Executive Summary

Literature Review

Impact of Gasoline Blended with Ethanol on the Long-Term Structural Integrity of Liquid Petroleum Storage Systems and Components

JUNE 2002

API
American Petroleum Institute

EXECUTIVE SUMMARY

Literature Review

Impact of Gasoline Blended with Ethanol on the Long-Term Structural Integrity of Liquid Petroleum Storage Systems and Components

sponsored by

American Petroleum Institute
Washington, DC

Fiberglass Tank and Pipe Institute
Houston, Texas

Steel Tank Institute
Lake Zurich, Illinois

Western States Petroleum Association
Glendale, California

prepared by

Simpson Gumpertz & Heger Inc.
297 Broadway
Arlington, Massachusetts 02474
Tel.: 781-643-2000
Fax: 781-643-2009

Comm. 20667 June 2002

SPECIAL NOTES

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

API is not undertaking to meet the duties of employers, manufacturers, or suppliers to warn and properly train and equip their employees, and others exposed, concerning health and safety risks and precautions, nor undertaking their obligations under local, state, or federal laws.

Information concerning safety and health risks and proper precautions with respect to particular materials and conditions should be obtained from the employer, the manufacturer or supplier of that material, or the material safety data sheet.

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. Sometimes a one-time extension of up to two years will be added to this review cycle. This publication will no longer be in effect five years after its publication date as an operative API standard or, where an extension has been granted, upon republication. Status of the publication can be ascertained from the API Standards department telephone (202) 682-8000. A catalog of API publications, programs and services is published annually and updated biannually by API, and available through Global Engineering Documents, 15 Inverness Way East, M/S C303B, Englewood, CO 80112-5776.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this standard or comments and questions concerning the procedures under which this standard was developed should be directed in writing to the Director of the Standards department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005. Requests for permission to reproduce or translate all or any part of the material published herein should be addressed to the Director, Business Services.

API standards are published to facilitate the broad availability of proven, sound engineering and operating practices. These standards are not intended to obviate the need for applying sound engineering judgment regarding when and where these standards should be utilized. The formulation and publication of API standards is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

FOREWORD

The contents and findings of this document and its supporting research are the work of an independent contractor and do not necessarily reflect the views of API. API does not warrant the accuracy or validity of findings or supporting research contained in this document, and disclaims any liability for reliance thereon.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any federal, state, or municipal regulation with which this publication may conflict.

Suggested revisions are invited and should be submitted to API, Standards department, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

Table of Contents

CONTENTS **Page**

1. INTRODUCTION

This report summarizes the results of a literature review conducted for the American Petroleum Institute on the impact of gasoline blended with ethanol on the long-term structural integrity of liquid petroleum storage systems and components.

It is anticipated that the use of ethanol in motor fuels will continue to increase. This has generated interest about the potential long-term structural effects of ethanol on liquid petroleum storage systems, including underground storage tanks (USTs), underground piping, and associated components.

The objective of the literature review is to determine the state of industry knowledge and research on the effects of ethanol/gasoline blends on the long-term structural integrity of UST systems and components. This review is intended to assist decision-makers on further research requirements and needed changes or supplements to existing standards for underground storage systems and components used for storing and dispensing gasoline blended with ethanol.

2. LITERATURE REVIEW

Attached in Appendix A are the synopsis' and bibliographic information for all articles reviewed for the project. The report is organized by article index numbers. Reference numbers cited in this report refer to the article index number.

3. FINDINGS

3.1 Overview of Ethanol in Gasoline Fuel

Ethanol is an alcohol produced through the fermentation of biomass, typically corn, although other sources may be used. Ethanol containing some water is called "hydrated"; ethanol that is further processed to remove all water is called "anhydrous". As a fuel oxygenate, ethanol is blended with gasoline to increase the oxygen content of the fuel. The resulting mixture is typically a blend of 10% ethanol and 90% gasoline, conventionally termed "gasohol," although other mix proportions have been used. Ethanol is also used as a volume extender and octane enhancer in gasoline fuels. The term "ethanol fuel" refers to the use of ethanol as the primary energy containing substance. Storage systems may be called upon to store any concentration of ethanol. Therefore, while focusing on gasohol, this literature search examines all ethanol blends. Furthermore, studies pertaining to higher concentrations of ethanol are relevant when examining effects of the lower layer of a phase-separated ethanol/gasoline blend.

Methanol, an alcohol produced from natural gas, is also used as an oxygenate or fuel substitute. It has been suggested that methanol studies may be indicative of worst case limits for ethanol compatibility; however, this has not been proven for all materials. Multiple sources indicate that methanol is much more aggressive than ethanol to materials used in fuel storage (49, 97, 130).

Ethanol has been used as an oxygenate in the Midwest for over 20 years (239). Relatively few material compatibility problems have been reported with the use of 10% ethanol blends (56) and no recorded major leak or failure has been directly attributed to ethanol use (248). The most often reported problems are swelling, hardening, or minor leakage of elastomeric seals and o-rings (66). Notwithstanding this experience, there is interest to determine the long-term effects of exposure of storage system materials to ethanol/gasoline blends and to determine if there are legitimate concerns about possible leaks in the system due to shrinkage and cracking of seals and o-rings in dispensing equipment in systems that are switched from ethanol service to non-ethanol service.

3.2 Phase Separation and Water Bottoms

Water and gasoline are immiscible, and phase separation will result from almost any quantity of water in gasoline, separating into water and gasoline layers. The lower water phase is termed “water bottom” in fuel tanks. Unlike gasoline, alcohol is a polar molecule and will therefore mix readily with water, up to various levels of saturation depending on other soluble and suspended components in the mixture. Alcohol is also miscible with gasoline but has a higher affinity to water than to gasoline and will adhere preferentially to the water. If sufficient water is present, the ethanol and water will separate from the gasoline. This process is called phase separation and will occur at approximately 0.5% water content for 10% ethanol / 90% gasoline blends (58, 106). The blend separates into an alcohol/water lower phase (water phase) and an upper phase consisting of gasoline with a slightly reduced alcohol concentration (hydrocarbon phase) (186). No study reports the exact composition of each phase, but one paper states that the lower layer consists of 75% ethanol, cosolvents, and 25% water (124, 135).

Phase separation is a concern because it creates an alcohol rich water bottom, which can increase the potential for localized corrosion of steel tank walls (50, 124). Higher corrosivity has been attributed to increased oxygen content and increased conductivity of the ethanol/water phase (50, 73, 135). No test data are available to quantify the change in the conductivity and associated corrosion rate in alcohol-rich water bottoms. Other effects include the dissolution of corrosion by-products by the alcohol (55, 56, 58), thus exposing the metal to continued corrosive activity, and the presence of other fuel components in the ethanol/water phases (such as acetic acid) that accelerate corrosion rates (161). Conversely, one study indicates that alcohol-rich water bottoms are no more corrosive than non-alcohol water bottoms (55). However, the study did not include the effects of impurities in the solution. The higher alcohol content in water bottoms may be locally detrimental to FRP tank walls that are qualified only for low alcohol blends; however, no such problems have been reported or evaluated in the literature.

In order to reduce the likelihood of phase separation, efforts must be taken to avoid water infiltration into systems containing ethanol/gasoline blends (44). Tanks should be free of water prior to initial filling and all precautions should be taken to minimize the potential for water infiltration and condensation in the tank (58). Removal of the water layer is recommended by API (132). Manual and automatic methods are available to detect the presence of a water phase in buried tanks (177).

One article suggests that the presence of ethanol reduces the likelihood of water bottoms by maintaining the water in solution (295). The dissolved water is carried out of the system with fuel consumption. This mechanism relies on small quantities of water entry as required by current specifications such that the water quantity does not exceed the threshold for phase separation.

Microbial growth in storage tanks can be fostered by water bottoms (177, 243). Microbial contamination can affect both certain metallic and non-metallic materials. Microbes, both bacterial and fungal, can enter a storage system through fuel transfers, vents, and equipment and can grow wherever water is present, for example at the fuel/water interface in water-bottoms and on the upper walls and ceilings of tanks where condensation is prevalent.

Microbial growth can be controlled through cleaning and use of biocides (254, 243). Existing literature suggests that ethanol may increase the occurrence of microbial attack, but provide no specifics on the extent of reported increase (243).

