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EROSION–CORROSION: RECOGNITION AND CONTROL

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A. INTRODUCTION

A major prerequisite for the control of erosion–corrosion is the recognition or determination of the relative roles of accelerated corrosion and erosion. Only then can the appropriate action be taken.

If *accelerated corrosion* following damage to protective films is the problem, there are two alternatives:

- Take steps to avoid damage to the film.
- Accept the film damage and use corrosion control methods.

If *erosion* of the underlying metal is a major factor, design and materials selection solutions should be sought.

Recognition of the type of erosion–corrosion is sometimes relatively straightforward. Erosion–corrosion by both single-phase aqueous flow and suspended solids is characterized by the presence of smooth grooves, gullies, shallow teardrop-shaped pits, and horseshoe-shaped depressions most often with an obvious flow orientation. The characteristic pattern of attack often starts at isolated spots on the metal surface and subsequently spreads to a general roughening of the surface [1, 2]. With cavitation and liquid droplet impingement attack, the damage starts in the form of steep-sided pits, which may coalesce into a honeycomb-like structure. The Corrosion Atlas [3] and the NACE International Corrosion Recognition and Control Handbooks [4, 5] contain photographs of all the various forms of erosion–corrosion with suggested control methods built around a large number of case histories.

B. CONTROL OF TURBULENT FLOW ATTACK

In single-phase aqueous flow, the erosion–corrosion of metals such as copper tubing is a process of accelerated corrosion following erosion of the protective film. Control of this type of attack is usually achieved by modifying the design of the system to reduce the hydrodynamic forces and/or by choosing an alloy with a more erosion-resistant film.

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B1. Design

Design factors, for example, for copper tubing carrying potable water, are the control of the velocity and the minimization of abrupt changes in the flow system geometry. Maximum velocities in the range 0.8–1.5 m/s have been suggested [3, 6]. The tubing should be reamed where it is pushed into fittings such as elbows prior to soldering [7] to mitigate the erosion—corrosion shown in Figure 18.2 (Chapter 18). Recent studies [8] have shown that 1-mm forward- or backward-facing steps are sufficient to initiate film disruption. Reaming in excess of that required to remove the burring on cut tubing may be required to prevent erosion–corrosion. Plastic inserts can be used to solve heat exchanger–tube inlet problems.

B2. Materials

Materials selection could involve, for example, the substitution of copper tubing in hot water distribution systems by stainless steels or plastics [3]. As noted above, only in extremely severe conditions would single-phase aqueous flow damage the passive film on stainless steels leading to erosion–corrosion. The possible pitting and crevice corrosion of stainless steels in the presence of chlorides should be taken into consideration. A range of copper alloys with increasing velocity limits can be used in heat exchangers (Table 18.2). If a very high velocity is required, in a corrosive environment, stainless steel, nickel alloy, or titanium tubes can be considered [9, 10].

B3. Inhibitors

Inhibitors are used in recirculating cooling water systems and steam condensate return lines but find limited application in once-through production systems because of the cost. A notable exception is the extensive use of inhibitors in oil/gas production.

B4. Cathodic Protection

Cathodic protection has very limited throwing power down the inside of pipes and other restricted geometries. Impressed systems can be used in heat exchanger water boxes to protect the important entrance length region for copper alloy tubes [1, 11] carrying seawater. Care must be taken to avoid hydrogen evolution, which can lead to the formation of air/hydrogen pockets at dead zones [1]. In addition to safety problems hydrogen can lead to the embrittlement of titanium and other alloy tubing.

C. CONTROL OF SOLID-PARTICLE IMPINGEMENT ATTACK

Erosion–corrosion problems observed in the presence of solid particles suspended in aqueous solutions are more difficult to solve. The relative role of corrosion and erosion can often only be assessed following testing involving weight loss measurements to determine the total loss with simultaneous electrochemical measurements (polarization resistance) to determine the contribution of corrosion [12, 13]. The relative importance of erosion and corrosion will vary between nondisturbed and disturbed flow and testing should be done in a flow system that simulates both the chemical and the hydrodynamic conditions found in the full-scale process equipment.

