Basic Mechanisms of Slurry Erosion & Possible Methods of Prediction

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Credit: 5 PDH

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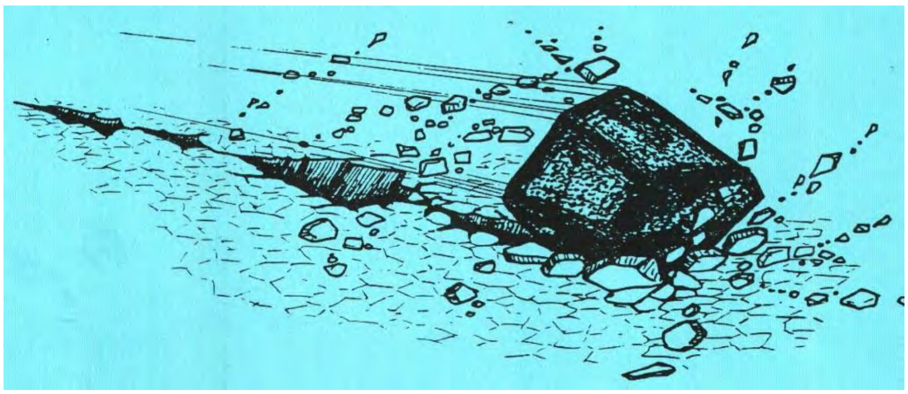
Chapter 1 – Introduction

As preparation for this course, it is assumed that the student is BS level graduate, preferably in Chemical or Mechanical Engineering, and familiar with the selection or design of valves, pumps and materials handling equipment in general.



Definition
Erosion is what happens when any suspension of solids in gas or liquid in motion impinges upon or is contained by a solid surface, which is gradually worn away by continuous impacts by the suspended particles. For example, this could be the sculpting of rocks by wind-born or water-born sand. But for the purpose of this course, we shall focus on liquid slurries of abrasive raw materials or products. All the principles discussed, however, also apply to gas-born solids or sliding granular solids.

The rate of material loss from a pipe wall, control valve trim, or other surface is proportional to:

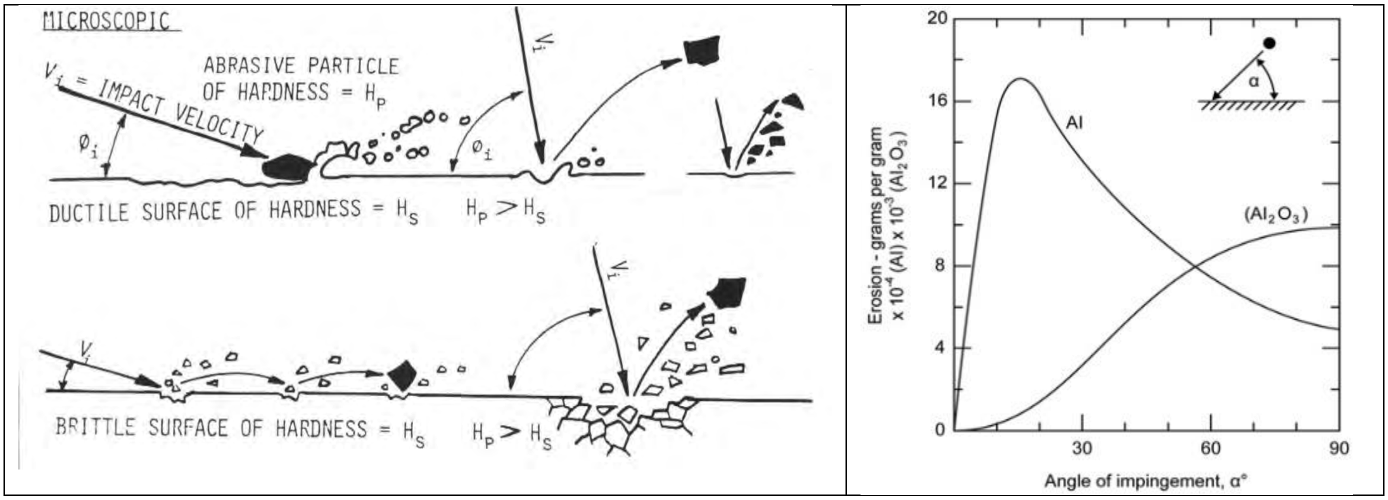
(1) The velocity of impact of single particles,
(2) The angle of impact of single particles.
(3) The frequency of impacts.
(4) The relative hardness of the particles, H_p, to the surface material, H_s.
(5) The kind of surface: Metallic, amorphous, crystalline, glassy, etc.

For most practical applications, factors (1) and (2) can be combined as the degree of turbulence. Factor (3) amounts to the solids loading (weight of solids per volume of carrier fluid) times flowing velocity.

Figure 1 below shows possible kinds of surface damage on a microscopic scale, by a single particle of hardness Hp, on a surface of hardness Hs. For a ductile surface, such as plastics, where surface is removed by a gouging action, with $H_p > H_s$. If $H_p < H_s$, the particle will bounce and more likely shatter, doing little or no damage to the surface, as shown in the upper right corner of the sketch. For a brittle surface, either crystalline or glassy (amorphous), damage will be by brittle fracture, as shown. In the right panel of Figure 1, we see the effect of the angle of impact

(Factor 2) on different kinds surfaces (Factor 5). With all other factors held constant. The surfaces are ductile aluminum, and hard brittle aluminum oxide. These were done by a focused jet of air-born abradant, which was not specified. The relative rates of erosion can be quantifed in many different ways. The simplest is the rate of surface lost (gm/hr) for a given set of all factors held constant, which could be reported in comparison with a separate rate for a different material – surface or abradant – or simply a qualitative/visual comparison with some design variation. Examples will be shown later.

Fig.1 Mechanisms of erosion by single particles.



Classification of materials by kind of surface is not always well defined, Aluminum, for example, like all metals, is of a micro-crystalline structure, but is still quite ductile in its fracture behavior. Glass, on the other hand, is structurally amorphous, but quite brittle. Similarly, “hardness” of materials is actually two completely different properties, depending on how it is measured. Reference data for metals is normally reported as a variety of standard penetration tests which are described in detail in Chapter 2. Most abrasive materials are brittle minerals whose hardness is defined by the Mohs scratch test standard (also discussed in Chapter 2). As a further complication, most abrasive slurries, handled as slurries, are made up of mixtures of materials that are not available in particles big enough to perform the Mohs scratch test. Thus we do have a need for empirical quantification of slurry hardness.

While damage by slurry erosion can be a problem throughout a process system, such as wear of piping walls, most serious problems happen at small points of very high velocity and turbulence, such as control valves trim, centrifugal pump impellers, mixer blades and piston pumps. For example, Figure 2 shows the simplest kind of control valve, where flow rate and turbulence are

Fig.2. Simple Control Valve.

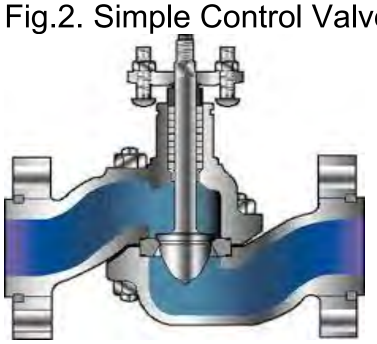
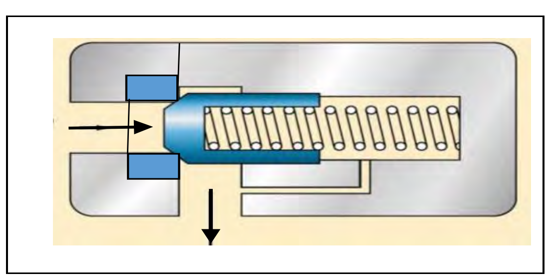


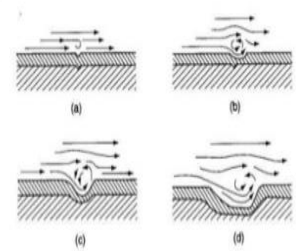
Fig. 3. Conceptual Control Valve.



greatly accelerated in a very narrow constriction between plug and seat, which is where serious erosion occurs. Figure 3 shows a more hypothetical version of a of a simple control valve, where the “trim” components - seat and plug – are identified in blue. These parts are made of much harder, expensive materials, whose frequent replacement is the main cost of erosion by slurries. While slurry valve design is too broad a subject to be covered in this course, a basic objective is to limit the maximum impingement velocity (if possible) to surfaces of extra hard (and expensive) materials of components that are replicable. In the case of Fig.3, that would be the plug and seat, that are indicated in blue. This course will deal primarily with the materials of surfaces and granular abradants and measurement of their hardness in order to predict erosion rates and (to a lesser degree) how to reduce replacement costs.

While slurry erosion is most severe at points of constriction, it also happens throughout any piping system. Under normal flowing conditions, the fluid layer against the wall is mostly laminar, especially for slurries, because their viscosity is higher (sometimes much higher) than for the carrier liquid alone. So particles contacting the wall hit at angles approaching zero, so impact damage is minimal. However, any slight roughness of the wall creates a spot of minimal turbulence, as shown in Figure 5, causing more high angle impacts of single particles and accelerated erosion.

Figure 4. Effect of Roughness



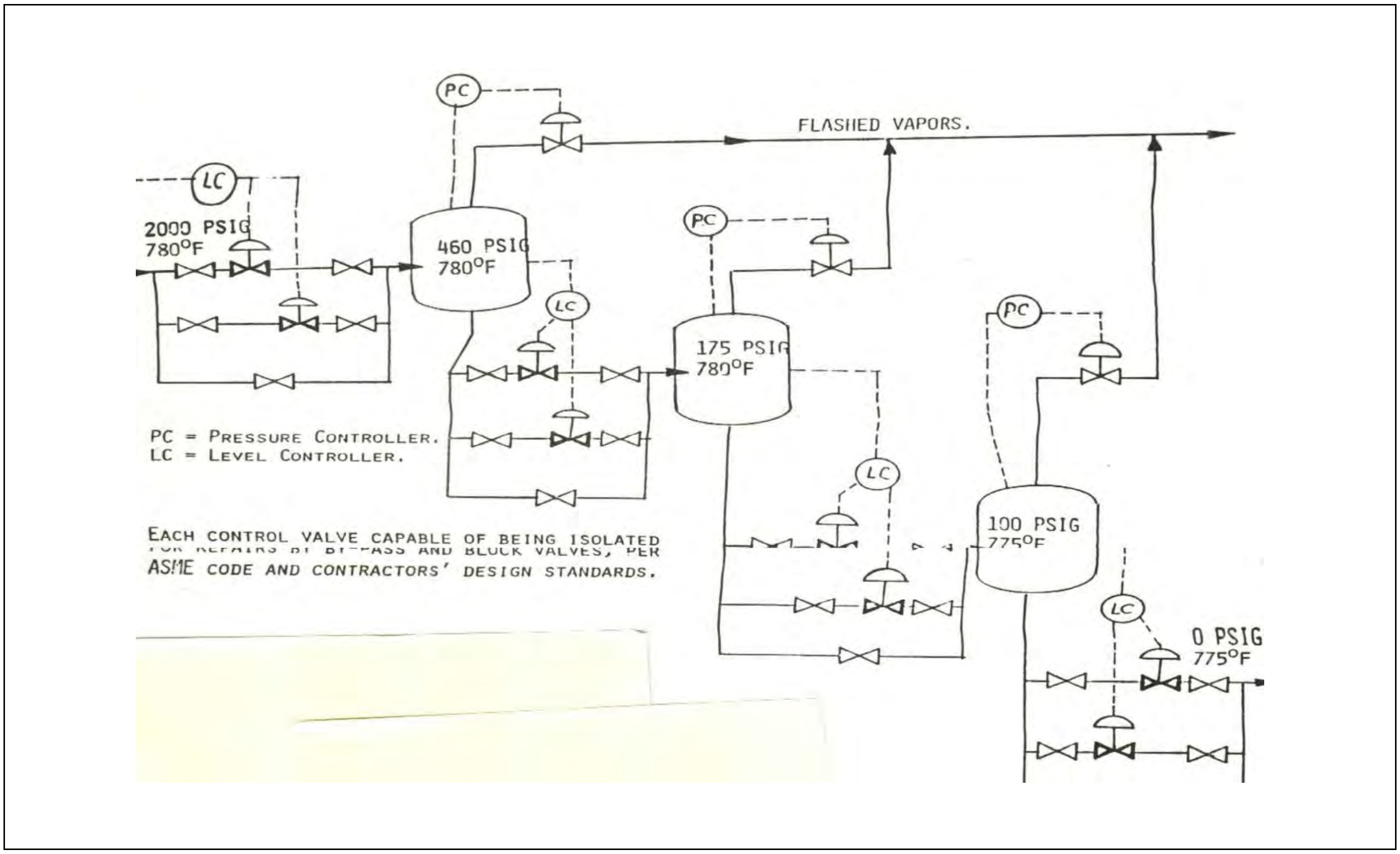
While the scope of this course is limited to (or at least focused on) erosion, it cannot completely ignore cavitation, which accompanies erosion as a major contributor to valve or pump damage at the same points where erosion happens. Cavitation occurs due to instantaneous vacuum creating bubbles in the carrier liquid, because of the Bernoulli effect at points of very high velocity. The sudden, violent collapse of these bubbles against the surface imposes a high destructive level of momentum upon the surface, removing material, with a result indistinguishable from accompanying erosion. These sister subjects both contribute to the same problem, but erosion is limited almost entirely to slurries, while cavitation can occur with clear liquid, depending on pressure drop and its vapor pressure. To keep this course within convenient limits, cavitation is introduced in detail in Appendix A.

Most of the experimental data discussed herein, in Chapter 3, is from projects perpetrated under funding by the US Department of Energy, inspired by concern with the problem of slurry letdown valves for coal liquefaction processes under large scale development in the 1970s and ‘80s. One such pressure letdown scheme is shown in Figure 4, for a process under development[1] in the 1970s. The process was a 2000 psig catalytic process, from which the effluent stream was a slurry consisting of a petroleum-like synthetic liquid carrying the catalyst plus the coal ash particles. The ash would be a near-infinite variety of natural minerals, depending on the source and geological history of the bituminous coals used. In these schemes, the erosive wear is distributed over three sets of letdown valves between flash tanks, where volatile components of different boiling point ranges are separated. All of the valves are capable of being isolated for the replacement of eroded trim as needed.

