Processing canola oil products

The following article was prepared by John Ward, a consultant, on the request of Reg Bacchus of POS Pilot Plant, Saskatoon, Saskatchewan, Canada, Associate Editor for JAOCS *News for Processing. It is based on a presentation made by Ward at a POS short course held in August 1988.*

Historically, U.S. and Canadian refiners have taken different approaches concerning the formulation of shortenings and margarines. Prior to 1970, Canada did not have domestic edible oil available in substantial tonnage and, thus, was dependent on various oils supplied by other countries. The U.S., meanwhile, had substantial domestic quantities of oils—first cottonseed oil and then soybean oil.

Soybean and cottonseed oils are very flexible in that they can be used either as a liquid or with various levels of hydrogenation for baking, frying and confectionery applications. Consequently, most American refiners learned to operate with a minimum of hardstocks to meet specific applications. By contrast, European and Canadian refiners, possessing limited quantities but generally greater variety of oils, combined a great number of hardstocks in their formulations.

Between 1975 and 1985, when increasing tonnage of canola became available to Canadian refiners, we learned to accommodate it. To be truthful, if soybean oil had been available at equivalent prices in those years, we would have opted for soybeans every time. We persevered with canola, learned its peculiarities, its shortcomings and its advantages.

One simply cannot process and formulate canola as one would soybeans. Because of its fatty acid composition, a canola oil hydrogenates and crystallizes somewhat differently than soybean oil. This can be both a curse and a blessing for the processor. It is in the liquid (not hydrogenated) form that canola excels and, from a nutritional point of view, maximizing the liquid oil fraction should be one of your aims.

Hydrogenation

If you try to match a soybean hardstock using canola oil, there will be a tendency for the canola hydrogenation to develop a slightly steeper solid fat index (SFI) curve, possessing slightly higher *trans* or elaidic acid and slightly fewer saturates. To keep your catalyst usage similar to that for soybeans, you will probably have to run your "gas on" temperature about 20°F higher and let your "run" temperature go 20-25°F higher than you would for soybeans.

A Canadian refiner usually will have canola hardstock such as:

- C 05 with 50°F solids, 5 max.
- C 20 with 50°F solids, 20 max.
- C 30 with 50°F solids, 30 max.
- C 40 with 50°F solids, 40 max.
- C 50 with 50°F solids, 50 max.
- C 60 with 50°F solids, 60 max.

The C 20, 30 and 40 are generally flatter or nonselective SFI curves. C 40 and 50 either are nonselective or selective curves, with the C 50 and higher generally selective or steep SFI curves. To achieve the flatter nonselective curve, one would use the same hydrogenation temperature as that for soybean oil. However, 10-15% more catalyst will be needed with canola to duplicate the soy curve.

Formulation and blending

A well-deodorized canola oil can be used in any application calling for a liquid oil component. Such uses include salad and cooking oil applications, mayonnaise, dressings for nuts and dried fruit, pan releases and greases.

Emulsion systems with other liquid oils will be successful with canola. These include both high- and low-pressure homogenization systems, the whole range of oil-in-water and water-in-oil systems, as well as the HLB (hydrophylic/lipophylic balance) range of surfactants.

The leading salad dressing product in Canada was reformulated with canola in 1975 and has continued to use canola. If and when oxidation flavors are evident after a long shelf life, they tend to be savory.

One can substitute liquid (unhydrogenated) canola oil for a lightly hydrogenated soy oil in formulations where the purpose of lightly hydrogenating the liquid soybean fraction was for stabilization only. This substitution achieves the same stability (in terms of A.O.M.) while also reducing total saturates. Liquid canola has excellent solubility in such formulations and does not readily "leak."

A lightly or "brush" hydrogenated canola has superior stability to a similarly hydrogenated soybean oil, yet can be used in exactly the same manner as soy, with one exception: If you refrigerate a lightly hydrogenated canola oil, it will not form as discrete a crystal as soybean oil and is more difficult to filter. However, "brushed" canola, under controlled chilling and distribution of the crystal evenly throughout the mass, will give superb performance as a pourable frying or shortening product. Canola has been described as "naturally winterized," not requiring brush hydrogenation and having a cold test far superior to other vegetable oils.

Let's examine the phenomenon of the steeper (higher *trans*-containing) hydrogenated canola SFI. There are some products from which we might like to copy a lauric fat behavior: higher solids, lower melt point and quicker set.

Years ago, lauric fats were preferred as filler fats for biscuit/cookie sandwich cremes and as a spray oil on crackers. A canola oil, selectively hydrogenated to give solids at 50°F in the 35-45 range, will provide a very satisfactory spray oil/filler fat product and still "machine" well as a general-purpose cookie dough shortening.

A similarly selectively hydrogenated canola will provide a very stable heavy-duty frying fat where "pick-up" by the product being fried is not high. The higher solids achievable with canola (due to its *trans* or elaidic acid) is credited with giving a quicker "seal" to products being fried. Quite obviously, such fried products would be in the "dry" or shortening category, not the "oily" category.

What is the crystallization problem with canola and are there any advantages to be gained from this phenomenon?

Because the fatty acids of canola are almost all of 18 carbon chain-length and initially 70% monunsaturate, the oil is beta-tending when votated. In pastry baking, where a flaky product is desirable, lard is supreme. However, a shortening with some beta crystal can give a flakiness similar to that of lard. Canola shortening with a proportion of beta crystals can make a flakier pastry than its soy counterpart. For croissants and some sweet doughs, a flaky tendency is preferred.

Previously, I mentioned canola's use as a frying fat, spray oil and filler fat and in cookie doughs. These are products shipped either in cube form, where the crystal state will not be subject to critical appraisal, or bulk shipped in liquid form, to be votated and used almost immediately in baking formulations. The danger with beta crystals is their tendency to agglomerate with time to form larger crystals, thus losing any advantage of flakiness in pastry.

In the case of packaged-type shortenings, where a product with a broad plastic range and a storage-stable beta-prime crystal form is sought, my recommendation would be to include 35% of a substantially hydrogenated nonselective soybean oil, with the balance being hydrogenated and liquid canola oil to duplicate an all-soy formulation. (When I say "all-soy," I'm recognizing that the stearine portion is likely cotton or palm.) Such a formula could be votated readily with no special precautions.

It should be mentioned that canola is not usually a good candidate for stearines for general edible-oil formulations. A beta-prime tending oil such as palm or cottonseed is best. A palm stearine is usually preferred in canola formulations because of the higher C16 of palm.

When canola is hydrogenated to a C 30 hardstock or harder, it will be beta-tending and that is not all good. That is why I mentioned the few specific advantages first. The following list can be used as a guideline for basic canola formulations:

- Frying fats can be formulated from 100% canola.
- Soft margarines can be formulated from 100% canola.
- Baking shortenings should have several canola hardstocks as well as 10–15% palm content.
- Stick margarines should have several canola hardstocks as well as 10–15% palm content.

Finished-product crystallization

The key in the "finishing" of most edible oil products, other than salad or cooking oils, is the controlled crystallization process generally known as votating.

A Votator is a swept-surface heat exchanger, but not all swept-surface heat exchangers are Votators. There are Kombinators and Perfectors, as well as Thermutators, and they all do the same thing; however, as there are more Votators on this continent, we have adopted the habit of calling the process votating.

In votating, there is a general understanding that an "A" unit is a chiller unit, where the liquid fatty product is introduced to the annular space between a rotating mutator shaft fitted with scraper blades that bear on the internal surface of a cylinder. The cylinder is in a refrigerated environment; ammonia or Freon rapidly carries heat away from the product in the cylinder. The rapidly rotating scraper blades remove crystallizing fat from the cylinder surface, promoting an effective heat exchange. The supercooling or shock-chilling accomplished in such a manner maintains the flowing fatty product in a liquid and fluid state.

For most shortenings or margarines feedstock, temperatures are usually 10–15°F higher than the point where crystal nuclei might be present. Remember, the crystal must be formed under controlled conditions.

It is usual to have a minimum of two A or chiller units, although three or four are sometimes needed, either for sophisticated products or to match high-speed packaging machinery.

A "B" unit can be either a static unit—having no agitation and no chilling—or a working unit or blender, in which the shaft carries a number of tines that clear a series of static tines mounted internally along the barrel or cylinder. Such a blender or worker is not normally chilled by refrigeration, although sometimes provision is made for hot or cold water through water jacketing.

To complicate matters, a B unit is not necessarily the last unit in the sequence. Sometimes a worker or blender is put between A units to achieve a specific objective.

Although not all that common, there also is a "C" unit. This is a chiller unit much like the A unit, except that the mutator shaft is offset, presenting an eccentric annular space between shaft and cylinder. This has the effect of kneading or dynamically working the fatty product as it is chilled. It is claimed that a shortening processed through a C unit as the final process step does not require as much post-votating tempering. The C unit is sometimes desirable but is not as essential as A and B units.

Fats made up of glycerides melting over a wide temperature range have desirable plastic properties. Fats made up of glycerides with a narrow melting range produce products with sharp softening and melting points and do not have the same desirable plastic properties.

Through supercooling, mechanical working and post-votating tempering, it is possible to change a fat not normally predisposed to plastic properties into having acceptable properties.

The supercooling conditions of a votator or similar equipment have a large effect on the formation of the desirable amount of critical crystal. Mechanical working or static conditions will contribute only to a limited degree.

Post-votating tempering conditions can contribute substantially to the final stable crystal form. Palm oil was mentioned earlier for formulations. Palm is a slow crystallizer, although beta-prime tending. It can have its greatest influence in post-votating tempering.

I can remember when soybean oil was replacing cottonseed oil in the U.S. Several processors at that time said soybean oil would never replace cotton oil. Their comments: "It didn't votate the same." "You'll never make a margarine out of soybean oil; it channels and it's grainy!"

Certainly, cottonseed and soybean oils did not votate in identical fashion as they had different fatty acid compositions; a lower palmitic content for soybean oil caused it to crystallize differently. However, processors learned to change votating conditions to handle soybean oil. Canola oil, in turn, has a different fatty acid composition than soybean oil, specifically a much lower palmitic content. In Canada, we have learned that we can achieve the plasticity and performance normally attributed to soybean or cottonseed oil formulations by increasing the palmitic content of a substantially hydrogenated product with the addition of palm oil or palm stearine, by using a greater number of canola hardstock fractions, and by somewhat different votator conditions, as well as strict attention to post-votator tempering.

Shortening

The objective of votating a shortening is to seed sufficient beta-prime crystals to ensure its progression into being the dominant crystal form in the finished product. If there are not sufficiently mixed triglycerides in the formulation, greater shock-chilling or supercooling is necessary to produce sufficient seeding crystal of the beta-prime configuration.

The beta-prime crystal, approximately 5 microns in size and almost spherical, is a key factor in the broad plastic range required in a shortening. In a margarine, particularly stick margarine, there is a narrow melting range yet we require the beta-prime crystal for a smooth textural feel on the tongue as well as for smooth spreading and the good light reflection that the smaller beta-prime crystal provides.

For shortening, in view of the lower level of palmitic acid and high levels of oleic and *trans* fatty acids in hydrogenated canola, lower votating temperatures and effective cylinder-scraping are desirable to produce sufficient crystals in the beta-prime state. The use of three or more canola fractions or hardstocks in a formula also gives better votational response.

Attention also should be paid to the sharpness of votator blades and the smooth condition of the chilling cylinders. For shortening, normal routing should be as follows: refrigerated A unit, followed by working B unit, with A unit exit-temperature perhaps 5°F lower than one would use for soybean oil. This should be followed by warm tempering in wintertime, if a C unit is not used.