C1. Corrosion Control

Corrosion can be controlled by the use of inhibitors and/or solution conditioning. Some *inhibitors* work very well in the presence of very abrasive slurries, including silica, which is one of the most common abrasive components. Chromates and nitrites at high concentrations act as passivating inhibitors [14] whereas chromates at low concentration act as cathodic inhibitors [15, 16] and were used in the first long-distance coal-slurry pipeline [17]. Chromates are, of course, toxic and very low effluent limits < 0.05 ppm have been set in some jurisdictions [18]. Nonchromate inhibitors used in cooling water systems, zinc, sodium tripolyphosphate ($Na_5P_3O_{10}$), and nitrilotris (methylene) triphosphonic acid (NTMP) $N[CH_2PO\ (OH_2)]_3$, showed little benefit [15] in sand or coal slurries when used alone or along with chromates, in contrast to the synergistic effect normally observed in cooling water.

Solution conditioning involves raising the pH and/or deaeration. Both of these methods of corrosion control have been applied to long-distance slurry pipelines. A problem with raising the pH to control corrosion is the greater likelihood of pitting at elevated pH values where thick scales are more easily formed. Indeed, pitting caused some concern with the Bougainville copper concentrate line [19] which was treated with lime to maintain the slurry at $pH > 9.5$. Temporary overdosing with lime led to calcium carbonate deposits in the first portion of the Samarco iron ore concentrate line [20] which was maintained at $pH \geq 10$. Deaeration can be achieved with oxygen scavengers, sodium bisulfite or hydrazine, or nonchemical steam stripping or vacuum deaeration. The latter two methods of deaeration have not been used with slurry pipelines. They are used extensively, for example, with oil well water injection systems [21].

If the corrosion following the removal of the protective film is liquid-phase mass transport controlled, the flow velocity can be reduced. However, the effect of reducing the velocity will be of secondary importance to controlling the corrosion by inhibitors or solution conditioning. A lower limit is the velocity required to keep the particles in suspension [22]. For example [23], the flow of a 20 vol % silica sand slurry, mean particle diameter 0.43 mm, in a 50-mm horizontal diameter pipe requires a minimum velocity of ~ 2 m/s