3.3 Fiberglass Reinforced Plastic (FRP) Tanks

FRP tank laminates are composites of thermosetting resins and glass fibers. Some thermosetting resins (e.g. orthophthalics) do not perform well in alcohols and alcohol fuels (20, 201), and are not known to have been used for this service. Resins typically used in FRP tanks (e.g. isophthalics, terephthalics, and vinyl esters) exhibit some level of swelling (with weight gain) and softening when exposed to alcohols, including ethanol (20, 50, 56). Methanol produces more pronounced effects than ethanol (148), and ethanol/gasoline mixtures may be more aggressive than pure ethanol (20, 50). Softening can be measured as reduction in hardness and material stiffness, which can be measured by mechanical tests for Barcol surface hardness and modulus of elasticity. These physical changes are a function of permeation, which can be measured by absorption and swelling tests, and are largely reversible if the laminate is allowed to dry (18, 22, 24). After desorption of alcohol, some permanent loss of mechanical properties may occur, but the mechanism is not well defined (22). Reduced stiffness, along with creep, results in a lower resistance to buckling, a key design criterion for FRP tanks. This behavior may affect the adequacy of safety factors for buckling design of FRP tanks exposed to ethanol/gasoline blends (50).

The U.S. standard governing the manufacturer of FRP underground storage tanks (UST) is Underwriters Laboratories (UL) 1316 “Glass-Fiber-Reinforced Plastic Underground Storage Tanks for Petroleum Products, Alcohols, and Alcohol-Gasoline Mixtures” (107). The standard was first published in 1983. Since 1987 this standard has required long term (180 days) immersion tests on FRP tank laminates in ethanol and ethanol/gasoline blends for tanks intended for that service. Prior to the 1987 edition, the standard did not require testing for ethanol or other alcohol exposure. The current standard does not require tanks intended for petroleum products only to be tested for alcohol immersion. For tanks intended for ethanol/fuel mixtures, after high-temperature, double-sided exposure of test specimens, the material must retain 50% of its short-term flexural strength and stiffness, and impact resistance when test results are extrapolated to 270 days (107).

UL 1316 does not examine creep, creep buckling or creep rupture. Creep buckling is a gradual increase in the amplitude of buckles with time, and is a function of both the stiffness of the FRP laminate and the resistance to deformation provided by the soil envelope around the tank. Currently, there are no published data on creep buckling of FRP underground tanks, and only limited data on creep rupture of FRP laminates (32).

Major manufacturers of FRP USTs currently provide warranties for single-wall tanks used for storage of gasohol (10%ethanol/90%gasoline blends) and other blends up to 10% ethanol, and some manufacturers warrant double-wall tanks for higher ethanol concentrations (60, 61, 258, 259, 260, 261, 262). At least one tank manufacturer provided a similar gasohol warranty as early as 1981 (262), and has since stated that pre-1981 tanks should perform equally as well as later tanks when used to store 10% ethanol blends (264, 109). Another manufacturer has stated that resin types have not changed since the inception of its tanks and that tanks were qualified for gasohol storage as early as 1980 (60). However, since ethanol immersion testing was not required by UL 1316 prior to 1987, the literature does not indicate how these earlier tank laminates were qualified by manufacturers for ethanol exposure. One recent state governmental advisory suggests that manufacturers began testing tank laminates for ethanol exposure in 1984 and advises users to obtain compatibility performance information for tanks manufactured prior to this date before converting tanks to ethanol storage (52). Lack of documentation of industry experience has raised the issue about the susceptibility of FRP tanks to ethanol attack (112) and led to the US Department of Energy's recommendation to install a chemical-grade rubber lining in FRP tanks prior to ethanol fuel use (130). However, the Department of Energy's basis for this requirement did not examine specific resins and therefore is too broad to apply to all FRP tanks.

Tests conducted in 1992 on certain resin types found that isophthalic resins tested did not meet UL 1316 requirements when immersed in 30% ethanol blends (24). A 1986 study, showed, based on retention of short-term strength and stiffness properties, that "older" tank laminates perform adequately in 10% ethanol blends, but not as well in 20% ethanol blends. "Newer" tanks were found to perform adequately in all ethanol blends (148). It is believed that most FRP tanks will perform satisfactorily for storage of gasohol (10% ethanol) (56). Field experience has indicated no adverse effects from gasohol storage (64, 248). However, few analytical or experimental data have been published to show how reduced properties due to ethanol exposure (e.g. softening and stiffness reduction) relate to long-term performance under sustained (creep) loads such as caused by soil and hydrostatic pressure on underground tanks. Stress corrosion cracking (degradation of strength of glass fiber reinforced composites under sustained stress) has been studied in acidic aqueous environments, but no results have been reported for ethanol blended fuels (37).

Creep rupture tests on FRP with E-glass fibers subjected to water indicated a rupture strength after 10,000 hrs. of sustained stress of about 30 to 50% of the short term strength (26). One study showed that ethanol exposure was less severe than water exposure in contributing to creep rupture failure of FRP piping (173). Note that FRP tanks containing ethanol/fuel mixture are exposed to water or brine on their exterior surface, depending on whether they are single or double walled tanks. Properties of FRP laminates change through permeation and swelling and accompanied by a slower process of resin relaxation (38). Caution must be used in analyzing and interpreting results of creep tests (32, 34, 36, 38). Creep properties under full absorption conditions must be analytically distinguished from time dependent deformation associated with the initial absorption, swelling, and softening. Otherwise, incorrect estimates of the creep response will be obtained. This topic is not adequately covered in the literature. In addition, the effects of soil-structure interaction must be accounted for in analyzing creep buckling, especially for the single-walled tanks.

Some studies have focused on absorption tests as a means to gage the effects of liquid immersion on FRP (146, 192). Currently, the relationship between absorption and structural performance has not been addressed adequately.

FRP may be susceptible to degradation from microbial bacteria that grow at the fuel/water interface at water bottoms (219). However, the literature search revealed no occurrences of deleterious effects of microbial degradation in FRP tanks due to the presence of ethanol.

3.4 Steel Tanks

Alcohols do not permeate or react chemically with carbon steel. However, several studies have found that alcohols, including ethanol, can contribute to increased corrosion of steel. As with other materials, ethanol is less aggressive than methanol.

Pure ethanol does not significantly increase the corrosion rate of steel (158, 167, 239), but water, which can be dissolved in the ethanol, can increase the corrosion rate (151, 154, 158, 167). The ability of ethanol to dissolve water increases the conductivity of the fluid and can lead to increased potential for galvanic and electrolytic corrosion, although there is no indication that this poses any significant increase in risk to steel tanks (135, 233, 239). Corrosion of steel in ethanol blends is highest in single-phase blends with 20% ethanol (150) and in the mixture of water and alcohol present in the water phase of a separated blend (167).

Corrosion has been found to occur in phase-separated blends in the water-alcohol layer. A phase-separated mixture in a steel tank will result in an increased initial rate of corrosion decreasing to zero over time. Corrosion of steel in the water-alcohol layer tapered off and stopped in stationary (55) and refilling (167) immersion tests, suggesting the creation of a passivating film. Corrosion may actually be less severe in phase-separated ethanol blends than it is in water layers at the bottom of gasoline tanks containing no ethanol (55,167). Water-bottoms of gasoline fuels can be created through any addition of water to the system. Water can dissolve gasoline contaminants, such as salts and acid residues, and thereby increase the corrosivity of the water-bottom (161). Furthermore, detergents and corrosion inhibitors may be preferentially attracted to one of the phases, rendering them useless in the other (135).

Chloride ions, water, acids, bases, and other contaminants can significantly increase corrosion of metals exposed to ethanol and ethanol blends (50, 161). Chloride ions are the most corrosive of these contaminants, but a combination of all of these contaminants provided a significantly higher corrosion rate than a single contaminant (42). Corrosion inhibitors are recommended and employed for limiting corrosion of steel exposed to ethanol blends (42, 133, 297).

Increasing concentrations of acetic acid, which forms from acetaldehyde by oxidation of ethanol, increases the corrosion rate of steel (154). Other studies report the acid-corrosion link (152,158).

Stress corrosion cracking (SCC) and environmental stress cracking (ESC) may be affected by the influence of alcohol, but no studies were found that relate SCC or ESC to damage of carbon or other steels in normal temperature ethanol environments (159, 50). This literature search did not find evidence of any stress corrosion cracking or environmental stress cracking of UST systems as a result of ethanol use.

Oxygenates, including ethanol, may encourage microbial growth, and thus microbial corrosion, in steel tanks, however there is no definitive research linking ethanol to increased corrosion in steel tanks (243, 244). Microbial induced corrosion results from the depassivation of the steel surface (220, 254). Microbes can also create a biofilm that enhances electrolytic corrosion. Further, microbes can generate acids that can involve hydrogen in the corrosion process and cause hydrogen embrittlement of steel (220). The significance of these effects has not been determined. Periodic removal of accumulated water in tanks is recommended to minimize microbial growth (243), and API recommends the immediate removal of any water bottom in ethanol blends (132). Tanks can be inspected for slime films indicative of microbial presence and biocide additives may be useful in controlling microbial growth (184, 242, 243).