There is a story (unconfirmed here) of German research to develop a similar high pressure process to produce synthetic fuels from coal, which was near the end of World War II after the allies had bombed the Polesti (Romania) oil fields and consequently eliminating the Nazis’ main source of petroleum. It was said that erosion of valve trim, even having used the hardest materials available, was so severe that it had to be replaced <u>daily</u> or oftener. This was done in desperation, but would not be an option for extended operation under normal commercial economic conditions. While the anticipated need for coal liquefaction currently appears politically out of fashion, this clearly shows the importance of slurry erosion as a problem that needs to be understood and mitigated wherever possible. This is the motivation for this course.

The examples of severe letdown valve erosion in coal liquefaction processes, as described above, are extreme and rather rare. But similar problems arise throughout the process industries, particularly in mining and mineral processing, power generation, and pulp/paper. In these processes, replacement of worn valve trim, pump impellers and other components is a normally accepted maintenance expense. Where it is desired to minimize this expense, whether in the design or selection of equipment, basic knowledge of abrasion/erosion and how to predict or minimize it can be useful and sometimes critical.

Fig. 5. High pressure letdown system for a USDOE coal liquefaction process[1].



Summary

Erosion rates of solid surfaces by slurries is proportional to the:

- Velocity of impact of single particles,
- Angle of impact of single particles.
- Frequency of impacts.
- Relative hardness of the particles, H_p, to the surface material, H_s.
- Kind of surface: Metallic, amorphous, crystalline, glassy, etc.
- Velocity of flowing slurry.
- Degree of turbulence.
- Concentration of solids in slurry.

Solid surfaces may be crystalline, amorphous, brittle, metallic, glassy, etc., and these definitions may overlap and be different when considering the surface on a theoretical, microscopic or a practical, macroscopic scale.

Erosion is most severe where flow is accelerated through points of constriction, such as control valves.

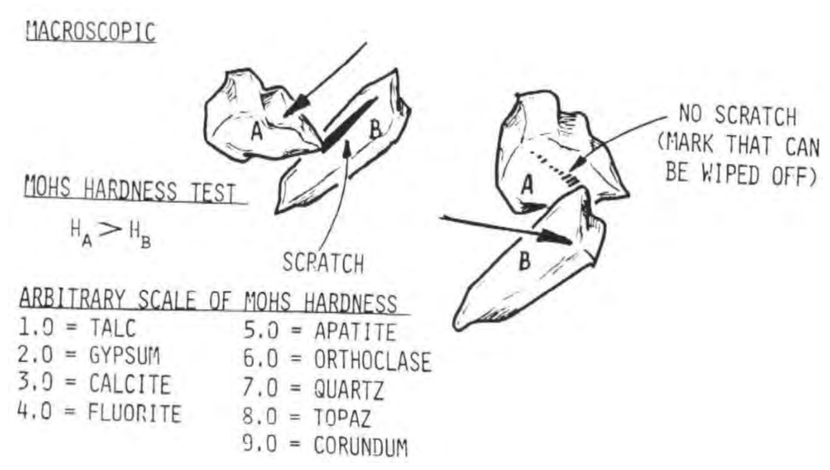
~~ End of Chapter 1 ~~

Chapter Two - Hardness Testing Methods

Definition: In general, hardness can be defined as a material's resistance to damage or fracture by moving contact with another object. The most literal measure of this property is a scratch test. Hardness is a material's ability to resist being marked by scratching. The traditional measure is the Mohs hardness test, based on a series of natural minerals available in large chips / fragments which can be used to make a scratch on, or be scratched by any material. As shown in Figure 6, any of these nine standard materials will make a permanent scratch on one of the next lowest number, but cannot be scratched by the next lowest number. Thus any flat sample of test material is scratched by each of the nine standards. Its hardness is reported as the lowest numbered standard that made a permanent scratch on it. Standards of lower numbers did not scratch the sample, but may have left a smudge of the standard mineral. Ideally, this scale of 1 through 9 only reports whole numbers. But sometimes the visual distinction between a minimal scratch and a mere smudge is not obvious, so the sample surface hardness is reported as a range. For example, a typical carbon steel was definitely scratched by orthoclase (6) and higher standards, but showed only a permanent smudge – or maybe a minimal, microscratching - by apatite (5). So the hardness of this steel was reported as "Mohs 5~6."

Fig. 6-a. Definition of Mohs hardness scale – traditional and more recent.

Traditional Mohs Hardness Scale (Since 1812)

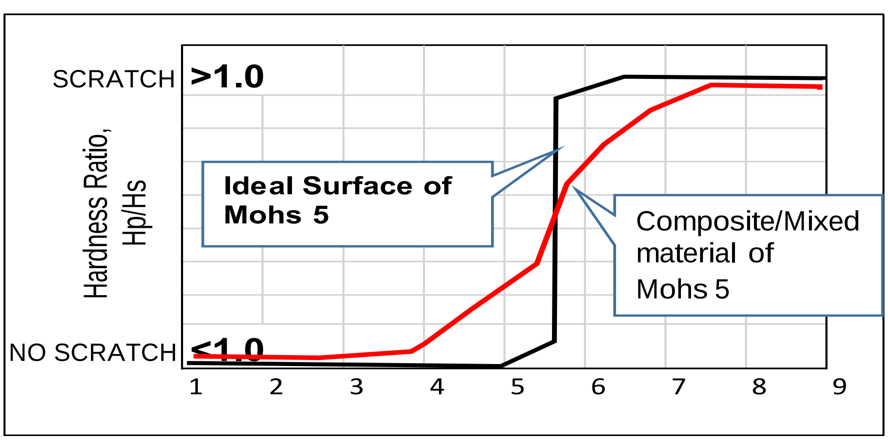


Modern, Extended Mohs Hardness Scale

Mohs Substance	Hardness
Vitreous pure silica	7
Quartz	8
Topaz	9
Garnet	10
Fused zirconia	11
Fused alumina	12
Silicon carbide	13
Boron carbide	14
Diamond	15

The major limitation of Mohs hardness measurement is that it only reports hardness in whole numbers. For a pure substance, of uniform molecular/crystalline structure, the test lump either does or does not scratch the surface. If we define a scale of scratchability or scratch resistance, we have a variable of only 2 values, >1/0 or <1.0, where the variable is simply ratio of hardness of the particle or the surface, as plotted in Fig. 6-b. The figure shows a simple step function for a substance of Mohs 5, which says that the substance is clearly scratched by a Mohs 5 particle but a particle of it will not scratch a Mohs 5 surface. This applies to only pure substances, however. Most mineral products are mixtures of different composition and crystalline structures that may have quite different hardness properties. So, to establish a Mohs description for them would require multiple points, defining a curve like the red line of Fig. 6-b, where the curve's mid-point or steepest slope can be called an average or effective hardness. This is often done, approximately and very crudely, by guesstimating the hardness based on micro-scratches or smudges above or below the most clear/obvious scratch.

Fig. 6-b Scratch Resistance vs. Mohs Hardness.

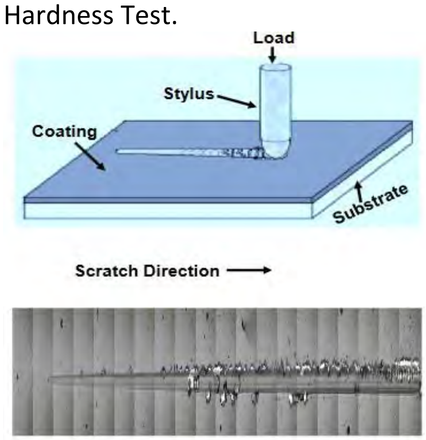


The Mohs scale assumed diamond, the hardest known material, as standard ten (the top of the scale) which is not shown in Figure 6-a. The Mohs test was originally designed as a field tool for geologists and prospectors to identify various minerals. In more recent times, various synthetic materials have been invented with hardness between corundum and diamond. So the scale has been extended, using diamond defined as fifteen and this scale is added to Figure 6-a. Unfortunately, there is a discrepancy between the traditional and modern scales, in the range of Mohs 7 to 9. According to a reputable handbook source[2], Quartz (SiO2) hardness = 7, Topaz ($Al_2SiO_4(F,OH)_2$) hardness = 8, Corundum (Al_2O_3) hardness = 9. Garnet is poorly defined, being an igneous rock, composed of any of several aluminosilicates, cited for use as an industrial abrasive with no hardness given. These handbook numbers are thus consistent with the traditional Mohs scale.

For any serious engineering effort to "guesstimate" erosion rates, caution is recommended in deciding which Mohs scale to use. A basic Mohs test kit, with pieces of all nine references minerals, is available from Amazon.com for $23.00 (Late 2019). More elaborate test kits are offered[3], using stylus pens, with hardness points made of durable metals and alloys of equivalent Mohs' hardness ranging up to Mohs 9. The actual specification of these metallic reference standards is proprietary and not available.

Another scratch hardness test[4], recently developed and far more "scientific," is available as ASTM G171-03 III. This is done with a tribometer which is a precise modern instrument. A diamond stylus makes an indentation in a specimen to a standard depth, then the specimen is moved to make a scratch. The scratch width is measured as indications of surface hardness along with the coefficient of friction,. It can be applied equally to brittle or ductile/metallic surfaces. As an example, several tests on variants of hard coating material reported a range of 89 to 228 microns. A web search found no further public data comparing this method with other means of hardness measurement. For more details, ASTM charges $50.00 for a license. Relatively basic tribometers are available for as low as about $8,000.

Figure 7. ASTM G171-03 III, Scratch Hardness Test.



So far, we have reviewed scratch hardness tests, which remove small amounts of a test surface by brittle fracture or gouging, depending on the nature of the surface. The great majority of standard hardness tests, however, involve penetration by a stylus and measurement of the load applied, depth of penetration, and/or dimensions of the resulting pit. These have all been developed primarily for metals. No material is removed. So these are measurements of plastic deformation, which is quite a different property from scratch resistance.

Well used penetration hardness tests are the Rockwell, Brinell, Vickers, and Knoop. Details for all of these is beyond the scope of this work. But the Knoop test (ASTM E384-11e1) is the one most often used to compare data with Mohs hardness. Details of the Knoop test[4] are as follows.

The **Knoop hardness test** is a test for mechanical hardness used particularly for very brittle materials or thin sheets, where only a small indentation may be made for testing purposes. A pyramidal diamond point is pressed into the polished surface of the test material with a known (often 100g) load, for a specified dwell time, and the resulting indentation is measured using a microscope. The geometry of this indenter is an extended pyramid with the length to width ratio being 7:1 and respective face angles are 172 degrees for the long edge and 130 degrees for the short edge. The depth of the indentation can be approximated as 1/30 of the long dimension.[1] The Knoop hardness HK or KHN is then given by the formula:

$$HK = \frac{\text{load(kgf)}}{\text{impression\ area(mm}^2)} = \frac{P}{C_p L^2}$$

where:
L = length of indentation along its long axis
C_p = correction factor related to the shape of the indenter, ideally 0.070279
P = load

HK values are typically in the range from 100 to 1000, when specified in the conventional units of $kg_f \cdot mm^{-2}$. The SI unit, pascals, are sometimes used instead: 1 $kg_f \cdot mm^{-2}$ = 9.80665 MPa.

The test was developed by Frederick Knoop and colleagues at the National Bureau of Standards (now NIST) of the United States in 1939, and is defined by the ASTM E384 standard. The test was devised in 1939 By using lower indentation pressures than the Vickers hardness test, which had been designed for measuring metals, the Knoop test allowed the hardness testing of brittle materials such as glass and ceramics. Even though it is a non-scratch, penetration test, it is commonly used for a variety of vitreous and brittle mineral materials.

The advantages of the test are that only a very small sample of material is required, and that it is valid for a wide range of test forces. The main disadvantages are the difficulty of using a microscope to measure the indentation (with an accuracy of 0.5 micrometer), and the time needed to prepare the sample and apply the indenter. Variables such as load, temperature, and environment, may affect this procedure, which have been examined in detail."

While the Knoop test essentially measures plastic deformation under a given load, it is officially (US Bureau of Standards) recognized as an acceptable comparison of hardness. It might be expected, however, that for an extremely brittle surface, the neat stylus indentation pattern may be less well-defined.

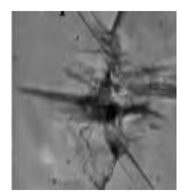
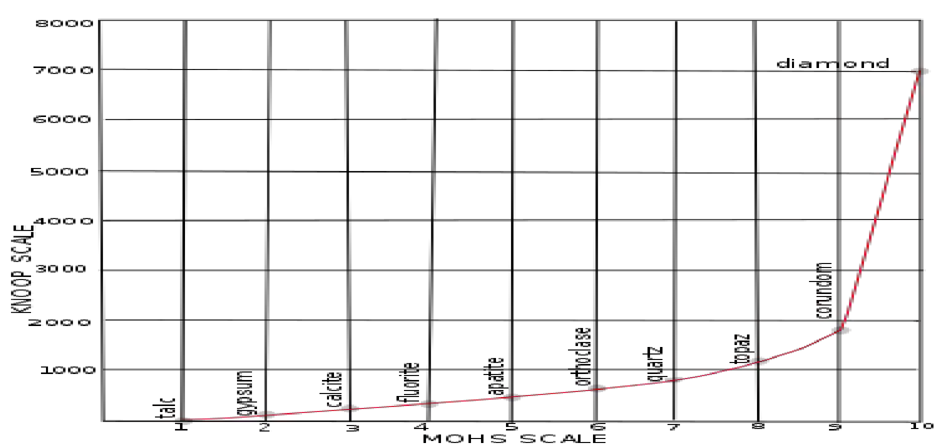


Fig. 8. Comparison of Mohs and Knoop Scales



Knoop Sample Values

Material HK
Dentine 68
Gold Foil 69
Tooth Enamel 343
Quartz 820
Silicon Carbide 2480
Diamond 7000

Correlation of Mohs and Knoop hardness for a broad range of different materials is shown in Table 1 below, collected from multiple sources[6].