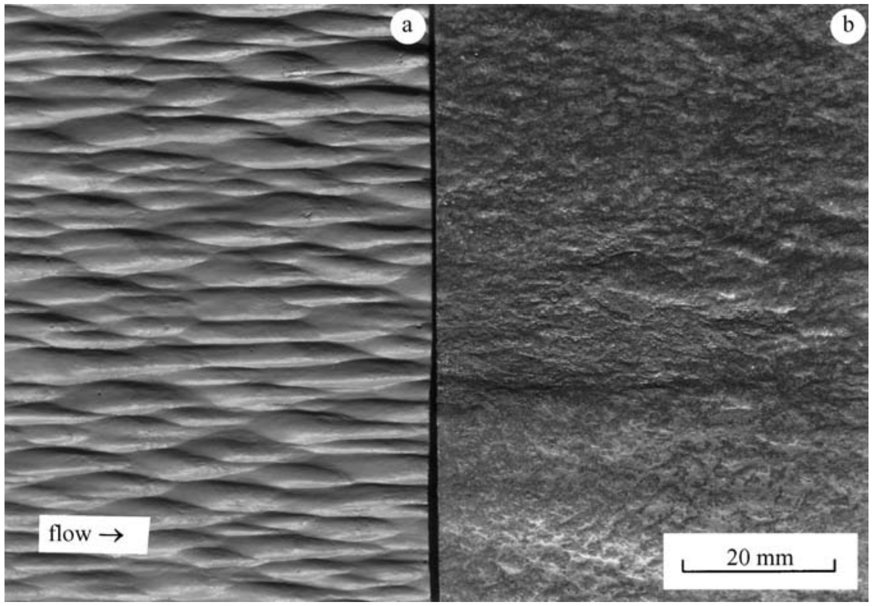

FIGURE 65.1. Variation in erosion–corrosion wear pattern around the circumference of a horizontal 200-mm diameter commercial pipeline carrying an abrasive mineral slurry. (a) Pipe bottom. (b) Pipe top. *Note*: The erosion–corrosion wear pattern in (a) is not characteristic of sliding bed wear. Sliding wear is characterized by long horizontal grooves.

and a 20 vol % slurry of iron ore concentrate mean particle diameter 0.04 mm a minimum velocity of ~1.3 m/s. Lower velocities may result in the *sliding abrasion* of a horizontal pipe bottom. At velocities above the critical velocity to keep the particles in suspension, there is a large concentration gradient from the top to bottom of horizontal pipelines carrying commercial heterogeneous slurries [22]. This can result in a much different erosion–corrosion wear pattern and rate around the circumference of the pipe (Fig. 65.1).

If necessary more corrosion-resistant materials than carbon steel pipe can be chosen, including stainless alloys, ceramics (e.g., cast basalt lined pipe, Mohs hardness ~8), and plastics (e.g., high-density polyethylene pipe or polyurethane linings).

Stainless alloys, with their rapidly healing films, have a greater resistance to corrosion in slurries, but the extra resistance comes at a cost that may not be acceptable. Ceramics and plastics may not have the mechanical and thermal properties for the construction of the particular process equipment. Long-distance pipelines are constructed from carbon steel. More expensive alloys and lined pipe are an option for in-plant operations, including tailings disposal. Titanium alloys perform well in flowing seawater with abrasive solids in suspension [24].

C2. Erosion Control

Erosion can be controlled by design and materials selection. Design involves optimizing the particle size (by grinding, where there is a choice of size) and the flow velocity [22]. The flow system geometry should be designed to minimize any effects of disturbed flow, for example, by using long-radius elbows, gradual changes in the flow cross section, and specifying maximum weld root protrusion. Other design possibilities are:

- Increasing the thickness of materials in critical areas
- Use of impingement plates to shield critical areas
- Acceptance of a high erosion rate with regular inspection and replacement that may be less costly than using more expensive materials and a practice used extensively in the minerals processing and oil/gas industries
- In some situations pipe rotation, for example, to extend the life of tailing lines

Since there is a major decrease in the erosion rate when the metal surface is harder than the particles, it might be thought to be a simple matter to choose an alloy with a hard surface and eliminate the erosion problem. This is not the case for two reasons:

- The hard alloys that resist erosion are generally cast alloys that are difficult to weld, often brittle, and in general difficult to handle.
- If corrosion is a factor, the alloy must have a suitable corrosion resistance and many alloys that are hardened

by the precipitation of carbides during solidification have a relatively poor corrosion resistance.

Alloyed white cast irons (the most abrasion resistant iron-base alloys), including high-chromium, chrome-moly, nickel–chrome, and pearlitic white irons [25], are noted for their erosion resistance. The relationship between the Cr and C content of the high-chromium cast irons is complex. A high C content is required for the formation of carbides to give erosion resistance, but this leaves less Cr in the matrix for corrosion resistance [26]. The minimum Cr content in the matrix to form a passive film is 12% and the *Cr* required to form carbides is $10 \times \%$ C. The suggested minimum Cr for corrosion resistance is

$$\%\ \mathrm{Cr} = (\%\ \mathrm{C} \times 10) + 12$$

The erosion resistance increases and the corrosion resistance decreases with an increase in the C content and the alloy must be chosen carefully to accommodate the corrosive and erosive properties of the particular slurry being handled. Alloys containing 20–28% Cr and 2–2.5% C with 2% Mo have good resistance to slurry erosion–corrosion at pH values down to 4. Alloys with less C are required for more corrosive environments [26]. Nickel-hard alloys (4% Ni–2% Cr) find extensive use in abrasive service in sand and gravel pumps handling abrasive but mildly corrosive slurries [27]. Natural rubber is an alternative for pumps to handle abrasive slurries with particles less than 3 mm diameter.

