# 4-0 DURABILITY

## TABLE OF CONTENTS



### Tables



### Figures



*BUYER/USER IS RESPONSIBLE FOR SERVICEABILITY OF THE PRODUCT IN ANY GIVEN APPLICATION. SELLER IS NOT RESPONSIBLE FOR INJURY OR DAMAGE RESULTING FROM IMPROPER INSTALLATION, NONCOMPLIANCE WITH THESE GUIDELINES FOR INSTALLATION OF PRODUCT, OR USE OUTSIDE THE GUIDELINES SET FORTH HEREIN.*

# 4-1 OVERVIEW OF DURABILITY CONSIDERATIONS

In a drainage system, adverse conditions challenging the durability of the materials involved may be found in the soil, air, and effluent. This section covers the three primary durability concerns in non-pressure drainage applications:

1) Corrosion,
2) Erosion (abrasion) from effluent, and
3) Weathering effects such as sub-zero temperatures, freeze/thaw cycles, or exposure to ultraviolet radiation.

In any particular installation, it is quite likely that more than one adverse condition will be present. When this occurs, the rate of material deterioration may be greater than the sum of each problem alone.

Thermoplastic is one of the most durable materials available for drainage applications. Plastics, including polyethylene and polypropylene, are some of the most inert materials in today's storm drainage market. They are also highly resistant to the effects of abrasives and are immune to galvanic corrosion. Unlike metals, such as steel and aluminum, which are affected by the pH and galvanic corrosion. In many cases, corrosion problems are compounded when abrasives are also present.

This section, while discussing corrosion, erosion, and weathering effects on an individual basis, provides suggestions for appropriate materials when a multitude of durability factors are present.

The intent of this information is not to determine the life of materials in a particular installation, but to provide a qualitative means to compare the durability at various conditions. For specific installations located in an environment known to be highly aggressive, the manufacturers of drainage material alternatives should be consulted to ensure the suitability of their products.

# 4-2 CORROSION

## CHEMICAL CORROSION

The initial runoff following the onset of a storm, termed the “first flush,” contains rather high concentrations of road salt, motor oils, fuels, and other compounds that have accumulated on the ground surface since the previous storm. Pollutant concentrations are relatively high during the first flush and then taper off to more diluted levels as the storm progresses.

Chemical corrosion occurs when aggressive chemicals in the effluent, individually or in combination, attack the pipe. In some installations, it may be the soil environment, not the effluent, that causes the corrosion. In either situation, the end result is a pipe with reduced strength and, in some cases, negative effects on hydraulic capabilities.

Pipe materials react differently under chemically corrosive environments. Individual states often make recommendations on environments where specific products can be used based on their past performance. Soil environments fluctuate widely making it nearly impossible to offer blanket statements about product suitability throughout the country.

Polyolefins, such as high density polyethylene (HDPE) and polypropylene (PP) are stable materials. Polyethylene and polypropylene have been extensively tested with many potentially corrosive chemicals with few chemicals having any effect on the material. Of those chemicals that were not acceptable, fewer still could be expected in a storm sewer in sufficient concentrations and at a high enough temperature to create problems even on a rather long-term basis. For further information regarding chemical resistance of polyethylene and polypropylene, and additional considerations when evaluating applications, refer to Technical Notes 4.01: *Chemical Resistance of Polyethylene and Elastomers* and 4.02: *Chemical Resistance of Polypropylene and Elastomers.*

Gasket material must also be considered for projects where abnormal chemicals or abnormal concentrations of chemicals are present. Like many common stormwater and sanitary sewer pipe materials, ADS storm and sanitary sewer products utilize gaskets manufactured to meet the requirements of ASTM F477. In most cases, this gasket material is resistant to many of the common chemicals found in storm sewer systems. However, there are chemicals, which may negatively affect the gasket material, such as high concentrations of hydrocarbons. In environmental conditions where a standard gasket material is not suitable, ADS may be able to provide alternative gasket materials to meet the needs of most project requirements. For further information regarding chemical resistance of gasket materials, refer to Technical Note 4.01: *Chemical Resistance of Polyethylene and Elastomers* or 4.02: *Chemical Resistance of Polypropylene and Elastomers.* There is no material difference between the gaskets provided on polyethylene and polypropylene products, but elastomer chemical resistance charts are provided in both technical notes for ease of reference when researching polyethylene or polypropylene materials.