In Table 1, note the wade ranges of values for natural materials. This is because of the extreme difficulty of finding samples of pure materials with flat surfaces big enough for scratch tests, by either method. So these entries are composites of multiple tests on irregular surfaces with impurities.

Table 1. Mohs and Knoop Hardness Data for Various Materials, Collected from Multiple Sources[6].

Material	Mohs Scale	Knoop Scale
Original Mohs Reference		
Gypsum	2	15~90
Calcite	3	100~160
Apatite	5	450~690
Orthoclase	6	650~930
Quartz	6	1000~1500
Topaz	8	1420~2000
Corundum	9	2050~2750
Extended Mohs Reference		
Garnet	10	
Zirconia, Tantalum, Carbide	11	
Fused Alumina	12	1635
Tungsten Carbide	12	
Silicon Carbide	13	2000
Boron Carbide	14	2230
Diamond (with inclusions to pure)	15	6000~10,000
Metals		
Aluminum	2.0~2.9	
Copper	2.5~3.0	
Iron	4.0~5.0	
Lead	1.5	
Manganese	5.0	
Silver	2.6	
Tin	1.7	
Zink	2.5	
Chromium	9.0	
Stainless Steels		
AISI 304		150±
AISI 316		150±
“Cast Ni steel for abrasion resistance”		360~670
Advanced Coating Materials		
BN		3700~4000
T_4C		3700
TiB_2		3350
TiC		2800~3000
SiC		2500~3000
WC		1800~2200
Other minerals, found in coal		
Shales	2.0~2.5	
Illite		19~34
Muscovite		40~85
Kaolins	2.0~2.5	
Kaolinite		31~38

Sulphides	6.0~6.5	
Markasite, FeS_2		760~1650
Pyrite, FeS_2		1000~1840
Carbonates		
Calcite	3.0~3.5	
Rhodochrosite $MnCO_3$		240~370
Siderite $FeCO_3$		370~440
Smithsonite $ZnCO_3$		500~660
Ancorite $(Ca,Mg,Fe)CO_3$		350~490
Dolomite $(Ca,Mg)CO_3$		480~575
Albite $NaAlSi_3O_8$	6.0~6.5	1682
Anorthite $CaAl_2Si_2O_8$	6.0~6.5	150
Magnesite Fe_3O_4	5.5~6.5	480~740
Hematite Fe_2O_3	5.5~6.5	750~1100
Kyenite Al_2SiO_5	4.0~7.0	500~2150
Lepidocrocite $Fe_2O_3.H_2O$	5.0~5.5	150~465
Tourmaline	7.0~7.5	1190~1480
Zircon $ZrSiO_4$	7.5	1110~1510
*Coals***		
Misc. Bituminous	2.5±	
By approximate Carbon content		
92% Anthracite		40~60
90%		22~29
86%		26~30
80% Bituminous or subbituminous.*		31~35
75%		29~34
70%		23~27
65% High-ash Lignite*		14
Composite for all Bituminous and lower rank coals		12~35

(* Author's experience: Due to extreme difficulty in machining/grinding smooth surfaces on crumbly low rank coals, for any kind of testing/measurement, these numbers are considered dubious.)

Figure 10 is a plot[6] correlating the Mohs and Knoop hardness of materials from Table 1. Where the tabular data gives ranges rather than single values, these are shown as rectangles rather than compact points. Any attempt to credibly measure the Mohs hardness of a clip/particle of an unknown material requires a smooth surface of at least a square inch or two. Note the discontinuity above Mohs 12, reflecting the discrepancy between the basic and extended Mohs scales. Fig. 11 shows Mohs hardness of various materials determined by scratching with the nine basic Mohs standard materials[6], all of which were simply handy samples around the laboratory and were selected randomly. Ideally, such tests should use hard metal alloy surfaces of known composition, such as the pens described in Mohs test kit mentioned above[2], which however were not available.

Fig. 9 - Mohs vs. Knoop Hardness for Various Materials[7].

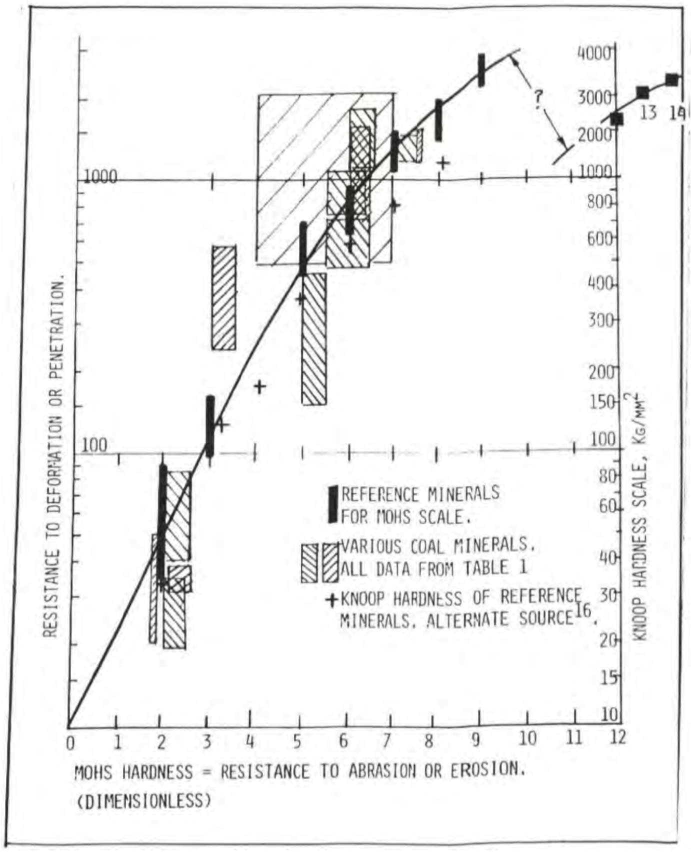
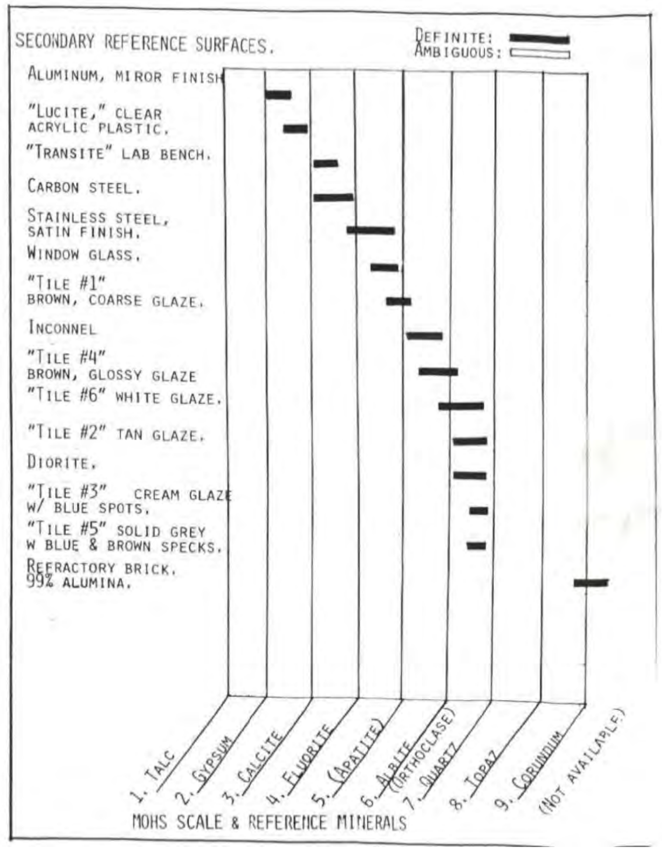


Fig. 10. – Mohs Hardness of Various Handy Materials as Potential Future Reference Standards[7].

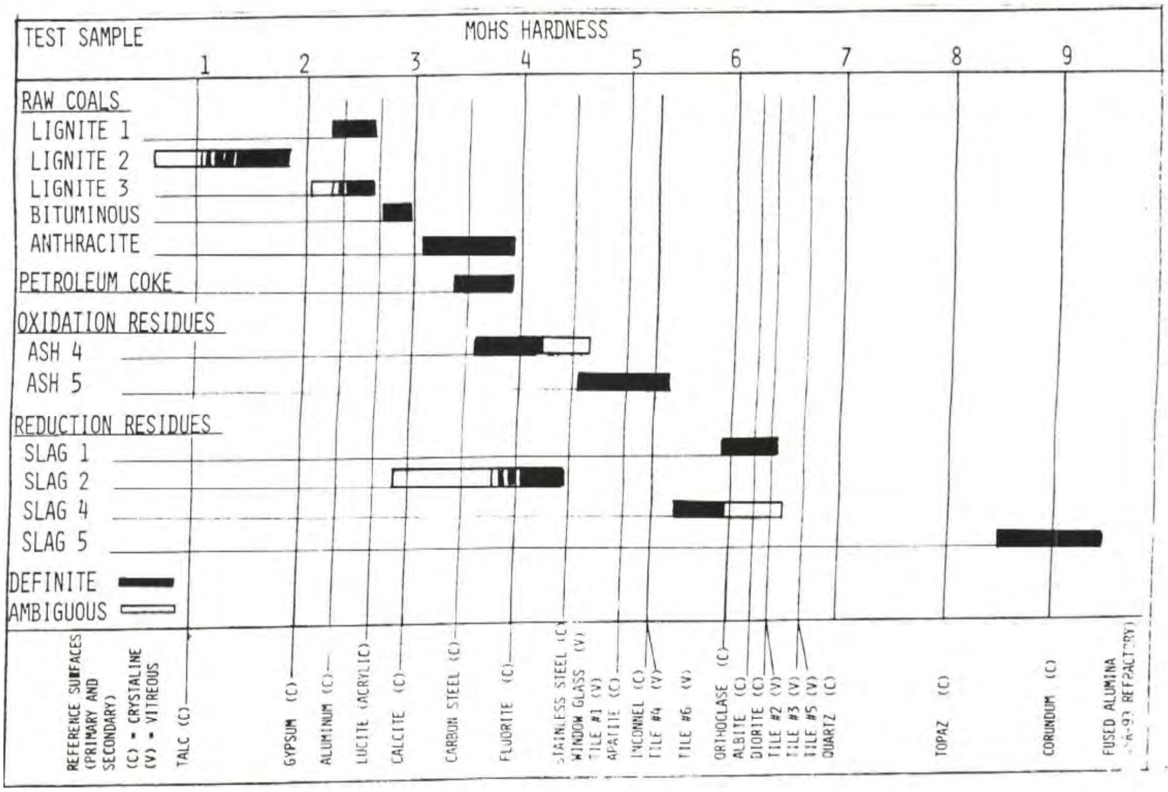


Any scratch test should use the same procedure to establish reference surface hardness as used to determine hardness of materials for which chips or granular samples may be available. The following data compares variants of a procedure by which a selection of coals and residues were determined, using reference standard surfaces selected from Fig. 11 above[6].

The Primary Mohs hardness reference surfaces selected were as follows.

Mohs	Material	Mohs	Material
1	Aluminum	4	"Tile 1"
2-	Lucite Plastic	5-	"Tile 4"
2+	Transite (Asbestos Cement)	5+	"Tile 6"
3	Stainless Steel	9	Refractory Brick

Fig. 11 Mohs hardness of Various Coals and Residues[7].

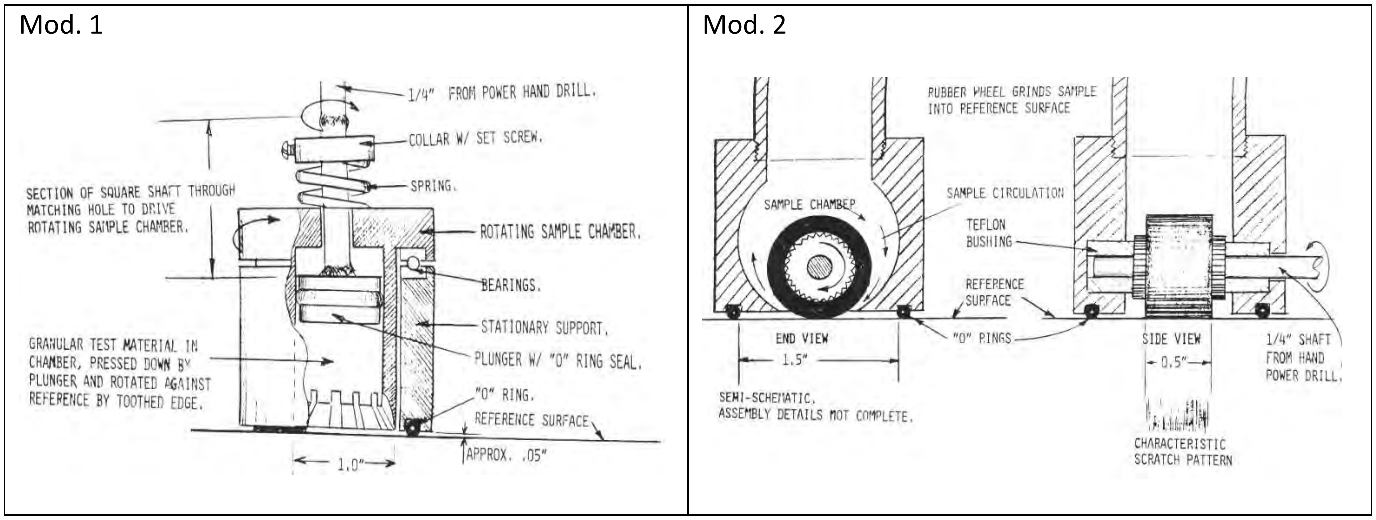


All of the samples tested in Figure 12, were fairly random with respect to consistency and uniformity of structure, so that samples may not be truly "typical." The oxidation residues were agglomerations or "clinkers" of coal ash, consisting of a wide range of very different mineral components found in the coals. The slag samples were vitreous lumps of lignite ash leaving a slagging gasifier in a molten state, at up to 2000ºF. Slag 5, in particular was known to contain components of refractory brick (See Fig. 11), containing some chromium oxides, which become partially soluble in molten slag under highly reducing conditions at these temperatures.

<u>Conclusion</u>: Notwithstanding the sloppiness of the experimental method in this case and the inherent randomness of sample chips/lumps of materials available, the Mohs test gives a fairly credible measure of relative hardness. It is recommended that more care should be used in selecting and completely identifying reference surface materials.

