Identification, Repair, and Mitigation of Cracking of Steel Equipment in Fuel Ethanol Service

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Contents

Contents

Page

Figures

Tables

Identification, Repair, and Mitigation of Cracking of Steel Equipment in Fuel Ethanol Service

1 Scope

Usage of fuel ethanol as an oxygenate additive in gasoline blends is increasing both in the United States and internationally. This document discusses stress corrosion cracking (SCC) of carbon steel tanks, piping, and equipment exposed to fuel ethanol as a consequence of being in the distribution system, at ethanol distribution facilities, or end user (EU) facilities where the fuel ethanol is eventually added to gasoline. Such equipment includes but is not limited to:

— storage tanks,

— piping and related handling equipment, and

— pipelines

that are used in distribution, handling, storage, and blending of fuel ethanol. However, data for pipelines in ethanol service is limited and caution should be used when applying guidelines from this document that have been derived mainly from applications involving piping and tanks in ethanol storage and blending facilities. SCC of other metals and alloys is beyond the scope of this document, as is the corrosion of steel in this service.

It is realized that SCC of steel in fuel ethanol is a topic where knowledge of the subject is actively growing through documentation of recent experience and through research in progress. This document deals with handling of cracks in existing equipment and reduction of SCC occurrence in new equipment as a result of exposure to fuel ethanol per ASTM D4806 (or other international specifications), ethanol fuel blends, and pipeline transmixes involving fuel ethanol and conventional hydrocarbon fuels (gasoline, diesel, or jet fuel). It includes guidelines for carbon steel construction materials, including their fabrication, inspection, and repair to help assure safe and reliable operations.

This document is based on current engineering practices and insights from recent industrial experience and research. Older equipment may not conform exactly to the information contained herein, but this does not imply that such equipment is being operated in an unsafe or unreliable manner. It is also recognized that facilities may vary and may need to be modified depending on specific operating conditions, inspection, and maintenance experience. Each user company is ultimately responsible for its own safe and reliable operations.

The steels referred to in this document are defined by the ASTM or API designation systems or equivalent steel grades contained in other recognized codes or standards. Welded construction is considered the primary method of fabrication in equipment exposed to fuel ethanol.

Terminology used herein is given in Section 3.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Specification 5L, *Specification for Line Pipe*

API Publication 327, *Aboveground Storage Tank Standards: A Tutorial*

API 570, *Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-service Piping Systems*

API Recommended Practice 574, *Inspection Practices for Piping System Components*

API Standard 579-1/ASME FFS-1, *Fitness-for-Service*

API Recommended Practice 580, *Risk-Based Inspection*

API Recommended Practice 582, *Recommended Practice and Welding Guidelines for the Chemical, Oil, and Gas Industries*

API Standard 620, *Design and Construction of Large, Welded, Low-pressure Storage Tanks*

API Standard 650, *Welded Tanks for Oil Storage*

API Standard 652, *Lining of Aboveground Petroleum Storage Tank Bottoms*

API Standard 653, *Tank Inspection, Repair, Alteration and Reconstruction*

API Publication 939-D, *Stress Corrosion Cracking of Carbon Steel in Fuel Grade Ethanol—Review, Experience Survey, Field Monitoring, and Laboratory Testing*

API Standard 1160, *Managing System Integrity for Hazardous Liquid Pipelines*

API Recommended Practice 1626, *Storing and Handling Ethanol and Gasoline-ethanol Blends at Distribution Terminals and Filling Stations*

API Standard 2015, *Requirements for Safe Entry and Cleaning of Petroleum Storage Tanks*

API Standard 2016, *Guidelines and Procedures for Entering and Cleaning Petroleum Storage Tanks*

API Standard 2217A, *Guidelines for Work in Inert Confined Spaces in the Petroleum and Petrochemical Industries*

API Standard 2610, *Design, Construction, Operation, Maintenance and Inspection of Terminal and Tank Facilities*

API Publication 4261, *Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components*

ASME B31.4 [1], *Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids*

ASTM D4806 [2], *Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel*

ASTM D6423, *Standard Test Method for Determination of pHe of Ethanol, Denatured Fuel Ethanol, and Fuel Ethanol*

NACE TM0111 [3], *Slow Strain Rate Test Method for Evaluation of Ethanol Stress Corrosion Cracking in Carbon Steels*

NFPA 326 [4], *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair*

RFA Publication 960501 [5], *Fuel Ethanol, Industry Guidelines, Specifications and Procedures*

STI SP001 [6], *Standard for the Inspection of Aboveground Storage Tanks*

U.S. DOE [7], (Alternative Fuels Data Center) *Handbook for Handling, Storage and Dispensing E85*

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1 ASME International, Two Park Avenue, New York, New York 10016-5990, www.asme.org.
2 ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.
3 NACE International (formerly the National Association of Corrosion Engineers), 1440 South Creek Drive, Houston, Texas 77084-4906, www.nace.org.
4 National Fire Protection Association, 1 Batterymarch Park, Quincy, Massachusetts 02169-7471, www.nfpa.org.
5 Renewable Fuels Association, 425 Third Street, Suite 150, Washington, DC 20024, www.ethanolrfa.org.
6 Steel Tank Institute, 944 Donata Court, Lake Zurich, Illinois 6004, www.steeltank.com.
7 U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585, energy.gov.

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1.1
coating
Any thin material, liquid or powder, which applied over a structure, forms a continuous film to protect against corrosion.

3.1.2
cold working
Plastic deformation of a metal under conditions of temperature and strain that induce strain hardening and residual stress, usually, but not necessarily conducted at ambient temperature.

3.1.3
corrosion inhibitor
A chemical formulation that is added to an environment to reduce the severity of corrosion.

3.1.4
denature
The process of adding a substance (i.e. denaturant) for the purpose of making it unfit for human consumption.

NOTE In the case of fuel ethanol, natural gasoline is intentionally added. See Table 1 for limits of denaturant addition to fuel ethanol per ASTM D4806.

3.1.5
ethanol-containing fuels
In the United States, conventional gasoline is blended with up to 10 % by volume fuel ethanol (referred to as E10). It is also blended with 51 % to 83 % ethanol, depending on geography and season. This blend is referred to as E85.

3.1.6
fuel ethanol
fuel grade ethanol
FGE
Nominally anhydrous (<1 % volume water) denatured ethanol intended to be blended with natural gasoline at 1 % to 10 % volume for use as a spark ignition automotive engine fuel. In regions outside the United States, fuel ethanol may be available with lower water (anhydrous ethanol) or higher water content, up to 4.9 %v (6.1 %m) water, which is referred to as “hydrous ethanol.”

NOTE Fuel ethanol is typically produced from organic sources such as corn, grain, grapes, sugarcane, and other forms of starch or sugar-based feedstocks.

3.1.7
intergranular cracking
Cracking produced in a susceptible metal that propagates along the grain boundaries within the material.

3.1.8
mixed-mode cracking
A term related to fracture by SCC whereby it has features of both intergranular cracking and transgranular cracking.

3.1.9
normalizing
Heating a ferrous metal to a suitable temperature above its transition temperature to form austenite, holding for a suitable time, and then cooling in still air (or atmosphere) to a temperature below the transition temperature.

3.1.10
plastic deformation
Permanent deformation produced by stressing beyond the elastic limit of the material into the plastic region, creating a permanent set in the material.

3.1.11
postweld heat treatment
PWHT
Any thermal treatment performed to a weldment following the process of welding, usually with the intent of reducing residual stresses or reducing hardness in the weldment.

3.1.12
residual stress
The stress that exists in a metal or alloy that arises from either plastic deformation, welding, and/or thermal expansion.

3.1.13
stress corrosion cracking
SCC
Environmental cracking in a susceptible metal produced by the simultaneous application of a tensile stress and exposure to particular corrosive environments.

3.1.14
stress relieving
A form of PWHT involving heating a metal with the specific intent to reduce residual stress and then cooling slowly enough to minimize the development of new stresses.

3.1.15
tempering
A form of heat treatment or PWHT involving heating for the purpose of decreasing the hardness of weldments and the strength of a material while generally increasing the toughness.

3.1.16
transgranular cracking
Cracking produced in a metal that propagates across the grains within the material.

3.1.17
transmix
Also known as "interface," the product removed from a pipeline system between two separate product batches (e.g. fuel ethanol and gasoline) that, in some cases, cannot be blended with the first or second product.

3.1.18
weldment
The portion of a component on which welding has been performed, including the weld metal, the heat-affected zone (HAZ), and the adjacent parent metal.

3.2 Acronyms and Abbreviations

ACFM	alternating current field measurement
DFMT	dry fluorescent magnetic testing
EC	eddy current
EFT	external floating roof tank
EU	end user
FGE	fuel grade ethanol

HAZ	heat-affected zone
HIC	hydrogen induced cracking
IFT	internal floating roof tank
IG	intergranular
ILI	in-line inspection
MIC	microbiologically influenced corrosion
MTBE	methyl tert-butyl ether
NDE	nondestructive examination
NDT	nondestructive testing
PA	phased array
PRCI	Pipeline Research Council International
PT	penetrant testing
PTBE	pounds per thousand barrels of ethanol
PWHT	postweld heat treatment
RT	radiographic testing
SCC	stress corrosion cracking
SRB	sulfate reducing bacteria
TMCP	thermomechanically controlled processing
TOFD	time of flight diffraction
U.S. DOT	U.S. Department of Transportation
UT	ultrasonic testing
WFMT	wet fluorescent magnetic particle testing

4 Background on SCC in Fuel Ethanol

4.1 Description of Fuel Ethanol

Ethanol as a fuel additive (i.e. fuel ethanol) has been used in the United States for more than 25 years. In the early 1990s, the U.S. Congress passed the Clean Air Act that required that oxygenate be added to gasoline in specific regions of the country. Commonly used oxygenates include ethanol and methyl tert-butyl ether (MTBE). Recently, MTBE has been found to contaminate groundwater and many states have banned its use. Additionally, the federal government has passed energy legislation (Energy Policy Act of 2005) that among other things, phases out the use of MTBE, promotes the use of ethanol in gasoline, eliminates some oxygenate requirements, and phases in increasing requirements for the use of renewable fuels like ethanol and other formulations. Consequently, the use of fuel ethanol as an additive and/or extender to gasoline is increasing. Additional considerations for use and distribution of fuel ethanol and alcohol fuels are available in API 1626 and API 4261.

Modern production of ethanol from starch or sugar-based feedstocks (grain, fruit, sugarcane, and other biomass) is similar to processes that have been used for centuries, but which have been considerably refined in recent years. There are two production processes for grains: wet milling and dry milling. The main difference between the two is in the initial treatment of the grain. In the final process, the starch and any remaining water from the mash is converted to sugars that can then be fermented to produce ethanol that is recovered by distillation. Once produced and ready for distribution, the ethanol is denatured (typically by the addition of unleaded gasoline) and a corrosion inhibitor is added.

4.2 Relevant Standards for Fuel Ethanol

In the United States, fuel ethanol is currently governed by ASTM D4806, which gives the compositional and physical limits for fuel ethanol. These are shown in Table 1.

Table 1—Quality Specification for Fuel Ethanol per ASTM D4806

Property	Units	Specification	ASTM Designation
Ethanol	%v min	92.1	D5501
Methanol	%v max	0.5	—
Solvent-washed gum	mg/100 mL max	5.0	D381
Water content	%v max	1.0	E203
Denaturant content	%v min %v max	1.96 5.00	D4806
Inorganic chloride content	ppm (mg/L) max	10 (8)	E512
Copper content	mg/kg max	0.1	D1688
Acidity as acetic acid	%m (mg/L)	0.007 (56)	D1613
pHe	—	6.5 to 9.0	D6423
Appearance	Visibly free of suspended or precipitated contaminants (e.g. clear and bright)		
NOTE The limit for inorganic chlorides was reduced in ASTM D4806 (2009) from a higher level of 40 ppm in the previous edition of this standard.			

While fuel ethanol in the United States is made in conformance with this standard, most of its properties are also defined by other ASTM designated standards (see Table 1). Additional information can be found in RFA Publ 960501. The purpose of the ASTM D4806 standard is to provide parameters so ethanol/gasoline blends will perform satisfactorily in a wide range of fuels used in consumer vehicles and not for any attributes regarding corrosion or SCC that the fuel ethanol might have in the supply chain prior to blending with gasoline. Fuel ethanol may also have properties not specified in ASTM D4806 but that may influence susceptibility to SCC. Some of these properties are discussed in 4.5.

A parameter that is commonly used in evaluation of fuel ethanol is the pHe as defined by ASTM D6423. The pHe value is a measure of the acid strength of high ethanol content fuels and their constituents and is applicable to fuels containing nominally 70 % volume ethanol or higher. This parameter is similar in some regards to the pH parameter used in aqueous solutions. An important difference is that neutrality in pHe units is near 9.5 as opposed to the familiar 7.0 pH that defines neutrality in aqueous solutions under ambient conditions. The pHe value may not directly correlate to the pH scale for aqueous solutions. Most importantly, pHe does not appear to correlate with the corrosion or SCC behavior of fuel ethanol in the supply chain prior to blending with gasoline.