3.5 Coatings/Linings

Protective coatings and linings can be used on both FRP and steel tanks. Coatings can also be used on piping. Thermoset resins qualified for use in FRP tanks storing ethanol/gasoline blends (e.g. isophthalic polyesters and vinyl esters) are suitable for use as coatings and linings (18, 20). As for FRP tanks, compatibility must be tested for the intended concentration of ethanol since some resins may not be suitable for concentrations higher than 10% ethanol (239). The effects of resin softening and reduction of mechanical properties must be considered in assessing structural performance of coatings (22). Polymer coatings may also be subject to microbial attack. (219). Electrochemical studies have shown that some vinyl ester coatings offer better resistance than others to water bottom conditions in steel tanks (8). Urethane and ethylene acrylic acid polymer have been successfully used as coating material in various applications (50) and many newer formulations of internal coatings are compatible with ethanol blends (239). Polyester resin and Polyvinylidene Fluoride (PVDF) barrier layers have been shown to reduce permeability of ethanol blended fuels in automotive fuel lines (227).

Gasohol has been found to be incompatible with certain epoxy coatings (50). Older steel tanks internally lined with a general purpose lining materials may not be suitable for storage of ethanol blends (52, 239).

Various metal coatings for automotive fuel tanks were tested and exhibited variable compatibility with water and ethanol mixtures (230).

3.6 Piping

Piping materials used in petroleum storage and distribution systems include FRP, steel, and thermoplastics. Pipe failures are responsible for more petroleum releases than underground tanks (232). Research findings discussed above for FRP tanks, steel tanks, and coatings and linings apply similarly to like materials used in piping for fuel storage systems. Other materials used in fuel piping and in other parts of the storage system, including elastomers and thermoplastics are discussed in subsequent sections of this report.

In the U.S., FRP and other plastic piping are governed by UL 971 Nonmetallic Underground Piping for Flammable Liquids (165). This standard was issued in 1997 as the first edition; however, a preface notes that the standard is substantially in accordance with a 1995 bulletin on the subject. Tests required by UL 971 include immersion in different fuels, including alcohol and alcohol/fuel blends, for up to 270 days. Similar to the FRP tank standard, the material must retain 50% of its mechanical properties after 270 days. UL 971 also requires permeability testing. Permeability limits for both primary and secondary pipe are listed. No research data was found to support the limits. Underwriters Laboratory Canada's (ULC.ORD-C107.19-1992) "Secondary Containment of Underground Piping for Flammable and Combustible Liquids" requires immersion in liquids representative of service conditions and includes alcohols, but does not include blends explicitly (144). The ULC requires 70% retention of properties after immersion for 180 days. It is not clear how non-metallic piping was qualified for ethanol and ethanol/gasoline blends prior to the issuance of these standards. One governmental advisory advises users to obtain ethanol compatibility performance information for single wall piping manufactured prior to 1984 (52).

Fuel line piping for automotive use is extensively studied, primarily with respect to permeation, and new EPA requirements. In general Nylon 12 will not meet these new requirements due to excessive permeation, but multiple means of resolving this problem have been found, including barrier layers of polyester, Polyvinylidene Fluoride (PVDF), or Ethylene Tetrafluoroethylene (ETFE). (82, 227, 228).

Warranties for secondary containment piping (FRP, high density polyethylene, and urethane) cover only limited (less than 72 hours) exposure to fuel (239).

Piping, flexible or otherwise, requires joints, which are typically secured with adhesive. This adhesive may be incompatible with ethanol if the adhesive was not properly mixed and cured (239).

Corrosion of metals in storage systems may be more severe in the vapor recovery and secondary containment systems due to the presence of oxygen and an inability to guarantee the presence of a corrosion inhibitor in these systems (75).

3.7 Other Components

Liquid storage systems contain numerous other material components that may be affected by ethanol exposure. Research tests and experiential data on ethanol compatibility have been reported for many of these materials and have led to the changeover to more compatible materials in storage systems converted to ethanol service (66).

Alcohol blends are excellent solvents and have the ability to loosen rust, scale, gums, and other deposits. This can lead to increased rate of filter fouling and may increase wear by the suspended particles (239). Consequently, before a system is switched to ethanol blend service, it should be thoroughly cleaned (44, 56). The system should also be fully dried to avoid the addition of water to the fuel (56, 132). Filters should be checked frequently during the first usage and changed as required (56).

Elastomers are commonly used in seals and gaskets in petroleum storage systems. Elastomers not intended for use with ethanol blends may swell, shrink, tear, or allow an unacceptable amount of permeation. Elastomers are subject to extraction of the plasticizer, resulting in shrinkage, which may be masked by swelling effects. Embrittlement, cracking, and shrinkage can result in leakage especially when the elastomeric seals and o-rings are no longer exposed to ethanol and the associated swelling subsides (50). Elastomers are subject to increased permeability with alcohol-blended fuels (135). Elastomers are available which are resistant to ethanol blends, and barrier technologies are available that effectively protect the elastomer from contact with ethanol, reducing permeability. Material compatibility information for elastomeric materials is available from several sources (50, 81, 86, 102, 132).

Buna-N seals, used in submersible pumps in the U.S. have failed when they were used in higher oxygenate fuel. This problem is unlikely to occur or be as severe with more recently produced Buna-N products (73). Elastomers used in automobiles before 1975 are susceptible to incompatibilities, but those used more recently will have few problems. In 1992, gasohol was introduced into 39 metro areas, with no problems (124).

Some pipe dope is alcohol based and may therefore wash out if not properly dried, but is generally acceptable if properly installed (50). Cork and natural rubber are incompatible with ethanol blends (130). Teflon, fluorocarbons, fluorosilicones are compatible (133).

Pumps and other moving parts may be subject to increased corrosive wear (150) and loss of lubrication (135).

Cast iron pump rotors have rusted into place in only a week of service of ethanol with 7% water when periodically exposed to air. The rotors were designed and tested for continuous submergence in ethanol with 7% water. The introduction of air into the system allowed corrosion to occur (73). These tests were conducted in Brazil using ethanol with high water content, which may not be representative of ethanol fuels and fuel blends sold in the U.S.

In one study, lead, zinc, and brass have been found to have increased corrosion rates with high alcohol concentration fuels (130). Stainless steel, and bronze are considered compatible with ethanol and ethanol blends (132). Most carbon steels are compatible with ethanol (132), but corrosion of carbon steels in ethanol solutions increase with high oxygen content (73) and contaminants (50, 161). Some studies show aluminum to be compatible with ethanol blends (132) while others suggest increased corrosion rates (73).

The American Automobiles Manufacturers Association recommends “soak testing” followed by electrical conductivity, chemical stability and filter tests to determine compatibility of metals with ethanol fuels (130). Conductivity tests are also recommended in the field. High conductivity can indicate metal contaminates in the fuel because of corrosion, and can result in higher rates of galvanic corrosion.

Permeation through some non-metallic materials increases with the addition of ethanol to gasoline. Permeation rates in ethanol have been found to be lower than in methanol (97). For untreated high-density polyethylene (HDPE), the permeation rate is highest for 10 to 30% alcohol, with higher permeation rate for pure gasoline than for ethanol alone (97). Barrier technologies intended to reduce the permeation rate of HDPE have been found effective for gasoline service and less so for ethanol blends (97). Interior linings and other asymmetric barriers may provide resistance to swelling and loss of structural properties due to ethanol exposure, but asymmetric testing would be necessary to confirm this.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary of Findings

Following summarizes the significant findings of this literature review:

- Gasohol has been used as a motor vehicle fuel for over 20 years with relatively few reported compatibility problems with materials used in fuel storage systems. The predominant problems reported have been swelling and minor leakage of incompatible elastomer seals and o-rings. Nevertheless, compatibility issues have not been fully investigated and little is published about the long-term performance of materials exposed to ethanol/gasoline fuels.

- Water bottoms occur in all gasoline storage tanks when water contamination separates from the gasoline and collects at the bottom of the tank. The water layer increases the potential for localized corrosion of steel tanks. In ethanol/gasoline fuels, ethanol mixes with the any water that enters the system. At certain water concentrations, for example a 0.5% water to gasohol ratio), the water/ethanol mixture “phase separates” from the fuel to form an alcohol rich water bottom. Water bottoms caused by phase separation in ethanol/gasoline fuels can be controlled by following current recommendations to prevent entry of water into the system and by monitoring for and removing the water bottom when it forms.

- Some studies suggest that hydrated ethanol may increase corrosion potential of steel by increasing conductivity or dissolving protective layers on the steel surface. Also, dissolved products such as acids may promote increased corrosion activity. Currently, there is no definitive research data showing that ethanol has a significant effect on the long-term performance of steel tanks. Further research may be needed to characterize both the composition and corrosivity of the fuel phase and water phase in steel tanks.