Lightly hydrogenated 100% canola oil, with solids up to 5% at 50°F and linolenic acid content less than 3%, makes a very stable pourable frying or liquid shortening. Although pourable, the crystals will remain nicely dispersed throughout the mass, if it is chilled to an A unit exit temperature of 60°F, and then put through the working B unit blender to the filler. However, packaged product should be held in a 50°F cooler for 48 hours to achieve stable dispersed crystal.

Margarines

Margarine is not 100% fat. In fact, in the U.S., it can be almost any percentage fat. By contrast, margarine in Canada must be less than 40% or more than 80% fat. Consequently, when I mention margarines and indicate 100% canola, I am referring to the fat phase. It is the fat phase that must be controlled by votating; the water phase is less influenced by votator conditions.

Tub or soft margarines

In Canada, soft margarine is more popular than the stick variety, whereas in the U.S., stick margarine is slightly more popular than soft. A 100% canola formula that has a combination of hardstock and liquid or lightly hydrogenated oil will votate very well and compare favorably with soybean formula except in the area of total polyunsaturates.

This is why soybean oil is used mainly for soft retail margarines in Canada. We have regulations that say polyunsaturation cannot be labeled unless there is more than 25% polyunsaturates, and at the same time, there should be less than 25% saturates. While we would be well under on the saturate level, we cannot attain the necessary polyunsaturates, although linolenic levels (which may well be of increasing interest and importance) would likely be higher than in similar soft soybean-based margarine. This means that soft canola margarine in Canada is usually found in the institutional market.

Stick margarines

As I mentioned earlier, a narrow melting range and a sharp melt point (mouth break) are required for flavour emphasis in margarines and particularly in stick margarine. Consequently, we face a paradox with canola: We need the steeper curve hardstock for the narrow melting range, but at the same time, we know that this is more difficult to votate.

In the earlier days with canola, sometimes by trying and other times by not trying, we encountered all three crystal states: beta-prime, beta and agglomerated beta existing in one product.

Beta-prime crystals of about 5 microns give a smooth spreadable, desirable margarine state. Beta crystals, larger than 25 microns, can give a sandy, floury, grainy texture to the margarine. Agglomerated beta results in crystals so large that the margarine texture can become crumblike, similar to cottage cheese. The worst cases cannot be cut by a knife; instead, the product simply breaks apart. This phenomenon is similar to what might be seen in hydrogenated sunflowerseed oil or hydrogenated fish oil margarines.

Operating tolerences are narrower for canola stick margarine. The following are some precautions. Use:

- As many hydrofractions as possible.
- Palm content (or CSO) to increase levels to 10% palmitic.
- Sharp votator blades (preferably steel).
- Smooth chilling cylinders.
- Low A unit exit temperature.
- Mandatory cool room tempering—48 hours at 40-50°F. This allows the beta-prime crystal to multiply and reach a stable state. This is of paramount importance for soft and stick margarines.
- A crystal inhibitor if you really want insurance. Sorbitan tristearate is more effective than diglycerides.

Choosing proper stainless steel

The following talk was presented by John C. Tverberg, vice president of technology for Crucible Materials Corp.'s Trent Tube Division, East Troy, Wisconsin.

Corrosion. We see its presence everywhere. Our automobiles rust, lawn furniture pits, pipes leak, condensers leak so badly the product is ruined, centrifuges crack, valves lose pieces of metal, exhaust stacks "rot away" and our bridges rust to the extent that they are taken out of service. Whether we are at home, at work or on vacation, we are the unwilling victims of corrosion. And it costs us, as a nation, over $100 billion each year.

What is corrosion? Simply stated, it is the return of a metal to its most stable thermodynamic state. Corrosion is the reaction of a metal or nonmetal with its environment to form a stable oxide, sulfide, amine, amide, sulfate, carbonate, nitrate or any other compound related to the environment. In the process of corroding, the physical dimensions are altered, the metal's strength is reduced and its ductility is decreased. Because the cross-section of the component may decrease, the moment of inertia may change, leading to increased vibration and possible fatigue or stress corrosion failure.

Corrosion may be the result of an unwise choice of materials, a change in the environment or something unknowingly done to the material in the fabrication of the component or erection of the plant. By recognizing the types of corrosion and the factors that cause each, it is possible to select proper materials to minimize the destructive force and the impact on the cost of plant operation.

There is no one material that is immune to all types of corrosion. Every material is attacked to some degree. The problem is matching the proper material with the environment. The other problem is cost. Corrosion-resistant materials cost more than those that corrode. But, in most cases, the difference in cost can be justified on the basis of replacement cost, downtime and lost production.

There are five basic types of corrosion that attack all materials: uniform or general corrosion; galvanic corrosion, which includes pitting and crevice corrosion; intergranular corrosion; stress-corrosion cracking; and microbiologically influenced corrosion. Usually they occur independently in the initial stages, but once one type starts, the others join in "the fun."

Corrosion highlights

The four articles included in this section were presented in Session U, Corrosion and Materials of Construction, as part of the 1988 AOCS annual meeting in Phoenix, Arizona, in May. Topics and speakers were:

- Choosing Proper Stainless Steel, John C. Tverberg
- Proper Selection of Material and Welding Techniques for Process Equipment, Ken Krysiak
- Corrosion in Heating Coils, James R. Smith
- Choosing Correct Material for Plate Heat Exchangers, James A. Carlson

Serving as cochairpersons for the session were Glenn Brueske and George E. Anderson, both of Crown Iron Works, Minneapolis, Minnesota.

Uniform corrosion

As the name implies, this is the uniform dissolution of a material's surface exposed to a corrodent. Uniform corrosion is expressed as a regular rate of metal loss over the entire surface. Whenever a corrosion allowance is made in the design of equipment, it is done on the basis of a uniform corrosion loss. It is expressed in depth of penetration as inches per year (ipy), mils (0.001 inch) per year (mpy) or sometimes as weight loss for a given area such as milligrams per square decimeter (mg/dm^2). A word of caution: do not be lulled into a feeling of security because you have a corrosion allowance in your design. An extra 10% of metal does not mean a thing to the four other types of corrosion.

Metals derive their corrosion resistance from the formation of a protective oxide or other compound on the exposed surfaces. With some metals, this layer is only several molecules thick. It does not increase in thickness until some catastrophic event, such as an increase in temperature, upsets the equilibrium. This type of film is called a passive film and is characteristic of such metals as stainless steels, chromium-nickel alloys, titanium, zirconium and aluminum. The other metals form their protective film by allowing the film to grow to a finite thickness, then the outer layer sloughs off, allowing diffusion of oxygen or other corrodent to react with the base metal. This is called an active film and is characteristic of such metals as copper and its alloys, zinc, cast iron and carbon steel. Given enough time, these metals will be completely consumed by their environment.

General corrosion results from the uniform breakdown of the passive film or the accelerated formation or removal of the active film over the entire surface of the metal. Acid-cleaning is an exaggerated example of general corrosion. Thus, every time a copper or carbon steel-tubed evaporator, condenser, centrifuge or kettle is acid-cleaned, the metal walls are being thinned because of uniform corrosion.

Uniform corrosion may be reduced or even essentially prevented by proper selection of materials that are resistant to the corrosive environment. By using the published tables of general corrosion rates, it is possible to determine the resistance of a given alloy to a given environment. The *Corrosion Data Survey*, published by the National Association of Corrosion Engineers, Houston, Texas, is an excellent source.

Galvanic corrosion

When two dissimilar metals are suspended in a common electrolyte and are electrically connected, an electrical potential will develop between the two. One of the metals will dissolve in the electrolyte more readily than the other; this becomes the anode. The more noble metal provides the electrons to cause the first metal to dissolve. The noble metal is called the cathode. The cathode shows no weight loss even though it could if it were not in contact with the anodic metal. This forms the basis for cathodic protection of metals in which electrons are injected into the electrolyte equal to that required if the metal were corroding.

TABLE 1

Galvanic Series of Metals and Alloys

Electromotive Series		
Metal	Volts	Practical series: material or alloy
Corroded end (anodic or least noble)		
Magnesium	-1.55	Magnesium
Aluminum	-1.33	Aluminum 2S
Zinc	-0.76	Zinc
Iron	-0.44	Steel or iron Stainless steel (active)
		Alloy 20 Cb-3 (active)
		Hostelloy C (active)
Nickel	-0.23	Nickel (active) Inconel (active)
		Hostelloy B
Hydrogen	0.00	
Copper	+0.34	Brasses Copper Monel
		Nickel (passive) Inconel (passive)
		Stainless steel (passive)
		Alloy 20 Cb-3 (passive)
Silver	+0.80	Silver
Gold	+1.36	Gold
		Platinum
Protected end (cathodic or most noble)		

By comparing metal pairs in sea water, it is possible to establish a galvanic series of metals ranging from the least noble (anodic) to the most noble (cathodic). Such a chart is presented in Table 1. This chart can be used to determine which metal will go into solution, that is, which metal will corrode.

Keep in mind that it is necessary to have an electrically conductive solution and the two dissimilar metals must be in electrical contact. The basic rule for preventing galvanic corrosion is to avoid electrical contact of dissimilar metals in a conductive solution. This also provides some clues for preventing corrosion of metals:

- Attach a sacrificial anode to the part to be protected. The anode must be less noble or more anodic, such as zinc on iron. This provides the basis for galvanizing or the anodic protection of ship hulls.
- Impress a direct current on the part to be protected with a potential in the range of -0.85 volts. Actual voltages should be determined empirically for each metal combination.

Electrical coupling of dissimilar metals should be avoided when the cathode has the larger surface area. If the anode has the larger area, the corrosion rate may be so low that it makes little difference. For example, placing SEA-CURE stainless steel or titanium tubes in a Muntz metal tube sheet with saline water as an electrolyte will result in rapid pitting attack of the Muntz metal in the ligament section of the tubesheet. This is because the tubes have a very large surface area, compared with the surface of the tubesheet. If the situation is reversed, the galvanic attack will be minimal. This also explains why coated, plated or painted anode metal surfaces in contact with a cathode will fail if a pinhole develops in the coating. The entire cathodic current is concentrated at the small pinhole, thus generating a tremendous driving force.

Most corrosion is electrolytic in nature. Therefore, an understanding of galvanic attack gives an appreciation of the more complex types. Pitting and crevice corrosion are two of the forms galvanic corrosion assumes.

Pitting is a seemingly random corrosion attack of the metal surface. The rate of attack is greater in some areas than in others. The depth of pitting is more significant than the number of pits because one deep pit will limit component life more than a larger number of shallow pits. Corrosion theory states that pitting occurs where the corrosive medium penetrates the passive film at only a few points. This is contrasted to uniform corrosion, where the passive film is penetrated over the entire surface to the extent that the passive film is no longer maintained.

Stainless steel occupies two positions on the galvanic series chart: one near the cathodic end and the other near the anodic end. In stainless steel, pitting corrosion is simply galvanic corrosion on a surface where both the anode and cathode coexist. Because the cathode area is very large, intense current densities are created at each tiny anode. Rapid metal loss occurs, usually in acid chloride solutions. Not all stainless steels are sensitive to such pitting attack. Those that have high chromium and molybdenum have excellent resistance to such attack. Figure 1 illustrates the effect of molybdenum, pH and relative chloride content on pitting corrosion. Generally, an austenitic alloy with the molybdenum level shown will not suffer localized attack when the combination of pH and chloride content falls below the line. Combinations of these variables above the line may cause localized attack.

Once pitting starts, the reaction becomes self-feeding. The depth and contour of the pit retain the electrolyte and exclude the oxygen necessary to repassivate the surface. This is called concentration cell corrosion, in which the pit acts as a battery that consumes its container.