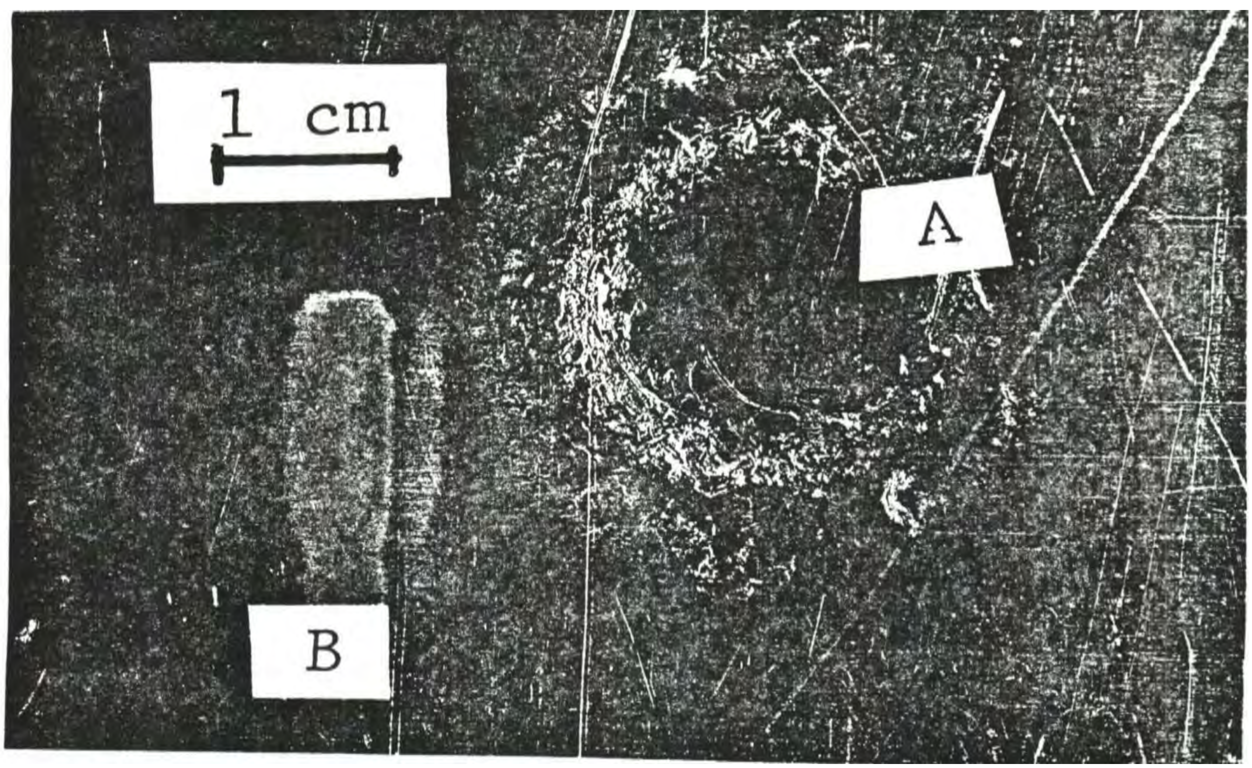
Most materials/products handled as slurries are mixtures of different mineral components of widely varying hardness, and available only in fine granular or powdered form. Therefore, to perform any kind of scratch test on a reference surface of known hardness, samples of the slurry solids must be ground onto the surface to leave a scratch pattern. Here are two examples of simple contraptions made for this purpose[7]. Both are quickly-conceived, pocket-sized devices which use a hand-held electric drill to provide motion.

Fig. 12 Simple powder abrasion test devices.



Typical scratch patterns made by these two devices are shown below as Figure 13. In cases where the powdered abradant was less hard than the reference surface, there was negligible pattern, thus defining the abradant’s hardness on the Mohs scale.

Fig. 13 Typical scratch patterns made by tester Models A and B.



Surface: Aluminum Mohs hardness = 2.3 ± 0.2 Grinding time, both cases = Approx. 5 seconds.

A. Circular pattern of Model 1 device, with -20 mesh (0.8 mm) Quartz. Hardness = 7. $H_p/H_s = 3.0$
B. Smudge pattern of Model 2 device, with -100 mesh (0.15 mm) Petroleum coke. Hardness = 6.5 ± 0.5 $H_p/H_s = 2$.

Fig. 14 Abrasion Data with Model 2 Testing Device

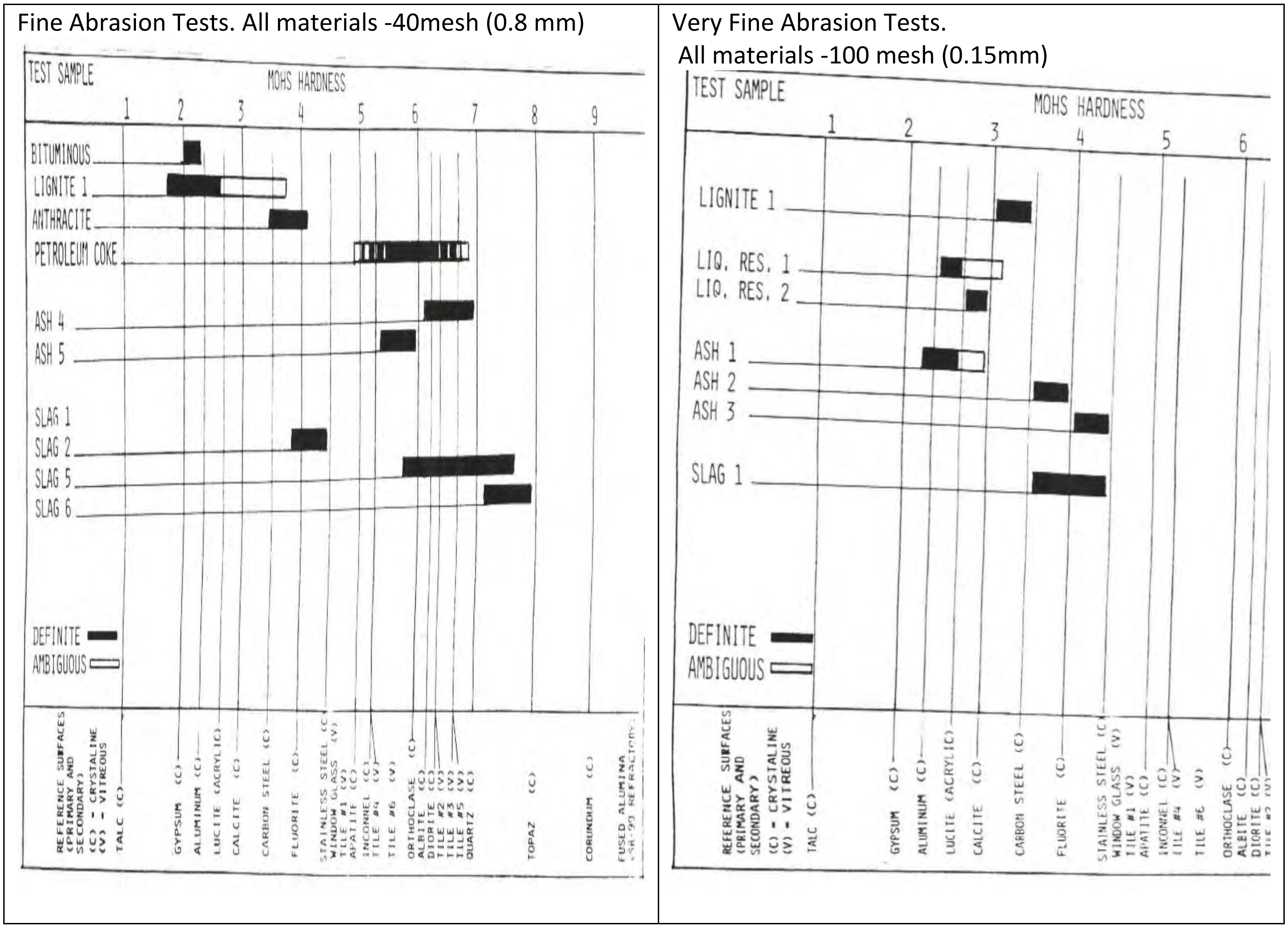
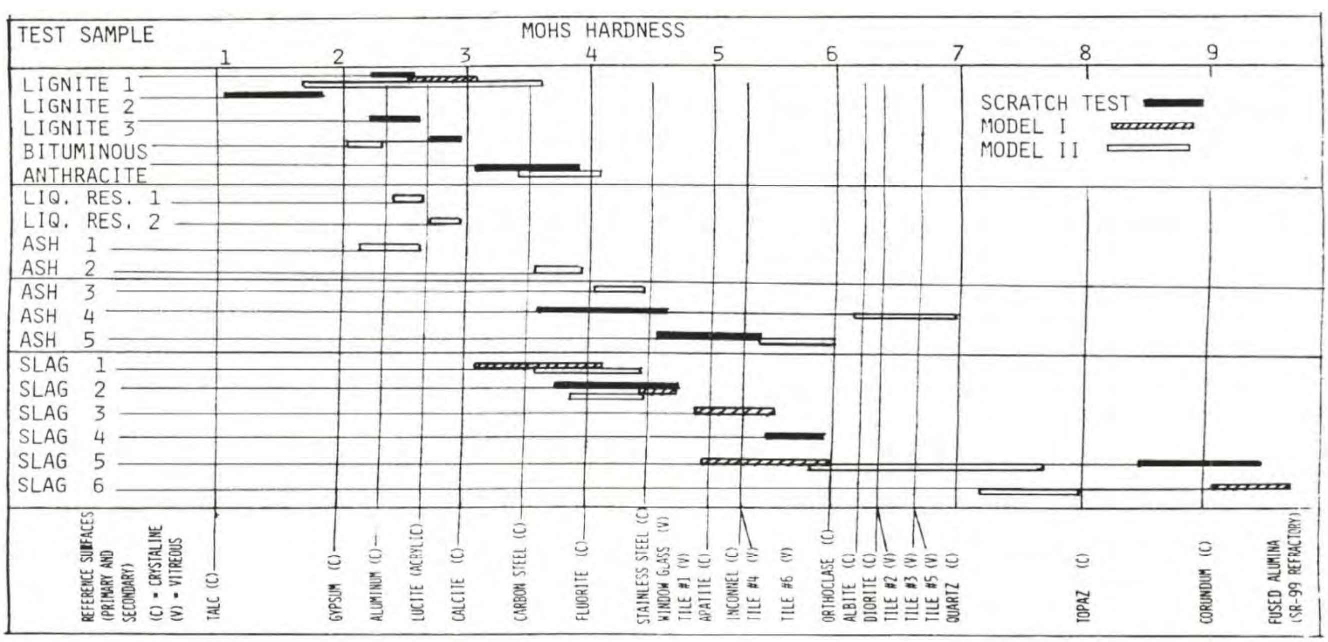


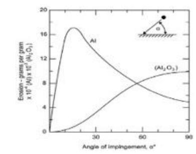
Fig.15 Comparison of Hardness Test Methods and Apparati.



Another dimension in the kinds of scratch resistance, as shown in Fig.1, is for non-rigid surfaces (specifically tough, flexible rubber) that shows impressive resistance to erosion and is used for pinch valves, which also claim to reduce erosion by maintaining flow as parallel as possible to the containing surface, notwithstanding high turbulence. Here a flexible rubber sleeve is pinched shut, and is the replaceable part as it wears out.

Besides the erosion resistance of a flexible surfaces, it also concentrates the maximum pressure drop and turbulence in a constriction where flow is parallel to the surface. However, for non-brittle surfaces, as shown part of Fig.1, erosion of the surface is at maximum for very low impact angles.

Recalling the matter of how impact angle affects the definition of hardness, as raised by Fig. 1, the abrasive scratch tests described by Figs. 12 through 15 all involve zero degree impacts. This then must cast some doubt on whether the damage to a brittle surface, such as the tiles or glass, are valid equivalents of Mohs hardness or predictions of turbulent erosion resistance where high angle particle impact is dominant.