Fuel ethanol is not sold with zero water content, where it would be referred to as anhydrous ethanol. Denatured fuel ethanol made to ASTM D4806 specifications typically contains up to 1 % water and other constituents as mentioned in the ASTM D4806 standard. Denatured ethanol with less than 0.5 % water is considered “anhydrous ethanol.” Ethanol with higher water content up to 4.9 %v (6.1 %m) is usually referred to as “hydrated ethanol.” Such hydrated ethanol is uncommon in the United States but has been used as a fuel in Brazil. Brazil also makes anhydrous ethanol used for blending into gasoline. Both anhydrous and hydrated grades of fuel ethanol made in Brazil are made from primarily sugarcane and the amount of each produced fluctuates with the price. Recent accounts indicate that the Brazilian market for fuel ethanol is dominated by anhydrous ethanol. There has been no documented experience with SCC in hydrated or anhydrous ethanol derived primarily from sugarcane despite over 20 years of research and their use as automotive fuel in Brazil.

4.3 Supply Chain for Fuel Ethanol

Once fuel ethanol is produced at a manufacturer’s facility, it is held in storage tanks until it is released for distribution. Manufacturers generally add the denaturant prior to or during on-site storage, and an inhibitor is added during storage or just prior to release of the shipment for distribution. This may be one reason for the apparent difference in SCC experience between manufacturer and downstream facilities (i.e. no reported failures at manufacturer facilities, and SCC at some downstream facilities); see 4.5.7 for more information on the effect of inhibitors. Once the fuel ethanol enters the distribution system, it can be transported by many methods. Transportation methods include barge, railroad tanker car, tanker truck, and pipeline.

The period that fuel ethanol is in the chain can vary considerably from days to months depending on the location of the manufacturing facility, the availability of intermediate distribution storage, the location of gasoline blending terminals, and the transportation mode used. Once fuel ethanol enters intermediate liquids storage and distribution terminal or a gasoline blending facility, the ethanol is held in storage tanks. The residence time in these tanks likewise varies depending on usage and traffic requirements. In some cases, it can be held for months during a period of inactivity. In some cases at gasoline blending facilities, however, the residence time in the storage tank is very short as incoming ethanol deliveries and outgoing shipments of blended gasoline are a near continual process. Observations of SCC have been limited to the portion of the supply chain involving the intermediate liquids storage through the gasoline blending facility and may be related to changes that occur in the fuel ethanol or conditions that develop in the distribution system.

4.4 Significance of SCC in Fuel Ethanol

4.4.1 General

A review of service experience with fuel ethanol and the literature for cited cases of SCC ethanolic environments was conducted by API and is referenced in API 939-D (see references). Highlights from this work have also been published in the open literature. This study revealed that there has been SCC of carbon steel exposed to ethanolic environments and that the range of conditions causing SCC has gained in understanding as highlighted in references found in the recent updated version of API 939-D that includes work funded by the Pipeline Research Council International (PRCI) and United States Department of Transportation (U.S. DOT). The published literature and service experience with methanol has shown for some time that methanol is a known SCC agent for steel. Water content, various impurities, temperature, and metallurgical condition of the steel determine methanol SCC susceptibility.

A follow-up research program was conducted by API in cooperation with the RFA to identify the variables that control SCC of steel in fuel ethanol. This in-depth study involved:

a) gathering of further service experience;

b) field corrosion and SCC monitoring; and

c) laboratory research on environmental and metallurgical variables pertaining to steels commonly used in tanks, pipes, and pipelines handling fuel ethanol.

The work product of the API and API/RFA studies provided the basis for this standard. The detailed results of these studies and related information are also found in API 939-D.

Several documented cases of SCC in steel equipment exposed to fuel ethanol obtained from the aforementioned study are presented in Annex A. These findings indicate that documented failures of ethanol process equipment have dated back to at least the early 1990s. Additionally, this work indicated that SCC failures continue to be observed in various parts of the distribution system for ethanol, albeit being reported less frequently in recent surveys since the guidelines contained herein have been published. A form for reporting additional failure incidents resulting from SCC in fuel ethanol to API is available in Annex B. Companies experiencing what they think are cases of SCC in fuel ethanol (or ethanol fuel blends) are encouraged to confirm these cases through review and documentation of service conditions, as well as metallurgical analysis of the cracked or failed components that includes metallographic or fractographic examination of the cracks to confirm similarity to known cases of SCC given herein and to provide a summary of this information to API using the form provided in Annex B. For more information on the identification of SCC in fuel ethanol, see 4.4.2, and the examples in Annex C. Information on ethanol SCC failures or leaks provided in this form will be utilized to further this document with the name of the submitting company not associated with the information. Such information is of benefit in confirming the extent of the ethanol SCC problem and in future updates to this document.

4.4.2 Identification of SCC in Fuel Ethanol

SCC cracks of steel in fuel ethanol have a similar appearance to the cracks caused by other cracking environments. Examples of SCC in steel equipment exposed to fuel ethanol are shown in Annex C. The cracks are typically branched and may be intergranular, transgranular, or mixed mode. In laboratory testing, both intergranular and transgranular cracking may occur depending on the composition of the ethanol and testing methods used. Most cracks documented from field failures show predominately intergranular cracking. When analyzing a field failure in fuel ethanol service, internal surface originating intergranular cracking suggests ethanol SCC, but transgranular or mixed-mode cracking may also exist. Cracks generally are tight and often filled in corrosion product, making visual detection on the surface difficult in some cases and thus requiring alternative methods as discussed herein.

4.4.3 Cited Example Cases of SCC

Cases of SCC of steel components in fuel ethanol have been reported in the following types of equipment in fuel ethanol distribution and gasoline blending facilities:

a) welds and adjacent metal in tank bottoms, floating roofs, and associated seal components (e.g. seal springs);

b) facility rack piping, fittings, and associated equipment (e.g. air eliminators);

c) vertical seam and nozzle welds in lower tank shells located off bottom; and

d) pipeline used to transport fuel ethanol from terminal to EU facility.

A total of 34 cases of SCC have been reported in the API survey efforts conducted from 2003 through 2011 and include cases of SCC that go back through the early 1990s. Many of these involved multiple occurrences of cracking at the same location over time or instances of SCC in multiple equipment types at the same facility at the same time. All but one case of ethanol SCC was in equipment exposed to fuel grade ethanol (FGE). The one case not in FGE occurred in a small shop-built tank used to hold an E85 ethanol fuel blend. It was complicated by the presence of pitting that occurred while in prior waste oil service and a high degree of plastic deformation and residual stress occurring during manufacturing. Time to failure by ethanol SCC has been observed to range from 3 months to over 10 years from the date when the equipment was placed in FGE or ethanol fuel blend service.

A listing of the documented instances of SCC from the API surveys and the percentages they have occurred in each type of application are given below:

— tank floor plates seam welds—seven cases (20.6 %),

— tank floor/sidewall fillet welds—three cases (8.8 %),

— tank sidewall first course butt weld—three cases (8.8 %),

— tank floating-roof seam welds—three cases (8.8 %),

— tank nozzle—one case (2.9 %),

— tank roof springs—two cases (5.9 %),

— shop-built tank in E85—one case (2.9 %),

— facilities piping/fittings—eight cases (23.5 %),

— facilities piping/supports—two cases (5.9 %),

— pipeline—two cases (5.9 %),

— ancillary equipment—two cases (5.9 %).

Examples of many of these types of failures are provided in Annex C.

It is significant to note that thus far, all but one failure was in fuel ethanol and that no SCC failures have been documented in the following cases:

a) ethanol manufacturer facilities (storage tanks, piping, or associated equipment);

b) intermediate supply chain equipment, barges, tanker cars, or tank trucks; and

c) blending or transportation facilities handling products containing fuel ethanol after it has been fully blended with conventional grade gasoline (E10).

The reasons for this latter behavior may be related to reduced susceptibility to SCC in these portions of the supply chain, but it could also be related to a lack of reporting. A form for reporting failure incidents resulting from SCC in fuel ethanol to API is available in Annex B.

4.4.4 Experience with SCC in Fuel Ethanol

A survey of five major EUs in North America determined that approximately 100 tanks were in ethanol service (of which 75 were currently coated). It was reported that the average age of the tanks was approximately three years and represented 120 tank years in fuel ethanol service. The number of reported SCC events was 19, with some including multiple occurrences per event that increases the number to approximately 24. More information on reported failure occurrences through February 2005 is available in Annex A. Additional information is available in the recent update to API 939-D.

In the 2011 API survey, a canvass of the NACE International pipeline and refining committees indicated the following new information on recent experience with ethanol SCC from the following sectors.

— Ethanol SCC incidents:

  — 13 % failure, 37 % leak, 25 % cracked, 50 % nonfailure (crack found before leakage), 0 % severe corrosion or polymeric material incompatibility (some reported more than one category);

  — 50 % reported conducting an investigation to document ethanol SCC cracks, leaks, or failures (balance had no investigation).

— Equipment:

  — 0 % tank (bottom, side, roof), 17 % facilities piping, 33 % pipe fittings, 50 % other components and equipment.

— Regions:

  — United States and Europe.

— Time to SCC incident once in ethanol service:

  — 40 % less than 1 year, 20 % 1 to 3 years, 20 % 3 to 10 years.

— Time equipment in prior (nonethanol) service:

  — 60 % none, 40 % 10 to 12 years.

- Type of ethanol:
  - 60 % fuel ethanol, 0 % E85, 40 % other ethanol fuel blends/transmixes.
- Ethanol within D4806 composition:
  - 50 % yes, 25 % no, 25 % other standard (EU).
- Mode of shipment to point of use:
  - 20 % rail, 40 % pipeline, 60 % other (tank truck and barge).
- Use of postweld heat treatment (PWHT):
  - 20 % yes, 80 % no.
- Internal coatings used:
  - 100 % no.
- Were inhibitors, deaeration, additives used to mitigate SCC:
  - 100 % no.
- Was any type of monitoring used (corrosion coupons or probes, oxygen, electrochemical):
  - 100 % no.

4.5 Factors Related to SCC

4.5.1 General

On the basis of the API/RFA studies of service experience and laboratory research conducted to date as documented in API 939-D that includes the results of recent investigations performed for the PRCI and the U.S. DOT Pipeline and Hazardous Materials Safety Administration, several factors have been identified that appear to relate to susceptibility to SCC of carbon steel components in fuel ethanol systems and exposed to ethanol fuel blends. These factors are described below in the following sections.

4.5.2 Stress/Strain

Failures by SCC in fuel ethanol have been observed in locations that are characterized as having high applied or residual tensile stresses, high local concentration of strain, and/or local cold working. Some examples of these situations are found in:

a) nonstress relieved welds;

b) tank bottoms in areas of high stress, flexing, or coning;

c) low heat input tack welds in rack piping;

d) lap welds in tank bottoms or floating roofs;

e) cold worked fabricated components (e.g. spherical heads on air eliminator);

f) areas of localized bending due to mechanical fit-up or movement;

g) pipeline segments where field bending was involved.

High stress or strain is the mechanical driving force that promotes SCC crack initiation and propagation. Research has shown that the threshold stress for the onset of ethanol SCC in steel is likely above the material yield strength for most cases. The driving force for cracking may be exacerbated further when combined with cyclic loading (see 4.5.3).

4.5.3 Variable Stress/Strain

Many reports of SCC failures have been reported in tank bottoms, floating roofs, or roof components that by the nature of their design, construction, or service, undergo bending or flexing that produces load fluctuations and resultant variable stress conditions. These load cycles may increase susceptibility to SCC through the following mechanisms:

a) fracturing of surface films produced by corrosion thus exposing locally fresh substrate material,

b) promoting local plastic deformation at the crack tip, and

c) introducing fresh corrodent (fuel ethanol and other species) into the crack.

4.5.4 Ambient Air Absorption

Fuel ethanol is not normally handled with procedures designed to exclude oxygen during shipment and storage. However, the results of the API/RFA research study have shown a greater susceptibility to SCC in simulated fuel ethanol environments under conditions of imposed aeration intended to simulate conditions of ambient air absorption during handling and storage. Field corrosion monitoring also showed higher corrosion rates and tendencies for localized corrosion during and after tank loading and unloading operations. This behavior is likely the result of increased corrosion activity (particularly localized corrosion activity within pits and cracks) when fuel ethanol becomes aerated and/or when surface corrosion films become disturbed by agitation. The oxygen solubility of ethanol and similar alcohols is about an order of magnitude greater than that of common aqueous solutions. The greater oxygen solubility in ethanol could make aeration a major factor in corrosion mechanisms and the severity of SCC in fuel ethanol. Recent laboratory studies show that the level of aeration needed to sustain SCC in ethanolic solutions is only a few percent of ambient air saturation. At 2 % to 3 % of air saturation and below, there appears to be no susceptibility to SCC in fuel ethanol.

4.5.5 Corroded Steel

Based on the results of the API/RFA study, it was observed in laboratory tests that the susceptibility of steel specimens to SCC in ethanolic environments was greater when galvanically coupled to sections of corroded (mill-scaled) steel. A similar affect may occur in service when local stress or strain breaks mill scale or corrosion product films on the surface of the material.