- Microbial growth may be fostered by water bottoms in fuel tanks. Microbial growth may increase corrosion activity in steel tanks and may degrade FRP materials. Ethanol may increase microbial activity but no definitive findings or reported occurrences were found on this subject.

- Ethanol tends to soften FRP and reduce its mechanical stiffness. Immersion tests conducted according to the UL 1316 tank standard qualify FRP tank laminates for ethanol storage based on the retained strength, stiffness, and Isod impact resistance. Most tanks meet the requirements of UL 1316 for the storage of gasohol (10% ethanol content). There is concern that tanks that pre-date the UL testing (i.e. tanks produced prior to the early 1980s) may not be ethanol compatible; however, major tank manufacturers indicate that the tanks are constructed of similar resins and should perform satisfactorily.

- The published literature does not adequately cover the effects of reduced material stiffness due to ethanol storage on the creep buckling strength of FRP tanks. This issue requires further research and/or evaluation of manufacturer test data, analyses, and research findings on the subject.

- Issues of compatibility of gasohol with FRP and steel tanks also apply to FRP and steel piping. No specific studies have been conducted on the compatibility of steel piping. Non-metallic piping is tested for immersion in ethanol blends for the intended service in accordance with UL 971. This testing was standardized beginning in 1995. Compatibility of earlier non-metallic piping materials may have been determined by manufacturers. Manufacturers should be consulted on this issue prior to conversion to ethanol/fuel mixtures.

- Experiential and research data on ethanol compatibility of other components used in fuel storage systems have been developed and published. Some elastomers and sealants have not performed well and must be replaced with more compatible materials when systems are converted to ethanol storage. Moving parts in steel and cast iron pumps have exhibited increased corrosion and corrosive wear in hydrated ethanol service when exposed to air. Some metals other than steel are not compatible, including aluminum, zinc, and magnesium. Manufacturers must be consulted on material compatibility of their products. This suggests the need to develop uniform test standards.

4.2 Possible Research Needs

Published information concerning compatibility and long-term durability of fuel storage materials in ethanol/gasoline blends may not be complete. Further research may be appropriate in several key areas:

Phase Separation and Water Bottoms

- Characterization of the composition of ethanol-rich water bottoms, including ethanol/water content and the presence of contaminants, fuel constituents and by-products.

- Studies on the effects of ethanol-rich water bottoms on the growth of microbial bacteria and the local environments created by such microbes in storage systems.

FRP Tanks

- Standard procedures for compatibility testing of FRP tank laminates that have not been previously qualified for ethanol storage by either third party tests such as UL 1316 or by manufacturers documented in-house tests.

- Experimental and analytical studies on the performance of FRP tanks under sustained loading, accounting for the permeation of ethanol/fuel mixture through the FRP laminate and on its effects on creep, softening, creep buckling, and creep rupture. The effects of fuel exposure on one side of FRP laminates and exposure to water or brine solution on the other side, representative of actual storage conditions should be investigated. Studies should account for the high ethanol content present in water bottoms. Analytical models should include the effects of initial swelling.

Steel Tanks

- Tests to quantify the change in conductivity and thus the increase potential for corrosion of steel exposed to ethanol/gasoline blends.

- Characterization of the corrosivity of water bottoms in steel tanks and the mechanism(s) of corrosion, including the effects of other fuel constituents and byproducts contained within the ethanol/water phase.

Piping

- Compatibility testing of non-metallic piping not previously qualified by third party testing such as UL 971.

- Development of improved barrier layer technology for certain thermoplastic piping materials, to reduce permeability rates and associated effects on long-term structural properties.

- Corrosive wear studies on steel piping subject to ethanol/gasoline blends.

Other Components

- Continue research in the qualification of existing materials and development of new materials for long-term performance in ethanol/gasoline blends, including HDPE in secondary containment applications.

- Study the mechanisms of corrosive wear of steel parts exposed to ethanol/gasoline fuels and methods to mitigate premature material failure.

REFERENCES

1. Wolynec, Stephan, Tanaka, Deniol L., Corrosion in Ethanol Fuel Powered Cars: Problems and Remedies, 1984, National Research Council of Canada.

3. Arnold, J. C., The Influence of Liquid Uptake on Environmental Stress Cracking of Glassy Polymers, 1995, Materials Science and Engineering.

4. Arnold, J. C., Eccott, A. R., The Effects of Physical Ageing and of Prior Immersion on the ESC Behavior of Polycarbonate in Ethanol, 1993, Materials Research Society.

8. Balbyshev, V. N., Bierwagen, G. P., Electrochemical Studies of Vinyl Ester Coatings for Fuel Tanks, 1996, American Chemical Society.

10. Ali, M., Al Beed, A. A., Tank Bottom Corrosion Caused by Inappropriate Construction Practices. In: Corrosion '98 Meeting, San Diego, 1998, National Association of Corrosion Engineers.

12. Shelley, S., Upgrading Underground Storage Tanks, 1997, Chemical Engineering.

13. No author, Steel/FRP (Fiberglass Reinforced Polyester) Tanks Ensure Safe Storage. In: Pollution Engineering, V. 24, p. 83, 1992, Pollution Engineering.

14. Perey, J. F., The Growth of Vinyl-Ester Based GRP (glass fiber reinforced plastic) for Corrosion-Resistance Applications, 1990, Corrosion Prevention and Control.

15. CAMREX, Coatings/CAMREX Launch New Tank Coating, 1988, Shipcare and Maritime Management.

16. Gibbs, L. M., Horn, J. C., Gilbert, B. J., (Contra Costa County, Calif.'s) Three Years Fleet Experience with Gasohol. In: National Petroleum Refiners Association Meeting, San Antonio, 3/25-27/84, 1984, National Petroleum Refiners Association.

17. Pierce, R. J., Marshall, G. L., Effects of Elevated Temperature Exposure to Automotive Fuel Blends of Rigid Thermoplastic Polyurethanes. In: Antec '91, 49th Annual Technical Conference, Montreal 5/1991, Society of Plastics Engineers.

18. Craigie, L. J., White, M. N., Svatek, M. J., Under (sic) Fiberglass Storage Tanks for Motor Fuels Containing High Concentrations of Alcohols: 41st Annual Conference, Reinforced Plastics/ Composites Institute, The Society of the Plastics Industry, Inc., 1986, Reinforced Plastics/ Composites Institute.

20. Burrell, P. P., O'Hearn, T. P., Solvent Resistance of Selected Polyesters and Vinyl Esters, 1982, Reinforced Plastics/ Composites Institute.

22. Hojo, H., Ogasawana, K., Chang, W. L., Tsuda, K., Degradation Behavior of Unsaturated Polyester Resins in Alcohols, 1994, Advanced Composite Materials.

24. Kamody, John F., Damiani, Annemarie, Stadelman, Richard J., The Use of FRP with Alcohol-Containing Fuels, 1992, The Society of the Plastics Industry, Inc..

26. Carswell, S. W., Environmental Effects on Fatigue and Creep Rupture of Glass Reinforced Composites. The Twelfth Annual Energy-Sources Technology Conference and Exhibition, Houston, Texas, ASME, 1989.

28. Pearson, L. E., FRP Underground Storage Tanks - Long-Term Corrosion Resistance for Petroleum Fuels (Experimental Station Bulletin No. 113)., 1974, West Virginia University Engineering.

30. Thomas, W. F., Factors Affecting the Impact Strength of Glass-Fibre-Reinforced Polyester Composites, 1973, Composites.

32. Pritchard, G., Speake, S. D., Effects of Temperature on Stress-Rupture Times in Glass/Polyester Laminates, 1988, Composites.

34. Philips, M.G., Prediction of Long-Term Stress Rupture Life for Glass Fibre Reinforced Polyester Composites in Air and Aqueous Environments. In: Composites 14 No. 3, 1983, Composites.

36. Aveston, J., Kelly, A., Sillwood, J. M., Long Term Strength of Glass Reinforced Plastics in Wet Environments. In: Advances in Composite Materials. Vol. 1 (Proceedings ICCM-3, Paris, France), 1980, Pergamon.

37. Jones, F. R., Rock, J. W., Wheatley, A. P., Stress Corrosion Cracking and its Implications for the Long Term Durability of E-glass Fibre Composites. In: Composites 14 No.3, 1983, Composites.

38. Pritchard, G, Speake, S. D., The Use of Water Absorption Kinetic Data to Predict Laminate Property Changes. In: Composites 18 No 3, 1987, Composites.

39. Murphy, M. J., Ketola, H. N., Raj, P. K., Volpe National Transportation Center, Clean Air Program: Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuel (Final Report), 1995, Advanced Composite Materials.