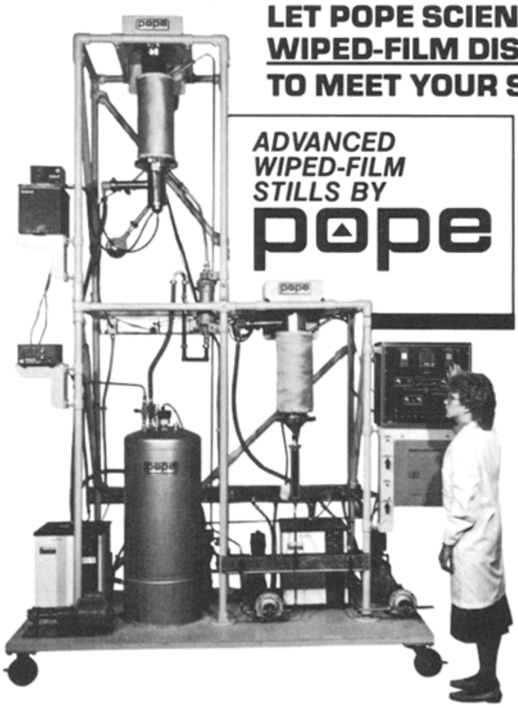
Crevice corrosion is a specialized type of galvanic corrosion. Whereas pitting is random, crevice corrosion is localized and predictable. The only required conditions are an electrolyte and a crevice-former. It is not even necessary for the crevice-former to be a dissimilar metal; it can be the same metal, a nonmetallic deposit or paint. Generally, the tighter the crevice, the worse the situation. Also, crevice corrosion is more severe than pitting because it occurs at lower temperatures and lower ion concentrations.

The situation is worst when the electrolyte contains a halide (chloride, fluoride, iodide or bromide) and when the pH is low (acidic). In this case, the halide can displace oxygen in the protective film and allows the area under the crevice-former to become anodic.

Alloy content has a great influence on minimizing crevice attack. Figure 2 illustrates the relationship between gap, alloy and time for initiation of crevice attack. With a chromium-containing steel, increasing the molybdenum is generally the most important in retarding crevice attack. The presence of nickel also helps. The data in this chart represent a single temperature and a single concentration of sea water. If the pH is changed or the temperature increased, conditions can be such that even Alloy 625 will crevice-corrode.

Intergranular corrosion

Intergranular corrosion attack is restricted to the grain boundaries of the metal. The corrosion fissures that follow the grain boundaries occasionally can be seen with the unaided eye, but microscopic examination usually is needed to confirm this type of corrosion. Normally, intergranular corrosion is a result of carbide precipitation along



the grain boundaries where carbides or some other precipitates form a continuous network.

All austenitic stainless steels contain a small amount of carbon in solution. In the temperature range of 1050–1600°F (565–870°C), carbon will combine with the available chromium to form chromium carbide. This commonly is called sensitization. More chromium is required to form the carbides than is available immediately around the carbon atom, so chromium is taken from the surrounding area to form the carbide, depleting the area in chromium. This creates a zone low in chromium, below which a passive film on the metal can form. A galvanic cell is established, leading to rapid grain boundary attack. This corrosion can occur in pure water, acids or even caustic solutions. An especially bad condition is the presence of polythionic acids. Polythionic acids are the reaction product of a sulfide with moisture and oxygen, usually from the combustion of sulfur-containing fuel. Attack usually happens during shutdown. Polythionic acid rapidly attacks the sensitized grain boundaries and, when a stress is applied, intergranular stress-corrosion cracking takes place. One solution is to use a stabilized sulfuric acid-resisting grade, such as 20Cb-3.

There are three rules to prevent intergranular corrosion:

- When the metal has been sensitized by welding or by heating in the sensitizing temperature range, it must be solution-annealed to take the carbides back into solution. This is usually in the temperature range of 2000°F. It must be rapidly quenched to prevent the carbides from reforming after cooling to room temperature. Welded pipe and tubing made by reputable mills will have been properly annealed and quenched before receipt by the end-user.
- Minimize the carbon content of the alloy by specifying an "L" or low carbon grade. These grades contain less than 0.03% carbon and do not precipitate carbides during short exposures to the sensitizing temperature range. This allows field-welding without the need for solution heat-treating. Today, the low carbon grades are easily produced

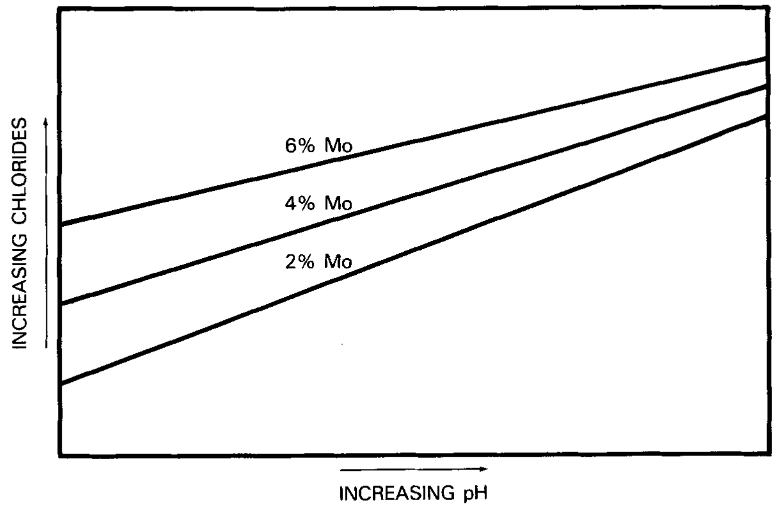


FIG. 1. Effect of pH, chloride content and molybdenum content on localized attack. Note: Alloys with Mo level shown do not experience localized corrosion below the line.

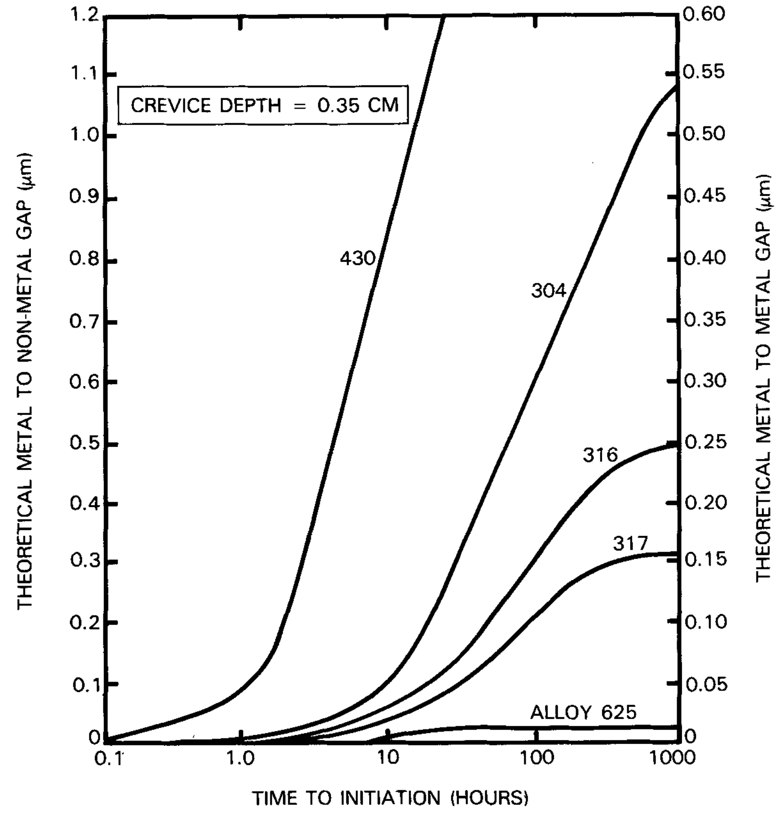


FIG. 2. Effect of crevice gap on time to corrosion initiation for various alloys in ambient temperature seawater. Source: A.J. Sedricks, "Corrosion of Austenitic Fe-Cr-Ni-Mo Alloys in Marine Environments," June 1982.

and are relatively low in price. This type of corrosion failure constitutes over 75% of all the corrosion failures we evaluate. In almost every case, use of an "L" grade would have prevented the corrosion failure. There is one word of caution, however. Prolonged exposure in the range of 1000°F (540°C) may lead to carbide precipitation. This is illustrated in Figure 3.

- Use an alloy that contains a "getter" for the carbon such as niobium or titanium. The additions form either titanium or niobium carbides preferentially to the formation of chromium carbide. They also have more resistance to the long term precipitation of carbides when held in the sensitizing temperature range.

Stress-corrosion cracking

All metals are subject to stress-corrosion cracking. Table 2 lists some of combinations for the different metals. Three conditions are necessary for stress-corrosion cracking to occur: a suitable environment, a tensile stress and a sensitive metal. With copper-containing alloys, an ammonia-containing environment leads to stress-corrosion cracking. With the low alloy austenitic stainless steels, a chloride-containing environment is necessary. The solutions do not need to be concentrated; often, a solution containing just a few parts per million of the critical ion is all that is required. Temperature also is critical. Usually there is a threshold temperature below which stress-corrosion cracking will not occur. The same is true for pH.

Tensile stresses are required to trigger the failure mechanism. If the part is in compression, stress-corrosion cracking generally will not occur. The tensile stress must approach the yield strength of the metal. Often, pits, which act as stress concentration sites, will initiate stress-corrosion cracking. Residual stresses from welding, straightening, erection, bending or accidental denting of the component can lead to cracking. Over-rolling of tubes into a tube sheet can lead to stress-corrosion cracking.

Alloy content is very important, with nickel content the key. Neither the nickel-free ferritic stainless steels nor the high nickel alloys are sensitive to stress corrosion cracking. The worst alloys are the common stainless steels with a nickel content of 7–10%. These are the most common grades: Types 304, 304L, 316, 316L, 321, 347, 303, 302 and 301. As the nickel content increases to about 30%, the alloys become more resistant to stress-corrosion cracking. Above 30%, the alloys become essentially immune. There is a synergistic effect of molybdenum. As the molybdenum content increases, the alloy becomes more and more resistant to stress-corrosion cracking.

Identification of stress-corrosion

cracking generally must be done by microscopic examination. Stress-corrosion cracks are transgranular and tend to branch out at the ends to give a feathery appearance. It is important to determine the type of failure before replacing the failed component because the type of failure will dictate the type of alloy to be used.

Microbiologically influenced corrosion

During the past decade, corrosion engineers became aware that "classic" corrosion mechanisms could not explain all corrosion failures. It was finally realized that bacteria have a direct link in the corrosion process. Bacteria exist that go after every metal. Bacterial action can cause corrosion:

- indirectly, by producing carbon dioxide, hydrogen sulfide, ammonia, organic and inorganic acids. They do this by metabolizing the environment.
- by metabolically producing organic products that act as depolarizers or catalysts for corrosion reactions.
- when the corrosion process involves using the metal as a metabolic link in the nutritional chain.

With copper, the worst conditions are those in which bacteria produce hydrogen sulfide or sulfur acids. With common stainless steels, bacteria can concentrate manganese from the environment and, if chlorine is present, hydrochloric acid is produced, leading to rapid pitting attack. Table 3 lists some of the more common corrosive bacteria.

The best defense against bacteria-induced corrosion is a good offense. Where possible, use a good bacteriacide or a continuous cleaning system such as sponge balls. Sometimes it is possible to kill the bacteria by heating the surfaces to a high temperature. If one specific type of bacteria is causing problems (generally because of the type of food available), an alloy change may be the answer.