## ELECTROCHEMICAL CORROSION

Electrochemical, or galvanic, corrosion can occur when metals having differing electrical qualities are in direct or indirect contact in the presence of electrical current. Corrosion can occur between entirely different metals or even between areas on the same pipe having different electrical properties. It can also occur between the pipe and its environment.

Stray electrical currents in the soil encourage galvanization. This is especially true where, in larger metropolitan areas, power generation stations, subway systems, or buried electrical transmission lines provide a good source of stray electrical current. Nearby pipe may pick up these currents and create the environment for galvanic corrosion to occur at an accelerated rate.

Metals with good conductivity, namely steel and iron, are most prone to galvanic corrosion. The advanced stages of galvanic corrosion show as a pitting of the pipe wall and as relatively harmless rust deposits. The end result of the problem is a gradual weakening of the structural integrity of the pipe and a lessening of its hydraulic qualities.

Several methods are available to prevent or reduce the rate of galvanic corrosion although, depending on the environment, they may prove to be rather costly solutions. One alternative uses blocks of “sacrificing” metals, such as zinc or magnesium, in contact with the pipes. These materials corrode at a faster rate than the pipe allowing the pipe to remain relatively free of corrosion. The sacrificing metal block must be checked routinely and periodically replaced in order for the system to work properly.

Another method of preventing corrosion is to coat the metallic pipe with a material that cannot support electrical activity. Polymers and asphalt materials are often used for this purpose.

A third alternative is to install a material that is unable to support galvanic corrosion, such as thermoplastics like polyethylene, polypropylene and PVC. Thermoplastics are unable to carry electrical current and therefore do not require precautions such as coatings or sacrificing metal blocks. Thermoplastics provide a cost-effective drainage alternative immune to electrochemically corrosive environments.

## STRESS CRACK RESISTANCE

The durability of a material directly impacts structural performance. For HDPE pipe, the stress-crack resistance of critical structural members must be accurately assessed to determine the long-term implications on the pipe and installation integrity. Service life, therefore, directly impacts structural integrity and provides the basis for requiring materials to meet or exceed the specified performance life of the facility, which in many cases approaches 100 years.

To verify the base material has adequate stress capacity for a given application, the base HDPE material is subjected to a Notched Constant Ligament Stress (NCLS) test. Both of the industry accepted national standards for corrugated polyethylene pipe used in storm drainage applications, ASTM F2306 and AASHTO M294, specifically require a 24-hour NCLS test to be conducted on the base polyethylene material used in pipe production.

In addition to the NCLS test on the base resin, the service life of dual wall corrugated HDPE pipe has historically been assessed based on stress cracking at the pipe's inner liner and corrugation wall interface[1]. Although this circumferential cracking is easy to observe and assess, it does not represent a critical structural component of the pipe. The fact that one could remove the entire inner liner of a dual wall corrugated HDPE pipe and not influence its structural performance is evidence of the error of basing a service life on such a non-critical component. The highest tensile stress locations of buried corrugated HDPE pipe occur in the outer most fiber of the corrugation, where the bending strains are the greatest. Compression related strains do not result in any long-term stress cracking, so one must concentrate on tensile strains. These tensile bending strains are associated with deflection, which is a key AASHTO design parameter. The stress-crack resistance of these corrugation members under bending strains, therefore, reflects the critical structural components to evaluate for stress-crack resistance[2].

For applications encountering continuous pressure, high peak pressures, or extreme applications resulting in high induced stresses, HDPE materials with a higher NCLS value or an HDB pressure rated material may be required. Contact ADS engineering for additional guidance on these types of applications.

Polypropylene, while similar in many others aspects, is not similar to polyethlyene with respect to stress cracking. Polypropylene has a significantly higher stress crack resistance and is therefore not susceptible to cracking at the same magnitudes at which HDPE may crack.