41. Whitaker, R. B., Brown, C. R., Carlson, R. S., Trainer, P. D., Effects of Solvent Exposures on Poly (Etheretherketone) (PEEK) and PEEK--Fiberglass Composites., 1986, National Technical Information Service (NTIS).

42. Walker, M. S., Chance, R. L., Corrosion of Metals and the Effectiveness of Inhibitors in Ethanol Fuels. In: SAE Automotive Corrosion and Prevention Conference , Dearborn, MI, 1983, Society of Automotive Engineers (SAE).

43. Brytus, V., Advances in Epoxy Resins for Hostile Environments In: National Association of Corrosion Engineers, "Corrosion/87" Meeting, San Francisco, 3-9-13/87, National Association of Corrosion Engineers.

44. Miller, Everett L., Alcohol/Gasoline Blends as Automotive Fuel. In: 1981 AIPE Conference (American Inst. Of Fuel Engineers), Reno, Nev., Oct. 1981, American Institute of Plant Engineers.

46. Wares, Richard, Ferrara, Augusto M., The Performance of Alternate Fuels in General Aviation Aircraft. In: Future Fuels for General Aviation, STP 1048 (ASTM), Strauss, K. H. & C. Gonzalez, eds., 1988, American Society for Testing and Materials (ASTM).

48. Eveleth, Edmund L. "Skip", Ethanol and Methanol in Intermittent Combustion Engines. In: Future Fuels for General Aviation, STP 1048, ASTM, Strauss, K. H and Cesar Gonzalez, eds., 1988, American Society for Testing and Materials (ASTM).

49. Ferrara, Augusto, M., Investigations into Gasoline/Alcohol Blends for Use in General Aviation Aircraft. In: Future Fuels for General Aviation, STP 1048, Strauss, K. H. And Cesar Gonzalez, eds., 1988, American Society for Testing and Materials (ASTM).

50. California State Water Resources Control Board, State Water Resources Control Board's Advisory Panel on the Leak History of New and Upgraded UST Systems: Oxygenate Compatibility and Permeability Report (UST Team 1 Report), 1999.

52. California State Water Resources Control Board, Advisory to Underground Storage Tank Owners/Operators Regarding Ethanol Blend Fuel Compatibility, March 2000, California State Water Resources Control Board.

54. Couch, Kevin, Young, Thomas, Leaking Underground Storage Tanks (USTs) as Point Sources of MTBE to Groundwater and Related MTBE-UST Compatibility Issue, 1998, University of California-Davis.

55. Geyer, Wayne B., Compatibility of Steel with Oxygenated Fuels, Presented at 16th Annual ILTA Conference, 6/10-11/1996, Steel Tank Institute.

56. Archer Daniels Midland Company, Fuel Ethanol as an Octane Booster: Technical Bulletin, 1991, Archer Daniels Midland Company.

57. ICF Inc., Survey of Flexible Piping Systems: March 1997, Petroleum Equipment Institute.

58. Reeder. Carl, Answers to Some of the Most Frequently Asked Questions About Gasoline/Ethanol Blends.

59. Alcohol Blends May Void FRP Warranty In: Tank Talk, Jan/Feb. 1996.

60. Xerxes Corporation, Warranty: Single Wall Underground Petroleum Storage Tank (effective 7/1/91), 1991, Xerxes.

61. Xerxes Corporation, Warranty: Petroleum or Alcohol Fuels Storage Double Wall Underground Petroleum Storage Tank - With Resin Specifies for Expanded Fuels (effective 11/1/91), 1991, Xerxes.

62. Bridgeport Chemical Corporation, Technical Information Bulletin: Specifications - Glass Armor Repair of Gasoline Storage Tanks (Gasohol),"GA27 P Armor Spray" (Gasohol Coating), 1987.

63. Claie, A. L. (The Hinchman Company), Investigation of Internal Corrosion of Steel Fuel Storage Tanks, 1970.

64. Drake, D. E. (Mobil), Gregory, L. R. (Mobil), Hotaling, A. C. (Mobil), Effect of MTBE and Other Oxygenates on FRP Underground Storage Tanks - An Interim Report, 1995, Not Published.

65. Davidson, James M. (Alpine Environmental, Inc), MTBE Compatibility with Underground Storage-Tank Systems, 1997, Western States Petroleum Association.

66. American Petroleum Institute, Effects of Oxygenated Fuels and Reformulated Diesel Fuels on Elastomers and Polymers in Pipeline/Terminal Components: API Publication 1132, 1994, American Petroleum Institute.

69. Davidson, James M., MTBE & UNDERGROUND Storage Tank Systems: A Question of Compatibility. In: LUSTLine Bulletin 28, 1997.

71. SAE Cooperative Research Program, Gasoline/Methanol Mixtures for Materials Testing (SAE Cooperative Research Report), 1990, Society of Automotive Engineers (SAE).

72. Farahnak, Shahla D., Leak Detection: Are Leak Detection Methods Effective in Finding Leaks in UST Systems?: California Survey Uncovers Some Cold, Hard Facts. In: LUSTLine Bulletin 28.

73. Mittermaier, Gene, How New Gasoline Formulas Can Affect Petroleum Equipment. In: Petroleum Equipment & Technology, August 1998, Petroleum Equipment & Technology.

75. EA Mueller Consulting Engineers, An Engineering Analysis of the Effects of Oxygenated Fuels on Marketing Vapor Recovery Equipment (Final Report), 1990.

76. Stevens, R. D., Fuller, R. E., Fuel Permeation Rates of Elastomers after Changing Fuel: SAE Technical Paper Series No. 970307, 1997, Society of Automotive Engineers (SAE).

77. Addeo, A., Raveglia, M., Gasoline Vapors Barrier Process for Plastic Tanks and Testing Methods: SAE Technical Paper Series No. 905184, 1984.

78. McCaulou, Douglas R., Jewett, David G., Huling, Scott G., The Compatibility of Non-Aqueous Phase Liquids and Other Detected Chemical with Remediation, Well Construction, and Sampling Materials (EPA Ground Water Issue), 1995, US Environmental Protection Agency.

79. McCaulou, Douglas R., Jewett, David G., Huling, Scott G., Nonaqueous Phase Liquids Compatibility with Materials Used in Well Construction, Sampling, and Remediation (EPA Ground Water Issue), 1995, US Environmental Protection Agency.

81. Nersasian, A., Use of Toluene/Isooctane/Alcohol Blends to Simulate the Swelling Behavior of Rubbers in Gasoline Alcohol Fuels: SAE Technical Paper Series No. 800790, 1980, Society of Automotive Engineers (SAE).

82. Gray, E. K., Hopf, G., Nylon-12 in the Automotive Fuel System Environment: SAE Technical Paper Series No. 880684, 1988, Society of Automotive Engineers (SAE).

83. Aloisio, Salvatore, Performance of Fluorocarbon Elastomers in MTBE/Fuel Blends: SAE Technical Paper Series No. 940956, 1994, Society of Automotive Engineers (SAE).

84. Yamanishi, H., Watanabi, Y., Takahata, S., Fuel Tube Alternate Fuels: SAE Technical Paper Series No. 932343, 1993, Society of Automotive Engineers (SAE).

85. Naegeli, D. W., Lacy, P. I., Alger, M.J., Endicott, D. L., Surface Corrosion in Ethanol Fuel Pumps: SAE Technical Paper Series No. 971648, 1997, Society of Automotive Engineers (SAE).

86. Alexander, James E., Ferber, Edward P., Stahl, William M., Avoid Leaks from Reformulated Fuels: Choose an Elastometric Sealing Material According to the Type and Concentration of Oxygenate (Ether and/or Alcohol) Added to the Fuel. In: Fuel Reformulation, March/April, 1994.

87. Black, F., An Overview of the Technical Implications of Methanol and Ethanol as Highway Motor Vehicle Fuels: SAE Technical Paper Series No. 912413, 1991, Society of Automotive Engineers (SAE).

88. Alternate Fuels Committee of the Engine Manufactur, A Technical Assessment of Alcohol Fuels: SAE Technical Paper Series No. 820261, 1982, Society of Automotive Engineers (SAE).

89. Smith, G. M., Choose Valves that will not be Affected by Oxygenate Degradation. In: Fuel Reformulation., 1994, Fuel Reformulation.

90. Nerasian, A., The Volume Increase of Fuel Handling Rubbers in Gasoline/Alcohol Blends: SAE Technical Paper Series No. 800789, 1980, Society of Automotive Engineers (SAE).

91. Shell Chemical, CARILON Polymer Fuel Permeation Information Sheets: Permeability of CARILON Thermoplastic Polymer Vs Other Engineering Plastics in Unleaded Gasoline, 1996, Shell Chemical.

