voirs. Initial pilot testing is encouraging. More production experience is necessary to prove the efficiency of the system.

Acknowledgment

The authors thank Wade and Wayne Dickinson, Petrolphysics Inc., San Francisco, Calif., who developed the system in conjunction with Bechtel, as well as the management at Bechtel Investments Inc., for permission to publish the data.

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BOOKS

The Resourceful Earth, *edited by Julian L. Simon and Herman Kahn. Published by Basil Blackwell Inc., 432 Park Avenue South, New York, N.Y., 10016. 593 pp.*

This book is a response to the Global 2000 report. It challenges the claims of that earlier work which forecast widespread environmental disaster by the turn of the century.

An independent team of world experts demonstrates in this book that on the basis of present trends, the world in 2000 will be less crowded, less polluted, more ecologically stable, and less vulnerable to resource-supply disruption than the world we know now.

Energy Policy in America Since 1945: A Study of Business-Government Relations, *by Richard H.K. Vietor. Published by Cambridge University Press, 32 East 57th St., New York, N.Y., 10022. 380 pp., $29.95.*

The author recounts the history of government intervention in U.S. energy markets since 1945. It is a saga, not of heroes and villains, says the publisher, but of ineffective institutions and administrative process.

Critical velocity examined for effects of erosion-corrosion

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Recent interest in the accuracy of the erosion-velocity equation presented in API RP14E has led to a review of the factors that affect erosion in the oil industry with the intent of better quantifying these parameters.

The API equation is stated as:

$$V_e = \frac{C}{\sqrt{\rho}}$$

where ρ = fluid density, pound per cubic foot; C = a constant, typically 100 – 125; V_e = maximum allowable velocity, feet per second.

This equation is specifically given for calculating a limiting velocity for erosion; however, it has often been extended to calculation of a critical velocity for erosion-corrosion.

In this case, critical velocity is the velocity that would remove a corrosion inhibitor film from the pipe surface or even prevent film from forming. Critical velocity also can be that velocity that would strip a protective corrosion product film from the pipe wall. It is this latter point that will be addressed in this article.

Salama and Venkatesh[1] have discussed several approaches to critical velocity, depending on well conditions.

The first approach, and probably the most satisfying from an intuitive sense, is to use a fluid-mechanics equation relating velocity to shear stress at the pipe wall.

If the shear stress of the inhibitor or the corrosion product is set equal to the shear stress created by the fluid being transported, then a critical velocity should be obtained. In fact, the result is not realistic, based on field experience.

The equation:[2]

$$V_c = \sqrt{\frac{8g\tau}{f\rho}}$$

where:

g = Gravitational constant 32.2 fps/sec

f = Friction factor

τ = Shear strength of inhibitor or corrosion product to pipe wall, pounds per square foot.

V_c = Critical velocity, feet per second

reduces to approximately:

$$V_c = \frac{100{,}000}{\sqrt{\rho}}$$

when typical values for f (0.03) and $\varkappa$ (8,000 psi = 1,152,000 psf) are inserted. A value for f of 0.03 is more consistent with a scale-roughened surface than using f = 0.0015 for smooth pipe.

As evidenced by the large numerator, very few conditions in gas and oil wells would ever produce a critical velocity under these circumstances. Therefore, removal of a protective corrosion product by shearing action alone, apparently is not the primary means of erosion-corrosion in tubulars.

Salama and Venkatesh presented another equation they attributed to P. Griffith and E. Rabinowicx,[3] for erosion due to liquid impingement:

$$U = \frac{2Kv\rho^3V^6}{729g^3P^3\epsilon_c{}^4}$$

U = Wear volume rate, cu ft/sec

v = Impacting fluid volume rate, cu ft/sec

ρ = Fluid density, lb/cu ft

V = Impact velocity, fps

P = Target material hardness, psf

ϵ_c = Critical strain to failure

g = Gravitational constant, 32.2 fps/sec

K = High speed erosion coefficient, ~ 10^{-5}

By replacing v = AV where A is the cross-sectional area of the pipe and defining an erosion rate h = U/A the equation becomes:

$$V = \sqrt[7]{\frac{364.5\ g^3\ P^3\ \epsilon_c^4\ h}{K\ \rho^3}}$$

Rather than substitute values for ϵ_c, P, and h for steel as Salama and Venkatesh did, the limiting condition for erosion-corrosion in many cases is the presence of a corrosion product film.

Very little information is available concerning the critical strain for failure of oxides, sulfides, and carbonates which are of interest in oil and gas production.