4.5.6 Chloride

Another factor that contributes to susceptibility of steels to SCC in fuel ethanol environments is the presence of chloride ions. The ASTM D4806 standard for fuel ethanol provides for an allowable level of inorganic chloride to be present. Previously, the specified limit was 40 ppm (32 mg/L) maximum of inorganic chloride, but this has been reduced in the 2009 version of this standard to 10 ppm (8 mg/L). It was reported in the API/RFA study that the presence of low level chloride (within this limit) could increase SCC severity, and data from recent laboratory studies show that the propensity for ethanol SCC (in terms of crack density and velocity) increases dramatically in the range 1 to 10 ppm of inorganic chlorides in fuel ethanol. It has also been documented that SCC in fuel ethanol was predominantly intergranular in nature. In the presence of low levels of chloride, it was found that cracking can be transgranular or mixed mode (i.e. containing both transgranular and intergranular cracking). However, documented evidence of field failures due to SCC in fuel ethanol has reported a predominance of intergranular cracking. While the recent studies suggest that chloride may be a factor in SCC severity, it is not believed to be the predominant cause in actual fuel ethanol systems. Monitoring the chloride concentration in tank samples of fuel ethanol is recommended if chloride contamination is suspected or if a leak or failure from ethanol SCC has been encountered.

4.5.7 Inhibitors and Chemical Treatments

Fuel ethanol is normally provided with an inhibitor package that is added at the ethanol producer site prior to shipment during storage or at transfer. A range of different inhibitor formulations from various manufactures is available. These inhibitors are typically added in amounts that ranges from 10 pounds per thousand barrels of ethanol (PTBE) to 30 PTBE [4]. The API/RFA program did not find a conclusive effect of inhibition on SCC of steel in laboratory ethanolic environments produced from reagent grade chemicals. However, laboratory SCC tests conducted in actual fuel ethanol samples showed that the noninhibited sample did not show susceptibility to cracking even when aerated, whereas a downstream field sample with inhibitor showed susceptibility to SCC even without imposed aeration. The differences between these results are not presently understood, and there may be an influence of the inhibitor or possibly other variables on SCC susceptibility.

A point often misunderstood is that the inhibitors added to fuel ethanol are not added to prevent corrosion of equipment in the supply chain exposed to fuel ethanol, and they are specifically not intended to inhibit SCC of steel equipment. Rather, these inhibitors are intended to reduce corrosion in internal combustion engines where fuel systems and injection equipment are exposed to blends of ethanol and gasoline. Another feature of inhibitors is that they appear to adjust the pHe value so that it is within the range specified by the ASTM standard for fuel ethanol (see 4.2).

Other forms of chemical treatment have been examined in recent studies for their specific ability to mitigate SCC processes in carbon steel exposed to ethanolic environments. Three broad classes of chemicals that have shown benefits in reducing SCC susceptibility under laboratory conditions are:

a) chemical scavengers for dissolved oxygen in ethanol,

b) pH modifiers that increase the alkalinity of the ethanol,

c) organic inhibitors that actually suppress tendencies for SCC.

While certain compounds in these categories have been shown to work in the laboratory, it is recommended that such chemical treatments be evaluated prior to use in service for their efficacy against ethanol SCC, for conformance with EU and industry-accepted fuel ethanol specifications, and for any unintended issues that they may cause in the distribution system, association processes, or in the final fuel blend used in combustion engines.

4.5.8 Corrosion Potential

It has been observed that the range of corrosion potential for SCC in steel is often limited, but it may be influenced by other parameters such as temperature, galvanic interactions with corroded steel or other materials, level of aeration, and the influences of impurities or additives (e.g. chloride and methanol) in the service environment.

In the API/RFA research effort, in laboratory ethanolic environments, SCC was only observed when aerated conditions resulted in a corrosion potential of steel greater than 0.0 volts relative to an Ag/AgCl ethanol reference electrode usually in the range 100 mV to 200 mV versus this reference electrode. SCC of steel was not observed when conditions resulted in a corrosion potential of less than 0.0 volts versus the Ag/AgCl ethanol reference electrode. Differences in potential were observed when testing field ethanol samples. Monitoring corrosion potential may be a method to assess susceptibility to SCC in service environments. However, more work in this area is needed to provide a complete understanding of the role of potential on SCC, its use as a monitoring technique, and the possible impact of inhibitor additions and other differences between manufacturer and downstream fuel ethanol samples. This is a topic of ongoing research that suggests that monitoring of corrosion potential alone may not be sufficient and the monitoring of corrosion potential along with other variables including dissolved oxygen and possibly inorganic chlorides to provide meaningful and predictive results with respect to SCC.

4.5.9 Ethanol/Fuel Blend Ratio

Laboratory studies and survey work have shown that ethanol SCC may not be limited to only FGE per ASTM D4806. Originally, tests in an API program showed susceptibility to SCC in FGE and E85 (85 % ethanol, balance gasoline) under aerated conditions. Since then, further research has shown that ethanol-gasoline blends of 15 % ethanol or less (E15) do not cause SCC, but SCC growth does occur with higher blends (E20 and higher). These results have potential impact for nontraditional ethanol-containing fuels and in pipeline transmixes of ethanol and hydrocarbon fuels that may develop as a result of batched shipments via pipelines or where such transmixes are handled and stored.

4.5.10 Ethanol Sources/Manufacturing Processes

API-funded research supported by recent technical studies from other research suggest that there may be differences in SCC susceptibility depending on biosources and processes used to make FGE. In limited tests, corn-based ethanol samples produced by the wet milling process showed greater SCC susceptibility than that occurring in dry milled corn-based ethanol samples. Additionally, reduced ethanol SCC severity was observed in sugarcane-based ethanols and butanol under aerated conditions. While these results corroborate results from field surveys, further work is needed in this area.

4.5.11 Others

In addition to the documentation of actual failures by SCC in the United States, the original technical report on SCC in fuel ethanol searched for information on usage of fuel ethanol and its blends with gasoline in other areas of the world. It found extensive research and usage of a form of fuel ethanol called “hydrated ethanol” with higher water content than defined in ASTM D4806 standard. While this form of ethanol was found to be corrosive and certain impurities caused pitting in steel and other material, no reports of SCC were found (see API 939-D).

API research has indicated that susceptibility to SCC in ethanolic environments displays a trend with respect to water content. At very low water concentration (<0.1 vol%), susceptibility to SCC is negligible. In the range of 0.1 vol% to 1.0 vol% typical of ethanol made per ASTM D4806, maximum susceptibility to SCC is exhibited. At higher water concentrations (3.0 vol% or higher), susceptibility to ethanol SCC decreases, with ethanol containing at least 4.5 vol% water showing no susceptibility to SCC in accelerated laboratory tests.

Other impurities found to increase corrosion of nonferrous alloys (e.g. aluminum, alloys, zinc, and brass) exposed to fuel ethanol environments are chloride, sulfur, and peroxide.

There are applications in terminal operations involving the use of small diameter 316 stainless steel tubing subjected to bending and exposed to fuel ethanol. Laboratory tests employing slow strain rate testing techniques have not found ethanol SCC susceptibility in 316 stainless steel. There has been laboratory testing that shows pitting in some stainless steel in ethanolic environments outside of that specified by ASTM D4806 (e.g. high chloride and acetic acid contents).

5 Guidelines for Fabrication of Equipment

5.1 Materials of Construction

5.1.1 Steel

The combination of strength and low cost makes carbon steel the predominant material of construction for equipment used in the transportation, handling, and storage of fuel ethanol. Carbon steel is generally considered compatible from the standpoint of corrosion with fuel ethanol. Corrosion rates are typically low. However, the corrosion rate can periodically increase with the level of dissolved oxygen content of the ethanol, the presence of contaminants, and agitation.

In the API/RFA program, the field corrosion rate measurements in fuel ethanol indicated that the corrosion rates of carbon steel were normally very low, usually in the range 0.01 mpy to 0.1 mpy. This is generally below the level of normal engineering significance for storage and handling applications. During periods of tank loading and unloading, corrosion rates of the steel in the tank were shown to be as high as 1 mpy, which were 10 times those reported during static conditions. When loading and unloading through rack piping, short periods of still higher corrosion rates were found to occur at locations of high turbulence. The periods of higher corrosion rate commonly return to the intermediate or low values found during more quiescent periods when the movement of ethanol is stopped. Corrosion data from field monitoring of ethanol tanks and piping also indicate that these peak periods of corrosion often correlated with episodes of high localized corrosion activity, which suggest periods of increased susceptibility to SCC. While these events are notably short, the concern is for the cumulative effects over long time periods particularly where conditions can switch from passive to active states or vice versa. Under these conditions, localized corrosion processes and SCC processes have been shown in other systems to result in cracking especially in highly stressed or variably stressed components (see API 939-D for more information). During upsets in fuel ethanol composition leading to higher water contents than specified per ASTM D4806 (up to 10 % volume water), corrosion rates under laboratory conditions have been measured to be in the range 1 mpy to 10 mpy.

A microbial field survey has encountered microbiologically influenced corrosion (MIC) of a steel fuel ethanol spillage containment tank. Recent laboratory experimental results demonstrate that microbes isolated from the FGE facility were able to produce acetic acid (a metabolic derivative of ethanol) and accelerate corrosion of carbon steels to 10 mpy to 20 mpy in the presence of ethanol with water content over the range given by ASTM D4806 and also increased the fatigue crack growth rates by over an order of magnitude at intermediate levels of applied alternating stress or stress intensity (ΔK). Biogenic acetic acid produced from ethanol was also found to significantly accelerate MIC by sulfate reducing bacteria (SRB) under these high water conditions, resulting in corrosion rates in the range of 30 mpy to 100 mpy. These results demonstrate the need for awareness of MIC as a possible deterioration mechanism in systems containing ethanol fuels during water upset conditions.

Many grades of carbon steel are used in fuel ethanol service for piping and tanks, including but not limited to: ASTM A36, ASTM A53, ASTM A106, and ASTM A516-70. A pipeline made from API 5L, for example, 5L-X42 and 5L-X52 could also be used. On the basis of the experience survey and laboratory studies in the API/RFA program, susceptibility to SCC in fuel ethanol is not related to steel grade for conventional steels with ferritic/pearlitic microstructures. All grades cited above have exhibited SCC under certain circumstances and applications. No relationship has been found between steel grade and SCC susceptibility. However, aspects of design, fabrication, and operation that may increase SCC susceptibility include:

a) high strength/high hardness or cold worked material,

b) high residual or mechanical tensile stresses,

c) local area of stress or strain concentration, and

d) variable stresses and flexural loading.

Newer equipment and pipelines may involve newer, higher strength grades of steel. Work is in progress to examine API 5L-X70 and X80 grade steels made with lower carbon content, thermomechanically controlled processing (TMCP), and microstructures containing acicular ferrite and bainite for potential benefits with respect to resistance to SCC. While these steel have been found to have better resistance to ethanol SCC than older vintage piping and plate steels (e.g. ASTM A36 and A53), they still have a moderate susceptibility to SCC.

5.1.2 Other Metallic and Nonmetallic Materials

5.1.2.1 Some components used in tank roof systems may be made from aluminum or steel with a galvanized (zinc) coating. Some studies show aluminum to be compatible with ethanolic environments, while others suggest significant corrosion rates. Lead, zinc, and brass have been found to have significant corrosion rates in ethanolic environments, and they should not be used for components involved with containment of fuel ethanol.

5.1.2.2 Fuel ethanol and gasoline ethanol blends have been found to be incompatible with certain polymeric coatings. Therefore, selection of coatings for fuel ethanol service should be based on long-term compatibility of the coatings (and specific formulations) with ethanolic environments under conditions of full immersion obtained from either laboratory or field tests or field service experience. Older steel tanks that may have been internally lined for other types of service may have internal coatings not suitable for storage of fuel ethanol.

5.1.2.3 While nitrile and natural rubber may be considered incompatible with some ethanolic blends and fuels, fluorocarbons, fluorosilicones, and ethylene propylene diene monomer are generally compatible. A list of generally compatible (and incompatible) polymeric materials is provided in Table 2.

Table 2—Generally Compatible and Incompatible Polymeric Materials

Elastomer Compatibility with E10		Elastomer Compatibility with E85	
Suggested	**Not Suggested**	**Suggested**	**Not Suggested**
Acrylonitrile (hoses and gaskets)	Acrylonitrile (seals)	Nitrile rubbers	Natural rubber
Fluorocarbon	Urethane rubber	Polychloroprene	Cork gasket materials
Fluorosilicone	Polychloroprene (seals)	Polytetrafluoroethylene	Leather
Natural rubber		Fluorocarbon	
Polychloroprene (hoses and gaskets)		Acrylonitrile	
Polysulfide rubber			

5.1.2.4 Laboratory and/or field testing of new formulations of polymeric materials for seals and gaskets for fuel ethanol service is recommended that includes the range of ethanol concentrations, temperatures, and the applicable exposure condition (immersion, vapor, alternating exposures, etc.) anticipated in the service application, and that covers both static and dynamic sealing conditions.

5.2 Tank Foundations

There has been some indication that the foundation of the tank can influence the SCC behavior of tanks. Settlement of the tank can result in excessive bending and locally high stresses at locations on the tank bottom that are possible sites for SCC damage to occur. One case included bending of the bottom plates around the concrete ring wall on the outer perimeter of the tank due to poor soil compaction or backfill under the tank. The bending produced plastic deformation and high tensile stresses at this location on the inner surface of the bottom plates, resulting in SCC at multiple locations.

Ethanol tanks should be placed on secure foundations with acceptable resistance to subsidence and resultant high stresses that may initiate SCC. They should also include tank foundation designs that will provide for early detection of releases of fuel ethanol. Acceptable methods and guidelines for tank construction, foundations, and repair are provided in API 650 and API 653 for the refining sector, with additional information specifically for terminal facilities are available in API 2610.