Both Stellite (a cast cobalt alloy) and silicon carbide have excellent erosion resistance in aqueous slurries along with excellent corrosion resistance and can be considered for use under severe service conditions in valves and pumps [3, 28].

D. CONTROL OF LIQUID DROPLET IMPINGEMENT ATTACK

Impingement attack by liquid droplets suspended in high-speed gas flow can be controlled by *design* or *materials selection*.

Design involves optimizing the flow system geometry and the fluid dynamics [29] to reduce the amount of impacting liquid, the angle of impact, and the droplet size. For example, design modifications in steam turbines operating with wet vapor in the low-pressure section have included extracting moisture between blade rows, increasing axial spacing between stator and rotor, and local flame hardening or brazed-on shield of Stellite at the leading edge of the blade. Raising the temperature of the inlet gas above the dewpoint was suggested [4] as a remedy for the impingement attack of a process gas compressor. Impingement plates acting as flow deflectors can also be considered.

The behavior and range of materials utilized to solve high-speed liquid droplet impingement problems are similar to those chosen for resistance to cavitation attack. The "normalized erosion resistance" data shown in Figure 65.2 give an approximate ranking of materials to liquid droplet

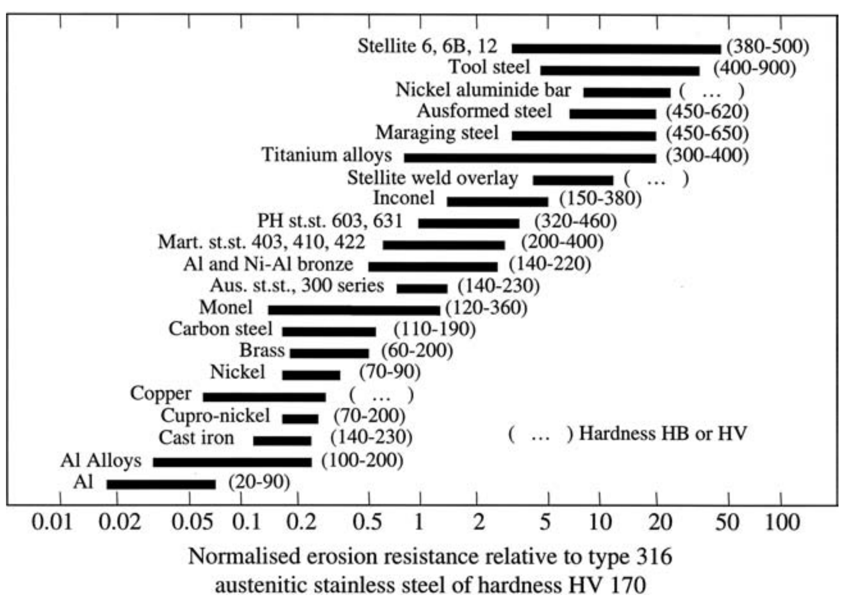

FIGURE 65.2. Normalized erosion resistance of various metals and alloys (the erosion resistance number according to ASTM G73). Selection of the data deduced by Heymann [41] from many sources, including both impingement and cavitation tests. Erosion test data are not very consistent, and the information herein should be used only as a rough guide. (Adapted from Heymann [41].)

impingement and cavitation attack. Such data should be used with great care. Materials selection for turbines includes the use of Stellite mentioned above, 12% chromium martensitic stainless steel, 17 Cr–4 Ni precipitation-hardened stainless steel, and "self shielding" blade alloys that harden under the action of impacts [29].