However, for discussion purposes, we may utilize data generated by Diegle and Vermilyea[4] for Fe_3O_4 formed under alkaline conditions at 190° F. For an Fe_3O_4 thickness of 10^{-4} cm, they found a critical strain of 0.003. The hardness of Fe_3O_4 is approximately 600 kg/sq mm.[5 6] Since h has units of fps, the rate of corrosion product film removal must be used rather than thickness. Thus, the critical velocity is that which is equivalent to or greater than film growth rate.

The film used here was grown in 91 hr so the rate is approximately 10^{-11} fps. When these values are substituted into the above equation, it reduces to the form:

$$V_c = \frac{150}{\sqrt[7]{\rho^3}}$$

Although this is not exactly the same form as RP14E, it does offer a less conservative approximation of critical velocity for erosion-corrosion in wells. This author could not locate critical strain data for other corrosion products; however, assuming h and ϵ_c remain essentially the same, and altering only hardness and composition of various films:

$$V_c = \frac{90}{\sqrt[7]{\rho^3}} \text{ for } FeCO_3 \ (P = 175 \text{ kg/sq mm})$$

and

$$V_c = \frac{95}{\sqrt[7]{\rho^3}} \text{ for } FeS \ (P = 200 \text{ kg/sq mm})$$

Thus it can be seen that critical velocity in producing wells will be a function of the composition of corrosion product formed on the pipe wall, film thickness, and critical strain.

Generally, as film thickness increases, critical strain increases;[4] however, this behavior is true only for relatively thin films. As the corrosion product layer thickens, internal stresses can cause fracturing and premature failure of the film itself. Thus, there is probably some optimum film thickness and associated fracture strain for resistance to erosion-corrosion damage.

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The assumption that film thickness and critical strain for FeS and $FeCO_3$ are similar to Fe_3O_4 is probably a poor one; therefore, the equations expressed should not be applied. These equations are presented only to show the expected dependence of V_c on corrosion film hardness and composition.

However, the equation considering Fe_3O_4 is more valid since Fe_3O_4 can be expected to form in CO_2-producing gas wells under certain conditions.[7] Therefore, to illustrate the difference between the equations developed here and RP14E, we consider a gas condensate density of 48 lb/cu ft (~ API gravity of 50).

By RP14E the critical velocity would be 14 fps, whereas the method presented here yields a critical velocity of 29 fps, certainly a significant difference. Therefore, it can be seen that corrosion product composition may have a profound effect on erosion-corrosion.

Although corrosion inhibitors do not interact with bare metal, they do absorb on a thin film of corrosion product on the metal's surface.[8] So it would be expected that stability of the inhibitor layer would also depend on the erosion resistance of the corrosion product layer.

This brief analysis does not take into account any of the electrochemical aspects of corrosion that may be significant in determining the overall erosion-corrosion behavior of a system. It should be recognized as only a first step in evaluating factors that are important in determining critical velocity for production of oil and gas wells.

Since liquid impingement has been assumed as a primary cause of erosion, this approach is probably most applicable to a wet gas environment.

Determining critical strain vs. film thickness and growth rate for carbonates and sulfides requires further study to evaluate this approach, as well as erosion testing to determine its accuracy.

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Gas's Contribution to UK Self-Sufficiency, *by Jonathan P. Stern. Published by Heinemann Educational Books Ltd., 22 Bedford Square, London WC1B 3HH, England. 95 pp., £4.50.*

This is one of a series of energy papers published as the British Institute's Joint Energy Policy Programme.

Emulsions and Emulsifier Applications—Recent Developments, *edited by S. Torrey. Published by Noyes Data Corp., Mill Rd. at Grand Ave., Park Ridge, N.J., 07656. 331 pp., $48.*

This book is based on U.S. patents issued between January 1982 and December 1983 that deal with emulsions and emulsifier applications.

Catalytic Cracking of Heavy Petroleum Fractions, *by Daniel Decroocq. Published for Institut Français Du Pétrole by Gulf Publishing Co.—Book Division, Box 2608, Houston, Tex., 77001. 131 pp., $39.95.*

Here is an introduction to catalytic cracking which explains the concepts and technologies of the process since it was first used in 1915.

The Natural Gas Industry—Evolution, Structure, and Economics, *by Arlon R. Tussing and Connie C. Barlow. Published by Ballinger Publishing Co., 54 Church St., Cambridge, Mass., 02138. 299 pp., $29.95.*

This book contains a composite of historical, economic, and technical background material for understanding the debate over U.S. natural gas policy.