# 4-3 EROSION

The amount of stones, grit, and other debris (abrasives) found in a storm sewer vary with the drainage installation. The velocity of or frequency with which the abrasive materials occur is also unpredictable. It is for these reasons that laboratory data representative of field conditions have been nearly impossible to generate. Much of what the industry currently knows about the effects of abrasives on the life of pipe has been discovered through visual inspections of existing systems and the reputation of well-established drainage products.

Laboratory tests are valuable, however, for developing relative wear rates. The Saskatchewan Research Council conducted a laboratory investigation on several materials to quantify the degree of wear that could be expected from abrasives applied in a controlled fashion. The Council compared a series of 2-inch (50mm) pipes, including polyethylene, steel, and aluminum. The abrasives included coarse sand (30 mesh) and fine sand (48 mesh). Each was used in a 40 percent by weight slurry and applied at a controlled temperature and velocities to a closed-loop system. The test ran three weeks at 15 fps (4.6 m/s) and six weeks at 7 fps (2.1 m/s). Material loss was then measured. Wear was assumed to be evenly distributed over the interior of the surface so that gouging, if it did occur, was not measured. Results from the study for velocities of 15 fps (4.6 m/s) were extrapolated to obtain wear rates on an annual basis as shown in Table 4-1.

***Table 4-1***
***Saskatchewan Research Council Wear Rates[3]***

| Material | Wear Rates (mm/yr) | | | |
|---|---|---|---|---|
| | Coarse Sand (30 mesh) | | Fine Sand (48 mesh) | |
| | @ 7 fps | @ 15 fps | @ 7 fps | @ 15 fps |
| **Steel** | 0.65 | 1.81 | 0.04 | 0.02 |
| **Aluminum** | 1.81 | 7.48 | 0.14 | 0.86 |
| **Polyethylene** | 0.06 | 0.46 | nil | 0.06 |

Lane Metal performed an abrasion resistance test in 1982 on several PVC pipes and Class III reinforced concrete pipe. The tests simulated an extremely harsh environment by filling a length of pipe with a stone/water slurry and sealing each end with a watertight cap. The pipes were placed on a rocker arm and rocked 45 degrees from the horizontal. Wear on the pipes was inspected on a daily basis and additional stone was added to maintain the abrasiveness. Following the 91 hour test, thickness measurements were taken along the path of heaviest wear. Results of the Lane metal test are shown in Table 4-2.

***Table 4-2***
***Lane Metal Wear Rates[4]***

| Material | Wear, $10^{-3}$ in/hr ($10^{-3}$ mm/hr) |
|---|---|
| PVC | 0.3 (7.6) |
| RCP | 0.9 (22.9) |

Some means of correlating Tables 4-1 and 4-2 was needed to be able to compare the results of both tests. As a similar thermoplastic, PVC and polyethylene could be expected to behave much the same, and it was this assumption that was used to further the investigation.

A study was performed in 1975 by a team of Swedish scientists dealing with the effects of mechanical cleaning methods on polyethylene and PVC pipe. Both materials were about equal in performance with polyethylene outperforming PVC at times, and PVC outperforming polyethylene in other instances. It was concluded that PVC and polyethylene are approximately equal in abrasion resistance.

In each of the three laboratory tests reviewed, the pipes under study were subjected to an environment that was harsher than they would probably experience in an actual installation. Laboratory testing could also not account for the increased rate of corrosion and/or abrasion that would occur on steel and concrete pipes after the first few resilient layers had been removed.

While test data for polypropylene is less extensive due to its previously limited use in drainage applications, two types of tests were conducted to determine polypropylene's abrasion resistance and provide a means for a relative comparison to other pipe materials.

One test placed high density polyethylene and polypropylene plaques in a closed-conduit system with water flow carrying abrasive sand going over the plaques in order to determine the mass loss over time. Results indicated that while polypropylene performed slightly better than high density polyethylene, both materials performed well and have comparable abrasion resistance.

The second test, performed by Polymer Diagnostics, Inc., used the Taber abrasion method where rotating abrading wheels were placed in direct contact with the material to create a rub-wear action. Results provide a mass loss of the sample. The Taber test included HDPE, PP and PVC samples. The HDPE and PP samples had minimal percent mass loss. While the PVC samples had a slightly higher percent mass loss, it can be concluded that all three materials have comparable abrasion resistance.