92. Acurex Environmental Corporation, Methanol Fuel Station Survey - State of California: Volume 1: Technical Data, 1992, .

93. Dunn, J. R., Pfisterer, H. A., Resistance of NBR-Based Fuel Hose Tube to Fuel-Alcohol Blends: SAE Technical Paper Series No. 800856, 1980, Society of Automotive Engineers (SAE).

94. Geyer, W., How Do Your Tanks Measure Up? Part 1: Underground Storage, 1996, Chemical Engineering.

95. Stahl, W. M., Stevens, R. D., Fuel-Alcohol Permeation Rates of Fluoroelastomers, Fluoroplastics and Other Fuel Resistant Materials, 1992, Society of Automotive Engineers (SAE).

97. Kathios, Daniel J., Ziff, Robert M., Petrulis, Algis A., Bonczyk, John C., Permeation of Gasoline-Alcohol Fuel Blends through High-Density Polyethylene Fuel Tanks with Different Barrier Technologies: SAE Technical Paper 920164, 1998, Society of Automotive Engineers (SAE).

98. Kampouris, E. M., Regas, F., Polychronakis, S., Migration of PVC Plasticizers into Alcohols : In Polymer 16 (1975), pp. 840-844, 1975, Polymer.

99. Miller, R. F., Rider, P. E., The Hostile Effects of Oxygenated Solvent Interaction with Type II Rigid Poly (vinyl chloride). In: ACS Symposium Series, 229, pp. 193-203, 1983, American Chemical Society.

100. Puisais, M., Mollard, M., Dawans, F., The Behavior of Organic Materials with Regard to Oxygenated Fuels. In: Revue De L'Institut Francais De Petrol, 40, pp. 819-830, 1985, Revue De L'Institut Francais Du Petrol.

101. Abu-Isa, I. A., Effects of Ethanol/Gasoline and Methyl T-Butyl Ether/Gasoline Mixtures on Elastomers. In: Rubber Chemistry and Technology, 51(169), 1983, Rubber Chemistry and Technology.

102. Nerasian, A., Compatibility of Fuel Handling Rubbers with Gasoline/Alcohol Blends. In: Elastomerics, 26 October 1980, Elastomerics.

103. Alexander, J. E., Ferber, E. P., Stahl, W. M., Leak Prevention and Seal Longevity for Containment of Oxygenated and Reformulated Fuels. In: AICHE Spring Meeting, Houston, TX, 1995, American Institute of Chemical Engineers (AICHE).

104. DeSouza, J. P., Mattos, O. R., Sathler, L., Impedance Measurements of Corroding Mild Steel in and Automotive Fuel Ethanol With and Without Inhibitor in a Two and Three Electrode Cell. In: Corrosion Science, 27, pp. 1351-1364, 1987, Corrosion Science.

105. Nakajima, K., Yahagi, Y., Corrosive Wear of Steel with Gasoline-Ethanol-Water. In: Transactions of the ASME, 105, pp.552-558, 1983, American Society of Mechanical Engineers (ASME).

106. Thring, R. H., Another Look at Alternative Fuels. In: Automotive Engineering, 92, pp. 60-64, 1984, Automotive Engineering.

107. Underwriters Laboratories Inc., UL 1316, Second Edition "Glass-Fiber-Reinforced Plastic Underground Storage Tanks for Petroleum Products, Alcohols, and Alcohol-Gasoline Mixtures", 1996, Underwriters Laboratories Inc..

109. O/C Tanks Corporation, Mance, Andrew A., Letter Re: Fiberglas Tank Compatibility, 1992, Not Published.

112. Alexander, J. E., Ferber, E. P., Stahl, W. M., Leak Prevention of Reformulated Fuels and Oxygenates. In: First International Pipeline Corrosion Conference, Houston, 10/17-20/1994.

115. Curran, Sullivan D., Permeability of Synthetic Membranes for the Containment of Petroleum Products. (from web site: www.fiberglasstankandpipe.com), 1999, Fiberglass Tank & Pipe Institute.

116. US Environmental Protection Agency, 40 CFR 280 (sections 11, 12. 32): Technical Standards and Corrective Action Requirements for Owners and Operators of Underground Storage Tanks (UST), US Environmental Protection Agency.

119. Geyer, Wayne B., New Underground Understandings as EPA's 1998 Compliance Deadline Approaches, UST Managers and Manufacturers Address Evolving Issues (from website), 1998, Steel Tank Institute.

122. Oxygenated Fuels Association (OFA), State Winter Oxygenated Fuels Programs, September 28, 1998 (from Oxygenated Fuels Association website - www.ofa.net).

123. Health Effects Institute, Program Summary: Research on Oxygenates Added to Gasoline, 2000, Health Effects Institute.

124. Chevron Products Company, Chevron Motor Gasolines Technical Review, Chapter 4: Oxygenated Gasoline (from website - www.chevron.com), 1996, Chevron.

126. Chevron, Chevron Technical Bulletin: Use of Oxygenated Gasolines in Non-Automotive Engines (from website www.chevron.com), 2001, Chevron.

127. Chevron, Chevron Gasoline: Questions and Answers - Federal Reformulated Gasoline (RFG) (from website - www.chevron.com), 2001, Chevron.

128. Chevron, Chevron Gasoline Questions and Answers: Oxygenated Gasoline (from website - www.chevron. Com, 2001, Chevron.

130. U.S. Department of Energy, Argonne National Laboratory. Energy Systems Div., Guidebook for Handling, Storing, & Dispensing Fuel Ethanol, 1992, US Department of Energy.

132. American Petroleum Institute, Storing and Handling Ethanol and Gasoline-Ethanol Blends at Distribution Terminals and Service Stations: API Recommended Practice 1626, 1985, American Petroleum Institute.

133. American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components: API Publication 4261- 2nd edition, 1988, American Petroleum Institute.

135. Curran, Sullivan D., Mittermaier, Armin E., Is Ethanol a Good Replacement for MTBE?, 2001.

138. Haskew, Harold Associates, Ethanol Effects on Permeation (Presentation - notes), 2000.

142. Underwriters' Laboratories of Canada, Ducted Flexible Underground Piping Systems for Flammable and Combustible Liquids: ULC/ORD-C107.4-1992, Underwriters' Laboratories of Canada.

143. Underwriters' Laboratories of Canada, Under-Dispenser Sumps: ULC/ORD-C107.21-1992, Underwriters' Laboratories of Canada.

144. Underwriters' Laboratories of Canada, Secondary Containment of Underground Piping for Flammable and Combustible Liquids: ULC/ORD-C107.19-1992, Underwriters' Laboratories of Canada.

146. NACE International, Chemical Resistance of Polymeric Materials by Periodic Evaluation: Standard Test Method TM0196-96, 1996, National Association of Corrosion Engineers.

148. Skaper, Gregory N., Hofer, Kenneth E., Establishing the Effect of Long-Term Exposure of Fiberglass Reinforced Polyester Material to Alcohol-Gasoline Mixtures, 1986, Steel Tank Institute.

150. Yahagi, Yoshiaki, Mizutani, Yoshiyuki, Corrosive Wear of Steel in Gasoline-Ethanol-Water Mixtures. In: Wear, V. 97, N. 1, 1984.

151. Persiantseva, V. P., Rozenfel'd, I. L., Zorina, V. E., Wnikeer, E. Kh., Corrosion of Aluminum, Copper, and Steel in Aqueous Ethanol. In: Protection of Metals, V. 15, N. 3, 1979.

152. Kabasakaloglu, M., Kalyoncu, I., Kiyak, T., The Polarization Behavior of Mild Steel in Ethanol/Water/Sulfuric Acid System. In: Applied Surface Science V. 135 (1-4), 1998, Applied Surface Science.

153. Rodrigues, P. R. P., De Andrade, A. H. P., Agostinho, S. M. L., Benzotriazole as Corrosion Inhibitor for Type 204 Stainless Steel in Water-Ethanol Media Containing 2M H sub 2 SO sub 4. In: British Corrosion Journal V. 33, (3), 1998, British Corrosion Journal.

154. Simoes Goncalves, R., Coradini, N, Y., Xaubet Olivera, W., The Inhibition Effect of the Acetate Ion on the Corrosion of Low Carbon Steel in Hydrated Ethanol. In: Corrosion Science V. 33 (11), 1992 Corrosion Science.

155. Borges Domingos, L. M., Sathler, L., Losada Diaz, S. I., Domingos, L. M. Borges, On the Addition of Ethanol to the Propargyl Alcohol Inhibited Acid Solution Used in Oil Well Stimulation: The Effects of the Corrosion Protection of Steel. In: 7th European Symposium on Corrosion Inhibitors--Proceedings. Vol. 1, Ferrara, Italy, 1990, European Symposium on Corrosion Inhibitors.