5.3 Fabrication of Tanks

Guidelines and related information for the design and construction of atmospheric storage tanks (including aboveground, flat-bottom storage tanks) are given in API 650. Acceptable methods for tank construction for terminal facilities are available in API 2610. Refer to API 582 for guidance on weld fabrication.

Certain fabrication practices can help reduce the likelihood of cracking in carbon steels in fuel ethanol service. These are discussed in the following section. Generally, hardness of carbon steel weldments is not the foremost concern in ethanol service since most of the materials exhibit low hardness (<200 HB) value even without subsequent PWHT. Also, most SCC in fuel ethanol has been located in the base metal adjacent to welds and not actually in the weld HAZ. This suggests that the mechanism of SCC of steel in fuel ethanol in not related to hydrogen charging but rather associated with local anodic mechanisms as in the case of SCC in other environments.

5.4 Fabrication Guidelines to Minimize SCC

5.4.1 Most SCC failures of carbon steel components in fuel ethanol have initiated at locations of high tensile stresses resulting from residual, mechanical, and/or flexural sources. Therefore, care should be taken to review piping and tank designs and fabrication and installation techniques to minimize various sources of excessive tensile stress. The following guidelines are provided as general information.

Minimize the use of lap seam welds that create a natural concentration of strain in the base metal adjacent to the weld. Where possible, the use of butt welding is suggested as these welds produce a more uniform overall stress condition with lower concentration of bending and mechanical stress than lap seam welds. In some applications, such as floating roofs, use of the double lap welds might be considered since they could reduce the problems associated with single lap welds.

Other fabrication procedures that increase resistance to SCC include the following.

5.4.2 Minimize cold working and plastic deformation in fabrication, fit-up of piping, plates and components, and field bending of pipeline segments. This will reduce the levels of residual and mechanical tensile stresses. Whenever possible, shop or controlled bending or hot forged elbows or induction bends should be used. The use of PWHT should be considered. See 5.6 for more information on PWHT.

5.4.3 Full penetration welds and fillet welds should be utilized as partial penetration welds and stitch welds have higher stress concentrations and associated tensile stresses.

5.4.4 Minimize changes in section size of piping with fittings that, in the case of mismatch, can be a site for concentration of bending, pit-up stress, and plastic strain.

5.4.5 Make sure that the tank foundation is secure and will not result in subsidence that will locally stress bottom plates, particularly in the region of the floor to side wall welds and where the floor may be cantilevered downward from the ring wall by subsidence.

5.4.6 For new weld construction and repairs, PWHT has been used to reduce susceptibility to SCC by reducing the level of tensile residual stresses in weldments to lower levels. These procedures have been mainly used in applications involving piping and equipment in ethanol storage and blending facilities where SCC has been observed or is anticipated. It is recognized for storage tanks that under most circumstances, such stress relief procedures are impracticable or not possible.

5.4.7 Where PWHT is impractical or not possible, other methods may be required to reduce the local susceptibility to SCC. Alternative methods may include the following.

a) Application of ethanol resistant polymeric coatings that act as a barrier between the steel and the fuel ethanol at locations of greatest susceptibility. Experience has shown that as long as the coating remains intact and an effective barrier between the steel and the fuel ethanol, it will eliminate cracking. However, if the coating barrier is impaired by chemical attack, or penetrated by cracking, crazing, or disbonding of the coating, SCC can occur.

b) Tanks with riveted constructed, by their nature, have highly stressed steel rivets, a likely source of SCC initiation. No experience has been cited to date for ethanol SCC in riveted tanks. The use of these tanks is not preferred. More information is needed to evaluate the use of these tanks in fuel ethanol service.

5.5 Specific Guidelines for Minimizing SCC in Various Components

5.5.1 General

This section provides guidelines for methods to minimize susceptibility to SCC of steel components and equipment in fuel ethanol service. The methods presented herein may not be applicable in all cases. It is the user’s responsibility to assess the applicability and need for any of the procedures described in this section.

5.5.2 Tank Bottom and Roof

Most tank bottoms and floating roofs are made by lap seam welding and naturally involve flexing during tank loading and unloading operations. Lap seam welding has been the common method of construction for these items for reasons of economy. However, application of resistant coatings on exposed bottom and roof surfaces has been used successfully to minimize SCC. This requires sealing, caulking, or welding of the lap seams to exclude intrusion of ethanol and to provide an acceptable surface for coating.

5.5.3 Shell

Most SCC observed in shells of tanks has been at the shell-to-bottom interface, nozzle penetrations, or around vertical or seam welds in the lower portion of the tank. However, SCC was observed at higher locations (up to 8 ft) in a storage tank exhibiting prior corrosion damage and wall thinning. To minimize the occurrence of SCC, only the bottom portion of the tank has been coated. The need for coatings and the height of coating on the shell may be based on experience in particular applications.

5.5.4 Piping

The predominance of SCC in piping has been around non-PWHT welds and low heat input tack welds in rack piping. Replacement piping should receive full penetration welds, PWHT to reduce residual stresses, and minimization of cold bending and deformation in pipe fit-up. Additionally, care should be taken to provide sufficient support to minimize vibration and stresses resulting from thermal expansion and contraction.

5.5.5 Pipelines

Data for pipelines in ethanol service are limited, and caution should be used when applying guidelines from this document that have been derived mainly from applications involving piping and tanks in ethanol storage and blending facilities. There have been two reported occurrences of ethanol SCC in steel pipelines: one in the United States and one in Europe. These were both in a bend region of high local tensile stress, not necessarily associated with a girth weld. Therefore, preventative action for fuel ethanol pipelines should include minimizing local mechanical and resultant tensile residual stresses through design, maximizing bend radius to reduce the level of plastic strain, and where practical or applicable, use of heat treatment following welding or forming operations (see 5.6).

Other aspects unique to buried pipeline applications that need to be considered in terms of SCC susceptibility are

a) the range of ethanol concentrations produced in transmixes with other hydrocarbon fuels;

b) impact of using chemical additives (oxygen scavengers, pH modifiers, and SCC inhibitors) as SCC mitigation methods;

c) methods for in-line inspection (ILI) for detection of internal SCC versus external SCC detection that is more commonly necessary for buried pipelines. A recent case of ethanol SCC in a pipeline found in the API survey was cracking identified prior to failure by use of hydrostatic testing to 1.3 times the design pressure of the line;

d) the presence and severity of dents that can be locations of high residual stress, local strain, and cold work;

e) field bending practices where the use of field trimmed, segmented elbows, induction bends, and precise survey techniques for field bending are critical to reduce residual stress, especially at tie-in locations.

5.6 Guidelines for PWHT

There have been limited studies documented on the effect of PWHT on SCC of steel in fuel ethanol. Recent studies by API, PRCI, and U.S. DOT provided to be inconclusive on the effect of PWHT and other weld procedure modifications designed to reduce residual stresses due to a lack of crack initiation. However, API surveys have not identified any cases of ethanol SCC in weldments with PHWT using the procedures defined later in this section.

It is expected that PWHT is of benefit primarily through the reduction of residual tensile stresses in the area of weldments and areas of plastic deformation and it should be considered the primary SCC mitigation technique available for facilities piping. A procedure for PWHT documented from one EU for stress relief of piping in fuel ethanol service involved heating to 611 °C (1150 °F) minimum and holding at this temperature for 1 hour per 25 mm (1 in.) of metal thickness, or fraction thereof, with a 1-hour minimum hold time.

5.7 Organic Coatings for Internal Protection of Tanks

5.7.1 General

When considering the coating of ethanol tank bottoms, several major decisions need to be made as well as several subdecisions within the context of the major decisions. The major decisions with respect to coating tanks to prevent SCC are:

a) coating the bottom and up the sides (and how far up),

b) coating the shell and the bottom, and

c) coating of all wetted surfaces including the floating roof.

5.7.2 Coating the Tank Bottom

When the bottom is coated, it is traditional to coat both the inside corner weld as well as about 2 ft to 3 ft up the shell for several reasons. First, any water bottoms will tend to corrode both the bottom as well as several inches up the sides due to the layer of water sitting in the tank bottom. Another reason is that the incremental cost of protecting this area with coating is small when compared to the cost of coating the overall bottom. When considering bottom coating for the purpose of preventing ethanolic SCC, then it is reasonable to coat as much of the shell as feasible without attempting to coat the floating-roof seal area that is usually located from 5 ft to 7 ft when the floating roof is landed in the “high roof” position. For the most part, tanks storing ethanol would use a floating roof with a seal due to the volatility and hazards of ethanol vapor.

If the tank has a floating roof, it is usually feasible to coat up to within about 1 ft of the bottom of the floating-roof seals. This distance, of course, will vary as stated above. Since the most flexure of the tank bottom is within the bottom several feet, it would make sense to coat as much of this area as possible.

5.7.3 Coating the Tank Bottom and Shell

Because some cracking has occurred in tank shells as well as tank bottoms, and depending on various risk factors, a company may wish to ensure the prevention of SCC by coating the bottom and shell. This of course increases the costs significantly. The major factors that affect this are:

a) the tank floating-roof seal must typically be removed to do the coating,

b) scaffolding is typically required for the coaters to work at height, and

c) the volume of air that may have to be heated or dehumidified may require substantial air conditioning systems to ensure proper coating.

5.7.4 Coating All Wetted Surfaces

The ultimate degree of protection against ethanol SCC in storage tanks is to coat all wetted surfaces, including those of the floating roof. However, there is a significant problem associated with coating floating roofs. Typically, the underside (or wetted side) of the floating roof is lap welded. Experience has shown that caulking these laps does not work. Therefore, it is essentially impossible to keep ethanol from contacting bare steel surfaces between the laps on the underside of the roof. One possible solution is to seal them by welding. For an existing floating roof, this could be cost prohibitive because the laps would have to be forced together and there is no easy way to do this. For new tanks, it is much easier, though still costly compared to a typical floating roof, to use full lap welds on the entire underside of the floating roof. The need to take the extraordinary measures to prevent SCC in a floating roof must be weighed against the site and business specific risks associated with suffering an unanticipated failure in service.

Coating effectiveness depends on the coating acting as a chemical barrier between the fuel ethanol and the steel. Coatings with demonstrated chemical resistance to ethanol and gasoline mixture under conditions of full immersion are needed for this service. It has been found the some epoxy coatings (e.g. novolac or phenolic epoxies) should provide acceptable performance over a period of several years of service. When a coating disbonds and the effectiveness of this barrier is lost, ethanol SCC can occur. The most frequent cause of coating disbondment and coating failure is insufficient surface preparation. To use coatings effectively for ethanol SCC mitigation, the coating must be compatible with fuel ethanol service and must be applied properly. See API 652 for further guidelines on coating and lining of tanks.

6 Inspection of Existing Equipment

6.1 General

The guidelines given in this section are intended for the inspection and repair of existing equipment used to handle and store fuel ethanol. Examinations referred to in this section emphasize inspections for cracks produced by SCC in steel equipment exposed to fuel ethanol. API 653, API 574, API 510, and API 570 as relevant to specific equipment, provided guidance, and procedures for inspection. Inspection of equipment in ethanol service should be conducted or supervised by experienced, certified inspectors who have comprehensive knowledge of the specific equipment, its materials of construction, and its operating, maintenance, and inspection history The owner should take responsibility to determine the operator competency level in the use of all inspection methods for identification of ethanol SCC.

In most cases, the surface that has experienced SCC in fuel ethanol will not be severely attacked by corrosion due to the inherently low corrosion rate of steel in this service environment. However, many tanks used to store fuel ethanol have been converted from other service applications and may have some degree of internal corrosion present.

Inspection for SCC is complicated by the fact that such cracks are tight. Furthermore, cracks produced by SCC are internal, are not always oriented exclusively axially or circumferentially, and in piping, pipelines and equipment and they may not be in locations readily accessible for visual or surface inspection methods and may also complicate other forms of nondestructive testing (NDT). In extreme cases after significant SCC growth and crack opening, cracks may be visually apparent, but at this point, leakage may be near or have already occurred. Frequently, the only way to observe cracks arising from SCC in carbon steel is with the aid of nondestructive techniques.

In several cases of SCC in fuel ethanol, locations of cracking were first identified by visual indication of leakage from pipe joints or from around the bottom of storage tanks. However, examination for leakage is not a good method for detecting SCC in ethanol system because the high volatility of ethanol facilitates evaporation.

6.2 Inspection Intervals

Many steel tanks and related equipment have not experienced SCC in fuel ethanol for several years. However, there have been several cases where SCC has been experienced in less than 12 months after the equipment was placed in fuel ethanol service. Experience to date is insufficient to establish a recommended inspection interval. Therefore, the appropriate inspection interval is up to the user to determine. It should be realized that because of the nature of SCC, crack initiation and growth rate may vary substantially depending on local stress exposure conditions from time-to-time.

On the basis of laboratory tests, the stress intensity for SCC of steels appears to be in the range of 35 ksi $\sqrt{in.}$ to over 50 ksi $\sqrt{in.}$, indicating that the range of stress for the initiation of ethanol SCC is rather high compared to other forms of SCC. Crack growth rates of steel for environmental conditions supporting ethanol SCC have been observed in the range of less than 1×10^{-6} mm/sec to over 6×10^{-6} mm/sec. This range of crack growth rates is high enough that this form of SCC cannot be mitigated by inspection alone.