Summary

- The only methods available for measuring hardness, defined as resistance to erosive damage, are the Mohs, Knoop, and ASTM G171-03 III tests.
- The Mohs hardness number is defined by the ability of a particle of one material to make a scratch on the surface of another.
- The Knoop hardness number is defined by the applied load and size of the resulting impression.
- Most common hardness tests, such as Rockwell, Brinell and Vickers, are penetration tests, designed for metals, and measure plastic deformation rather than brittle fracture resistance.
- Most slurries are composed either of mixtures of different minerals or products that exist only in fine particulate form, and are not available as lumps or surfaces for conventional Mohs or Knoop hardness testing.
- If these materials are available in dry form, their hardness may be roughly estimated by abrasion patterns when ground against reference surfaces.
- The severity of erosion to ductile or brittle surfaces may be quite different depending on the angles of impact, and thus on the pattern of maximum turbulence.
- The rate or severity of surface removal by abrasion or erosion is assumed to be proportional to the hardness ratio of particle to surface, H_p/H_s.

~~~ End of Chapter 2 ~~~

Chapter 3 - Accelerated Erosion Testing

So far, this course has covered the definition of hardness and established some experimental means of measuring it. We shall next consider means of quantifying and predicting rates of erosion by flowing slurries or suspensions of abrasive particles. As presented in Chapter 1, the rate of erosive damage (surface removal) by a flowing slurry is a function of (1) properties of the slurry and (2) configuration of the containing surface.

Erosion of a new surface generally starts with microscopic pits, which then increase microturbulence at the point, which increases the turbulence pattern, further expanding the damaged area. At very high velocities through a point of constriction and/or high turbulence, erosion is accompanied by cavitation, which results by the rapid formation and collapse of bubbles caused by local instantaneous vacuums (caused by the Bernoulli Effect). At such points, surface damage can occur even in clear liquids which do not contain suspended particles. At such points of cavitation, the rate of combined surface damage is a function of the surface velocity in contact with the solid surface and the vapor pressure of the liquid. Cavitation can cause serious damage, but is beyond the scope of this work.

Figure 16-a shows an example of damage to some control valves by a flowing slurry caused while the valve was near-shut. Note that the damage is concentrated on points where initial erosion made a small notches, providing a path of least resistance and accelerated velocity.

Fig.16-a Typical Erosion of some Control Valve Components in Contact with Slurries.

Fig. 16-b Types of Control Valves Showing Regions of Maximum Turbulence.

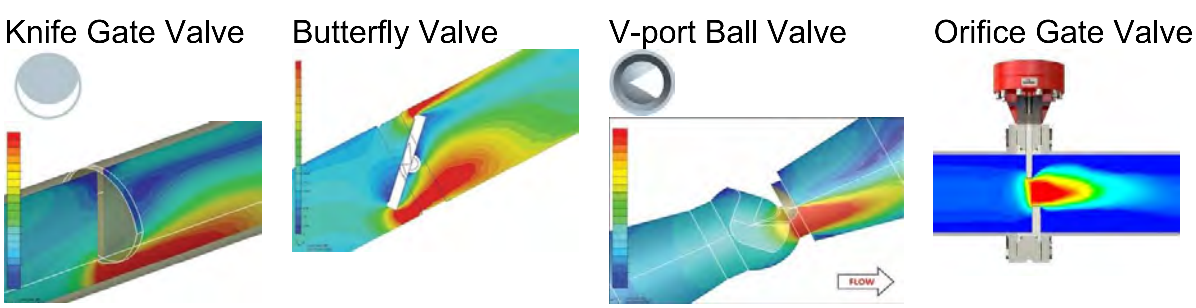


Fig. 16-b shows schematic examples of 4 types of control / letdown valves, with regions of maximum turbulence graded by color. These are areas in which the maximum pressure drop and accelerated velocity are present, and where maximum erosive damage is done to any surfaces that they are in contact with. These are also areas where cavitation will happen, if present, depending on the volatility and vapor pressure of the carrier liquid. In the first 3 blocks of Fig. 16-b which show knife gate, butterfly, and v-port ball valves, note that the areas of turbulence touch both the movable element and the enclosing wall, inflicting erosive damage on both. The last block shows a clever orifice gate design[9] where the violent destructive area contacts only a sliding gate and orifice plate, both of which are easily replaceable.

One should note, in Fig. 16-b, that the regions of maximum turbulence all start at some point where the accelerated flow is in contact with a sharp edge. The significance of this will be apparent later.

Figure 17 shows examples of different centrifugal pump impeller designs, in advanced stages of wear from pumping abrasive slurries. The 2 closed impellers, on the right are nearly worn away. Performance evidence of this is reduced capacity at normal operating RPM. The open impeller on the left obviously had vanes made of some hardened alloy to resist abrasion, while the mild steel base plate is massively worn away, mainly at its outer edge where particle impacts are more severe due to the high tip speed.

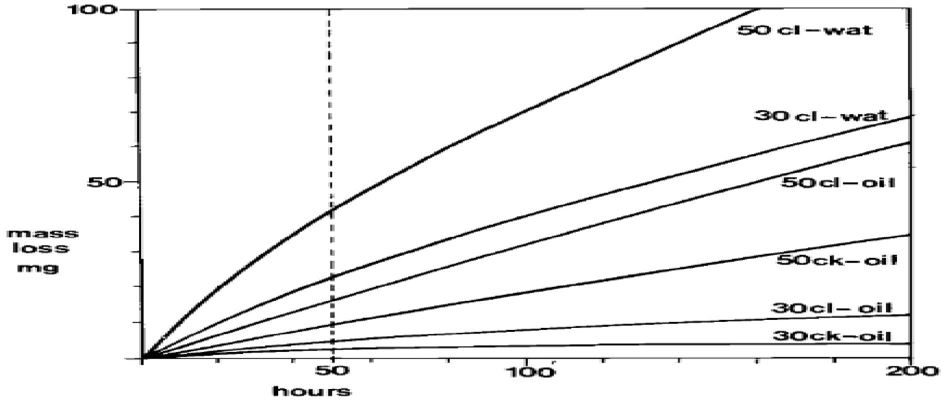
Fig. 17 Examples of Erosive Wear on Centrifugal Pump Impellers.

Chapters 1 and 2 dealt with the definition and measurement of abrasiveness of damage inflicted by flowing slurries. Here we shall look directly at slurry erosion and means of measuring and, where possible, predicting it.

For any flowing fluid against a surface, viscosity is defined as a measure of momentum transfer from liquid to surface, thus slowing down the liquid and resulting in a pressure drop through a pipe or valve. Fluid motion, at contact with a surface, is relative. In the case of centrifugal pumps, it is the surface that is moving, transferring momentum to the fluid, thus accelerating flow rate and imposing an increase in pressure. Whichever way momentum is transferred, slurry erosion rates increase in proportion to velocity *relative* to the surface, whether it the accelerated flow through the constriction of a control valve or the tip speed of an impeller.

To relate directly to the problem of pump erosion, consider a test device where test specimens of steel discs were attached to the end of a shaft and spun at 3459 rpm, with a tip speed of 18.3 m/sec, immersed in agitated slurries of Pittsburg No.8 coal (5.4% ash) and petroleum coke (=0.15% ash), both ground to -200 mesh[5]. Carrier fluids were water and a fuel oil. Some data plots are shown in Fig. 18. These curves confirm that for a given solids-carrier combination, erosion is more severe with higher solids loading. Slurries of coal, in water or oil, are more erosive than the same solid loadings for coke. This is partly because of the more stable carbonaceous structure of coal, but largely due to the presence of highly abrasive minerals of coal ash – in this case 5.4%. Coke is formed by condensation of petroleum-derived hydrocarbons from a vapor state, and thus contains no ash. Oil slurries were less erosive than water because the oil has higher viscosity, partially damping down turbulence, making flow more laminar and reducing impact angles of single particles.

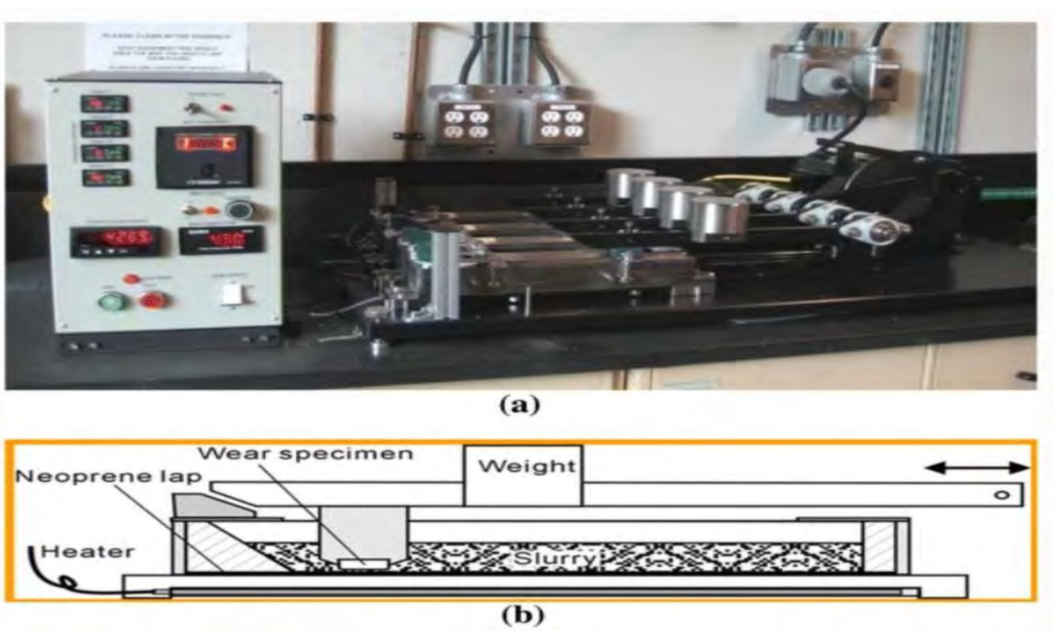
Fig. 18. Weight loss versus time curves for erosion testing of 304 stainless steel specimens in slurries of coal (cl) and petroleum coke (ck) in fuel oil and water[5]. Slurries were 30% and 50% solids.



With these curves, the *relative slopes*, quantified most simply as mg/hr of solid sample weight loss, are roughly equivalent to Mohs hardness ratios.

A current standard test (ASTM G75-15) for slurry abrasiveness (erosiveness) uses the Miller Tester[6], shown in Fig. 19. This is a sophisticated device in which a solid material sample is essentially polished by a slurry of any material, and the *weight loss vs. time* is the measure of relative abrasiveness, for 4 different solid sample specimens in the same slurry. Raw data consists of plots similar to those of Fig 18.

Fig. 19. The Miller Abrasion Tester and schematic.

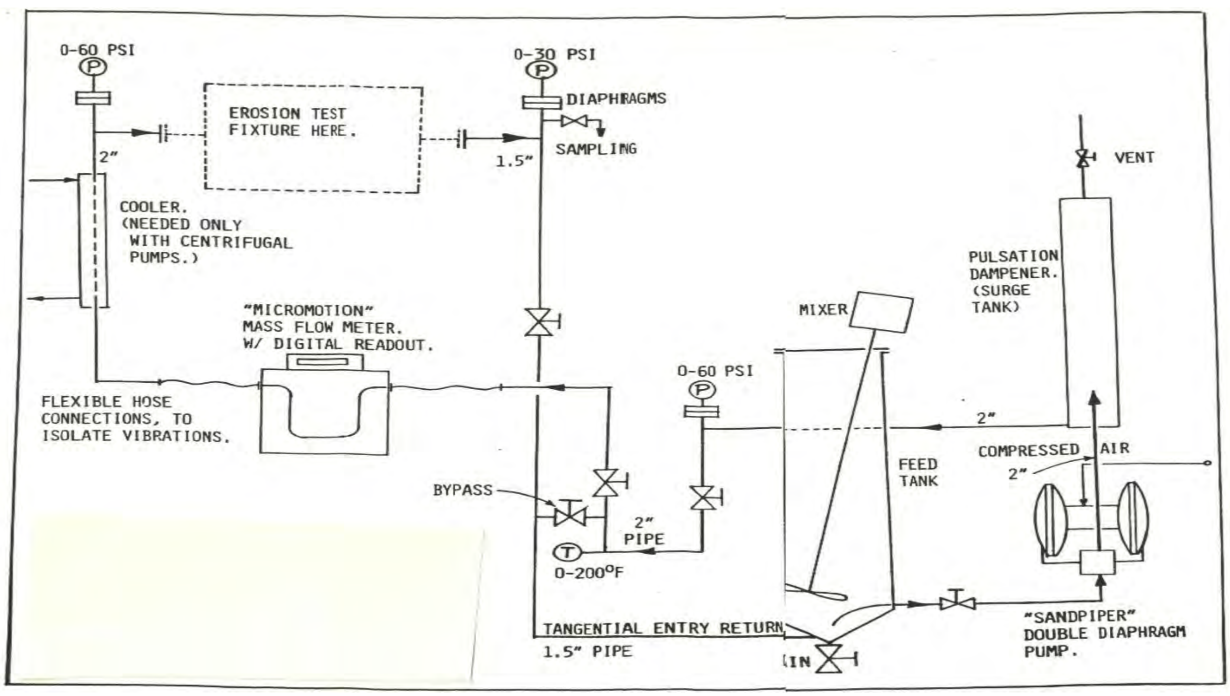


This Miller Tester can be considered a far more sophisticated version of the simple “homemade” gadgets of Fig, 12, using actual slurries instead of dry samples. If the Miller unit were used with slurries and solid samples made from standard Mohs reference materials, the results should be directly equivalent to Mohs hardness numbers and considerably more accurate. One should keep in mind that the Miller test, like the dry abrasive tests described in Chapter 2, only measures material removal for particles contacting the surface at zero degrees, or parallel to the surface. This fails to consider the range of impact angles occurring in turbulent flow against the surface.

The Miller device looks like it may have been inspired by earlier use of sample "lapping" machine used to prepare specimens for scanning electron microscope inspection. In this procedure, samples are encapsulated in multiple epoxy slugs, which are then slowly "lapped" on a rotating surface, with a circulating slurry of a very fine lapping compound, to produce a very smooth cross-section of the specimen for microscope. Several researchers (*Author included*) have used this technique, but no published data is available.

To this point, we have covered methods of quantifying hardness / abrasiveness of different slurries or powders and surfaces. Such data is useful to predict / estimate the relative rates of erosive damage to specific equipment configurations. Equally useful is a means to predict the rates of damage to different configurations by the same slurry. For this purpose, consider an experimental test loop shown in Fig. 20, and some 1985 experiments.

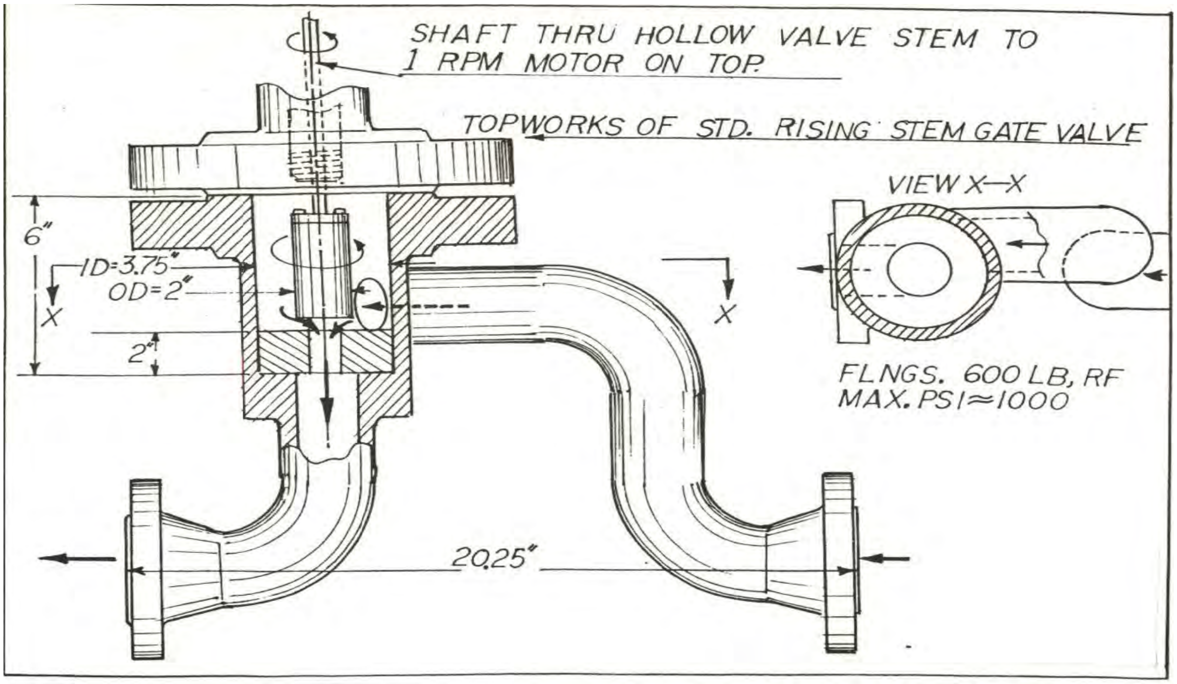
Fig. 20. Accelerated Erosion Test Loop[8]