Based on the results from both these tests, polypropylene is comparable to HDPE and PVC as it relates to abrasion resistance of the pipe materials. A full summary of these test methods and the results are available in Technical Note 4.03: *Abrasion Resistance of Thermoplastic Material*.

The results of all tests discussed so far, while not able to be compared directly, are highly valuable when comparing wear rates in relative terms. The wear rates of the materials were compared to those of the toughest materials, thermoplastics including polyethylene and polypropylene, to obtain relative wear resistance as shown in Table 4-3.

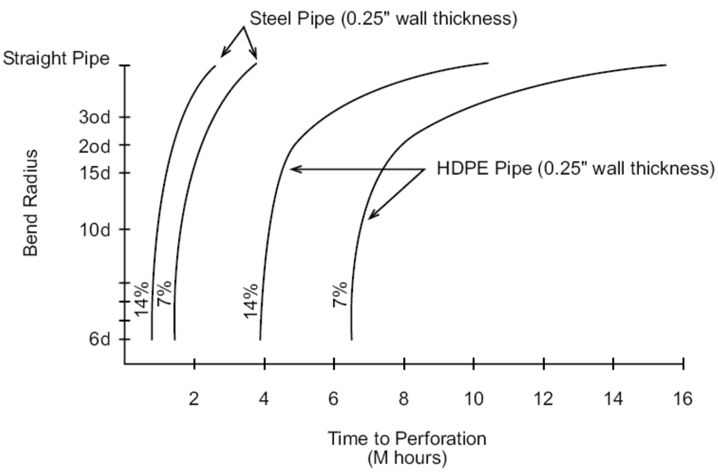
***Table 4-3***
***Relative Wear Resistance***

| | |
|---|---|
| Polyethylene | 10 |
| Polypropylene | 10 |
| PVC | 10 |
| RCP | 3 |
| CSP | 3 |
| CAP | 1 |

Tests conducted by Schreiber and Hocheimer to determine the effects of bends on the relative wear rates indicate a wear resistance for HDPE that is approximately four times better than the wear resistance of steel.

These tests were conducted with both 7% and 14% by volume quartz sand to water mixtures, with an average flow rate velocity of 23 fps. Figure 4-1 illustrates the results from this study.

***Figure 4-1***
***Abrasion Resistance of Pipe and Bends for HDPE and CMP[5]***




# COMBINED EROSION AND CHEMICAL CORROSION

When more than one adverse condition is present in a pipeline, the effects of both combine to form an environment with the potential to drastically shorten the design life. Acids or alkalis in combination with abrasives, acids in combination with freeze/thaw cycles, or abrasives in combination with freeze/thaw cycles are just a few of the combinations that can be present in an installation.

Acids and abrasives in combination are often present in storm drainage networks and were therefore selected as subjects in a study performed at California State University[6]. This combination was previously known to have a great deal of impact on concrete products, so the main focus of the study was on concrete and how it compared to polyethylene. Again, knowing polyethylene and polypropylene are both in the polyolefin group of plastics, their wear resistance is generally considered comparable where polypropylene will behave similarly to polyethylene under the same conditions.

A rocker-type mechanism was also used in the California State research. A "cycle" consisted of one end of the pipe swinging through an 83 degree arc and was completed in about ten seconds. A total of 100,000 half-cycles (50,000 complete cycles) were used in the tests.

For the abrasive materials a crushed quartz [1/2-inch to 3/4-inch (13-19mm)] and river run quartz gravel [2-inch (51mm) minimum] were selected. In order to reasonably simulate an installation, 2/3 of the abrasives were crushed quartz with the remainder being the river run gravel. Velocity of the gravel/fluid slurry through the pipe length was timed at 3 fps (0.9 m/s). Midway through the test the aggregate was examined for wear and it was determined that the abrasive should be recharged.