The priority of equipment examination should consider the associated risk of leakage and include consequences of a leak or a failure on the surrounding area, methods of containment, operating conditions, criticality of the equipment, and inspection and repair history of similar equipment at the facility. The general methodology for a risk-based approach for inspection is outlined in API 580 along with specific applications where SCC is a factor. At the date of publication of this document, a risk matrix for SCC in fuel ethanol has not yet been included in API 580 and may need to be developed by the user.

6.3 Inspection After Leakage Caused by SCC

Any equipment that has undergone a documented case of SCC at a particular location as identified by a failure analysis (with positive indication of ethanol SCC) after repair should be taken out of service at the first possible opportunity and inspected more completely for the extent of SCC. A review of all equipment in fuel ethanol service at this location should be made and prioritized for inspection for SCC. The highest priority locations for inspection are those that have been found to be likely locations for SCC in fuel ethanol handling and storage systems (see 4.4.3 for locations and percentages of SCC occurrence from survey results). In most cases, the cracks are in the base metal adjacent to the weld HAZs in non-PWHT welds, in cold worked material, or at highly stressed and/or cyclically stressed areas in equipment. These include the following common locations:

a) butt welds in piping and fittings;

b) seam and nozzle welds in the tank shell;

c) lap seam welds in tank bottom and floating-roof systems and in related equipment;

d) corner welds between the tank bottom and shell;

e) springs in floating roofs;

f) in piping, fittings, and equipment that have received cold work or have high mechanical stresses from misalignment or poor fit-up;

g) where field bending in pipeline segments has been performed;

h) sites of severe denting in pipelines

6.4 Initial Inspection Without Leakage

For equipment that has not leaked, an initial inspection should be made of any welded or cold worked steel in equipment, piping, and fittings that has not received PWHT. The locations and severity of cracking should be documented and prioritized relative to the risk and consequences of leakage. High priority locations (as noted in 4.4.3) should be checked for cracks at the next scheduled shutdown or when the tank is out of service for any extended period. Partial inspection of representative areas around weldments or in highly stressed locations with approximately 20 % coverage should be performed first. Additional inspections should be performed if cracking is detected by this initial examination. If cracking is found at a location, more in-depth inspection and evaluation techniques are needed, as given in 6.5.2 to 6.5.5.

6.5 Examination Procedures for Identification of SCC

6.5.1 Visual Examination

Visual inspection for SCC in fuel ethanol systems is complicated by the fact that such cracks are tight and filled with rust or corrosion products. Consequently, locations of SCC cannot be readily seen visually with the naked eye or even, in some cases, with low power optical examination. Therefore, visual examination is often limited to identification of a source of product leakage from the base of a storage tank, welded fitting, or other location.

Visual examination of noninsulated piping and tanks that are in operation can detect leaks at welds and other potential problem areas. However, due to the volatile nature of fuel ethanol, some small leaks may be occurring even when the leak is not easily apparent by visual means. The presence of a bubble in a painted surface of a tank, pipe, or around a weld can indicate the location of a tight crack produced by SCC. Such cracks can weep causing the paint to bubble. An actively dripping leak or seepage obviously indicates a problem that warrants immediate attention and determination of its cause.

6.5.2 Wet Fluorescent Magnetic Particle Testing (WFMT)

Dry fluorescent magnetic testing (DFMT) is used for tank inspection. However, it is not recommended for inspection of tight cracks produced by SCC that are typically filled with rust or corrosion products. WFMT is a more sensitive and commonly used method for detecting surface-connected cracks and discontinuities. Methods for using WFMT for internal tank inspection are generally similar to those used for inspection for other types of SCC (e.g. amine or carbonate SCC).

Two general methods are available for magnetizing the steel under inspection. These are AC yoke and half-wave DC prods. The AC yoke methods achieve greater sensitivity in locating surface defects and also reduce the effects of background interference. DC prods provide improved penetration of the magnetic field into the area but provide little additional benefit in locating surface connected SCC. Further, the use of DC prods can induce arc burns that could initiate future cracking.

WFMT requires surfaces to be cleaned to a near-white metal finish that meets the requirements of NACE No.2/SSPC SP 10. Additional light grinding may be needed to distinguish cracks from surface or weld discontinuities. However, the entire internal surface does not have to be prepared for inspection. Residual abrasive material and debris should be removed from the area before inspection. In some cases, inspection for some forms of SCC has been enhanced by subsequent cleaning of the surface using flapper wheels or flexible abrasive sanding pads. This careful surface preparation should be used at least on the most critical areas where SCC is most likely to occur.

Abrasive blasting or high pressure water jetting at a pressure of 70 MPa (10,000 psig), or higher, may also be used. If inspecting in the region of a weld, the area prepared for WFMT inspection should normally be 100 mm to 150 mm (4 in. to 6 in.) on either side of the weld encompassing the surrounding base metal. This allows for crack detection in the base metal adjacent to the weld, a location common for SCC in steel equipment exposed to fuel ethanol. A complication with surface inspection for SCC is that cracks have been observed on the internal surfaces where external attachment welds have been made. Additionally, internal cracks in lap seam welds have initiated remote from the visible weld seam where the underside plate ends. This location produces a concentration of bending and resultant high stress in this location, making it prone to SCC. Therefore, for internal inspection of lap seam welds, make sure that the area prepared for WFMT includes the overlap area of the weld.

6.5.3 Shear Wave Ultrasonic Testing (UT)

Shear wave UT, using either manual or automated methods, may be useful for detection of SCC in equipment not amenable to internal inspection by WFMT. UT methods include longitudinal wave, shear wave, crack tip diffraction, time of flight diffraction (TOFD), and phased array (PA). Longitudinal wave UT is mostly used for finding internal planar defects such as hydrogen induced cracking (HIC) and is not of interest for detection of SCC in fuel ethanol.

In the case of SCC, cracks initiate from an internal surface and generally grow in a through-thickness manner. Shear wave UT is useful for evaluation of through-thickness cracking by a number of mechanisms including SCC. Shear wave UT is particularly useful for inspection where direct examination of the internal surfaces is difficult or not possible. Such cases include piping or tank nozzles where access to the external surface is available.

TOFD can also be used to manually locate and map out SCC from the outside surface of the equipment, and it is a well-established technique. PA can also locate and map SCC as well as provide an electronic means of saving the inspection findings for future evaluation.

UT methods are most useful in locating and sizing the extent of through-thickness cracks that are deeper than approximately 3 mm (0.125 in.). However, the effective use of this inspection method depends highly on the UT operator's knowledge, skill, and experience levels. Small tight cracks produced by SCC may be overlooked by an inexperienced operator, or the cracking might be so tight, corrosion product filled, or shallow, that their UT signals are not easily identified. Manual shear wave over a large item may be tedious work. Therefore, the operator can become less reliable over time due to fatigue from looking for small indications.

Pipeline operators have suggested that UT shear wave sensors may also be used for ILI of pipelines used to handle FGE; however, the sensors need to be configured depending on the orientation of the cracks produced by SCC. Presently, most UT ILI tools are configured for longitudinal cracking, whereas the two cases of ethanol SCC found in pipelines thus far were cracks oriented circumferentially, likely produced as a result of the residual tensile stress from bending. In cases where ILI crack inspections involve possible cracks in both longitudinal and circumferential orientations, multiple passes of tools will likely be necessary.

See 6.1.1 for further information on crack geometry complicating inspection for ethanol SCC.

6.5.4 Alternating Current Field Measurement (ACFM)

ACFM is an electromagnetic technique that can be used to detect and size surface-breaking cracks in ferromagnetic materials such as steel. The method can be applied through thin coatings or mill scale and does not require as extensive surface preparation as needed for WFMT. The sensitivity of ACFM decreases with increasing thickness of the coating or scale. It is best used as a screening tool for rapid detection of cracking along welds, weld HAZs, or other cracking regions with little or no surface preparation, in lieu of WFMT.

There are some situations where ACFM can be used for sizing the length of cracks; however, the likely branched morphology of many cracks produced by SCC makes this technique more appropriate as a screening tool for evaluating steel equipment for SCC in fuel ethanol rather than a tool for quantifying actual crack length. Furthermore, ACFM has the same limitation when used for inspection of closely spaced cracks and nonthrough wall oriented cracks, which is also a characteristic of SCC. Interpretation of ACFM is more complicated than WFMT. Highly skilled, experienced operators are essential to the success of ACFM inspection.

6.5.5 Eddy Current (EC)

Many companies have worked hard to qualify EC procedures for crack detection, but thus far, there has been no documented field experience with its use to detect of SCC produced by fuel ethanol. Because of the minimal thickness of corrosion products on steel surfaces exposed to fuel ethanol, EC inspection may be a natural consideration. Overall, the results with EC inspection methods for detection of other environmental cracking mechanisms (e.g. wet H_2S cracking) have been good within certain limits. On the basis of this experience with wet H_2S cracking, EC methods should also be able to detect deeper SCC cracks (e.g. 0.050 in. or deeper). However, EC inspection will not generally identify shallow surface breaking flaws with a similar success as WFMT. Therefore, EC inspection is a developing technology that is increasingly being used for detection of environmental cracking. However, as with any nondestructive examination (NDE) technique, detailed procedures and qualified personnel are needed to achieve confidence in the results.

6.5.6 Other Inspection Methods

Other inspection methods commonly utilized to assess the conditions of operating equipment are radiographic testing (RT) and liquid penetrant testing (PT). RT methods are not very sensitive to SCC unless the cracks are reasonably large or severe. If cracks are observed with RT, a more extensive examination by UT should be considered. PT is not a recommended inspection method for SCC because it does not reliably reveal the tight cracks common to this mode of cracking.

In pipelines and other pressure-containing equipment, ethanol SCC may be detected by hydrostatic testing. One such case was reported in the detection of internal SCC in a pipeline exposed to fuel ethanol through hydrostatic testing at 1.3 times design pressure.

6.5.7 Destructive Sampling and Testing

The presence of a leak in a tank, pipe, or other equipment in ethanol service does not necessarily indicate the presence of SCC. The presence of leakage or cracking at multiple locations does suggest the possibility of SCC. Before remedial actions are implemented, it is recommended that a sample of the equipment from the cracked or leaking area be removed for metallurgical examination by a specialist competent in corrosion and SCC for positive determination of the mode and morphology of cracking. There have been several cases where SCC was suspected but where a metallurgical analysis revealed that the crack producing the leakage was from another cause, such as poor weld quality or mechanical failure.

7 Repair of SCC Damaged Equipment

7.1 General

The repair methods discussed in this section are generally for tanks and large diameter pipe. Small diameter piping [50 mm (2 in.) or less in diameter] can usually be replaced with new at a lower cost than in situ repair. Stress relief should be considered where needed based on assessment of risk and likelihood of SCC.

7.2 Assessment of Fitness-for-service and Risk

Before equipment with SCC is returned to service, it may need to be repaired or replaced. If further evaluation of the serviceability of the components are required, assessments of fitness-for-service and operating risk may be performed. General methods for evaluation, fitness-for-service, and risk assessment are provided in API 579-1/ASME FFS-1 and API 581, respectively. Since these documents do not currently include important aspects of SCC in fuel ethanol, they should be supplemented with information obtained from company-specific service experience and that provided herein or from findings described in API 939-D.

7.3 Temporary Repair by Clamps and Patches

In some cases where SCC is encountered in low pressure equipment or in low stressed areas of piping systems, clamps and patches have been used to stop leakage. Normally, these are considered temporary methods that allow continued operation of equipment until a system can be emptied or until an inspection can be scheduled and repairs implemented. Before using these remedial methods, assessment of operational risk and its consequences should be conducted.

Mechanical peening of the external surface of a leak in an effort to stop the leak is not an effective means of leak control for cracking initiating from the internal surface of the equipment. Peening can also induce plastic deformation and tensile residual stress. Therefore, it should not be performed or relied on as a method for controlling leaks due to ethanol SCC.

For pipeline carrying hazardous liquids, patches and half soles are not allowed. Options for repair or remediation of pipelines following identification of SCC should be application of a pressure-containing 360° circumferential sleeve as defined by ASME B31.4 and API 1160. The temporary repairs should be made in a safe manner and in accordance with the manufacturer's instructions. As soon as practical, the temporary repairs shall be replaced in a permanent manner or welded permanently, if so designed. Derating (lowering) the line's maximum operating pressure may be required until permanent repairs are made, depending on the conditions and the design of the temporary repair. Sealing materials used in repairs need to be compatible with exposure to fuel ethanol.

7.4 Crack Repair

7.4.1 General

This section provides reference to methods of removal or repair of cracks formed as a result of SCC in fuel ethanol. It should be realized that although these methods effectively remove cracks, they do not necessarily mitigate the situation that caused the cracks from ethanol SCC. Additional procedures may be necessary to provide extra protection from further cracking. These including the possible use of PWHT or coatings as discussed in 5.6 and 5.7, respectively.

7.4.2 Crack Removal by Grinding

Surface grinding is one method for removing cracks and other discontinuities found by inspection. It should be utilized only where it is an acceptable practice (e.g. tanks and facilities piping) and when the depth and extent of cracking is believed to be limited to within the corrosion allowance of the equipment or deeper, if analyzed and found acceptable per fitness-for-service methods found in API 579-1/ASME FFS-1. Caution needs to be used to limit excessive heating of the metal during this process. During grinding, the area in question should be periodically checked (preferably by WFMT) to assure that all defects are eliminated. In thin sections with extensive cracking, replacement may be a quicker and more reliable method of remediation than grinding.