Liquid droplet impingement attack observed in annular mist flow [Fig. 18.3(b)] in oil/gas production systems is an erosion–corrosion phenomenon, which can be controlled by the use of inhibitors or the use of stainless alloys [30]. Not surprisingly this erosion–corrosion is found to be the most severe under disturbed flow conditions at threaded connections in down-hole tubulars and at elbows, valves, and "Christmas trees" in above-ground facilities.

E. CONTROL OF CAVITATION ATTACK

Cavitation attack is usually controlled by design and materials selection. Tullis [31] has given an extensive discussion of the detailed design of pumps, valves, orifices, and elbows to avoid cavitation problems. Air injection is sometimes used to control cavitation damage. Air injected into the separated flow regime cushions the collapse of the cavities. Cathodic protection has been used, with the protection attributed to cushioning by the hydrogen bubbles evolved in addition to the normal corrosion protection. While this might be satisfactory for a propeller in an open system, the evolution of hydrogen in a closed system could be hazardous as well as leading to hydrogen blistering and embrittlement.

The range of materials available for solving cavitation–erosion problems is similar to those used for liquid droplet impingement, as shown in Figure 65.2. There is a wide range of polymers with good resistance to cavitation–erosion in addition to excellent resistance to corrosion. For example, high-density polyethylene has a cavitation–erosion resistance similar to that of nickel-based and titanium alloys [32].

The major design parameter for centrifugal pumps to avoid cavitation damage is the available *net positive suction head*, $NPSH_A$, the difference between the total pressure (absolute) and vapor pressure at the pump suction, expressed in terms of equivalent height of fluid, or "head," by

$$\mathrm{NPSH}_A = (p/\rho g) + (u^2/2g) - (p_v/\rho g)$$

where

p = static pressure (absolute)
p_v = vapor pressure of the flowing fluid
ρ = density
g = gravitational acceleration
u = flow velocity

The $\mathrm{NPSH_A}$ must exceed the value required by the pump, $\mathrm{NPSH_R}$. The latter value varies with the flow rate and is a function of the pressure changes as the liquid accelerates over the curved impeller and then decelerates as it approaches the volute. The $\mathrm{NPSH_R}$ values, which are supplied by the pump manufacturers, are based on pump efficiency and not on the dangers of cavitation attack. Significant noise and cavitation may occur before the efficiency of the pump begins to decrease. Thus a substantial margin of safety is required if erosion–corrosion is to be avoided. In practice, some cavitation can usually be tolerated and pumps are operated in the NPSH range between cavitation inception and a point where damage is unacceptable [31, 32]. If it is wished to maximize efficiency of the pump operation, more cavitation can be accepted and cavitation attack reduced by the selection of more resistant materials. One very important factor in setting the correct $\mathrm{NPSH_A}$ is the relative elevation of the pump and the vessel, from which the liquid is being pumped. Fluid friction in the suction line must also be taken into account, and the suction piping is usually a size bigger than the discharge piping.

F. CONTROL OF FLOW-ENHANCED FILM DISSOLUTION ATTACK

The control of this type of "chemical" erosion–corrosion of carbon steel pipes in power plants may involve one or more of the following [33]:

- Control of the water chemistry: pH and dissolved oxygen concentration
- Materials selection: replacement of carbon steel by low-alloy chromium, >0.1%; low-alloy chromium–molybdenum, 304 ss and in very severe conditions Inconel; or duplex piping with a thin inner layer of stainless steel or other high alloy
- Weld overlay: for protection and repair
- Flame spraying: minimum pipe diameter 600 mm
- Modification of operating conditions: temperature and quality, where wet steam is involved, and flow rate
- Changing the local geometry: for example, installing a larger control valve to reduce downstream turbulence

In general, orifice plates and control valves should be kept well clear, at least 10 pipe diameters upstream of bends, to avoid excessive turbulence and erosion–corrosion at the latter.