Alloy selection

The wide selection of alloys available today makes proper selection a seemingly bewildering experience. A number of factors must be con-

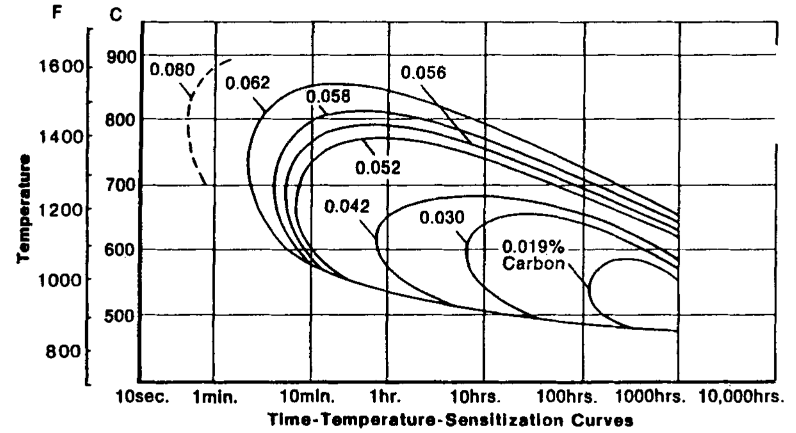


FIG. 3. Effect of carbon on carbide precipitation. Time required for formation of harmful amounts of chromium carbide in stainless steels with various carbon contents. Carbide precipitation forms in the areas to the right of the various carbon-content curves. Within time-periods applicable to welding, chromium-nickel stainless steels with 0.05% carbon would be quite free from grain boundary precipitation.

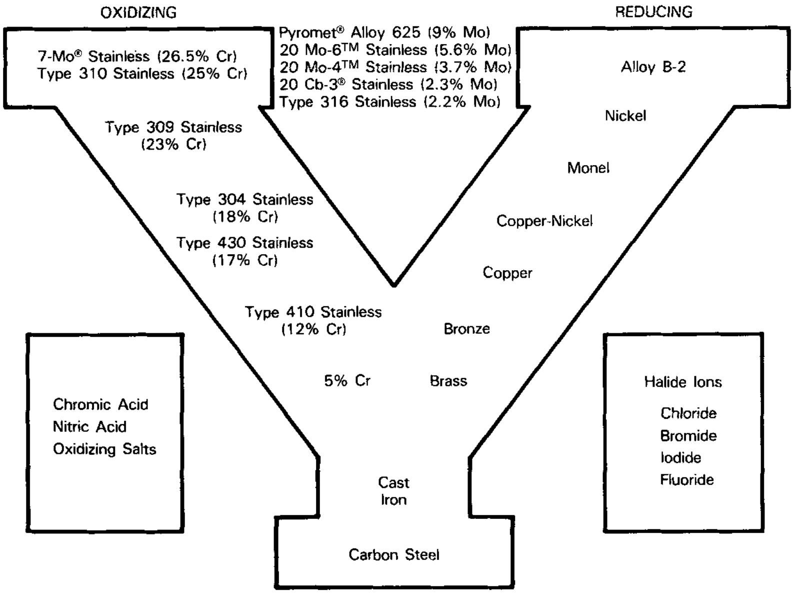


FIG. 4. The "Y" of corrosion for several metals and alloys. 7 Mo, Pyromet, and 20 Cb-3 are registered trademarks of Carpenter Technology Corp. 20 Mo-6 and 20 Mo-4 are trademarks of Carpenter Technology Corp. "Monel" is a trademark of International Nickel Company.

sidered: corrodents in the environment, pH, temperature, mechanical properties, construction, availability and cost. While cost is important, it should not be the final criterion for selection; this may mean going through the same selection process again after the low-cost material fails. This incurs the additional cost of replacement and labor.

Alloy selection can be simplified somewhat by the use of two charts. The first is called the "Y" of corrosion (Fig. 4). Reducing environments are on the right and oxidizing environments are on the left. A specific alloy will work on one side, but not the other. For example, Type 304 stainless steel will work on the oxidizing side but not on the reducing side. Alloy B-2 will work on the reducing side but not the oxidizing side. The high chromium-high molybdenum alloys bridge the gap between. Another selection guide is shown in Table 4. This simplified guide is helpful in selecting alloys for sulfuric, phosphoric or nitric acid service and for pitting, crevice or chloride stress-corrosion cracking resistance.

Because most extraction and concentration processes require heat, the steam cycle also must be considered. To prevent rapid oxidation of the carbon steel components, two things are done to the steam: the pH is adjusted upward to about 10 and hydrazine is added to combine with any dissolved oxygen. If the entire steam circuit is carbon steel or stainless steel, there is no problem. However, if copper or one of its alloys is introduced, the pH must be reduced to 8.5 to prevent rapid dissolution of the copper by uniform corrosion. This lower pH causes rapid corrosion of the carbon steel. The hydrazine reacts with oxygen and forms ammonia and water. The ammonia reacts with the copper in three ways: it forms heavy amide layers on the surface of the tube limiting heat transfer, it dissolves the copper where it runs down the sides, and it can lead to stress-corrosion cracking.

Acid-cleaning of components is another dangerous area. The favorite cleaning agent is muriatic acid. This can be dangerous for Type 304 stainless steel because it can lead to pitting, crevice or stress-cor-

TABLE 2

Alloy Systems Subject to Stress-Corrosion Cracking[a]

Alloy	Environment
Aluminum base	• Air • Seawater • Salt & chemical combinations
Magnesium base	• Nitric acid • Caustic • HF solutions • Salts • Coastal atmospheres
Copper base	• Primarily ammonia & ammonium hydroxide • Amines • Mercury
Carbon steel	• Caustic • Anhydrous ammonia • Nitrate solutions
Martensitic & precipitation hardening stainless steels	• Seawater • Chlorides • H_2S solutions
Austenitic stainless steels	• Chlorides-inorganic & organic • Caustic solutions • Sulfurous & polythionic acids
Nickel base	•Caustic above 600°F (315°C) • Fused caustic • Hydrofluoric acid
Titanium	• Seawater • Salt atmospheres • Fused salt

[a] Simplified. See Logan, H.L., "The Stress Corrosion of Metals," John Wiley & Sons, for comprehensive list.

TABLE 3

Corrosive Microorganisms[a]

Organism	Action	Problem
Desulfovibrio Clostridium Thiobacillus	Hydrogen sulfide producers (Sulfate reducers)	Corrosive to metals Reduces chromates Destroys chlorine Precipitates zinc
Thiobacillus	Sulfuric acid producer	Corrosive to metals
Nitrobacter Nitrosomonas	Nitric acid producers	Corrosive to metals
Gallionella Crenothrix Spaerotilus	Converts soluble ferrous ions to insoluble ferric ions	Produces iron oxide deposits Increases corrosion

[a] From "Identification & Control of Corrosive Microbilogical Organisms Found in Recirculating Cooling Water Systems," by Paul R. Puckorius, Corrosion 78, Paper Number 81.

TABLE 4

Stainless Alloy Selection Guide

	General corrosion			Localized corrosion	
Corrodent severity	Sulfuric acid	Phosphoric acid	Nitric acid	Pitting or crevice	Chloride SCC
Very severe to severe	20 Cb-3[a]	20 Mo-6[b] 20 Mo-4	7 Mo PLUS 20 Mo-4 20 Mo-6 SEA-CURE	SEA-CURE 20 Mo-6	20 Mo-6 20 Mo-4 20 Cb-3 SEA-CURE
Moderate to severe	20 Mo-4 20 Mo-6	20 Cb-3	20 Cb-3	20 Mo-4	
Moderate		SEA-CURE 7 Mo PLUS	Type 316 Type 304	7 Mo PLUS 20 Cb-3	
Mild to moderate	SEA-CURE 7 Mo PLUS	Type 316		Type 316	
Mild	Type 316	Type 304		Type 304	

[a] 20Cb-3 is a registered trademark of Carpenter Technology Corp.

[b] 20Mo-4 and 20Mo-6 are trademarks of Carpenter Technology Corp.

rosion cracking. If possible, use a different acid.

Mixed environments may require test racks involving many alloys to determine which material is best in that particular environment. There are standard rack designs that can be placed in nearly any environment. For a specific problem, contact a reputable material producer for assistance. Over the years, many tests have been conducted in many environments and a wealth of information is available. Someone else may have had the same problem and the solution might already exist. And yes, there is an alloy out there that will solve your problems.

Materials and welding techniques

The following talk was given by Kenneth F. Krysiak, principal engineer for materials engineering in Hercules Inc.'s engineering department, Wilmington, Delaware.

Selection of construction materials for process equipment involving the use of carbon steel and austenitic stainless steels is based mainly on corrosion performance. Therefore, it is necessary to consider what types of corrosion will be encountered.

Studies (1) have shown that for most stainless steel equipment, 60% of the failures in the chemical-process industries are due to stress corrosion cracking or localized attack in the form of pitting or crevice corrosion (flanged connections). Thus, awareness of alloy behavior in corrosion environments is important, not only for safety reasons but also for economic reasons. Although the use of higher alloys may seem advisable, their use is often restricted for economic reasons.

When selecting materials, the engineer also must give careful consideration to how these materials will be joined. Failures of equipment or piping systems often are related to welds. Consequently, the selection of welding filler metals is important.

Selecting materials

When selecting materials, the engineer must consider not only environmental factors, but also plant operating parameters. Some factors are pressure, temperature, presence of water, pH, phase separation, chlorides, oxygen and cycling effects. It is important not only to know the factors under normal operation conditions, but also to consider what could happen under upsets, shutdowns and standbys. The following have been known to occur:

- acid production caused by vapor condensation.
- stress-corrosion cracking due to (a) the boiling off of water phases, resulting in a concentration effect of chlorides or caustics, or (b) saturation of the thermal insulation on external surfaces, producing chlorides.
- microbiological corrosion during prolonged shutdowns (one such failure occurred in only three months during a shutdown in a Gulf Coast area plant).

Consideration also must be given to past plant experiences. If this information is not available, corrosion behavior can be estimated by plant or laboratory testing. In the case of carbon steel materials, a corrosion allowance (i.e., more metal than required for mechanical strength) often is used.

Experience has shown that every application seems to be unique or specific to its own environment or media. For example, in the case of rosin extraction from wood chips, wear is a factor that must be considered because of the large volume of sand present in the pine stump environment. In this case, the use of abrasion-resistant steels sometimes has proven successful. Smaller surface areas can be hardfaced to improve wear resistance, usually with an iron-based material for general use, or nickel-based for corrosive applications.

Corrosion considerations

The corrosion performance of carbon steel can be improved by small additions of chromium and copper. A good example is USS Corten, which has approximately five times the corrosion resistance of plain carbon steel in industrial stack applications.

Austenitic stainless steels (Table 1) exhibit unique corrosion behavior because of the influence of the key alloying elements chromium (Cr), nickel (Ni) and molybdenum (Mo). Super stainless steels, which are a little higher in alloy than other stainless steels, particularly Mo, are listed in Table 2. As illustrated in Figures 1 and 2, the improvement in pitting and crevice corrosion properties increases proportionately to Mo content. Commercial alloys like Type 316 and Type 317 are correspondingly less effective. Type 304 stainless steel is even more susceptible to pitting and crevice corrosion because it is not alloyed with Mo. Note that in these cases, the critical pitting or crevice corrosion temperature is that temperature below which attack will not occur in 10% $FeCl_3$.

Corrosion properties can deteriorate when alloys are autogenously welded (i.e., without the addition of filler metal). This problem is related primarily to the segregation of Cr and Mo. For this reason, the welding electrode (Table 3) must be carefully selected for each application. Corrosion testing frequently is the only way to determine the proper material of construction.

For best corrosion performance, the alloying elements must be homogeneously distributed throughout the base metal in solid solution. Because elements segregate during solidification, wrought material can be segregated if the cast ingot was not properly worked or heat-treated. Castings also must be solution-annealed to enable homogenization.