Tests were run in both a chemically neutral environment (pH 7.0) and with a moderately strong acid (pH 4.0). The acidity of the circulating fluid was checked at frequent intervals and adjusted, if necessary, with acetic acid. Controlling the acidity was especially important for the concrete pipe because of its tendency to raise the pH as a result of its alkaline composition.

Twelve-inch (300mm) HDPE smooth interior polyethylene pipe was tested with the results showing that the abrasive/acid slurry had an almost negligible effect when compared to the results of the abrasives in a neutral environment. In the neutral environment the maximum abrasion was 0.021-inches (0.5mm). The polyethylene allowed just 14 percent more abrasion along the invert in the acidic environment.

The results for the 12-inch (300mm) non-reinforced concrete pipe were quite different. In a neutral environment, wear along the invert was approximately 0.80-inch (20.3mm). The addition of acid to the slurry increased this wear nearly 90 percent. Had a reinforced pipe been used, the steel would have been exposed thereby creating a third durability issue, galvanic corrosion, as well as structural concerns from reduced wall strength.

***Table 4-4***
***California State University Abrasion Results***

| | Effluent | |
|---|---|---|
| | pH = 4.0 w/ abrasives | pH = 7.0 w/ abrasives |
| 12” Polyethylene | 0.021” (0.53mm) | 0.023” (0.58mm) |
| 12” Non-reinforced Concrete | 0.80” (20.3mm) | 1.52” (38.6mm) |

NOTE: None of the aforementioned tests in this section are intended to determine the life of any drainage pipe. In all cases, the tests simulated extremely harsh environments on a constant basis. It would be in error to extrapolate any wear rates presented, compare them with the pipe wall thickness, and then assign a life to the pipe in a typical drainage application.

These test results are intended to provide guidelines to compare the relative durability of some of the most popular drainage materials on the market today. Product life is dependent on many factors including wall thickness and exact material composition; size, shape, frequency, and velocity of abrasives; soil and effluent pH and composition; and the ability of the soil, effluent, and pipe to support galvanic corrosion.

The life of some of these materials can be improved by the addition of liners or coatings to reduce the effects of the abrasion or corrosion on the base material.

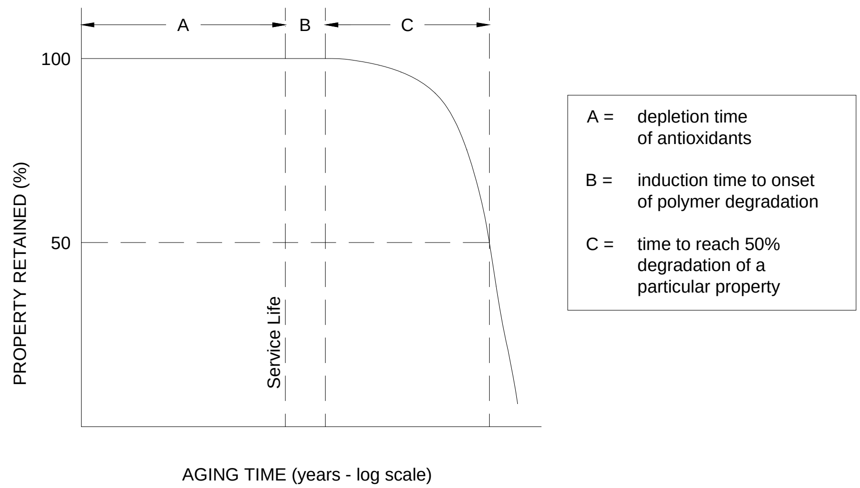
Further complicating the process of calculating the service life of materials is determining when the pipe is rated as "failed." Understanding the failure mode and the associated structural, hydraulic, and durability issues created at the failure point is as important as understanding the life of the product itself.

# OXIDATION

Oxidation is the process by which a polymer, such as polyethylene or polypropylene, first absorbs energy through heat, UV exposure or other methods. This first step in the reaction excites polymer molecules and creates radicals within the material. These radicals react with oxygen causing more radicals to form. Where oxidation occurs, the material can become more susceptible to stress cracking as the material molecular weight decreases causing the material to become more brittle or soften. As stated by Tisinger and Giroud[7], oxidation will continue until the radicals interact with antioxidants, recombine, or when the energy source is removed.