This system was used to observe the rate of erosive damage to cast epoxy or machined Lucite or aluminum (Mohs 2~3) copies of different equipment designs being compared. The highly abrasive slurry was of fine quartz (Mohs 8) in water. Flow was provided by a twin diaphragm pump with rubber ball check valves, and measured by a mass flow meter designed to handle slurries with no restrictions and minimum turbulence. Flow velocity was a constant 2~5 ft/sec in order to minimize pipe erosion. The 30 gallon slurry tank was stirred to maintain uniform suspension.

Recalling Fig. 16, note that erosion of valve seats is generally asymmetrical. It was proposed that if the valve stem were slowly rotated, this wear might be distributed symmetrically, so that the valve plug could be made of some cheaper sacrificial material, and slowly advanced to compensate for wear[8]. A series of tests were done to determine if this proposition were valid and to compare the extent of erosion for different valve configurations. The erosion test fixture for this series, inserted in the loop of Fig. 20, is shown in Fig.21.

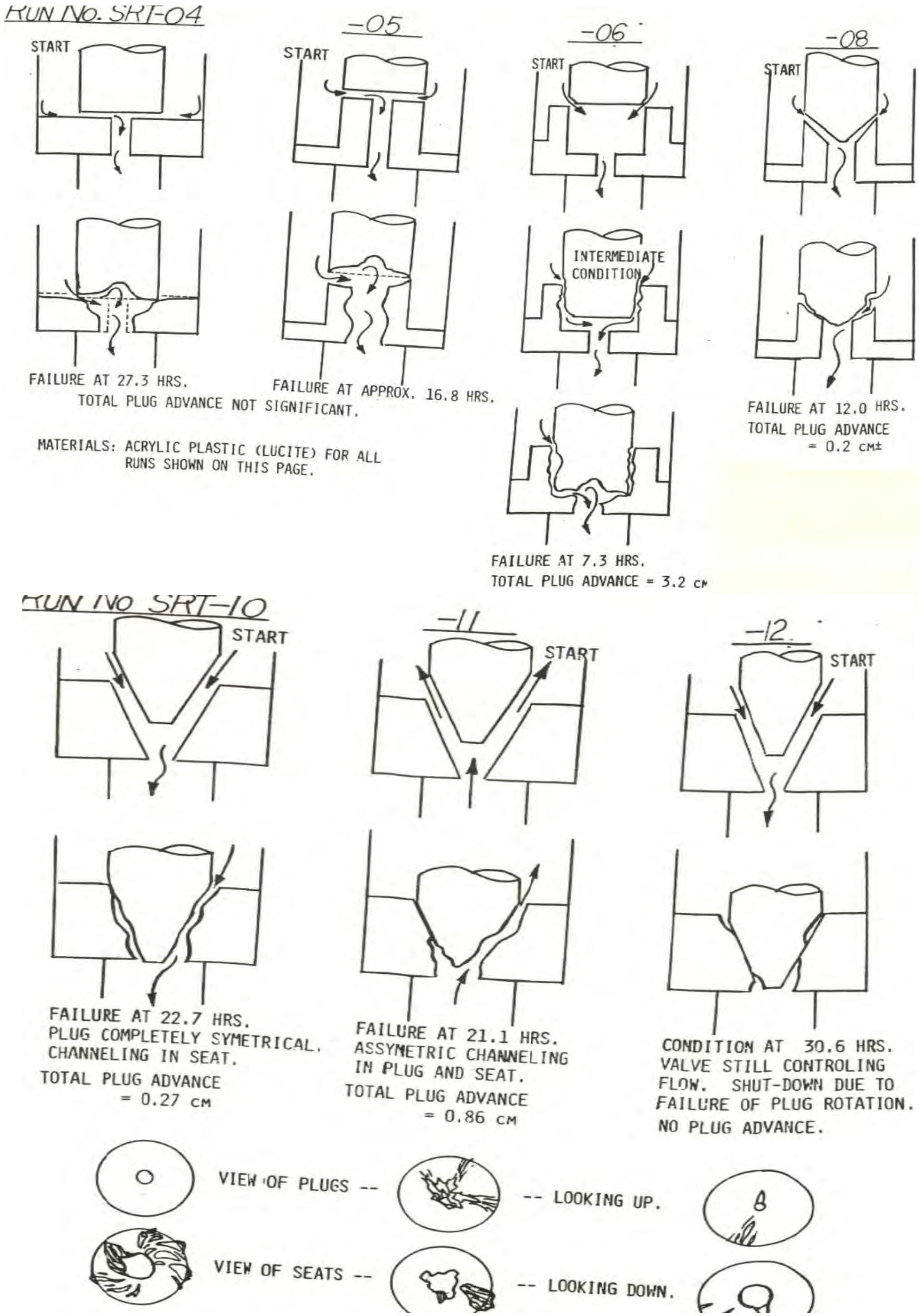
Fig. 21, The “Lathe Valve.” Test Device [8]



This device was designed to insert a wide variety of valve stem and seat designs for comparison. Fig. 22 shows a 2-page series of results. Tests with Lucite and aluminum trim were run with the quartz slurry for up to 30 hours at hardness ratios of 2.5 to 2.9, to achieve greatly accelerated wear. In typical process designs, hardness ratios are typically fractional values, generally far below 0.1 for most food and agricultural products. For a typical control valve with hardened high-Cr alloy trim, the hardness ratio would be typically around 0.6 for pumping or 0.3 for a limestone slurry, for example. With the high ratios of this test loop, erosive damage was achieved in hours, that would have taken months or longer in practical applications. During test runs, the plug position was adjusted frequently to maintain constant pressure drop, and the plug position was noted when the damage reached the extent that pressure control or even tight shut-off was no longer possible.

- Data summarized in Fig.22, provides a comparison of how well different configurations survive erosive wear. Several conclusions are obvious.
- The rotating plug, “lathe valve” concept was a bad idea and not useful.
- Erosion is reduced by maintaining streamlined flow, with minimum short turns or changes in direction, justifying the tapered plug design over the others.
- Aluminum resisted damage significantly longer than acrylic/Lucite, even though its Mohs hardness was slightly lower, according to Fig.10. This suggests that Mohs hardness measurement for a glassy, non-crystalline surface (See Fig. 1) may not be directly comparable to the number for a crystalline (metal or mineral) surface.

Fig.22. Test Result of Lathe Valve Configurations**.**



Run No. SRT-	4	5	6	8	10	11	12
Plug & seat material.	Acrylic plastic, Mohs hardness * = 2.8						Al, 2.3
Hardness Ratio, H_p/H_s	2.86						2.48
Running hours to failure.	22.5	16.8	7.5	12.0	22.7	21.1	30.6**
Total plug advance, cm	~0.0	~0.0	3.2	0.2	0.27	0.86	0.0

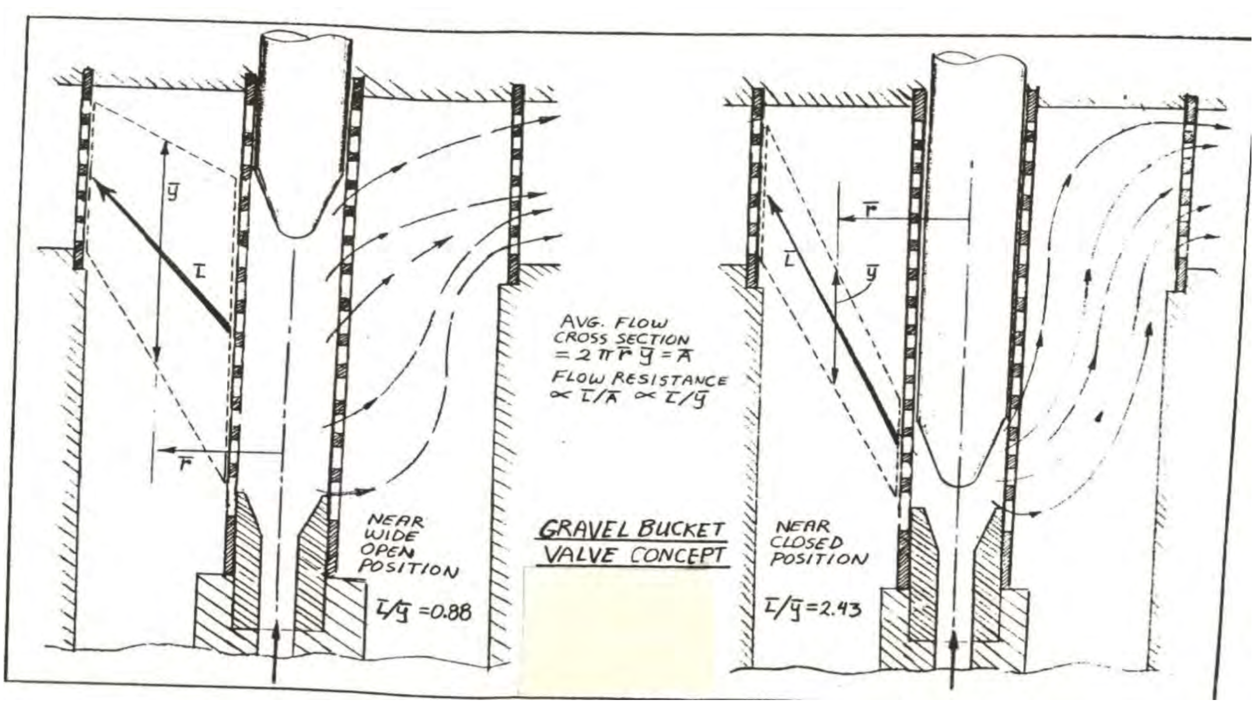
*Approximate Mohs hardness, from Fig.10.

**Shut down due to failure of rotation motor. Control still functional.

Another use of this flow loop was to evaluate a novel, proprietary centrifugal pump design, with an open impeller configuration intended to minimize erosion. An epoxy casting of the impeller (Mohs 2.3) was used with the erosive quartz slurry to observe erosive damage patterns in a few days, rather than presumably months of normal operations. Besides visual inspection of the impeller, the data collected include the flow and discharge pressure of the pump. The pump's performance was not encouraging.

The idea of using some cheap sacrificial valve trim material to distribute erosive wear over some greatly extended surface was expanded to several design concepts. One of these was the "gravel bucket," shown in Fig. 23. In conventional pressure letdown or control valves, a constriction accelerates flow to some very high velocity in contact with a very small surface area (generally on the order of a few square inches) of valve trim, which takes all the erosive and cavitation wear.

Fig. 23. "Gravel Bucket" Packed Bed Pressure Let-down Concept.



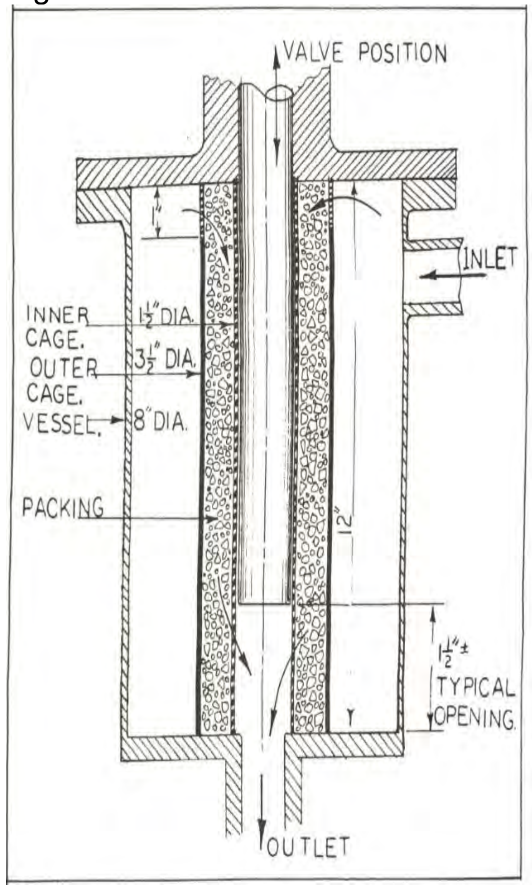
So consider a design where the erosive wear can be distributed over many square feet or even yards of some hard material, which also may be extremely cheap to replace. One such concept is shown here. The position of the valve plug controls the length through a bed of carefully sized crushed rock, providing the required pressure drop. The gravel size is such that a fine slurry flows freely through the interstitial space, without plugging. The length of flow path, cross-section, and gravel size determine the pressure drop.

A wide variety of configurations were considered, to provide for the release of trapped solids in the event of plugging, and ease of bed replacement. The choice of gravel bed material, which may slowly erode, must be compatible with the solid product in the slurry.

There is a possibility of plugging. It can be avoided by a minimum bed particle size much larger than maximum slurry particle size, as a trade-off against pressure drop. If flow is upward through the bed, and the bed weight is minimally more than pressure drop, plugging could increase pressure, thus raising the bed slightly. The expanded bed would then allow brief fluidization, thus releasing the fine material between larger particles. With the pressure drop reduced, the bed then re-collapses to its normal state. This concept was briefly tested and confirmed. The choice of gravel bed material, which will slowly erode, must be compatible with the solid product in the slurry.

A test unit, of the dimensions shown in Fig.24 was installed in the test loop of Fig. 20.

Fig. 24. “Gravel Bucket” Test Unit.



Tests were conducted for bed packings of limestone ($CaCO_3$, Mohs 3), gypsum ($CaSO_3$, Mohs 2), and gabbro (mixed minerals,50%+ anorthite, $(Na,Ca)AlSi_3O_8$. Mohs 5.7±), and for slurries of quartz (SiO_2 Mohs 7) and lignite (Mohs 2±). Bed packing was screened to a narrow range of 1/4” to 5/16”, with a void fraction of 46%. Flow rates covered the range of 3.8 to 7.5 lb/min. with pressure drops from 22 to 56 psi. Solids content of slurries ranged from 30% to 47%. Most tests used flow down-in, as shown in Fig.24. For 3 tests, flow was up-out, in which case the bed was clearly not fluidized, but “squirming,” or not completely immobile. There was no evidence of continuous plugging. Test durations ranged from 39 to 101 hours. An added variable was solubility of packing, which was essentially zero for the limestone and gabbro, but significant for gypsum. In general, these tests, though brief, appear to confirm the validity of the gravel bucket valve concept. After each of 8 tests, the bed material was removed, washed free of slurry and weighed. As expected, the weight loss recorded as a fraction of bed weight per hour due to erosion, was very small. Under the assumption that rate of bed loss is proportional to flow rate and slurry solids loading, the raw data was normalized to 30% solids and 400 lb/min slurry flow. These numbers for the 8 tests are shown in Table 2 below. Erosion rate, as fraction of bed weight loss per hour, are plotted against the particle/surface hardness ratio, H_p/H_s, in Fig. 25. (***Error**: The weight loss numbers on plot are actually decimal fractions – not % as shown*.)

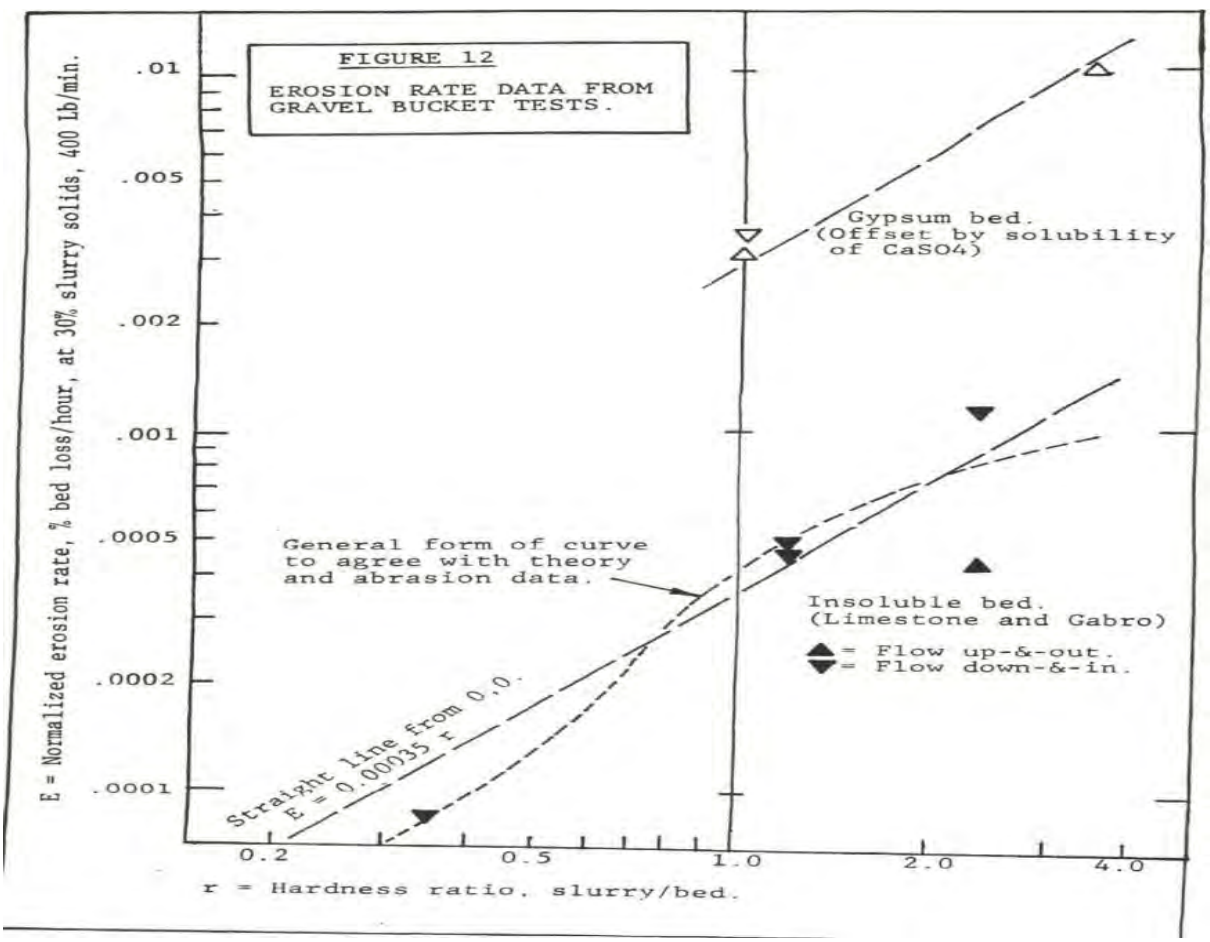
Gypsum was selected as a bed material because it is one of the basic Mohs hardness standards from Fig.6. But to complicate matters, gypsum is also somewhat soluble. This would explain the line on Fig.25 being offset above the straight line defined by the points for other bed materials. The rate of surface loss by erosion / abrasion is augmented by the loss due to solubility. But note that the slope of the gypsum line remains the same as for the other tests.

Table 2. Gravel Bucket Test Data

Run No.	1	2	3	4	5	6	7	8
Slurry Solids	Quartz	Quartz	Lignite	Lignite	Quartz	Lignite	Quartz	Lignite
Bed Mat'l.	Limestone	Gypsum	Gypsum	Gypsum	Limestone	Limestone	Gabro	Gabro
	Flow Out and Up			Flow In and Down				
Mohs Hardness								
Slurry	7	7	2	2	7	2	7	2
Bed	3	2	2	2	3	3	5.7	5.7
Ratio	2.3	3.5	1.0	1.0	2.3	1.2	1.2	0.35
Erosion Rate*	0.048%	1.03%	0.32%	0.36%	0.115%	0.047%	0.05%	0.0086%
*Approximate. Normalized to 35% solids and 400 Lb/min. Runs 2,3 and 4 adjusted for solubility.								

These were all free-flowing slurries, with noneshowing any propensity for plugging, even in the in-and-down flow diredtion. For many commercial products, highly thixotropic (shear-thinning) slurries may present such problems. For flow out-and-up, with some empty head space at the top, intermitent plugging would increase pressure drop, thus raising the bed to allow brief fluidation, releasing any plugged material.

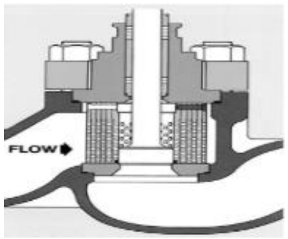
Fig. 25 Erosion Rate Data from Gravel Bucket Valve Tests[8].