The extensive and well-documented Electric Power Research Institute (EPRI) [33] report contains information regarding the detection and control of the problem.

G. PREDICTIVE MODELING

The application of *computational fluid dynamics* (CFD) to the problem of erosion–corrosion in single- and multiphase flow systems under conditions of disturbed flow can help to quantify the effects of the system geometry on rates of erosion–corrosion leading to design improvements. The flow field, including flow separation recirculation and reattachment, and rates of mass transfer can be predicted for a wide range of system geometries [34–39]. In addition the velocities and angles of impact of suspended solid particles with the flow system walls can be determined for application to the calculation of the erosion rate [40–42]. Computer modeling has been applied to the prediction of wear in slurry pumps [43]. Overall, such predictive modeling is still not as accurate as one would hope for [44], even if substantial progress has been made as our understanding of erosion–corrosion processes advanced accompanied by the ever-increasing computing power [45–47].

REFERENCES

1. G. Bianchi, G. Fiori., P. Longhi, and F. Mazza, "Horse Shoe Corrosion of Copper Alloys in Flowing Sea Water: Mechanism, and Possibility of Cathodic Protection of Condenser Tubes in Power Stations," Corrosion, **34**, 396–406 (1978).
2. J. Postlethwaite, B. J. Brady, M. W. Hawrylak, and E. B. Tinker, "Effects of Corrosion on the Wear Patterns in Horizontal Slurry Pipelines," Corrosion, **34**, 245–250 (1978).
3. E. D. D. During, comp., Corrosion Atlas: A Collection of Illustrated Case Histories, Vol. 1: Carbon Steels; Vol. 2: Stainless Steels and Non-Ferrous Materials: "Erosion-Corrosion of Copper Tubing," 06.05.34.01; "Valve Erosion," 04.01.32.01; "Pump Cavitation," 04.11.33.01; Elsevier, Amsterdam, 1988.
4. D. McIntyre (Ed.), Forms of Corrosion, Recognition and Prevention, NACE Handbook 1, NACE, Vol. 2, Houston, TX, 1997, pp. 89, 93.
5. C. P. Dillon (Ed.), NACE Handbook 1, Forms of Corrosion, Recognition and Prevention, NACE, Houston, TX, 1982.
6. A. Cohen, "Corrosion by Potable Waters in Building Systems," Mater. Perform., **32**, 56–61 (1993).
7. ASTM B 828, "Standard Practice for Making Capillary Joints by Soldering of Copper and Copper Alloy Tube and Fittings," in Copper and Copper Alloys, Vol. 02.01, ASTM, West Conshohocken, PA, 1998.
8. J. Postlethwaite, Y. Wang, G. Adamopoulos, and S. Nesic, "Relationship between Modelled Turbulence Parameters and Corrosion Product Film Stability in Disturbed Single-Phase Aqueous Flow," in Modelling Aqueous Corrosion, K. R. Trethaway and P. R. Roberge (Eds.), Klewer Academic, Dordrecht, Netherlands, 1994, pp. 297–316.
9. M. G. Fontana, Corrosion Engineering, 3rd ed., McGraw-Hill, New York, 1986, p. 95.
10. G. J. Danek, Jr., "The Effect of Sea-Water Velocity on the Corrosion Behavior of Metals," Naval Eng. J., **78**, 763–769 (1966).