Oxidation of polymers has been studied for a number of years through the gas pipe, geomembrane, and hot water pressure pipe industries. The result of this work, shown in Figure 4-2, clearly shows the onset of the mechanical property degradation is well beyond the design life of the product where an appropriate antioxidant and good stress crack resistance is present.

***Figure 4-2***
***Oxidation Cycle***




Source: Hsuan[1] (2003)

# 4-4 OTHER DURABILITY CONDITIONS

## SUB-ZERO CONDITIONS

Bitter cold conditions can make some plastic drainage products brittle. This results in difficult installations due to the precautions that must be taken to avoid damaging the pipe. This is particularly true of PVC which can become extremely brittle in freezing and sub-zero conditions. The difference between HDPE and PVC in sub-zero conditions is exemplified by the impact testing requirements of the two materials in their respective ASTM standard specifications. Section 7.7 of ASTM F2306 for HDPE requires an HDPE specimen to pass an impact test after being conditioned to a temperature of $4^o \pm 2^o$ C. Section 11.5 of ASTM D1784 for PVC requires a similar impact test, but with no low-temperature requirement.

While polypropylene can withstand temperatures slightly below freezing, to avoid susceptibility to cracking, the working temperature should not fall below $0^o$F (-17 C). The minimum working temperature of polyethylene is around $-40^o$F (-40 C).

While, polyethylene can endure continuous freezing temperatures without brittleness or any additional precautions in the installation, caution should be used when working with PVC or polypropylene at low temperatures. Metals and concrete are not affected by cold conditions.

## HIGH TEMPERATURE

The combination of direct sunlight and high ambient temperatures can cause black polyethylene to absorb heat, although generally not to the extent that will affect installation or performance of the pipe. Generally, the maximum working temperature for both polyethylene and polypropylene pipe is $140^o$F ($60^o$C), but is also dependent on the chemicals in the liquid carried. For any plastic, an increase in temperature reduces stiffness; a decrease in temperature increases stiffness.

A test was conducted in 1992 to determine the impact of high temperature on polyethylene pipe. The test, conducted during a clear day with temperatures in the low 80 degrees F (mid 20 C), involved putting a salamander space heater into a 36-inch (900mm) diameter smooth interior polyethylene pipe and raising the temperature of the outside of the pipe to 140° F ($60^o$C). The pipe was then backfilled and compacted to approximately 95% standard Proctor density to the top of the pipe. The heater was then turned off and seven feet (2.1m) of loose clay soil was added. The measured vertical deflection increased 4% immediately after the backfill operation and then decreased 1% from that value after the load was placed. This test represents an extreme condition, but nonetheless validates that high temperatures do not significantly affect the handling or installation of polyethylene pipe. As the pipe cools to the temperature of its soil environment, the original stiffness characteristics will return.

The coefficient of thermal expansion for polyethylene is $6.5x10^{-5}$ inch/inch length/degree F. Generally, this means the pipe changes 0.078-in per 100-ft length of pipe for each degree F. Polypropylene has a slightly lower coefficient of thermal expansion of $5.0x10^{-5}$ inch/inch length/degree F, with an upper limit value closer to that of polyethylene. The means polypropylene may change 0.06-in per 100-ft length of pipe for each degree F, or more. While the two materials have comparable expansion coefficients, the light grey color of ADS HP polypropylene pipe will have lower light absorption (thus lower heat conversion) when exposed to sunlight compared to black polyethylene.

Where there is a large temperature differential between the pipe and the installed condition, such as pipe stored on the ground in full sunlight then immediately placed in a trench and backfilled, lateral movement from thermal contraction is restrained by the backfill. This lateral restraint can result in impacting longitudinal stresses in the pipe wall. Additionally, if shrinkage were to occur in a longitudinal direction, the result could be joints opening as the pipe cools. Due to the coefficient of thermal expansion for polyethylene and polypropylene, precautions against longitudinal shrinkage should be taken in applications where there is an extreme temperature differential between the pipe and the surrounding conditions. This is especially critical in above-ground installations.