If the defect depth is less than the corrosion allowance, an acceptable repair could consist of removing the defect by grinding and feathering or contouring the edges of the grind out area to remove sharp edges, thus providing a smooth transition to the surrounding surface. Welding may not be necessary when this technique is used.

7.4.3 Crack Removal by Flame or Arc Gouging/Cutting

Flame or arc gouging/cutting (if used) must be performed with care, since these procedures may also cause the defects to grow as a result of thermal heating, residual stresses, and metal expansion. Gouging may be more appropriately used in thicker sections and should be followed by grinding and periodic WFMT to check for defect removal.

7.4.4 Crack Repair by Welding

Repair welding should be in accordance with the applicable code or standard. When all repairs are completed, repaired areas should be examined using the same NDT method that was initially selected or, at least, with WFMT. Other methods may be used to supplement the examination of these repairs, as needed. Since SCC in fuel ethanol appears related to areas of high strain or strain concentration and high residual stresses, consideration should be given to the use of low stress welded configurations and procedures, and PWHT should be given, where possible, or to the application of resistant coatings to act as a barrier between the fuel ethanol and the steel equipment where PWHT is not possible or practicable.

7.5 Stress Relief Heat Treatment Applied to Piping and Components

7.5.1 After the existing equipment has been repaired and thoroughly inspected, consideration should be given to performing a stress relief heat treatment.

7.5.2 PWHT is considered essential when weld repairs are performed on equipment that originally received PWHT.

7.5.3 If weld repairs are performed on equipment that did not originally receive PWHT, PWHT of repair welds should be considered.

7.5.4 If there is no history of cracking problems and if thorough inspection has revealed no evidence of cracking in the equipment, PWHT might not be warranted.

7.5.5 PWHT guidelines for repair welds in carbon steels should follow the guidelines given in 5.4 and 5.6.

7.6 Coatings

For cases where PWHT of welded fabrication or cold working is not possible, coating of the weld area should be considered. Guidelines for coatings are given in 5.7.

8 Monitoring of Fuel Ethanol

8.1 Sampling and Analysis of Fuel Ethanol

Sampling and analysis of fuel ethanol is generally accepted as a method to assure product quality for fuel ethanol and its blends with gasoline. Procedures are provided in ASTM D4806 and the standards referenced therein for sampling and analysis of fuel ethanol. A system of sampling and analysis should be maintained to assure that both deliveries and stored quantities of fuel ethanol conform to the standards in ASTM D4806. This system should include documentation of shipments of fuel ethanol upon receipt and sampling of fuel ethanol contained in storage tanks to the extent practicable. However, based on the results of the API/RFA program, such monitoring will not necessarily prevent the occurrence of SCC, but it may develop additional information for assessment of SCC risk. SCC was observed to occur in fuel ethanol compositions that were within the ASTM D4806 standard. The recent update of the ASTM D4806 standard reduced the allowable maximum level of inorganic chlorides to 10 ppm (8 mg/L) (see Table 1 herein). However, laboratory SCC tests conducted in the range of 0 to 10 ppm (8 mg/L) inorganic chloride in ethanol showed increased propensity for SCC over this range in terms of crack density and velocity. If ethanol SCC has been encountered, measurement of inorganic chloride content is recommended to determine if their presence might be a factor in the case of SCC.

8.2 Methods for Monitoring and Testing for Corrosion and SCC

Methods of assessing susceptibility to corrosion and SCC in fuel ethanol examined has included:

a) field electrochemical or electric resistance corrosion monitoring;

b) field exposure of stressed U-bend or wedge load fracture mechanics specimens (compact tension or double cantilever beam specimens;

c) laboratory slow strain rate testing per NACE TM0111 (with smooth or notched tension specimens);

d) electrochemical testing to determine the electrochemical potential of steel relative to that which has been shown in laboratory experiments to be necessary for ethanol SCC;

e) monitoring of dissolved oxygen concentration in the environment to determine the extent of oxygen saturation. The combination of high electrochemical potential and moderate to high dissolved oxygen concentration in ethanol have been shown in laboratory experiments to correlate with conditions where ethanol SCC can develop.

While none of these methods has thus far been completely able to identify occurrences of SCC, they have been shown to provide useful information for characterizing conditions that promote SCC. Detailed methods and test results for these techniques are provided in the reports contained in API 939-D.

Annex A
(informative)

Listing of Reported Cases of SCC in Fuel Ethanol and Remedial Measures

Case No.	Location	Equipment	Service Period	Source of Ethanol	Inhibitor	Steel	Description
A1 1	West Coast Terminal	EU (end user) tank: — built in 1940 — bottom replaced in 1991 — 78 ft diameter steel pan — internal floating roof	10 years	During the past 4 years: — 89 % reported to be domestic sources — 6 % one source unknown — <5 % from additional 10 suppliers	Dependent on source/not consistent	ASTM A36	— Double bottom tank — WFMT identified 18 cracks in or near bottom fillet welds — Plate/plate lap seams and corner welds — Floating-roof springs also failed — First course butt weld seam check but no cracks found — Cracks found in 1 nozzle weld — Metallurgical analysis performed — Repairs: cut out cracks in bottom, corner welds ground out — Remedial: Tank bottom and lower 3 ft of shell were epoxy coated
A2 2	West Coast Terminal	EU tank: — built in 1940 — bottom replaced in 1991 — 78 ft diameter steel plan IFT	10 years	Same as above	Dependent on source/not consistent	ASTM A36	— Double bottom tank—suspected leak — WFMT revealed numerous fine cracks — Cracks in or near bottom fillet welds (plate/plate lap seams and corner welds) — Floating-roof springs also failed — Metallurgical analysis performed — Repairs and remedial same as above
A3 3	Great Lakes Area Terminal	EU tank: — built in 1954 — bottom replaced in 1992 — 52 ft diameter EFT with dome	10 years	Past 18 months: 1 supplier—reported to domestic source	Yes Octel DCI 11 at 30 lb/1000 bbl	ASTM A36M	— Double bottom tank—suspected leak — Vacuum box test revealed long crack in annular plate butt weld — Metallography revealed IG SCC — Subsequent WFMT revealed numerous fine cracks near bottom fillet welds (lap seams and corner welds) and shell inset plate butt weld seams but none in the original shell vertical butt-weld seams — Repairs: Same repairs as described above are planned; annular ring segment will also be replaced

Case No.	Location	Equipment	Service Period	Source of Ethanol	Inhibitor	Steel	Description
A4 4	Great Lake Area Terminal	EU ethanol piping: constructed in 1995	7 years	Past 18 months: 4 suppliers—all reported to be domestic sources	Dependent on source/not consistent	ASTM A53 Gr B seamless	— Carbon steel, low pressure, ethanol piping developed small leak/seeps near pipe support — 2 coupons were sent for analysis that indicated IG SCC and a small area near largest crack with TG propagation — Cracks initiated near where pipe was welded to the support shoe — Repairs: Line is being replaced with new nonwelded pipe support, and piping will receive PWHT
A5 5	Mid-continent Terminal	UE ethanol piping: constructed in 1995	7 years	Past 18 months: 4 suppliers—all reported to be domestic sources	Depended on source/not consistent	ASTM A53 Gr B seamless	— Carbon steel, low pressure ethanol pipeline developed a small leak/seep near butt weld joint and at mechanical hanger support. No lab analysis — Repairs: Temporary repair made with pipe clamp with monitoring
B1 6–7	West Coast Location	2 EU tanks: new bottoms installed in 1991 when put in ethanol service	4 years	Most recent cargos before failures were fermented and distilled in Europe, shipped to South America; dewatered using benzene, shipped to the United States; then denatured using 3 % to 5 % unleaded gasoline	Unknown, probably not	ASTM A36	— Both tanks found leaking (substantial) in 1995 — Cracks found in bottom, generally parallel to weld outside HAZ — IG cracking noted with some branching — Scale was iron oxide, carbonate, no sulfate — Acetic acid found in water sample — Karl Fischer water analysis found 0.62 %v water in middle/top composite samples and 1.21 %v in bottom sample
C1 8–10	West Coast Location	3 EU tanks: — double bottomed and put into MTBE service in 1998; changed to ethanol in 2002 — double bottomed and put into ethanol service 2000 — marine terminal—double bottomed in 1996 put into ethanol service 2000	17 to 19 months	Foreign-supplied ethanol	Inhibited	ASTM A36	— 1 of 3 failed tanks was most closely examined — 3 indications found 12 ft to 48 ft long near bottom weld seams — 15 short indications at other areas, especially where plates were hammered down — 1 other tank had failure in underside of floating roof — Remedial: epoxy novolac coating to tank bottom, roof bottom, and 8 ft on shell

Case No.	Location	Equipment	Service Period	Source of Ethanol	Inhibitor	Steel	Description
C2 11	West Coast Location	EU ethanol piping: air eliminator	Not known	Various sources including foreign suppliers	Inhibited	Piping: ASTM A106 Eliminator: ASTM A516-70	— Cracking ran transverse to the welds in adjacent base metal — Cracks in formed head of air eliminator adjacent to butt welds
D	All Locations Including West Coast	EU ethanol storage and blending facilities	Most tanks are at least 10 years old				— No SCC cracking problems identified — Awaiting further information
E 12–13	2 West Coast Locations	2 tanks—1 at each location: evidence suggests SCC but no investigation documentation	Leaks reported in 5 months to 1 year	Not known	Not known	Not known	— Found cracking near welds of newly installed patch plates and striker plates, near the corners — Did not find any cracking in the shell or corner welds — Remedial: lining all tank bottoms
F	All Locations	EU ethanol storage and blending facilities					— No SCC cracking problems identified — Awaiting further information
G	14	— EU tank failure reported in early 1990s—first reported case — Also suspect case in barge	1 to 2 years				— Lap weld seam and slag line resulted in high stress condition in tanks — SCC observed in one tank — Other tanks repaired and no further incidence of cracking
H	Mid-continent	Manufacturer storage tank: — 120 ft diameter welded steel cone roof with aluminum pontoon floating roof — fabricated in 1974 — bottom made with lap welded plates	28 years	Corn fermented and distilled ethanol	No, added to shipment before departure	Unknown	— No evidence of SCC found — Weld areas checked include vertical shell welds, horizontal shell welds, corner welds, perimeter bottom plate welds, interior bottom plate welds, shell nozzle welds, bottom sump weld
J	Asia	9 petrochemical tanks	12 to 24 years	Methanol (99.8 % pure and others purity no known)		Grade—not specified but all welds received PWHT	— No evidence of SCC — Visual inspections every 2 years — MT, UT every 6 to 8 years
K	Mid-continent	Manufacturer storage tanks: 34 tanks in ethanol service	Since 1935	Domestic corn fermented and distilled ethanol	Not specified	Not known	— No evidence of SCC

Case No.	Location	Equipment	Service Period	Source of Ethanol	Inhibitor	Steel	Description
L1 15–17	Great Lakes	EU ethanol storage and blending facility: reoccurrence of leaks in same loading rack piping (see A4) but 60 ft to 80 ft upstream	7 years plus 1 year since previous SCC	See A4	See A4	ASTM A53 Gr B seamless	— Leaks in pipe at welded fitting on pipe between tank and loading rack — 1 was at a fillet weld on a sock-o-let — 1 at a fillet weld where the pipe shoe was welded to the pipe — 1 in a butt-welded joint — Tried to stop leak at sock-o-let by peening, but more leaks developed — Other leaks were repaired by a pipe clamp — Not confirmed by laboratory analysis but similar to previous SCC problems
L2	Great Lakes	EU ethanol storage and blending facility: ethanol storage tank	Follow-up to previous failure	See A3	See A3	ASTM A36M	— No leaks in piping or tanks since original leaks in 2002 — Loading rack piping was replaced and PWHTed; also changed piping support design to eliminate attachment welds — Ethanol tank was WFMT in Oct. 2003 with no evidence of SCC — Epoxy coating (Sherwin-Williams Phenicon—phenolic epoxy) was used on the tank bottom and lower 2 ft of shell
M 18	Gulf Coast	Ethanol distribution terminal: 165 ft diameter fixed-roof (internal floater) tank	Tank build in 1994. SCC after 10 years	Only in ethanol service. Converted from beverage (European) ethanol to fuel ethanol (domestic)	Yes, in fuel ethanol	ASTM A36	— Leak developed in bottom of tank — Tank emptied; examined visually and with WFMT — Cracks found in bottom plates transverse to welds where plates were bent over at ring wall due to subsidence and at internal supports for fill piping — IG SCC identified by metallography — Sulfate residue was found in tank
N 19	West Coast	EU ethanol storage and blending facility: cracking in roof plates near welds	Tank converted from gasoline to periodic ethanol—gasoline service in 1994; SCC after 10 years	Ethanol is taken primarily by marine delivery, but for the past year it was delivered by truck. Many sources of ethanol include domestic and wine derived ethanol	NA	ASTM A36 No PWHT	— Leakage was found through the roof — 19 leaks were found by diesel borne fluorescent medium. 1 was sloppy welds. 2 were major leaks at lap seam weld HAZ at leg sleeve reinforcing pads to deck welds. Remainder were transverse cracks across lap seam welds — IG SCC confirmed by metallography — Weld repairs did not include PWHT — Coating was applied to bottom side of roof

Case No.	Location	Equipment	Service Period	Source of Ethanol	Inhibitor	Steel	Description
O 20	West Coast	EU ethanol storage and blending facility	SCC—cracking alongside weld	ASTM A234 Gr WPB			— SCC in steel fitting — Cracks were found by leakage of product — Instead of performing more inspection, affected piping was replaced NOTE Awaiting more information
P 21	Mid-continent	EU ethanol storage and blending facility	SCC—cracking alongside weld		ASTM A53 GrB		— SCC in pipe tee — Cracks were found by leakage of product — Instead of performing more inspection, affected piping was replaced NOTE Awaiting more information
R	Mid-continent	Product storage tanks at 7 manufacturer sites	Up to 23 years	Domestic producers of ethanol from corn	Yes 6—Octel DCI 11 1—Baker	ASTM A36, A53, A283, others	— No observations of SCC — Mostly visual inspection

Annex B
(informative)

Form to Submit New Information on SCC in Fuel Ethanol Systems

API Reporting Form: SCC Problems in Fuel Ethanol Service

Date ____________________

API File No. ______________

Page ______ of ________

Name ____

Company ____

Address ____

____

Telephone _________________ Fax _______________________

Email ____

Type of Equipment ____
(pipe, tank, pipeline, other)

Material(s) Grade ____

Material Description ____
(wall thickness, pipe diameter, etc.)