156. Singh, V. B., Singh, V. FK., Corrosion Studies of Austenitic Stainless Steels in Alcohol + H sub 2 SO sub 4 Mixtures. In: Bulletin of Electrochemistry, V. 3 (4), 1987, Bulletin of Electrochemistry.

158. Cavalcanti, E., Wanderley, V. G., Miranda, T. R. V., Uller, L., The Effect of Water, Sulphate and pH on the Corrosion Behavior of Carbon Steel in Ethanolic Solutions. In: Electrochim. Acta V. 32, (6), 1987, Electrochim. Acta.

159. Matsukura, K., Sato, K., Effect of Metallurgical Factors of Low Carbon Steel Sheets on Stress Corrosion Cracking in Methanol Solution. In: Transactions of the Iron and Steel Institute of Japan, V. 18, (9), 1978, Transactions of the Iron and Steel Institute of Japan.

161. Uller, L., Baatos, S. M., Wanderley, V. G., DeMiranda, T. R. V., Detrimental Effects on Metal Corrosion by Some Impurities Present on Hydrated Ethanol. In: International Congress on Metallic Corrosion, Toronto, Canada, 6/3/1984, National Research Council of Canada.

162. Bergstrom, D. R., Liening, E.L., Selected Stress Corrosion Cracking Failures in the Chemical Industry. In: Corrosion '84, 1984, National Association of Corrosion Engineers.

165. Underwriters Laboratories, Nonmetallic Underground Piping for Flammable Liquids: UL 971, 1997, Underwriters Laboratories Inc..

167. Corrpro Companies, Wagner, John, Young, Walter, Haber, Philippa, Corrosion Analysis of Methanol/Fuel Blends on Carbon Steel (1st 6 pages, Section 2.2 only), 1990, Steel Tank Institute.

173. Carswell, W. S., Environmental Fatigue and Creep in Glass Reinforced Mats: Fibre Reinforced Composites 84-Proceedings of the PRI International Conference, 1984, PRI (UK).

174. McCammond, D., Hoa, V. S., Craze and Creep Resistance of High-Impact Polystyrene in Alcohols. In: Polymer Engineering and Science, V. 17, N. 12, December 1977, Polymer Engineering and Science.

176. Arimond, J., Methanol Fuel Resistance of Phenolic Composites. In: Antec '92, Proceedings of SPE Conference, 5/92., 1992, Society of Plastics Engineers.

177. Rosales, Blanca M., A Novel Tester for Corrosivity Evaluation in Fuel Tanks In: Corrosion Reviews, V. 14 N.1-2, 1996, Corrosion Reviews.

178. Arnold, J. C., The Effects of Physical Aging on the Brittle Fracture Behavior of Polymers. In: Polymer Engineering and Science, V.35, N. 2 January, 1995, Polymer Engineering and Science.

179. Arnold, J. C., Craze Initiation During the Environmental Stress Cracking of Polymers. In: Journal of Materials Science, V. 30, N. 1, 1995, Chapman & Hall.

180. Shinozaki, D. M., Howe, R., Creep Deformation Cracking of Polyethylene in Methanol. In: Journal of Materials Science, V. 21, N. 5, 1986, Chapman & Hall.

184. Southwest Research Institute, Johnston, Robert K., Bieberdorf, F. W., Weichlein, R. G., A Study of Existing Base Fuel Handling Procedures in Relation to Microbial Contamination, 1964, United States Air Force Systtems Command, Wright-Patterson AFB, Ohio.

186. Nakayama, Mitsushige, Water Tolerability of Methanol-Gasoline Blends (Phase Separation and SI Engine Performances). In: Third SAE International Joint Pac. Automotive Engineering Conference (Jakarta, November, 1985) Paper No. 852200, 1985, Society of Automotive Engineers (SAE).

188. Anonymous, Ethanol Group Touts Cheap Tank Upgrades In: Oil Price Information Service, 4/8/96, 1996, Oil Price Information Service.

190. Lukovkin, G. M., Yarysheva,L. M., Kabal'nova, L. Yu, Volynskii, A. L., Method of Describing Kinetic Curves for the Accumulation of Crazes in the Deformation of Amorphous Polymers Under Creep Conditions in Adsorption Active Media. In: Polymer Science USSR, V. 29, N. 1, 1987, Polymer Science USSR.

192. Haffane, N., Benameur, T., Granger, R., Vergnaud, J. M., Correlation Between the State of Cure of Unsaturated Polyester Coatings and Their Resistance to Ethanol. In: Polymers & Polymer Composites, V. 3, N. 2, 1995, Polymers & Polymer Composites.

194. Fitzgerald, John H., Don't Let Corrosion Get Your Underground Tanks. In: Materials Performance, V. 27, N. 4, 1988, Materials Performance.

195. Byrne, S. B., McNally, G. M., McNally, T., Murphy, W. R., Dynamic Mechanical Thermal Analysis (DMTA) of Barrier Materials Immersed in Automotive Fuel Components. In: Antec '99, Proceedings of Spe Conference, 1999, Society of Plastics Engineers.

196. Haffane, N., Bouardi, El, Vergnaud, J. M., Effect of the State of Cure and (gamma) Treatment on the Resistance to Ethanol of Thermosets. In: Polymer Testing, V. 20, N. 3, 2001, Polymer Testing.

200. Sahlin, Jennifer J., Peppas, Nikolaos, Penetrant Transport in Epoxy Resins. In: Industrial & Engineering Chemistry Research, V. 30, 1991, 1991, Industrial & Engineering Chemistry Research.

201. Hoa, S. V., Ouellette, P., Liquid Absorption of a Sheet Molding Compound. In: Polymer Composites, V. 2, N. 4, 1981, Polymer Composites.

203. McNally, T., McNally, G. M., Byrne, S. B., Murphy, W. R., Transport and Sorption Properties of Various Barrier Materials Used in Multilayer Fuel Line Tubing on Immersion in Fuel Components. In:Antec' 98, Proceedings of SPE conference, 1998, Society of Plastics Engineers.

207. McNally, T., McNally, G. M., Ahmad, M. N., Murphy, W. R., Sorption and Diffusion of Fuel Components in Various Nylons. In: Antec '97, Proceedings of SPE Conference, 1997, Society of Plastics Engineers.

210. Weber, A, Hubold, J., Muller, J., Linster, J. J., Testing Equipment for Measuring Fuel Permeability of Plastic Fuel Line Tubing, 1991, Society of Automotive Engineers (SAE).

214. Buck, Daniel M., Bauman, Bernard D., Hobbs, J. Peter, Evaluation of Process Parameters to Optimize Gasohol Barrier Properties in HDPE Fuel Tanks: SAE Technical Paper N. 871999, 1987, Society of Automotive Engineers (SAE).

216. McNally, Tony, McGarvey, John J., Dennis, Andrew, McShane, Paul, The Use of Fourier Transform Infrared-Attenuates Total Reflectance (FTIR-ATR) Spectroscopy to Characterize the Diffusion of Fuel Components in Polymers Used in Multilayer Fuel Line Tubing: Sae Technical Paper N. 1999-01-0374, Society of Automotive Engineers (SAE).

219. FQS (Fuel Quality Services Inc), The FQS Group, Fiberglass Tank Biodeterioration Risks: A Short Annotated Bibliography, 1997, FQS (Fuel Quality Services, Inc).

220. FQS (Fuel Quality Services) FQS Group, Microbially Influenced Corrosion of Steel Underground Storage Tanks: Annotated Bibliography, 1997, FQS (Fuel Quality Services, Inc).

221. , Internal Corrosion of Steel Tanks: A.S.P.C.E. - H.B.L. (September 30,1983-Revis. 6/12/84, 1984.

224. American Society for Testing and Materials (ASTM), Standard Guide for Microbial Contamination in Fuels and Fuel Systems: D6469-99, 2000, American Society for Testing and Materials (ASTM).

226. Buxton, L. William, Spohn, Peter D., Will, Rod R., Understanding How Molecules Permeate through Solid Substances: SAE Paper 940164, 1994, Society of Automotive Engineers (SAE).

227. Hopf, Gerhard, Ries, Hans, Gray, Edward K., Development of Multilayer Thermoplastic Fuel Lines With Improved Barrier Properties: SAE Paper 940165, 1994, Society of Automotive Engineers (SAE).

228. Krause, Edward K., Kuenzel, Kenneth J., ETFE-Nylon 12 Multi-Layer Fuel Lines and the Requirements of a Changing Fuel Line Environment: SAE Paper 940166, 1994, Society of Automotive Engineers (SAE).