11. W. Currer and J. S. Gerrard, "Practical Applications of Cathodic Protection," in Corrosion, 3rd ed., L. L. Shreir, R. A. Jarman, and G. T. Burstein (Eds.), Butterworth-Heinemann, Oxford, England 1994, p. 10:112.
12. J. Postlethwaite, M. H. Dobbin, and K. Bergevin, "The Role of Oxygen Mass Transfer in the Erosion-Corrosion of Slurry Pipelines," Corrosion, **42**, 514–521 (1986).
13. B. W. Madsen, "Corrosive Wear," in ASM Metals Handbook, Vol. 18, Friction, Wear and Lubrication Technology, ASM, Metals Park, OH, 1992, pp. 271–279.
14. J. Postlethwaite, "The Control of Erosion-Corrosion in Slurry Pipelines," Mater. Perform., **26**(12), 41–45 (1987).
15. J. Postlethwaite, "Electrochemical Studies of Inhibitors in Aqueous Slurries of Sand Iron Ore and Coal," Corrosion, **35**, 475–480 (1979).
16. J. Postlethwaite, "Effect of Chromate Inhibitors on Mechanical and Electrochemical Components of Erosion-Corrosion in Aqueous Slurries of Sand," Corrosion, **37**, 1–5 (1981).
17. D. R. Bomberger, "Hexavalent Chromium Reduces Corrosion in a Coal-Water Slurry Pipeline," Mater. Protect., **4**, 43–49 (Sept. 1965).
18. V. S. Sastri and M. Malaiyandi, "Spectra Studies on Some Novel Oxygen Scavengers and Their Use in Corrosion Control of Coal Slurry Pipelines," Can. Metall. Q., **22**, 241–245 (1983).
19. R. D. Coale, T. L. Thompson, and R. P. Ehrlich, "Bougainville Copper Concentrate Slurry Pumping System," Trans. SME, AIME, **260**, 289–297 (Dec. 1976).
20. M. E. Jennings, "SAMARCO's 396 km Pipeline: A Major Step in Iron Ore Transportation," Mining Eng., Feb. 1981, pp. 178–182.
21. A. G. Ostroff, Introduction to Oilfield Water Technology, NACE, Houston, TX, 1979, p. 293.
22. E. J. Wasp, J. P. Kenny, and R. L. Gandhi, "Solid-Liquid Flow: Slurry Pipeline Transportation," in Series on Bulk Materials Handling, Vol. 1 (1975/77), No. 4, Trans. Tech. Publications, Clausthal, Germany, 1977, p. 144.
23. J. Postlethwaite, E. B. Tinker, and M. W. Hawrylak, "Erosion-Corrosion in Slurry Pipelines," Corrosion, **30**, 285–290 (1974).
24. R. W. Schutz and D. E. Thomas, "Corrosion of Titanium and Titanium Alloys," in Metals Handbook, 9th ed., Vol. 13, ASM, Metals Park, OH, 1987, pp. 669–706, p. 696.
25. J. H. Tylczak, "Abrasive Wear," in ASM Metals Handbook, Vol. 18, Friction, Wear and Lubrication Technology, ASM, Metals Park, OH, 1992, p. 189.
26. J. Dodd, "High-Chromium Cast Irons," in Corrosion, 3rd ed., L. L. Shreir, R. A. Jarman, and G. T. Burstein (eds.), Butterworth-Heinemann, Oxford, 1994, pp. 3:128–3:137.
27. G. Wilson, "The Design Aspects of Centrifugal Pumps for Abrasive Slurries," in Proc. 2nd Int. Conf. on Hydraulic Transport of Solids in Pipes, BHRA Fluid Engineering, Cranfield, UK, 1972, pp. H2:25–H2:52.
28. E. Heitz, S. Weber, and R. Liebe, "Erosion Corrosion and Erosion of Various Materials in High Velocity Flows Containing Particles," in Proceedings of Symposium on Flow-Induced Corrosion; Fundamental Studies and Industry Experience,