To overcome many of these difficulties, it is recommended that materials be purchased to ASTM specifications. Material certification can be requested as well as certification to certain corrosion tests.

The choice of standard grade T304 T316 or T317 versus the low-carbon grades depends on the application. Welding does cause sensitization (in the range of 800 to 1550°F) in which Cr carbides precipitate out into the grain boundaries. The regions around the precipitates are depleted in Cr and are susceptible to intergranular corrosion by aggressive media such as nitric acid, mixed acids and organic acids such as acetic and formic. Several options are available to avoid this problem:

- use L-grade material (low-carbon).
- use a stabilized grade such as Type 347.
- solution-anneal (1900-2000°F) after welding. This method is not usually practical because of distortion problems or geometry, but there are exceptions.

The newer super-stainless steels are all low-carbon and now feature a nitrogen addition to further enhance corrosion behavior by retarding carbon mobility.

Stress-corrosion cracking probably is the most insidious of corrosion problems. Austenitic stainless steels are affected more from this problem than any other alloy system. Chlorides are known to produce failures under certain conditions, even when present in trace amounts. It is not unusual to have chlorides concentrate locally during start-up boil-off, in crevices or pits or at vapor-liquid interfaces. Conditions contributing to failure include: tensile stress; pH less than 9 (presence of water); chloride presence (1 part per million can be too much under the right conditions), and temperature over 175°F (some sources suggest 140°F).

Chloride stress-corrosion cracking will occur in austenitic stainless steel whether sensitized or not. There are some environments that will promote stress-corrosion cracking only when the base metal is sensitized. Two examples are T304SS (used in nuclear reactor piping) and polythionic stress-corrosion cracking of T304SS (used in the oil refinery industry). To overcome these difficulties, the following options can be considered:

- modify the environment (not always possible).
- use an alloy resistant to chloride stress-corrosion cracking.
- stress-relieve (possible problems with sensitization).
- shot peen (like stress-relieving, this usually is a delay tactic).
- design equipment to eliminate places where chlorides can concentrate, or reroute process streams.

Using an alloy resistant to chloride corrosion is the route most often taken. Duplex stainless steels (Table 4) offer a wide range of applications because of their high resistance to chloride stress-corrosion cracking. Some alloys also feature improved resistance to pitting and crevice corrosion over Types 304 and 316 stainless steels. This improved corrosion performance is attributable to the high chromium and molybdenum levels.

Nitrogen is an important alloying addition because it slows the precipitation kinetics of chromium and molybdenum during welding and enhances the reformation of austenite in the weld and the heat-affected zone during cooling (2). If proper procedures and techniques are not followed when welding, corrosion resistance will be impaired. Mechanical properties, especially impact toughness, also can be affected.

TABLE 1

Typical Austenitic Stainless Steel Compositions

	Composition, wt. %		
Alloy name	Cr	Ni	Mo
Type 304L	18	8	-
Type 316L	16	13	2.1
Type 317L	18	14	3.1

TABLE 2

Typical Super Stainless Alloy Compositions

	Composition, wt. %			
Alloy name	Cr	Ni	Mo	N
904L	20	25	4.2	-
JS700	21	25	4.5	-
AL-6XN	20	24	6.6	0.20
254SMO	20	18	6.1	0.20

TABLE 3

Typical Compositions of Filler Metals

	Composition, wt. %				
Alloy name	Cr	Ni	Mo	N	Fe
308L	19	10	-	-	bal.
316L	19	12	2.1	-	bal.
317L	19	13	3.1	-	bal.
309Mol	23	14	2.1	-	bal.
254SLX	20	24	5.0	-	bal.
Inconel 625	22	bal.	9.0	-	5.0 max.
Inconel 112	22	bal.	9.0	-	7.0 max.

TABLE 4

Typical Duplex Stainless Steel Compositions

	Composition, wt. %				
Alloy name	Cr	Ni	Mo	Cu	N
2205	22	5	3	-	0.15
Ferralium 255	25	6	3	2	0.20
7-Mo Plus	26.5	4.8	1.5	-	0.20
44LN	25	6	1.7	-	0.15

When two dissimilar metals are joined together and immersed in a conductive and corrosive solution, galvanic corrosion may occur. In most of these situations, the stainless steel (or the higher alloy) is the cathode. The ratio of the area of the anode to the cathode is of importance. A large cathode and small anode can lead to accelerated attack. Differences in chemical composition within the same alloy or weld metal have been known to produce rather dramatic galvanic effects. Welds also can be corroded preferentially.

Welding

Although there are times when welds show corrosion behavior superior to that of the unwelded base metal, the reverse is often true (3). Erratic behavior sometimes is experienced even though proper procedures were believed to have been followed, industry codes and standards used, and welds deposited correctly.

Experience has shown that one or more of the following factors can cause weldments to fail: weldment design, joint preparation, welding process, contamination, weld slag and spatter, incomplete weld penetration or fusion, porosity, cracks, improper choice of filler metal, oxide films and scale, iron contamination after welding (cleaning), final surface finish and metallurgical factors.

Weldment design

A good design must enable good fitup, allowing the welder to manipulate the electrode or torch to make proper tack welds. If backing rings are used, they must be fully fused or machined off after welding to prevent crevice corrosion (Fig. 3) or fatigue failure due to the stress raiser or notch effect, under cyclic loading.

Mismatch during fitup should be corrected by tapering (3:1) the thicker member to the thinner member, thus avoiding turbulence or stagnant areas.

A weld joint that is too narrow can promote slag entrapment, lack of fusion and incomplete penetration. Excessively wide joints require extra weld metal, a solution that is not cost effective and can lead to distortion problems.

Joint preparation

In order to avoid defects in welds, it is important that joint surfaces be properly cleaned. Grease, oil and dirt are particularly harmful to steel and stainless alloys because they can cause cracking and loss of corrosion resistance. Moisture pickup

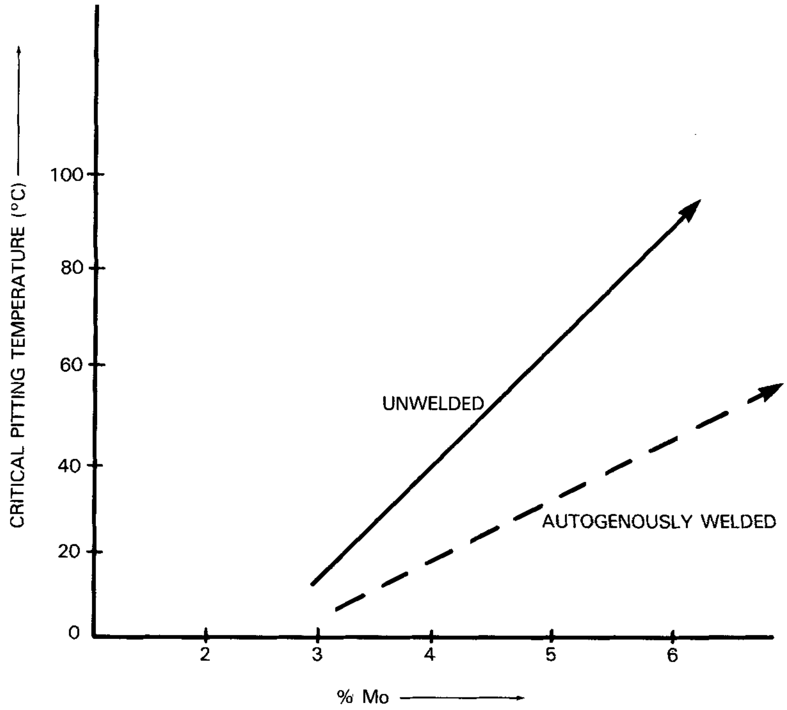


FIG. 1. Critical pitting temperatures versus Mo content for austenitic and super-stainless steels after testing in ferric chloride ($FeCl_3$).

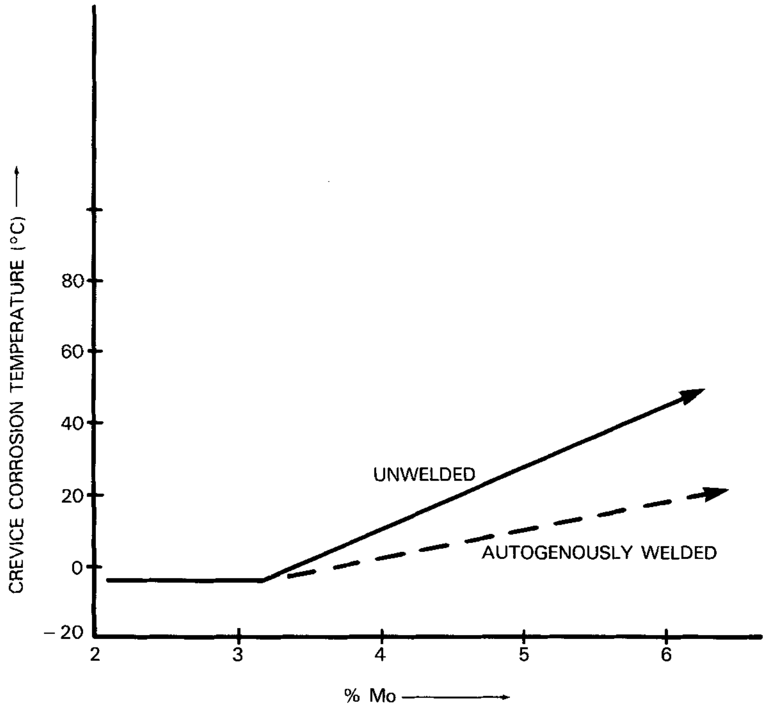


FIG. 2. Crevice corrosion temperatures versus Mo content of austenitic and super-stainless steel after testing in $FeCl_3$.

in electrodes can cause porosity or under-bead cracking when welding carbon or low alloy steels, as well as duplex stainlesses.

Heavy oxide films, resulting from thermal cutting or gouging, must be ground off to sound metal to avoid fusion defects or contaminated weld beads. With certain alloys, dye penetrant inspection after this preparation is sometimes recommended to ensure freedom from defects.

Solvent cleaning just before welding is essential. Contaminants must be removed from both sides of the joint. If plates are greasy to begin with, solvent cleaning should be performed first to avoid contaminating wire brushes or chipping and grinding tools.

Welding process selection

Shielded metal-arc welding (SMAW) with covered electrodes probably is the most widely used welding process. Care must be taken to avoid slag entrapment and to remove all traces of slag from the weld surface, where corrosion could begin.

To date, SMAW welds made with duplex filler metals are not as tough as those made with the gas tungsten-arc welding (GTAW) process. The problem is believed to be related to metal oxides dispersed throughout the weld. When welds of the best quality are needed, the GTAW process is preferred. To further improve GTAW welds, a gas lens shielding device is highly recommended. Gas flow with standard torch nozzles tends to be more turbulent and, consequently, air is siphoned into the molten puddle. Shielding gas flow with a gas lens is laminar, thus preventing the siphoning of air into or onto the molten puddle.

Gas metal-arc welding (GMAW), featuring the short-arc process, has been used successfully, but there are some limitations. The shielding gas must be chosen carefully in order to avoid loss of critical alloying elements through oxidation. Because this is a relatively cold welding process, fusion defects are common; thus, it is not allowed in critical applications.

Filler metal selection

It is standard practice that the choice of filler metal match that of the base metal. However, in certain environments where preferential corrosion is experienced, the need for a higher alloyed material may be warranted. Table 3 lists some of the common welding consumables currently in use in many chemical plants.