230. Storojeva, Lydia M., Corrosion Resistance of Different Coated Steels for Fuel Tanks. In: Anti-Corrosion Methods and Materials, v. 44, n.2, p. 84-89, 1997, Anti-Corrosion Methods and Materials.

232. Youngs, Andy, What Specifiers Need to Look for in Flexible Piping: In Petroleum Equipment & Technology, May/June 1998, Petroleum Equipment & Technology.

233. Lowinski, Jeff, Are Ethanol Concerns in Steel Tanks Overstated? In: Petroleum Equipment & Technology, 2000, Petroleum Equipment & Technology.

237. Farquhar, Gale B., Kane, Richaard D., Abayarathna, Dharma, Sanders, David H., Tests Show Best Corrosion Inhibitors for High Pressure, Temperature Pipeline. In: Oil & Gas Journal, May 5, 1997, Oil & Gas Journal.

239. New England Interstate Water Pollution Control Com, NEIWPCC, Health, Environmental, and Economic Impacts of Adding Ethanol to Gasoline in the Northeast States: Volume 3 - Water Resources and Associated Health Impacts, May 2001, NEIWPCC-New England Interstate Water Pollution Control Commission.

241. Passman, Frederick J., Uncontrolled Microbes Eat Earnings. In: National Petroleum News, 8/94, National Petroleum News.

242. Passman, Frederick J., Knowing When You Have Contamination. In: National Petroleum News, 10/94, 1994, National Petroleum News.

243. Passman, Frederick J., Opening Your Biocide Toolbox. In: National Petroleum News, 9/95, National Petroleum News.

244. Passman, Frederick J., World Experts Discuss Fuel Problems. In: National Petroleum News, 1995, National Petroleum News.

246. Owens, E.C., Marbach, H. W., Frame, E. A., Ryan, T.W., Effects of Alcohol Fuels on Engine Wear, 1980, National Technical Information Service (NTIS).

248. Downstream Alternatives, Reynolds, Robert E., Materials Compatibility of Gasoline Ethanol Blends with Underground Storage Tanks/Systems, 2000, Downstream Alternative Inc.

250. Harold Haskew & Associates, Emission Effects (Permeation) of Ethanol in Gasoline: Literature Search Survey, 1999, Harold Haskew & Associates.

252. Fiberglass Tank & Pipe Institute, Summary Documentation of Underground Steel Tank Internal Corrosion: Attachment A, Fiberglass Tank & Pipe Institute.

254. Passman, Dr. Fredrick J., Controlling Microbial Contamination. In: National Petroleum News, 1/95, National Petroleum News.

256. Curran, Sullivan D., Compatibility and Permeability of Ethanol-gasoline Fuel with Underground Storage and Handling Equipment, 2000, Fiberglass Tank & Pipe Institute.

258. Xerxes Corporation, Xerxes Corporation Warranty, 1988, Xerxes Corporation.

259. Xerxes Corporation, Limited Warranty: Petroleum or Alcohol Fuels Storage for Double Wall Underground Petroleum Storage Tanks with Resin Specified for Expanded Fuels, 1998, Xerxes Corporation.

260. Xerxes Corporation, Warranty: Single Wall Underground Petroleum Storage Tank, 1993, Xerxes Corporation.

261. Owens-Corning, Warranty: Standard Underground Petroleum Storage Tank, 1988, Owens-Corning.

262. Owens-Corning Fiberglas Corporation, Warranty, 1981, Owens-Corning.

264. Owens Corning, Bartlow, David, Letter from Owens Corning re: Pre-1981 Owens Corning Tanks Storing 10% Ethanol, May 8, 2000, Not Published.

265. Smith Fiberglass Products Company, Smith Fiberglass Products Company Facsimile Message re: Service Station Piping, May 24, 2000, Not Published.

266. Amoco Chemical, Unearthed: Further Evidence that Proves the Leadership of Isopolyesters in Corrosion Resistance (Amoco Chemical brochure), 1990.

267. Amoco Chemical, 25-Year-Old Tank Showcases Corrosion Resistance of Isopolyesters. In: Amoco Bulletin IP-88e, 1992, Amoco Chemical.

269. Owens-Corning, Owens Corning letter to tank customers re: Use of Fiberglass UST's produced by OC for the Storage of Ether and Alcohol Fuel Blends, April 14, 1995, Not Published.

270. Curran, Sullivan D., RFG in FRP - Fueling the Future, 1995, Fiberglass Tank & Pipe Institute.

271. Xerxes Corporation, Limited Warranty: Single Wall Underground Petroleum Storage Tank: Effective 1/15/98, 1998, Xerxes Corporation.

272. Xerxes Corporation, Limited Warranty: Petroleum or Alcohol Fuels Storage for Single Wall Underground Petroleum Tanks with Resin Specified for Expanded Fuels: Effective 5/15/93, 1993, Xerxes Corporation.

273. Fluid Containment, Warranty: Fluid Containment Warranty and Installation Information for Standard Double-Wall Tanks, Effective 1995, 1995, Fluid Containment.

274. Owens-Corning Fiberglas Corporation, Warranty: Standard Underground Petroleum Storage Tank, effective 1996, 1996, Owens-Corning.

276. Environ, Environ Warranty: 30year, 10year and 1 year for the GeoFlex System (flexible piping, containment sumps, pipe entry seals, etc).

277. Marley Pump, Submersible Pumps for Alcohol/Gasoline Blends: Red Jacket AG Pumping Systems, 1994, Marley Pump.

278. Dupont Elastomers, Viton (seal materials): Figures 5 and 6 and Table II on relative resistance to increasing concentrations of oxygenated fuels and value ranking of elastomer performance - Excerpted from Dupont Elastomers "Leak Performance of Reformulated Fuels and Oxygenated ...".

279. Gilbarco, Oxygenated Fuel Additives: Ethanol, Methanol, and MTBE Usage with Gilbarco Equipment, 1992, Gilbarco.

281. Environmental Protection Agency, Use of Reformulated Gasoline in Off-Road Engines: EPA 420-F-95-007, 1995, US Environmental Protection Agency.

282. Environmental Protection Agency, Achieving Clean Air and Clean Water: The Report of the Blue Ribbon Panel on Oxygenates in Gasoline:R-99-021, 1999, US Environmental Protection Agency.

286. ARCO Chemical Company, Compatibility of Fiberglass with Fuels Containing Oxygenate. In: Oxygenated Fuels Technical Bulletin, No. 8208, August 1982, ARCO Chemical Company.

287. Alcohol Update, Storing Alcohol in Fiberglass Doesn't Worry Majors. In: Alcohol Update: A Weekly Update on the U.S.Alcohol Fuel Industry, April 29, 1985, Alcohol Update.

289. U.S. Environmental Protection Agency, Leaking Underground Storage Tanks Containing Motor Fuels: A Chemical Advisory, 1984, US Environmental Protection Agency.

291. Temple, R.G., Sidhu, S. J., Acceptability of Alcohols as Gasoline Substitutes. In: American Chemical Society, Division of Fuel Chemistry (Preprint Paper), V. 37, N. 4 p. 1825-9, 1992, American Chemical Society.

293. Bechtold, Richard L., Alternative Fuels Guidebook: Properties, Storage, Dispensing, and Vehicle Facility Modifications., 1997, Society of Automotive Engineers (SAE).

295. , Changes in Gasoline III, The Auto Technician's Gasoline Quality Guide, 1996.

296. Downstream Alternatives Inc., Comment on RFG/MTBE Issues and Options in the Northeast, 1999, Downstream Alternative Inc.

297. Downstream Alternatives Inc., Compatibility of Reformulated and Oxygenated Gasoline with Fuel System Materials, 1997, Downstream Alternative Inc.

299. Modern Welding Company, Inc, Installation Instructions - Glasteel II Jacketed Steel Tanks, 1998, Modern Welding Company, Inc..

APPENDIX

A

Literature Review

APPENDIX A—LITERATURE REVIEW

Appendix A may be purchased separately as an electronic database file. The database is the synopsis' and bibliographic information for all articles reviewed for the project. The report is organized by article index numbers. Reference numbers cited in this report refer to the article index number.

Impact of Gasoline Blended with Ethanol on the Long-Term Structural Integrity of Liquid Petroleum Storage Systems and Components, Literature Review Database

Product Number: A1600D

To purchase contact:

API Publications
Global Engineering Documents
15 Inverness Way East
M/S C303B
Englewood, CO 80112-5576

Tel: 1-800-854-7179 (Toll-free in the U.S. and Canada)
1-303-397-7956 (Local and International)

Fax: 1-303-397-2740

Online: www.global.ihs.com

Additional copies are available through Global Engineering Documents at (800) 854-7179 or (303) 397-7956

Information about API Publications, Programs and Services is available on the World Wide Web at http://www.api.org

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005-4070
202-682-8000

Product No: A16000