Comparing the different slurry-packing combinations, an erosive quartz slurry (Mohs 7) eroded a limestone bed (Mohs 3) at a rate of 0.04 % of bed weight per hour. For extended operation, this would require complete bed replacement in about every 3 months. A much "softer" slurry of lignite (Mohs 2), which *may* be close to the outflow from a coal liquefaction process, eroded a bed of gabbro (Mohs 5,7) at only 0.007 %/hour, which would require complete bed replacement every 14,000 hours, or less than 2 years.

Visualizing the complex flow pattern of a slurry through the random labyrinthine passages of the bed of crushed rock, it is apparent that much of the microturbulence is produced as the flow crosses many sharp edges. Consider this phenomenon as was shown in Fig. 16-b above. Similarly, for the valve designs of Fig. 26, most of the erosive wear and cavitation will occur at points of high velocity in contact with constricting surfaces. Comparing these two valve designs, note that the perforated cage will distribute the same amount of high velocity contact over many more sharp edges than the simple seat of the plug valve.

Fig.26



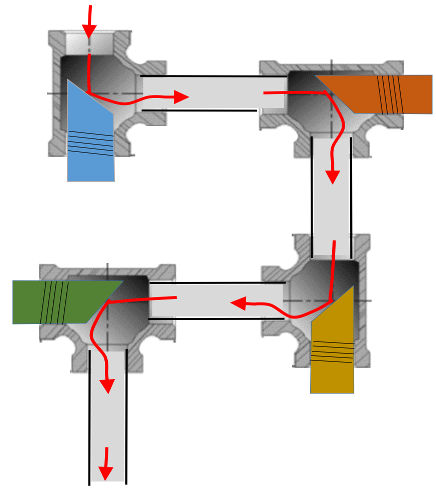
At high pressure drops, this cavitation generates a lot of noise, which is a problem with multi-micro-channel let-down devices used for high pressure gas flows. As with the gravel bucket concept above, the high turbulence contact is spread over a large area and the violence of it thereby reduced. If the sharp corners could be eliminated, this violence and thus rate of erosion could be reduced even further. Some extensive (unpublished) research back in the 1970s used devices similar to Fig.24, but packed with steel ball bearings to reduce noise levels. The experiments described above could be easily repeated with 1/4" or 5/16" steel bearing balls substituted for the crushed rock. Flow against the ball surfaces would be more uniformly streamlined, distributing wall friction or momentum transfer more evenly and reducing the rates of material loss. The '70s work found that such devices resulted in significant sound level attenuation, though no data has survived time and organizational reshuffling. It is interesting to consider that during the gradual erosion of chipped rock, in the packed bed of Fig. 24, all sharp edges would be rounded, and the particles would approach the rounded pebbles that make up the beds of swift-flowing rivers, probably with a reduction in pressure drop. Nature wins.

Referring to the incredibly high pressure of the proposed coal liquefaction plant[1] of Fig.5, assume a slurry solids hardness similar to lignite. Then assume a similar vertical flow rate per cross section as this test unit, which had an effective bed depth of about a foot. The test unit showed a 52 psi pressure drop for the Lignite-gabbro combination. Scaling up to the beyond-extreme coal liquefaction pressure of 2000 psig, an equivalent gravel bucket letdown device would have to be 38 feet tall. The cost of such a contraption, plus gabbro packing replacement, would be a trade-off against the replacement costs of expensive hard alloy valve trim for the 4 let-down valves shown in Fig.5. No data is easily available for the cost or replacement frequency of these valves, but the un-documented WWII German example in Chapter 1 suggests it may be quite excessive.

This beyond-extreme example is one approach to the idea of distributing pressure drop (momentum transfer) and thus erosion damage over a large area of cheap, sacrificial material. Another, much simpler idea would be to install a long run of much smaller diameter, thick-walled, off-the-shelf, carbon steel pipe in a process system, to take most of the pressure drop upstream from a control valve. The economic trade-of would then be replacing the reduced-diameter pipe spool, compared with expensive valve trim replacement.

Finally, another simple means of comparing materials for erosion resistance is shown in Fig. 26, that could be inserted in any process line in an operating plant handling an erosive slurry. It is made from off-the-shelf plumbing components, with threaded plugs of materials to be tested. When the process is briefly shut down, or the test piping simply bypassed, the plugs can be removed and weighed. With the Mohs or Knoop hardness of the plugs known/measured, resulting data (weight loss/time) could be a curve similar to that of Fig. 6-b, defining the hardness of the slurry. The device shown with 4 test plugs, but could be made with any number. It could also serve as a quality control tool to monitor constancy of product abrasiveness. Results would be comparable to lab tests using the Miller device, Fig.19, but more directly descriptive of operating plant performance.

Fig. 27. In-plant comparison of Erosion-Resistant materials for Slurry Service.



Summary

- Slurry erosion rates, to compare any equipment configuration or process parameter, can be greatly accelerated by use of soft (plastic or aluminum) copies of the equipment (such as control valves or pump impellers) and harder abradants for the slurry.
- Established standard testing procedures for material surface hardness are Mohs, ASTM G171-03 III and Knoop (ASTM E384) tests.
- A standard laboratory test available for compare abrasive weight loss for different surface-slurry contacts is the Miller Tester (ASTM G75-15).
- Erosion damage patterns through valves and piping is never symmetrical, but carves out random channels of least resistance.
- The “hardness” of a slurry is seldom a clear-cut number, but usually a curve, spanning an average / effective value, depending on the variety of abradants in it.
- Standard hardness tests or the Miller wet abrasion test do not take into account all the variables affecting erosive damage to actual 3-dimensional process equipment.
- Among established valve types for throttling a flow of erosive slurry, a full-bore ball, plug, pinch or knife valve offers the advantages that there is no increased turbulence against the adjacent straight pipe walls, pressure drop is minimal, and erosion of valve body reduced by lack of sharp turns in flow path.
- To change the design of a valve, to reduce cost of plug and seat elements, as they are worn out by an abrasive slurry, one can (1) use a cheaper material, as a trade-off against more frequent replacement, (2) find a harder material, if possible, at lower cost, or (3) design the valve for simpler, cheaper replaced parts and easier quick access for replacements.

~~ End of Chapter 3 ~~ End of Course ~~~

Appendix A

Minimize Valve Cavitation by Proper System Design

Provided By Onyx Valve Company (https://southwestvalve.com/cavitation/)

Textbooks address cavitation in ideal fluids. Real world process fluids are seldom ideal and valves do not always conform to textbook characteristics. This article was written to address cavitation issues related to pinch valve applications. Transposing these concepts to other valve types may be valid but might require considerable modification.

Cavitation

The formation of cavities in a flowing stream is a potential problem to hydraulic equipment designers. Symptoms include noise; it sounds like gravel flowing through the line, vibration, loss of efficiency, and physical damage. Valves subject to cavitation erode until components rupture or leak.

Most process equipment can tolerate some degree of cavitation without severely crippling system performance or creating an onerous maintenance burden. While it may be theoretically possible to design systems that completely eliminate cavitation, in many cases this is not really the optimum design.

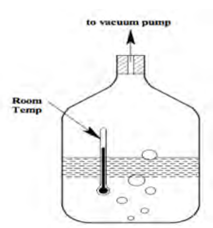
For example, if calculations indicate a throttling valve will occasionally operate in the cavitation range, the pressure drop could be dissipated across two valves in series. But if the cavitation is not too frequent or too severe, and the damage is concentrated in a short section of relatively inexpensive pipe, the capital expense entailed by the second valve may not be justified. The mathematical tools proposed herein are intended to provide some rule-of-thumb guidance to anticipate the severity and the consequences of cavitation under varying conditions.

What Causes Cavitation in Valves?

Valves have three ways to dissipate energy: 

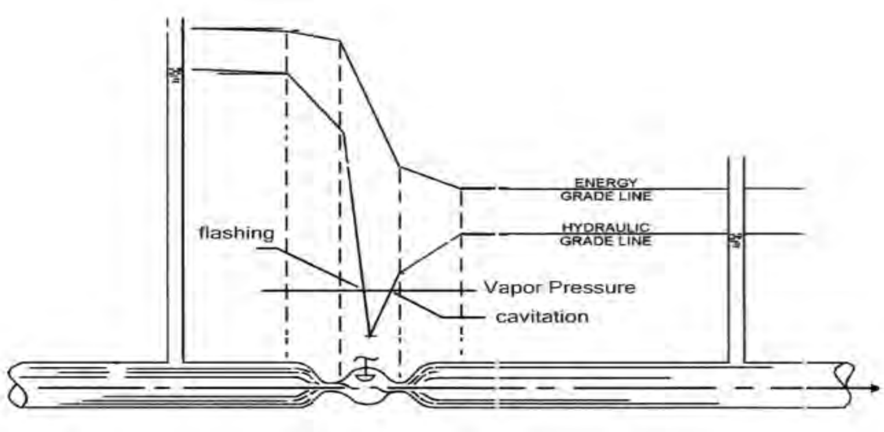
1. Turbulence: Changing direction of the fluid increases the shear rate. This extracts energy from the process liquid, converting it into non-recoverable heat and noise. The classic globe valve, due to its “tortuous path”, makes extensive use of this mechanism to reduce energy in the flow stream.

2. Energy exchange. A pump imparts energy to the flow stream. This energy has a dynamic component in the form of forward momentum and a potential component, which is pressure. After liquid leaves the pump, exchanges can occur between potential and dynamic energy but total energy cannot increase. As liquid flows through pipe it draws from this store of potential energy to overcome friction. That is why the pressure gradient through horizontal pipe slopes slightly downward. Liquid squeezing into a restriction accelerates to maintain volumetric flow. This increases kinetic energy at the expense of potential energy. Pressure falls as the liquid accelerates. These processes are considered adiabatic as there is no energy extracted during the pressure drop. The process is imperfect in that heat is generated in the fluid due to turbulence and friction that cause heat to be lost to the environment.