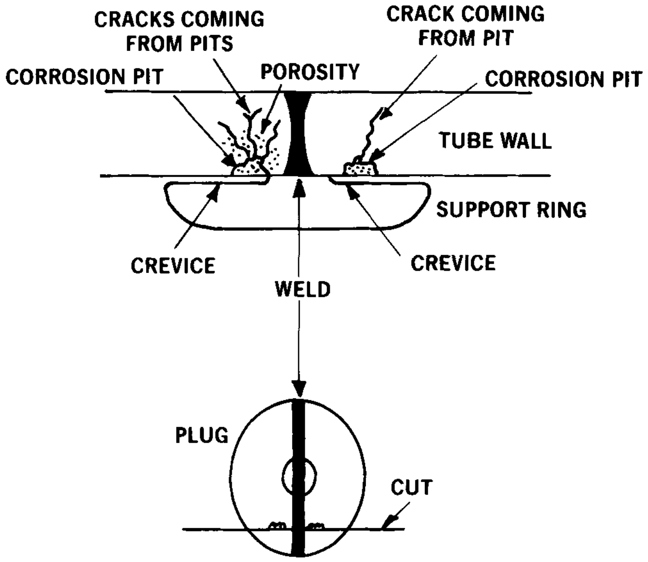


FIG. 3. Schematic of a nitrator cooling coil weld joint. Failure occurred because the backing support ring was improperly designed and not consumed in the welding process, thus leaving a crevice (3).

A unique situation exists with duplex stainless steels. The key to success with these materials is to use filler metal similar in composition, but enriched in nickel (up to approximately 9%). In this way, the delicate balance of austenite-to-ferrite is maintained. If the ferrite phase is below 25%, resistance to chloride corrosion is severely degraded. If the ferrite phase is greater than 75–80%, severe loss in notch toughness is encountered. The goal is to achieve 40–60% ferrite for best overall performance. Dissimiliar filler metals also have been used successfully.

When the stainless and super-stainless steels are welded, segregation of chromium and especially molybdenum occurs. Corrosion problems (specifically, preferential attack) are being encountered in alloys such as T316L and T317L, now made at the very low end of the molybdenum specification range. Corrosion-test data developed 25 years ago—when alloys with much higher levels of molybdenum were used—are no longer valid because of these microsegregation effects. To overcome these difficulties, filler metals higher in alloy now are used in many applications. For example, T316L can be welded with T317L or one of the 4.5% Mo grades. T317L has been welded with 4.5% Mo filler metals or a 9% Mo-grade such as Inconel 625. The super-stainless steels should only be welded with a filler metal such as Inconel 625 to ensure that the proper molybdenum level is achieved in the weld after segregation effects take place.

Welding techniques

Use of the largest gas nozzle with a gas lens optimizes the corrosion, and sometimes, the mechanical properties of GTAW joints. Keeping the filler wire tip within the shielding gas envelope minimizes the pickup of oxygen and nitrogen, which will form oxides and nitrides. By having a much broader area of the weld covered with inert gas, heat tint oxides can be minimized, especially when the arc is extinguished (this point is referred to as the weld stop or crater). It is preferable to use a foot current control device to avoid "snapping the arc" (i.e., lifting the welding torch up off the workpiece), as well as shielding gas loss. A postpurge of argon for six seconds or more is recommended to protect the weld bead from oxidation. Prepurging the torch also is beneficial.

One method of avoiding crater cracking is to extinguish the arc slowly, adding filler metal at the same time, to produce a slightly convex—rather than concave—bead shape. Another method is to increase the travel speed to reduce the size of the molten puddle just before extinguishing the arc.

Welds not passing radiography requirements often can be traced to the tack welds. The problem is related to the shape of the molten puddle and the tendency for bridging to occur rather than melting and fusing the tack weld fully. This problem is compounded when welding with a higher alloy filler metal, which tends to be more sluggish. The fix is to taper-grind the front and the back of the tack welds. This practice is called "feathering."

If joint prep is done properly, use of dry electrodes can overcome the problems of porosity and underbead cracking (i.e., delayed cracking in carbon and low-alloy steels). Portable electrode ovens at the job site are highly recommended for keeping electrodes free of moisture.

Finishing and weld testing

Although slag removal with AC/DC titania coated electrodes is readily achieved, slag entrapment difficulties are increased. Lime-coated electrodes, on the other hand, produce a slag that rapidly rises to the surface of the molten puddle but is more difficult to remove once solidified. Finishing the completed weld includes not only removal of any slag, but also heat tint oxides. It has been shown that, under certain conditions, the heat tint oxides can be sites for preferential corrosion. There seems to be some disagreement on how best to remove the heat tint oxides and restore surface integrity. Some methods currently used are:

- power wire brushing or grinding. Never use a carbon steel wire brush on stainless alloys or a stainless brush that was previously used on carbon or low-alloy steel.
- pickling paste or gel.
- grit or sand-blasting.

The only way to determine the preferred method for a particular application is to corrosion-test. Removal of weld spatter also is important because of potential corrosion problems as a result of minute crevices and oxide entrapment.

A word of caution: After hydrotesting stainless or carbon steel fabricated components, be sure to drain the water fully. Water left behind can induce rather severe microbiological corrosion with a preference for welds.

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Corrosion in heating coils

The following talk was presented by James R. Smith of Armstrong-Hunt Inc., based in Milton, Florida, and Steam Economies Co. Inc., based in Cincinnati, Ohio.

Corrosion of heating coils in process, as well as heating, ventilation and air conditioning (HVAC), systems can lead to premature equipment failure, temperature discomfort, production downtime and, ultimately, lost revenues.

The food-processing industries are more likely to have problems in their steam-heating coils than other industries, due to additional restrictions and controls put on water-treatment techniques. Although necessary to safeguard contamination of edible foodstuffs through direct contact with treated steam or water, those restrictions can lead to problems in steam-heated equipment. This is most evident in the area of large steam coils used in process drying, cooking and toasting applications.

There often is no one party to whom the plant can point an accusing finger. The water-treatment company follows rigid guidelines for areas such as alkalinity control, pH-level control, dissolved solids and oxygen scavenging. The heating-coil manufacturer follows traditionally acceptable material selection and construction techniques. The drainage-equipment manufacturer supplies equipment and makes standard recommendations that are well-proven in heating applications in other industries. And, the local power-house superintendent and boiler operations personnel keep a watchful eye on all steam system processes in conjunction with routine corrections and inspections by maintenance personnel.

With such excellent control, care and experience, how can corrosion ever cause difficulties in steam heating coils? It is not always the fault of a particular party or manufacturer when corrosion finally reveals itself in the form of a steam leak or system outage. The failure often is the result of small problems in one or more of the component parts which adversely affect system operations. The understanding of the role each component part plays in the system's ultimate success or failure is what must be addressed.

Water

Without water and heat, we have no steam. With steam, we have many of the things we need to accomplish the heating task, e.g., temperature, energy (latent heat of vaporization) and flow. We also have the components of the water which negatively affect the heating and condensing process, particularly CO_2 and O_2.

CO_2 comes to the steam via dissolved minerals in the water in the form of carbonates and bicarbonates. CO_2 is quite unusual in that it resides as part of the steam leaving the boiler in the gaseous state and yet has the ability to plate out (move to the film wall of the heat transfer device), negatively affecting heat transfer, and then dissolves in the cooling condensate leaving the heat exchanger. The O_2 enters the system through vacuum breakers and packing as free molecules during the boiling process.

CO_2, when combined with H_2O at the right temperature conditions, will result in a highly destructive and corrosive agent called H_2CO_3, better known as carbonic acid. This acid will result in severe grooving of the system condensate return-piping. If this occurs within the heating coil, H_2CO_3 can destroy sections of even heavy-wall 10–12 gauge tubes within a few short months, if left unchecked.

The presence of O_2 most often results in deep pitting of the steam/condensate system lines. The source of water for the processing plant usually is a river, lake or stream. By nature, these sources often produce high amounts of CO_2 and O_2 during steam production.

Water treatment

Unlike a steel mill, auto-manufacturing plant or other equipment or materials manufacturer, a food-processing facility is restricted by the U.S. Food and Drug Administration (FDA) to a limited number of additives and chemical treatments for control of water and steam systems. In general, treatment systems involving oxygen scavenging, deionizing and pH control show good results. Testing points at feedwater heater inlets, receivers or return lines show little or no presence of CO_2 or O_2. If this is the case, why should corrosion be a problem?

Treatments for reducing O_2 and CO_2 work effectively in the steam lines to the heat exchanger coils. However, evidence has shown that unless additional local dealkanization systems are added nearer to the coils, severe internal corrosion can result.

Employment of ammonia and hydrazine as oxygen scavengers can have an adverse effect on copper-tube materials. Copper leached from heating-coil tubes can deposit on boiler tubes, resulting in localized hot spots and boiler-tube failure.

It appears water treatment runs out within the heating coil tubes during the condensing process. In tubes removed from failed heating coils, examination of tube walls show evidence of water treatment working at the inlets and some distance into the condensing tubes. However, further down the tubes, there is little or no evidence of water treatment.

When pH has been checked at the typical sampling points, it usually reads neutral or slightly acidic (6–7 pH). Upon examination closer to the actual condensing area, there is indication that pH is extremely low (4–4.5 pH). The question is: "Why isn't the treatment working?"

Again, the answer may not simply be to use more chemicals, but rather to concentrate chemicals near heavy condensing areas and to examine the basic coil design used. Use of coils designed to evacuate condensate and noncondensables rapidly as they form may be critical.

Heating coil design

It may be thought that the coil in

finned-tube heat-transfer equipment is the innocent victim of the rest of the system. This often is the case when improper drainage, venting or control is involved. When these auxiliaries are not given enough thought, many coil problems do occur. However, the coil also can be a contributor to the problem.

The heating coil is composed of fins (made of aluminum, copper, steel or stainless steel) in some way attached to piping or tubing. Often, in light-duty HVAC applications, thin straight-edged fins are wrapped loosely around the tube. Tubes also can be expanded into fins punched from thin strips with holes and collars to give some contact at the fin base.

Heavier-duty applications require different methods of attaching the fins to tubes. These include thicker fins and tension-winding of formed L-footed or smooth shapes onto, or even into, the surface of the tube. On steam systems, the heavier tube walls do not effectively reduce heat transfer, but do increase corrosion allowances and structural integrity to extend life and reduce maintenance.

Tubes then are joined at headers (usually heavy-wall copper or schedule-40 carbon steel). The attachment techniques can range from brazed or soldered to rolled and welded. Tubes are mounted in both horizontal and vertical positions, perpendicular to the air flow.

With the potential for an exceptionally well-built heavy-duty design using 12 gauge (schedule-40) wall steel tubes and headers with thick fins (up to 0.024-inch), why should corrosion be a problem?

If pH drops to the level of 4–4.5, even heavy-wall materials will virtually disintegrate in a matter of months. This means not only the expense of premature coil replacement, but also production losses and poor quality control of the drying process.

Corrosion in heating coils

Coils can contribute to their own demise through internal circuiting problems. The circuit is the path through which the steam and, subsequently, the condensate must travel.

Parallel circuits allow steam to enter all tubes, in all rows, simultaneously. This may appear to be very helpful. However, since condensing does not occur in the same volume in all rows, short circuiting can occur. This uneven condensing causes some tubes to have lower steam pressures than adjacent or following tubes. The tubes with lower pressures will allow steam from an adjacent row to enter as a means of balancing the system pressure over the entire coil. This circuiting problem can be amplified by improper trapping and drainage techniques.

Remember, if gases in the tubes are not moving fast enough to be swept along the heat transfer surfaces, accumulations can occur. This can lead to corrosive wall thinning and pitting.

To avoid short circuiting, steam coils can be designed with series circuits, which allow the steam to travel in succession through the rows. When this design is used, it is important to have an intermediate separation or drain point to shed the forming condensate. These designs are called tandem, or series, circuit steam designs. This design differs from the light-duty HVAC serpentine or booster coil, which simply snakes a tube back and forth across the coil face to push the forming condensate in a slug ahead of the steam.