PWHT? Yes _____ No ______ Conditions ____

Coatings? Yes______ No ______ Type____

Nature of Problem SCC? Yes ______ No ______; please describe below.

____

____

____

____

Type of Facility____
(ethanol manufacturer, end user, midstream, rail, truck, barge, etc.)

Source of Ethanol ____________________________________ Mode of Delivery_______________________

Geographic Location ____

Service Temperature Min. _____________ Max. ____________

Service Conditions ____

Years in Ethanol Service ______________________________

Years in Other Service ______________________________

Other Contents ______________________________
(before or during fuel ethanol)

Method of Repair ______________________________

or Remediation ______________________________

Use of Coatings ______________________________

or PWHT ______________________________

Years of Service After SCC, Repair/Replacement ______________________________

Annex C
(informative)

Examples of Typical SCC in Fuel Ethanol

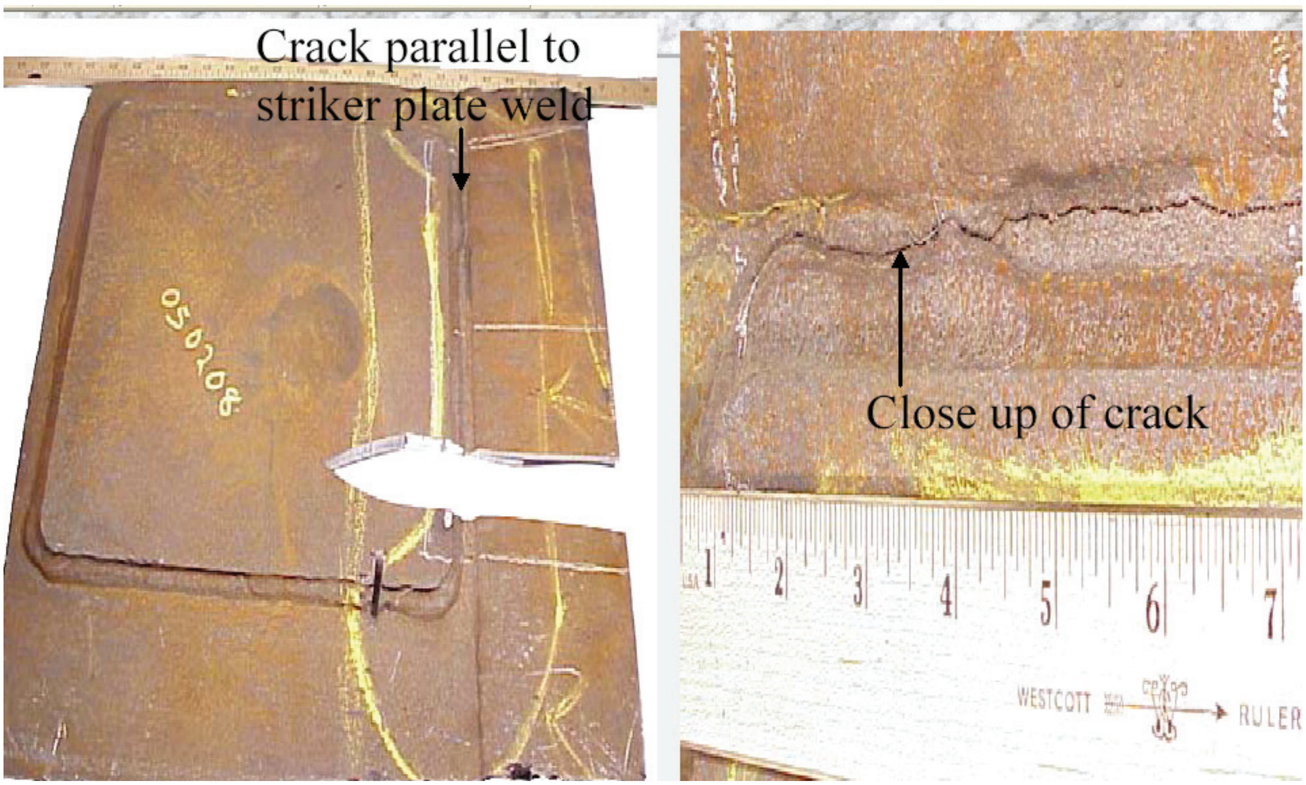
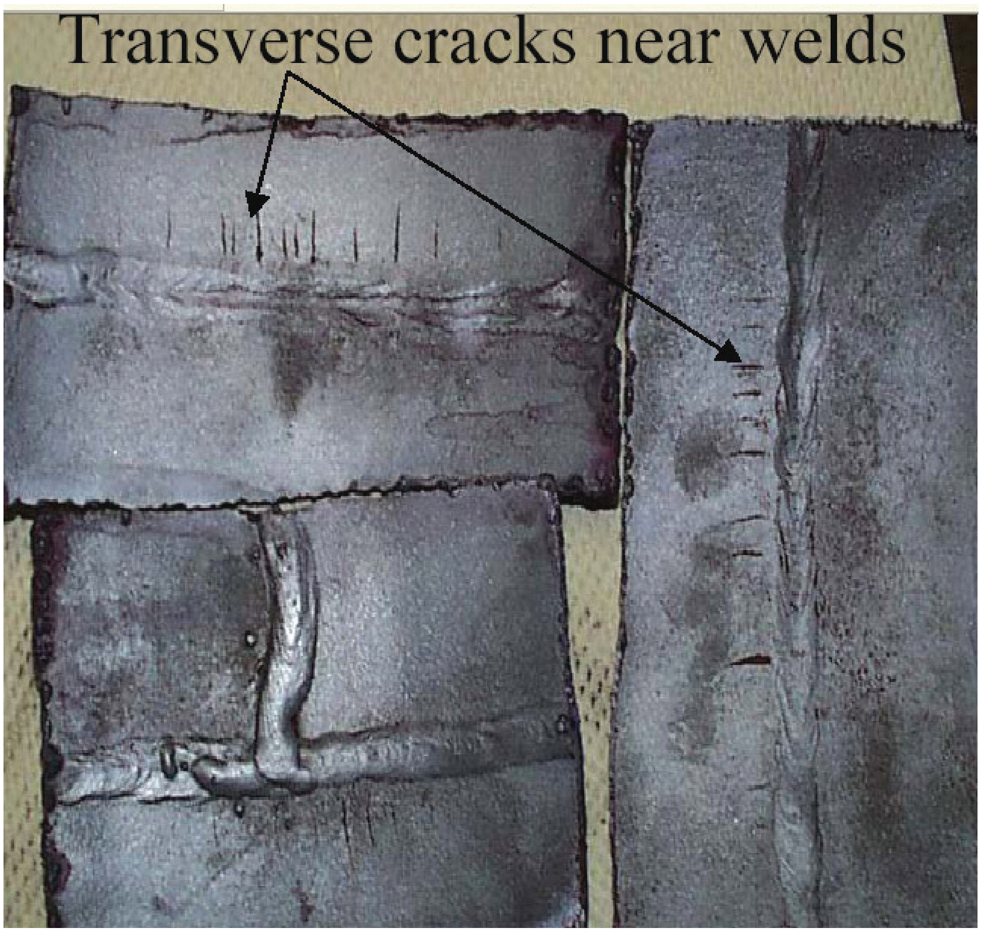


Figure C.1—SCC in Steel Tank Bottom



NOTE Cracks running perpendicular to weld.

Figure C.2—SCC in Steel Air Eliminator Vessel

NOTE Leak and bubbles in paint adjacent to welded fitting.

Figure C.3—Leak in Piping Resulting from a Crack Adjacent to the Weld

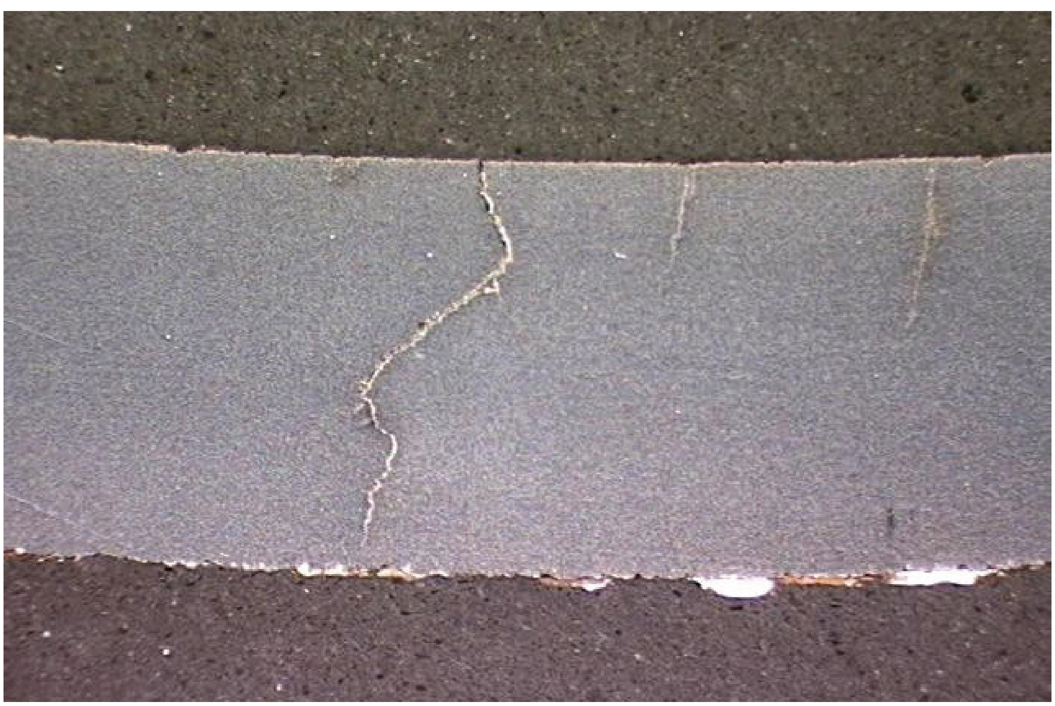


Figure C.4—Characteristics of SCC in Steel Exposed to Fuel Ethanol, Showing Multiple Crack Initiations and Through-thickness Propagation in Piping