ADS Triple Wall small diameter product has a titanium dioxide additive to make the exterior of the pipe white in color. By reflecting much of the solar heat, extreme temperature differentials within the pipe wall and around the circumference are eliminated. Maintaining consistent temperatures eliminates warping of the pipe during storage at the job site. Titanium dioxide is especially important to prevent warping in the more rigid long lengths of Triple Wall, but it also protects these products from exposure to ultraviolet radiation, discussed further in the following material.

## ULTRAVIOLET RADIATION

A certain segment of the sunlight spectrum, ultraviolet (UV) radiation, can cause unprotected plastic materials to degrade over time. In an effort to reduce these effects, ADS incorporates a high quality UV stabilizer and antioxidant package into all polyethylene and polypropylene products to protect any portion that is exposed to the sun. In polyethylene, a minimum content of 2% carbon black is required by ASTM D3350 for weather resistant grades. Carbon black is an excellent UV stabilizer and has a proven track record in the telecommunications and automobile industries. Polypropylene products incorporate an outdoor, weatherable pigment system plus a Hindered Amine Light Stabilizer, or HALS, to produce a pipe resistant to UV radiation over the life of the product. Ongoing testing being conducted in Florida, Arizona, and Ohio, shows no degradation in physical or rheological properties of the pipe after a year of direct exposure to sunlight. Titanium dioxide is added to ADS Triple Wall products to both protect the pipe from UV radiation and reflect sunlight to maintain a consistent temperature.

With the UV stabilizers incorporated into polyethylene and polypropylene, the radiation can only penetrate a thin layer into the pipe wall over the service life of the pipe. The amount of additive protects the pipe from UV damage for typical on-site storage periods in addition to the inventory storage time accounted for at the factory. It is important to understand that once the outer layer has been faded by the sun, it functions as a shield to protect the rest of the pipe from further degradation. A high percentage of the pipe's original strength properties remain intact because the majority of the wall remains unharmed. Thus, even the exposed ends of large diameter culverts remain structurally sound.

All thermoplastics, including PVC, are likewise affected by ultraviolet radiation. Metals and concrete pipes are not affected.

It is also important to realize that UV is only an issue during the time the pipe is exposed to sunlight. Following installation, UV radiation is no longer an issue for any thermoplastic product.

## ANIMAL ATTACK

Neither polyethylene nor polypropylene attracts or act as a nutrient for animals. As with any pipe material, rodents will gnaw through pipe if it acts as a barrier to food or water, but the occurrence is rare. Currently, no known microbes attack polyethylene or polypropylene.

## FLAMMABILITY

While the risk of fire occurring in storm or sanitary sewer pipe systems is very limited, there are applications involving culverts or outfall structures where fire may potentially occur. In these applications where fire does occur, nearly all pipe materials can be affected under the right conditions. The National Fire Protection Association (NFPA 704) has given both polyethylene and polypropylene a rating of 1 (Slow Burning) on a scale of 0 to 4, where higher ratings indicate a greater vulnerability. A report published by the Florida Department of Transportation entitled *High Density Polyethylene Pipe Fire Risk Evaluations* states "HDPE pipe is not at significant risk of fire when installed to present standards and exposed to fire such as that may be encountered in roadside grass fires".

The natural gas industry has utilized polyethylene pipe, in diameters up to 18 in., for more than 30 years without reported problems. Polypropylene is commonly used for cold and hot water distribution lines, among other uses, and has seen growing use internationally for years. For areas where flammability is of extra concern, all pipe materials can be protected with the use of inflammable end treatments such as the use of Rip-rap, gravel, or concrete headwalls around exposed ends.

# 4-5 FOOTNOTES

[1]Hsuan, Grace (2003). *"Laboratory Tests to Evaluate Crack Free Service Life of HDPE Corrugated Pipes."* Florida DOT Materials Report.

[2]Kurdziel, John M., P.E. and Palermo, Eugene F., PhD., *"Stress Crack Resistance of Structural Members in Corrugated High Density Polyethylene Pipe,"( Transporation Research Board, 2007).*

[3]Haas, D.B. and Smith, L.G., *Erosion Studies*, Saskatchewan Research Council, E75-7, Sept. 1975.

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