It may seem sufficient to build a coil using only heavy-duty materials and the tandem-series flow design, but even this is severely affected when involved with very long (8 to 14 feet or more) vertical tubes.

It appears that due to the heavy condensing formed in the very long vertical-tube designs, the volume of condensate falling off and down the tube walls leads to more rapid subcooling of the condensate. This subcooling to slightly below steam-saturation temperature will rapidly allow the CO_2 coming out of the steam during condensing to lower the pH in the traveling condensate. This lowered pH condensate, full of dissolved CO_2, now can be seen as mild-to-strong carbonic acid. This same phenomenon can be seen in large, horizontal-tubed coils with inner distribution tubes as used on freeze-resistant or distribution-tube coil designs.

Condensate reaching the header space between the end of the outer tubes and the beginning of the inner tubes cascades to the bottom of the header, passing over the inner-tube ends. This falling film of cooling condensate often picks up the dissolving CO_2 and forms a carbonic acid rain, which can result in cut-off inner tube ends. Use of 304L stainless steel inner-distribution tubes on horizontal coil designs appears to fend off this corrosive attack, but does not rid the system of the CO_2 or O_2.

Drainage and venting

Drainage and venting are of critical importance, but often are the least understood. There is an assumption that water formed from the condensing of steam always will find its way out of the heating coil to the drainage device (steam trap) and out of the system. Another assumption often made is that the balance of unwanted and noncondensed gases travels out of the coil and to the final venting location in the receiver or deaerator. Both assumptions can be fatal to the heating coil.

The condensate that forms in the tubes along the heat transfer surfaces must be removed as quickly as it forms. If it is allowed to subcool by even 2–3°C, severe corrosion will occur along the gas/liquid interface. This usually is in the form of carbonic acid.

Ideally, the steam will blow right through the coil and out to a vented tank. However, this approach results in high steam-pressure drops through the coil and eventually wasted energy through blow-through steam at the receiver vent. There is some validity in this approach because a constant, purging movement of gases along the heat transfer surfaces will continuously move noncondensables along and away.

The most accepted and successful practice is to use steam traps on the discharge side of the coil. These devices stop the live-steam blow and allow the steam to condense in the heat exchanger. Steam traps have various means of sensing the need to discharge the condensate that is collecting in their bodies or in the line coming to the trap. The best selection would be an inverted-bucket steam trap, with a large-bucket vent hole. This trap will discharge the condensate at steam temperature and cycle rapidly enough to assist in the purging and surging action of the gases in the coils.

Steam velocity is reduced within the coil when the trap valve is closed. When this occurs, condensate flows by gravity head only to the trap. This emphasizes the importance of placing steam traps well below the heat transfer equipment. The minimum distance below should be approximately 18 inches from the outlet connection of the coil to the orifice of the trap.

Unfortunately, the noncondensable gases CO_2 and O_2 do not gravitate to the steam trap. They must be induced by gas-pressure differential between the coil heat-transfer surface and the outlet pressure of the system. If there is no venting, bleed orifice or controlled gas-outlet device downstream from the coils on the discharge piping, these gases will stagnate within the coil and add to a reduction in effective heat transfer. Worse yet, they now may come in contact with condensate and reduce the pH, resulting in severe corrosion within the coil.

These gases occupy only a small portion of the poundage of steam coming into the heating coils. However, problems occur when they are allowed to accumulate in the process of heavy condensing in large coil dryers and heaters. This volume, often amounting to tens of thousands of pounds of steam per day, can leave thousands of pounds of residual noncondensables to destroy the system.

Some people advocate putting air vents on the inlets to coils and other high points in the system. These locations would only be effective on initial startup, when the system is full of noncondensables. They would not function once the system is up and running, because the lines then are hot and filled with steam. When the steam pushes into the heating coil, it pushes the existing noncondensables ahead of it on startup. Therefore, an air vent only on the coil inlet would take care of very few noncondensables.

If equipped with an air-venting device such as the thermostatic bellows in the float and thermostatic trap, the trap will handle all the air that gets to it. If the line to the trap becomes hot and full of condensate, the noncondensable gases will seldom be seen by the thermostatic vent during normal operation.

The best alternative is to install a unique air-vent line off the discharge of the coil, elevated at least 18–24 inches and of full discharge-line size. This line should be left uninsulated, acting as an air accumulator. The automatic air-venting device, bleed orifice or petcock should be installed on the top of this accumulator line. The line will become a continuous venting line in most circumstances and should be vented to an area away from personnel. Although some visible vapor and occasional moisture will emit from this discharge, it will be a primary venting device. The air vent is then the only control to insure that the gases are being purged on a continuing basis. If installed too close to the condensate line, the air vent will discharge liquid in large volumes and possibly show damage from water hammer and shock.

The steam trap is now nearly exclusively handling liquid, while the external air vent is handling virtually only gas.

Sometimes the discharge outlet of the vent is connected back into the condensate return line downstream from the steam-trap outlet. If return lines are oversized sufficiently, they may handle the extra volume of gas taking up the space. However, if the return lines are undersized and run full of condensate, a severe backpressure problem may occur in the return line to affect both trap and air-vent operation.

Instead, the vent should be to the atmosphere and the discharge of several coil vents should be combined in a single line vented out of the area to the atmosphere.

If the coil steam supply is controlled by a modulated control valve, a vacuum breaker should be installed in the air vent accumulator line, above the condensate line and well above the bottom of the coil. This will insure that the vacuum formed during valve modulation will be broken quickly, allowing the liquids to drain to the traps and keeping lines clear for the air-vent devices to operate.

All line sizes should conform to the manufacturer's suggestions and should never be reduced from the outlet of the coil to the trap take-off.

If condensate is to be elevated, then a secondary or safety-drain trap should be installed above the main trap but below the coil outlet. This trap must discharge to a gravity drain or sewer, and must not be subjected to elevation or backpressure.

Putting the air vent and vacuum breaker in the safety-drain trap is helpful, but has not proven to be the ultimate solution in accumulating large amounts of the noncondensables coming from the coil. It should always be used in conjunction with the air vent/accumulator to obtain the best results.

Using any steam trap that allows condensate to back up in a liquid head before entering the trap will result in severe subcooling of the condensate and increase the rate of corrosion. Continuous drainage devices such as inverted-bucket steam traps and float and thermostatic types are the only recommended choices.

Maintenance and operation

Startup conditions on large dryers/toasters may result in sudden and huge slugs of condensate forming in the coils and associated lines. Steam traps, vents and lines should be sized to adequately handle the surges associated with cycling operations.

Rapid venting of systems on startup can purge the heat transfer areas quickly and reduce system heat-up time considerably. Lack of adequate equipment can actually result in air-binding of the return lines at the traps, if they are not equipped to handle major air loads quickly. If the choice is to have the air accumulator/vents connected into the condensate return lines, an attempt should be made to vent the system to the atmosphere after the system has come up to temperature. Use of a three-way valve after the vent will work well. This approach will relieve excess pressure in the return and maximize dryer efficiencies.

Checking strainer screens before steam traps, especially in the early weeks of operation, can insure good drainage flow to the traps and also indicate any internal corrosion occurring (by evidence of red or black metal oxides filling the screen area).

Any large quantities of deposits should be cause for concern, especially during early operation.

Finned surface on coils should be cleaned with compressed air whenever the accumulation is enough to be seen. This is important not only for improved heat transfer but to keep moisture underneath the deposits from resulting in external corrosion to the fins or tubes.

Fin-spacing selection should be made based on expectation of deposits on the coil during normal operation and downtime. Normally, five to seven fins per inch are satisfactory in order to achieve adequate heat transfer and still allow larger particles to pass through the coil. If the fins selected are not rigid enough to withstand strong cleaning, they should be replaced by fins with a minimum of 0.016-0.20-inch thickness. The extra cost will be returned in longer fin-surface life.

Materials

Choice of materials often is a function of budgets, longevity and the expected suuoundings (internal and external) in which the coil must exist. If budgets are not the issue, then coils composed of the following materials should be the first choice:

- Tubes—minimum 1-inch o.d., 14-gauge (0.083-inch) wall, 304L stainless steel
- Fins—minimum 0.020-inch aluminum embedded (keyfin), 5-7 FPI
- Headers—304L stainless steel (minimum schedule-40)
- Tube/header joints—all welded
- Inner tubes—(if needed) 304L stainless steel, nonperforated
- Casings—galvanized steel, minimum 14-gauge
- Rows/circuitry—1-row parallel or 2-row series (tandem)

The above selection will insure optimum performance and longest life, but also will be the most costly. Alternates would include the following:

- Tubes—1-inch o.d., 12-gauge (0.109-inch) wall, carbon steel
- Fins—0.016-inch aluminum or copper/0.024-inch-thick carbon steel
- Headers—Schedule-40 carbon steel (with steel tube only)

Lighter-weight construction than these choices can cost less initially, but will cost more in the long run due to associated downtime for maintenance and lost production.

Looking for corrosion-related equipment failures and reduced performance in a facility begins and ends with a system approach. An apparent quick-fix solution to a complex problem such as corrosion in heating coils often conceals the problem. The best alternative is to look at each component of the heating coil system, from the boiler to the return tank. This may take longer, but in "the long haul," it may be the fastest track to higher profits and lower equipment outage.

An example of the above analysis, installation and ongoing follow-up was undertaken by National Sun Co. in Enderlin, North Dakota, several years ago. The result was reduced downtime and increased capacity for sunflowerseed and soybean processing through the facility's receiving and process dryers. Schlomo Nadel, National Sun's technical director, oversaw the changes which resulted in substantial production increases through the dryers. Wendell Nelson, maintenance supervisor, has performed the monitoring upkeep which has kept the system at peak performance. My thanks go to them for assisting with on-site follow-up of their system changes.

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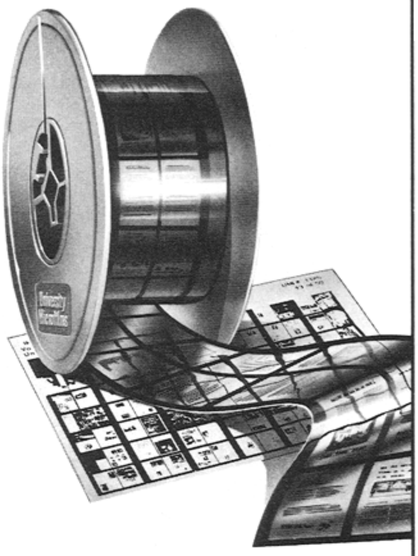

Plate heat exchanger materials

The following talk was given by James A. Carlson of APV Crepaco Inc., Tonawanda, New York.

In choosing the correct materials for plate heat exchangers used in the fats and oils processing industry, we are primarily concerned with three components of the heat exchanger that are wetted by the process or service: heat transfer plates, connections and gaskets.

First, let's review plate heat exchanger construction.

The typical range covers 0.27 square foot of heat exchange surface per plate with 0.75-inch connections, to 35 square feet of heat exchange surface per plate with 16-inch connections. Units in oil service generally have 4-inch or smaller parts, whereas those on deodorizer scrubbers are in the 6-inch to 12-inch size. A common unit used is the APV R57 Paraflow with 5.6 square feet of heat transfer surface per plate and 4-inch diameter ports.

The heat exchanger frame provides the structural support for the plate pack and consists of the head, follower, top and bottom carrying bars, tie bars and nuts, and the end-support column (Fig. 1). A bolted frame construction is an important consideration for installation in areas with restricted access and for future expansion of the unit in the field.

The frame, in conjunction with the high-tensile tie bars, forms a rugged structure to hold the plates in alignment and to maintain proper gasket compression. The carbon steel components (other than the tie bars) can be painted with a corrosion-resistant coating.