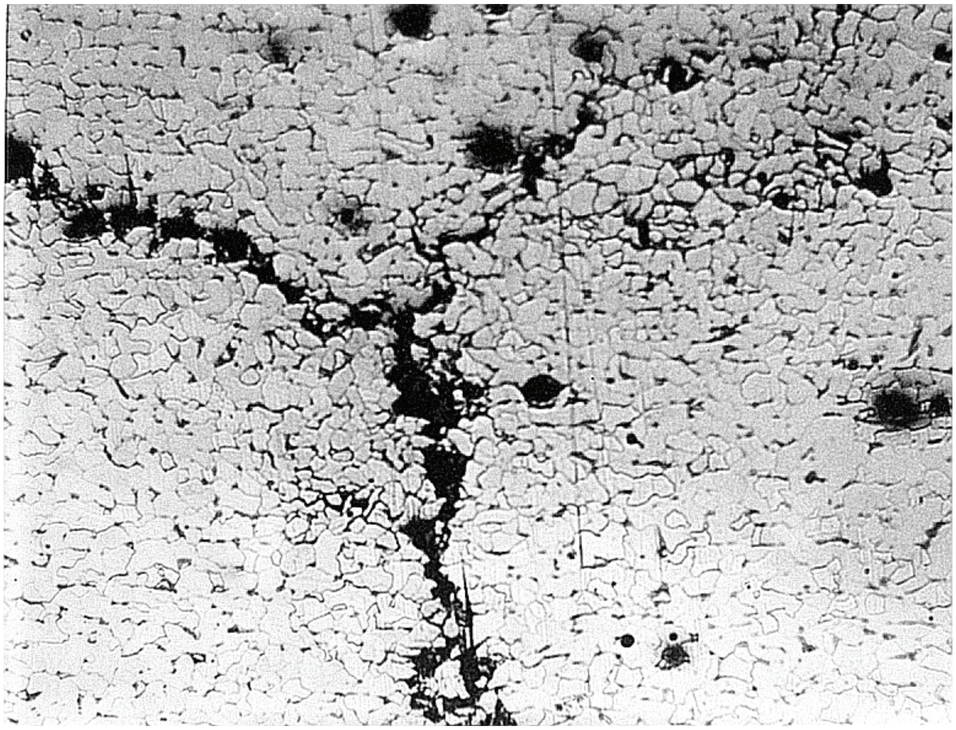
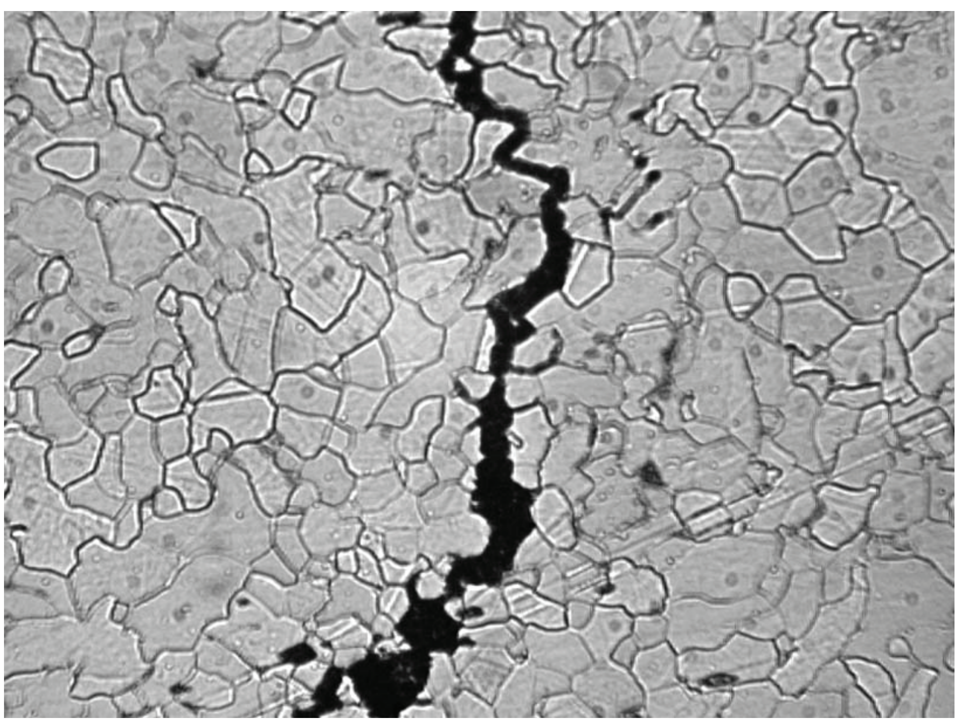
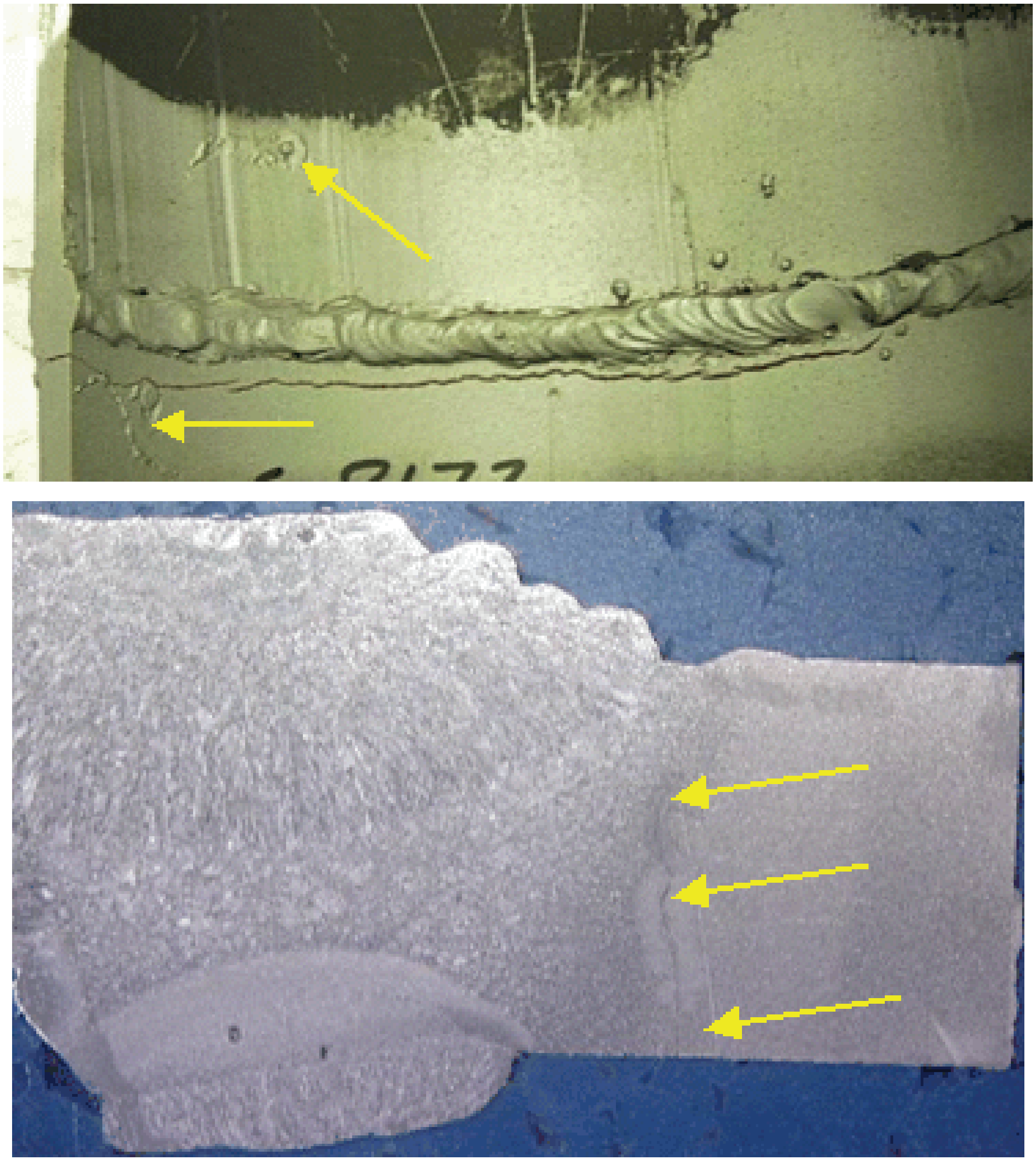


Figure C.5—SCC in Steel Tank Bottom Showing Highly Branched, Intergranular Cracks at 100X



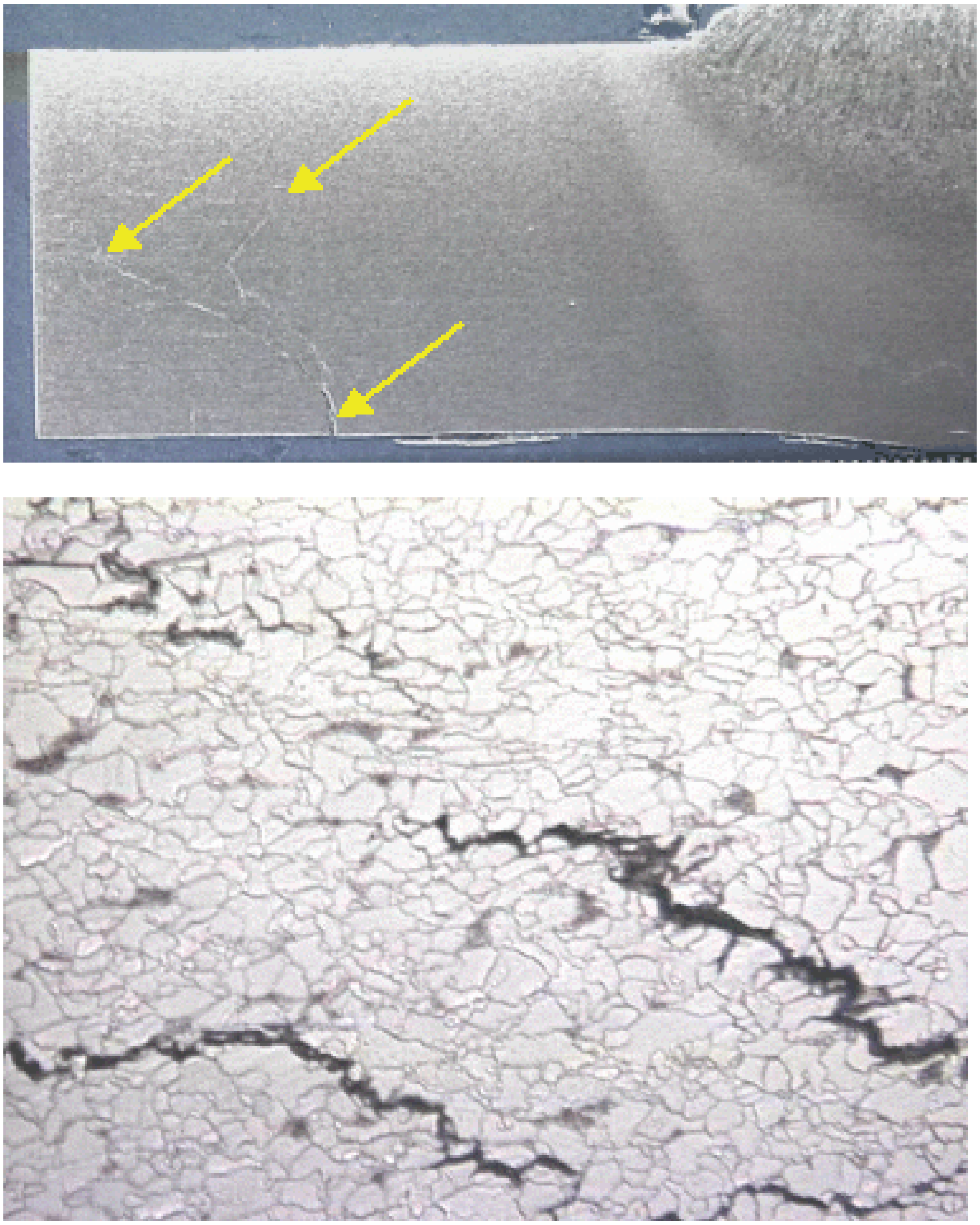
NOTE Note the intergranular cracking features.

Figure C.6—SCC in Steel Metallographically Prepared with Grain Boundary Etch at 500X



NOTE Top—7 in. (175 mm) long crack paralleling the root bead on the pipe ID surface.
Bottom—Cross section of above crack showing initiation outside the weld HAZ on the pipe's inside surface (nital etch).

Figure C.7—SCC in Steel Pipe from a Loading Rack Supply Line

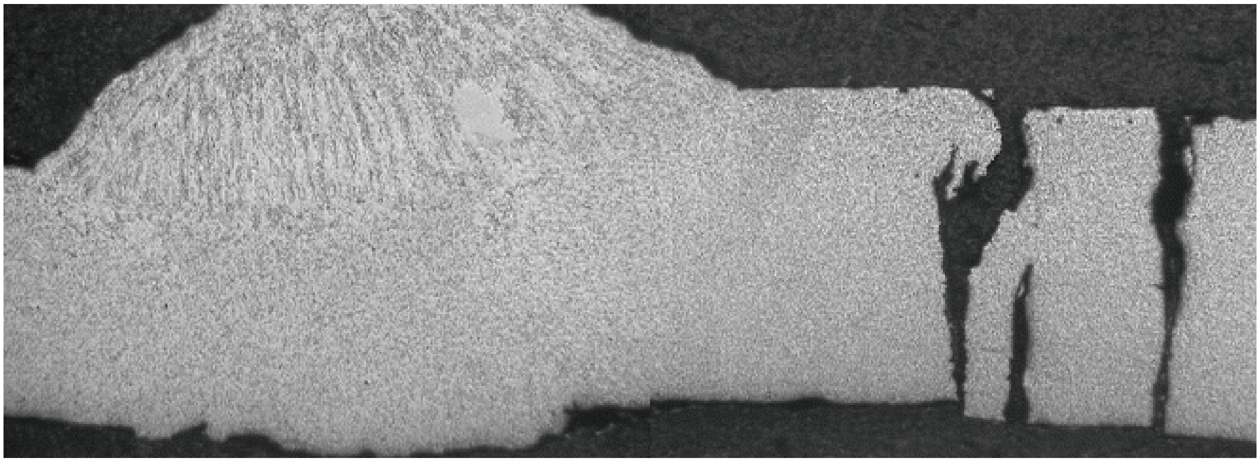


NOTE Top—Branched cracking in base metal adjacent to weld.
Bottom—Micrograph cracking shown above with predominately intergranular cracking (380X—nital etch).

Figure C.8—Cracking of Another Pipe Sample from Same Situation as Noted in the Previous Figure

NOTE Top—Crack parallels the pipe-to-tee circumferential weld.
Bottom—SCC visible adjacent to tee-to-run pipe.

Figure C.9—SCC of Steel Piping in a Fuel Ethanol System Return Line/Tank Transfer Line



NOTE Cracking occurred in base metal adjacent to weld (nital etch).

Figure C.10—Same SCC Incidence Shown in Previous Figure

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