceptable.

The alternative was to place the sensors are the inner radius of the section of pipe. This method causes no damage to the pipe, which means that residual stresses from sensor mounting need not be accounted for. Additionally any number of sensors can be mounted at the inner radius, meaning that current IFA's can be used to detect wear.

## Improvements and Future Study

Several improvements can be made to the analysis presented here. First of all, only oil and gas pipes of a certain radius were consider. An improvement would be to consider more types of pressurized cylinders along with other mechanical parts subjected to erosion. Furthermore, only common pipe sizes were used for a common internal pressure of 1000 psi, a better analysis could be achieved by considering a wide range of pipe sizes with different internal pressures. A better understanding of the possibility of the use of sensors can be determine if many situations are considered.

In the determination of the time to erode the pipes, several assumptions were made, though some are valid, calculations should be carried out for angles of attack less than $10^0$ and greater than $60^0$, particle sizes less than 30 um and differing compositions of abrasive. The most significant of these will be the differing compositions of abrasive, because unlike the other two it can change by factors of 10, producing a significant impact on the time to yielding.

Other improvements include finding different types of sensors and improving the data processing program to display the loss of volume and the time to failure. The loss of volume can be easily computed by subtracting the volume given by the current external radius from the volume given by the original external radius. The calculation of the time to failure will be more complicated because the erosive wear equation must be used to find it. This means that information on wind speed, composition of the air, angle of attack and size of the particles needs to be obtained dynamically.

Information on wind speed is gathered quite easily by using the common cup or vane type anemometers, which translate rotations of their parts into wind speed either electronically or mechanically [Considine 1976]. These provide data continuously so that the calculations of time remaining can be kept accurate.

The composition of the air is slightly harder to determine, but in could be accomplished by using a sonic type anemometer, which measures the properties of wind-bourne sound waves [Considine 1976]. The instruments operates of the principle that the propagation velocity of a sound wave in a medium is proportional to the composition of the medium. This means that by determining the propagation rate of sound in air of varying abrasive content, a relationship between the velocity of sound measured by the sonic anemometer and the amount of abrasive in the air could be determined. This technique might be applied to determine the size of the particles, by determining the relationship between the size of the particles in the air and the speed of sound.

Though the angle of attack should be determine dynamically, it was not clear how this would be accomplished. The best solution to this problem would be to keep the assumptions that the particles have an angle of incidence between $10^o$ and $60^o$, since this will provide the more conservative estimate of the time to yielding.

Other areas open to investigation include determining how to interface the sensors with the computer which performs the data analysis and improving the user interface of the data processing program.

## Conclusion

Currently pipelines are used extensively throughout the world. Many of these are subjected to erosive wear. It is often difficult to design a structure considering erosion. The present solution is to coat pipes and other structures subject to erosion with highly wear resistant materials or to attempt to reduce the concentration of erosive particles impinging on the surface. These are good techniques, but they cannot stop erosion, so it is important to know when a part has been subjected to excessive wear. For a thick-walled cylindrical pressure vessel, the critical wear volume was calculated and from this the time to yielding for different particle speeds was determined. Using this information the range of pipe sizes and particle speeds in which sensor can provide information was found. This information lead to a search for a viable sensor, which is a Integrated Force Array. The IFA contracts when a force is applied, causing a voltage to be recorded, this voltage can be converted into a force once a relationship between the maximum voltage and the yielding force is setup. A short computer program that reads in the voltages and determines the corresponding reduction in radius was written. There are several improvements that can be done to the analysis and the computer program which will increase the effectiveness of using sensors to detect erosive wear.

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Table 1: Summary of Calculations

| Ro | Ri | Rc | del V | Time to Failure in min for v = 10m/s | 25m/s | 50m/s | 75m/s | 100m/s | 150m/s |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 19.625 | 19.70 | 17959 | 7482 | 478 | 59 | 17 | 7 | 2 |
| 20 | 19.500 | 19.55 | 26837 | 11182 | 715 | 89 | 26 | 11 | 3 |
| 20 | 19.375 | 19.45 | 32719 | 13632 | 872 | 109 | 32 | 13 | 4 |
| 20 | 19.250 | 19.30 | 41484 | 17285 | 1106 | 138 | 40 | 17 | 5 |
| 20 | 19.125 | 19.20 | 47289 | 19703 | 1261 | 157 | 46 | 19 | 5 |
| 20 | 19.000 | 19.05 | 55941 | 23308 | 1491 | 186 | 55 | 23 | 6 |
| 24 | 23.625 | 23.70 | 21578 | 8990 | 575 | 71 | 21 | 8 | 2 |
| 24 | 23.500 | 23.60 | 28711 | 11962 | 765 | 95 | 28 | 11 | 3 |
| 24 | 23.375 | 23.45 | 39354 | 16397 | 1049 | 131 | 38 | 16 | 4 |
| 24 | 23.250 | 23.35 | 46411 | 19337 | 1237 | 154 | 45 | 19 | 5 |
| 24 | 23.125 | 23.20 | 56940 | 23725 | 1518 | 189 | 56 | 23 | 7 |
| 24 | 23.000 | 23.10 | 63922 | 26634 | 1704 | 213 | 63 | 26 | 7 |
| 28 | 27.625 | 27.75 | 21017 | 8757 | 560 | 70 | 20 | 8 | 2 |
| 28 | 27.500 | 27.60 | 33537 | 13973 | 894 | 111 | 33 | 13 | 4 |
| 28 | 27.375 | 27.50 | 41845 | 17435 | 1115 | 139 | 41 | 17 | 5 |
| 28 | 27.250 | 27.35 | 54252 | 22605 | 1446 | 180 | 53 | 22 | 6 |
| 28 | 27.125 | 27.25 | 62486 | 26035 | 1666 | 208 | 61 | 26 | 7 |
| 28 | 27.000 | 27.10 | 74779 | 31157 | 1994 | 249 | 73 | 31 | 9 |
| 32 | 31.625 | 31.75 | 24033 | 10013 | 640 | 80 | 23 | 10 | 2 |
| 32 | 31.500 | 31.65 | 33593 | 13997 | 895 | 111 | 33 | 13 | 4 |
| 32 | 31.375 | 31.50 | 47877 | 19948 | 1276 | 159 | 47 | 19 | 5 |
| 32 | 31.250 | 31.40 | 57362 | 23900 | 1529 | 191 | 56 | 23 | 7 |
| 32 | 31.125 | 31.25 | 71534 | 29805 | 1907 | 238 | 70 | 29 | 8 |
| 32 | 31.000 | 31.15 | 80943 | 33726 | 2158 | 269 | 79 | 33 | 9 |
| 36 | 35.625 | 35.80 | 21654 | 9022 | 577 | 72 | 21 | 9 | 2 |
| 36 | 35.500 | 35.65 | 37815 | 15756 | 1008 | 126 | 37 | 15 | 4 |
| 36 | 35.375 | 35.55 | 48552 | 20230 | 1294 | 161 | 47 | 20 | 5 |
| 36 | 35.250 | 35.40 | 64601 | 26917 | 1722 | 215 | 63 | 26 | 7 |
| 36 | 35.125 | 35.30 | 75262 | 31359 | 2006 | 250 | 74 | 31 | 9 |
| 36 | 35.000 | 35.15 | 91197 | 37998 | 2431 | 303 | 90 | 37 | 11 |