The head (fixed cover) of the plate heat exchanger forms the stationary end of the frame and generally contains all four product/service media nozzles.

The follower (movable cover) forms the movable end which compresses the plate pack against the head. The follower is suspended from the top carrying bar and is guided by the bottom carrying bar. Liquid nozzles can be fitted to the follower for multipass plate arrangements.

Nozzles on the head and follower transport the fluid in and out of the plate pack. Nozzle connections are most commonly of ANSI lap-joint design with carbon steel backup flanges.

The top carrying bar is bolted to the top of the head and end support and carries the weight of the plate pack, the follower and liquid contained in the heat exchanger. The bottom carrying bar is bolted to the bottom of the head and end support, and serves to guide the lower end of the follower and plates. The end support (carrying bar support column) supports the end of the carrying bars opposite the head.

Tie bars (closing bolts and nuts) bear against the outside face of the head and follower to compress the

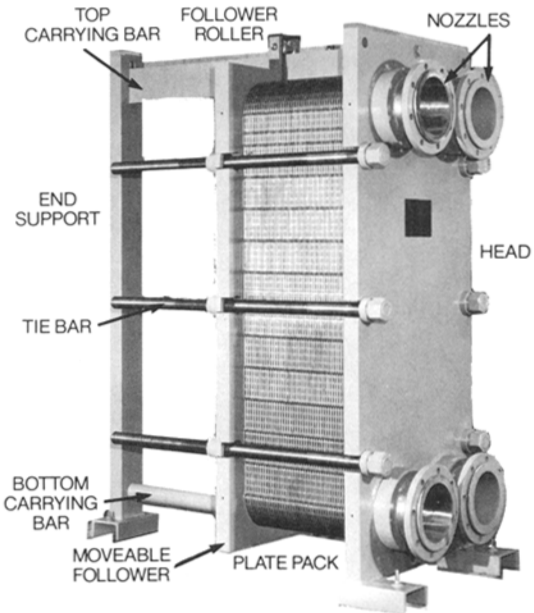

FIG. 1.

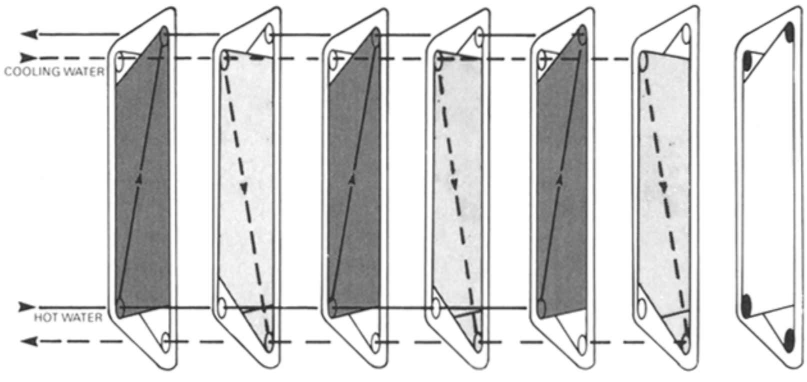

FIG. 2. Flow arrangement for single pass on both sides.

plate pack. The tie bars are held in place by heavy shouldered washers and nuts that fit key hold slots cut in the head and follower. This feature prevents the tie bars from moving out of position or slipping off the head or follower. In the case of larger machines or those that are opened frequently, pneumatic tightening wrenches are commonly used.

The plate pack—an assembly of gasketed plates—is compressed between the head and follower to form the two separate paths in which the heat exchanging liquids flow. The plates are arranged to provide multiple parallel flow channels with gasketing and port blanking directing the process and service streams into alternating channels; this allows multipass arrangements where necessary to handle the more demanding heat transfer duties (Fig. 2).

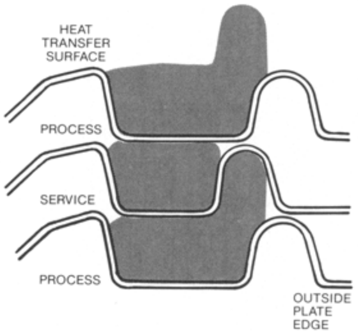

FIG. 3. Cross-section of gasket lug interlocking with adjacent plate.

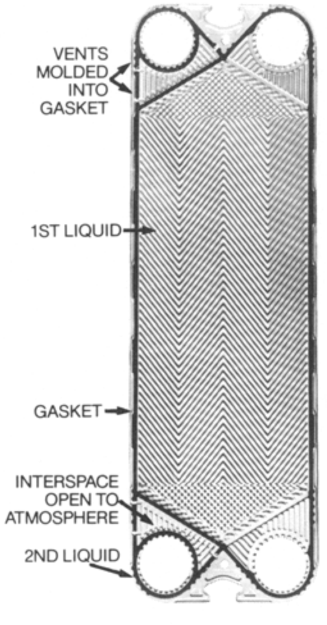

FIG. 4. Face view of gasketed plate showing detail of double boundary between fluids and associated vents to atmosphere.

The plates are formed from metal of 23 swg (0.024 inch) to 20 swg (0.036 inch) with the desired corrugation pattern. This forming operating also develops the gasket groove which, in the case of the APV exchanger, provides 100% support to the periphery of the gasket. Proper plate design and material thickness are required so that the plate pack can withstand the full unbalanced design pressure.

Elastomer gaskets for the APV exchanger are molded to fit the gasket groove in the plate and feature a raised lug that alternates around the gasket periphery to interlock with the adjacent plate (Fig. 3). The gaskets are retained in the groove with a temperature-curing adhesive, to assure proper gasket positioning during tightening and operation of the unit.

The gasketing in the through-port area of the plate is arranged to give a double seal between the liquid streams and make intermixing impossible (Fig. 4). The space between the seals is vented to atmosphere so that in event of leakage of either liquid, there is a visual indication and an escape path for the fluid.

A prime factor in the application of processing equipment is the selection of construction materials to maximize operating life without raising the initial cost.

Plate materials

Of the materials listed in Table 1, 316 SS is the most widely applied, certainly in the units we supply to the oil-processing industry. For the stainless steels and other alloys, chromium, nickel and iron are the alloying elements common to all.

The most frequently encountered corrosion on these materials is related to chlorides in the process or service streams. To counter this, a fourth element—molybdenum—is significant in reducing the adverse effect of chloride ions.

In the case of 304 SS (no molybdenum), chloride concentrations under 50 parts per million (ppm) can result in corrosion and failure. This is a level commonly found in cooling tower waters and even some well water. Even with lower levels, scaling can entrap and concentrate the chlorides, creating a localized corrosive environment.

Adding 2–3% molybdenum to 304 produces 316 SS with increased resistance to attack in service up to 150 ppm chlorides. This increased tolerance to chloride ions is the reason we consider 316 SS to be the minimum acceptable and most widely used material for plate heat exchangers in oil processing.

Where higher concentrations of chlorides are encountered and higher temperatures are involved, 904L (Avesta 254 SLX) and Avesta 254 SMO can extend the range to 1000 ppm and 30,000 ppm chlorides (sea water), respectively.

Hastelloy C-276, a high nickel alloy, is almost immune to attack by chloride ions at low pH. However, because of its expense, it sees limited used.

Incoloy 825 is included only as a point of reference as it has been replaced by 904L, which provides equal performance at a lower cost and is more readily available.

Titanium is the material of choice where brackish or sea water is used as a cooling medium. At temperatures above 212°F, palladium-stabilized titanium may be necessary to prevent chloride crevice corrosion. A further point to consider is that above 212°F, titanium and palladium-stabilized titanium show a sharp loss in strength, necessitating thicker material for a given pressure condition.

As is to be expected, increased corrosion-resistance comes at a premium cost. Using 304 as a base cost index of 1, 316 would be 1.1, 904L would be 1.3, Avesta 254 SMO would be 1.5, titanium would be 2 and Hastelloy C-276 would be 4 to 5. In our experience in the oil-processing industry, nearly 100% of the units installed have utilized 316 SS as the plate material.

Where an occasional failure has occurred, it has been traced back to chloride ion contamination, particularly as it concentrates in fouling and scale deposits. Not only is the chloride ion concentration normally very low in the bulk oil, but so is the water concentration. Because the source of the chloride will dissociate in the presence of water, low concentrations of each results in a high concentration of chloride ion in the water phase, thereby creating a corrosive micro-environment.

General corrosive attack is not likely to be encountered on stainless steel plates in the oil-processing industry. The exception would be in cases where cleaning/descaling solutions based on strong reducing mineral acids, such as sulfuric or hydrochloric, have been used.

This general attack would be characterized by uniform loss of metal thickness. The safe approach for descaling is to use phosphoric or nitric acid below 2% concentration and 140°F on a regular basis to avoid a heavy build-up of scale.

It is difficult to distinguish between crevice and pitting corrosion on 316 stainless steel heat exchanger plates because these two types of corrosion go hand-in-hand, particularly at the metal-to-metal contact points between plates. It is characterized as being highly localized and tends to be deep and undercut, thus resulting in plate failure by perforation.

The austenitic stainless steels are susceptible to this type of attack and in very broad terms, their susceptibility is an inverse function of molybdenum content of the alloy.

Stress-corrosion cracking (SCC) occurs when a metal under stress comes into contact with certain highly specific environmental conditions. In the case of the chromium/nickel alloys, this environment commonly contains chloride ions and is in excess of 140°F. Stress-corrosion cracking is characterized by a network of highly branched transgranular cracks. The source of the chlorides can be not only from the process or service streams, but also from the use of improper adhesive to bond the gaskets to the plates.

Detection of these types of failures can be achieved using a system consisting of a red dye penetrant that is sprayed on one side of the suspect plate and a white developer sprayed on the opposite side. A perforation of the plate is readily evident by the bleed-through of the red dye into the developer.

TABLE 1

Plate Heat Exchanger Plate Materials

	Alloy compositions (nominal)								
Alloy	Cr[a]	Ni[b]	Mo[c]	Cu[d]	Fe[e]	Ti[f]	Pd[g]	W[h]	Others
Stainless steels									
304	18	10			72.0				
316	18	10	2½		69.5				
904L (Avesta 254SLX)	20	25	4½	2	48.5				
Avesta 254SMO	20	18	6	¾	44.75				
Nickel alloys									
Hastelloy C-276	15½	57.5	16		5			3½	Co 2.5[i]
Incoloy 825	21½	42	3	2	31.5				
Others									
Titanium						>99			
Titanium palladium						>99	0.15		

[a] Cr—Chromium
[b] Ni—Nickel
[c] Mo—Molybdenum
[d] Cu—Copper
[e] Fe—Iron
[f] Ti—Titanium
[g] Pd—Palladium
[h] W—Tungsten
[i] Co—Cobalt

TABLE 2

Plate Heat Exchanger Gasket Materials

Material	Temperature rating
Paracril (nitrile rubber)	
nominal maximum temperature:	275°F
vegetable oil cooling applications:	300°F
Paradur (fluoroelastomer, i.e., Viton)	
nominal maximum temperature (nonaqueous service):	400°F
vegetable and animal fat regeneration applications:	to 450+°F

Gasket materials must be considered both in terms of operating life and in terms of meeting U.S. Food and Drug Administration (FDA) requirements when food-grade oils are being processed.

Gasket materials

Gasket materials are shown in Table 2. Paracril (nitrile rubber) is the standard material for applications, including heating under 275°F. In applications where hot oil (up to 300°F inlet temperature) is cooled by water, this material will have a reasonably economical life.

Although significantly more expensive than Paracril, Paradur (fluoroelastomer, i.e., Viton) gasket material has been used very successfully in oil-to-oil interchange service at temperatures to 450°F.