K. H. Kennelley, R. H. Hausler, and D. C. Silverman (Eds.), NACE, Houston, TX, 1991, pp. 5:1–5:15.

29. F. J. Heymann, "Liquid Impingement Erosion," in ASM Metals Handbook, Vol. 18, Friction, Wear and Lubrication Technology, ASM, Metals Park, OH, 1992, pp. 221–232.
30. J. S. SmartIII, "A Review of Erosion Corrosion in Oil and Gas Production," in Proceedings of Symposium on Flow-Induced Corrosion; Fundamental Studies and Industry Experience, K. H. Kennelley, R. H. Hausler, and D. C. Silverman (Eds.), NACE, Houston, TX, 1991, pp. 18:1–18:18.
31. J. Tullis, Hydraulics of Pipelines: Pumps, Valves, Cavitation, Transients, Wiley, New York, 1989, pp. 59, 78.
32. B. Angell, "Cavitation Damage," in Corrosion, 3rd ed., L. L. Shreir, R. A. Jarman, and G. T. Burstein (Eds.), Butterworth-Heinemann, Oxford, 1994, pp. 8:197–8:207.
33. Electric Power Research Institute (EPRI), Flow Accelerated Corrosion in Power Plants, TR-106611, EPRI, Pleasant Hill, CA, 1996, pp. 4:2, 6:25.
34. S. Nesic, G. Adamopoulos, J. Postlethwaite, and D. J. Bergstrom, "Modelling of Turbulent Flow and Mass Transfer with Wall Function and Low-Reynolds Number Closures," Can. J. Chem. Eng., **71**, 28–34 (1993).
35. S. Nesic and J. Postlethwaite, "Relationship between the Structure of Disturbed Flow and Erosion-Corrosion," Corrosion, **46**, 874–880 (1990).
36. S. Nesic and J. Postlethwaite, "Hydrodynamics of Disturbed Flow and Erosion-Corrosion, Part I-A Single Phase Flow Study," Can. J. Chem. Eng., **69**, 698–703 (1991).
37. S. Nesic, J. Postlethwaite, and D. J. Bergstrom, "Calculation of Wall-Mass Transfer Rates in Separated Aqueous Flow Using a Low Reynolds Number $\kappa - \varepsilon$ Model," Int. J. Heat Mass Transfer, **35**, 1977–1985 (1992).
38. J. Postlethwaite, S. Nesic, and G. Adamopoulos, "Modelling Local Mass Transfer Controlled Corrosion at Geometrical Irregularities," Mater. Sci. Forum, **111–112**, 53–62 (1992).
39. J. Postlethwaite, S. Nesic, G. Adamopoulos, and D. J. Bergstrom, "Predictive Modelling for Erosion-Corrosion under Disturbed Flow Conditions," Corros. Sci., **35**, 627–633 (1993).
40. S. Nesic and J. Postlethwaite, "Hydrodynamics of Disturbed Flow and Erosion-Corrosion. Part II—Two Phase Flow Study," Can. J. Chem. Eng., **69**, 704–710 (1991).
41. S. Nesic and J. Postlethwaite, "A Predictive Model for Localized Erosion-Corrosion," Corrosion, **47**, 582–591 (1991).
42. H. Zeisel and F. Durst, "Computations of Erosion-Corrosion Processes in Separated Two-Phase Flows," in Proceedings of Symposium on Flow-Induced Corrosion; Fundamental Studies and Industry Experience, K. H. Kennelley, R. H. Hausler, and D. C. Silverman (Eds.), NACE, Houston, TX, 1991, pp. 9:1–9:21.
43. M. C. Roco, "Wear Mechanisms in Centrifugal Slurry Pumps," Corrosion, **46**, 424–431 (1990).
44. B. Poulson, "Complexities in Predicting Erosion Corrosion," Wear, **233**, 497–504 (1999).
45. A. Keating and S. Nesic, "Numerical Prediction of Erosion-Corrosion in Bends," J. Corrosion, **57**, 621 (2001).
46. S. Nesic, "Using Computational Fluid Dynamics in Combating Erosion-Corrosion," Chem. Eng. Sci. J., **61**(12), 4086 (2006).
47. X. H. Chen, B. S. McLaury, and S. A. Shirazi, "Application and Experimental Validation of a Computational Fluid Dynamics (CFD)-Based Erosion Prediction Model in Elbows and Plugged Tees", Comput. Fluids, **33**, 1251 (2004).