3. Change of state. Conditions inside piping are not subject to the limitations that we experience in the outside world. The lowest pressure that we experience in our frame of reference is atmospheric, around 14.7 psi absolute. Pressure inside pipe and valves is not subject to this limitation and can drop into the vacuum range. The boiling point, the temperature at which liquid changes to gas, is a function of pressure. As pressure falls, the boiling point is depressed. As pressure ventures into the vacuum range, the

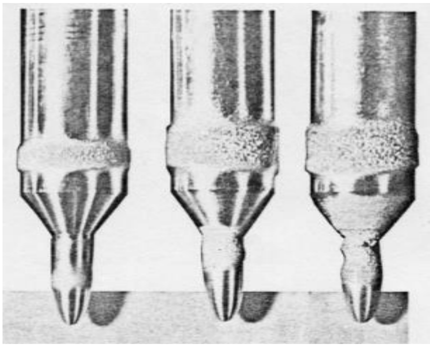
boiling point can be suppressed to a point lower than room temperature. The process of boiling extracts energy from the liquid, regardless of the temperature at which the boiling occurs.



Inside a valve, the “vena contracta” is the locus of minimum cross sectional area of the flow stream. This is where the flow stream achieves its highest velocity, so this is where pressure falls to its lowest level. If pressure at the vena contracta falls below the vapor pressure, the liquid changes state from a liquid to a gas forming pockets or cavities in the flow stream.

If the fluid pressure remains below the vapor pressure a fraction of the fluid remains in the gaseous state and a froth of liquid and bubbles continues downstream. This is flashing.

Flashing erosion creates smooth gouges with a polished appearance as seen in the picture at the left.



The process reverses itself when liquid emerges from the restriction. The fluid decelerates and pressure recovers. Pressure does not recover to its original magnitude since this process is not adiabatic. If pressure recovers beyond the vapor pressure the cavities collapse and re-liquefy. This is cavitation.

The collapse of these gas pockets is accompanied by intense micro shock waves generating localized impact pressure over 200,000 psi. Cavitation is generally more destructive than flashing. Cavitation damage produces a rough surface texture even if the process fluid is a liquid with no suspended solids.

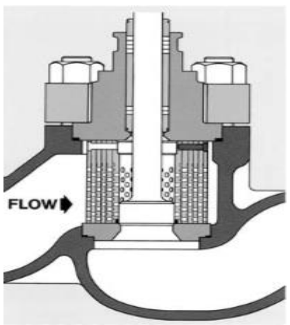
If the process fluid is abrasive you can have both abrasion and cavitation damage concurrently. It can be challenging to distinguish which demon is the larger culprit in destroying your valve.

As a general rule, abrasion damage tends to be localized in a single narrow zone right at the valve seat.

In contrast, cavitation damage frequently exhibits a sequential series of pitted areas as shown in the picture above, with observable damage occurring a considerable distance downstream of the vena contracta. Flow streams can have multiple recovery points and cavitation damage can occur in unexpected locations due to the turbulent nature of the flow stream.

How Can the Process Engineer Cope With Cavitation?

The ideal solution is to rebalance the pressure drop across the valve, preferably by increasing pressure at the valve exit. This might be possible by relocating the valve closer to the pressure source, or installing it at a lower elevation in the piping network, or reducing the pipe size between the valve and the system exit.



The process engineer often encounters a system where there is simply no practical way to diminish the overall pressure drop across the valve. In these instances the key to minimizing cavitation damage is to stretch out the pressure recovery that occurs when the liquid emerges from the valve throat.

Accelerating the fluid gradually in a series of small steps maintains sufficient pressure to avoid cavitation. One method to accomplish this is to insert a "cavitation cage" in the valve as shown in the picture at the right. This cage consists of a maze of sieves or washers that form a labyrinth of intricate passageways. Fluid passing through the valve traverses this tortuous path which staves off the sudden pressure recovery that initiates cavitation.

Unfortunately, a lot of fluids in the real world cannot tolerate these devices without clogging. The classic example is pressure letdown on tar sand slurries where a confluence of high pressure drop and a solute mix of sand and tar make cavitation cages impractical. Flow streams such as sewerage, sludge, sand slurry and mine tailings also pose significant challenges to the use of anti-cavitation cages.

Predicting cavitation

Cavitation prediction evolves directly from valve sizing. Every system engineer is familiar with the basic valve sizing equation:

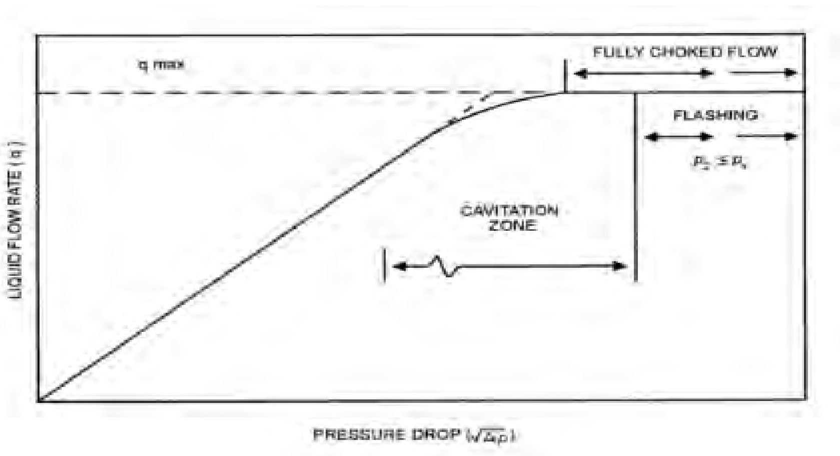
$$C_V = \frac{q}{N_1 F_p} * \sqrt{\frac{G}{P_1 - P_2}}$$

Where:

Cv = Valve Capacity
Fp = Piping geometry factor
G = Specific Gravity
N1 = Numerical constant for units of measure

P1 = Pressure at valve inlet
P2 = Pressure at valve exit
q = Volumetric flow rate

Valve sizing is simple. Plug numbers into equation 1, turn the crank, and calculate Cv. Then peruse catalogues and pick a valve with a published Cv greater than calculated Cv.



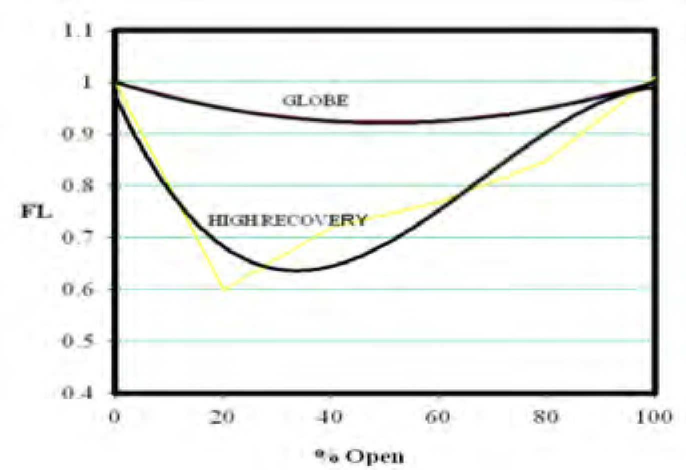
As long as the process does not cavitate, increasing ΔP increases flow in a linear fashion as seen in the graph, so equation #1 works fine.

But if you continue to increase the pressure drop by lowering P2, eventually the pressure drop reaches the point of incipient cavitation where bubbles start to form in the flow stream. These bubbles crowd the vena contracta obstructing the flow path. At a point called ΔPs (max delta-P allowable) these bubbles obstruct the flow path to the point where further increases in pressure drop no longer increase the flow through the valve.

At this point, ∆P=∆Ps where the valve is in chocked flow. Further increases in the pressure drop only result in more cavitation.

To find points of incipient cavitation and choked flow, the designer returns to the valve catalogue. Associated with every valve is a second constant, “FL”. This recovery constant represents the valve’s ability to resist cavitation. Higher FL values indicate greater resistance to cavitation.

Although FL is frequently referred to as the recovery ‘constant’, in reality it is really a variable function of valve opening. In torturous path valves like the globe type the variation is slight, so FL may be listed as a constant without adverse effect; no reference is made to the fact that it varies with stem position.



High recovery valves such as ball, butterfly, and pinch types may show FL in graphical format or a table, or they may simply publish a ‘worst-case’ minimum value to simplify calculations and incorporate a safety factor.

The current trend is towards valves with a ‘straight through’ design such as ball, butterfly, diaphragm, and pinch types. These valves are less expensive than the classic globe valve and they function well on slurries and suspensions.

The bad news is that straight through designs are more prone to cavitation, which is reflected in their lower FL numbers.

Equation # 2 determines if cavitation is present:

$$\Delta P_S = F_L^2 * [(P1 + atm) - R_{critivcal} * P_{vapor}]$$

∆Ps = Delta-P max allowable
FL = Recovery coefficient
P1 = Inlet pressure to valve
Atm = atmospheric pressure = 14.7 psi
Rcrit = Critical pressure ratio= 0.93 (typical)
Pvap = Vapor pressure

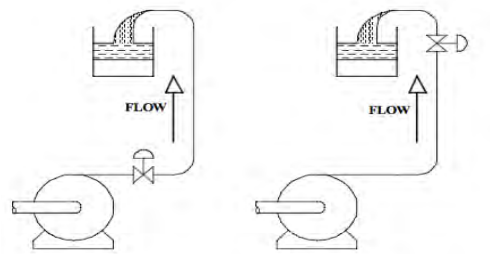
Quite simply, if AP ≥ APS then your process is in choked flow cavitation.

$$\begin{aligned} &If\ \Delta P > \Delta P_S \\ &Then: \\ &C_V = Q * \sqrt{\frac{G}{\Delta P_S}} \end{aligned}$$

Then : That's why ∆Ps is the ceiling value for AP in equation 1.If: ∆P in equation 1 is higher than ∆Ps,
Then: go back to equation 1 throw out the original ∆P, substitute ∆Ps, recalculate Cv and, if necessary, select a larger valve

Metal valves and rubber-lined valves respond differently to cavitation. Metal valves begin deteriorating between incipient cavitation and choked flow. Metal components with higher elastic stress limits tolerate cavitation better than softer metals.

Ironically, rubber fares better than metal under cavitation conditions. Rubber absorbs much of the shock of the imploding bubbles.



Good design. Higher inlet and backpressure reduces cavitation.

Less desirable. Lower pressures trigger cavitation.

Figure 8

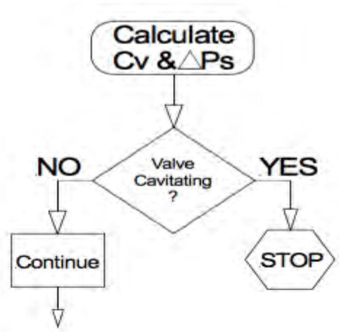
Equation #2 yields insight into ways to reduce or eliminate cavitation. The objective is to maximize ∆Ps.

One way to manipulate ∆Ps is to reduce the fluid temperature, which reduces PV and elevates ∆Ps

Another possible manipulation is to increase P1. Installing the valve at the lowest possible elevation, as close to the pressure source as practical, increases P1, which elevates ∆Ps.

If all else fails, split the pressure drop in half, installing two valves in series, each taking half the drop.

<u>Reality Check</u>



Cavitation problems trap engineers in an infinite loop. Textbooks warn of danger but seldom propose practical solutions. Process engineers solve equations; discover potential cavitation and stop, wondering what to do next.

The situation is not as hopeless as it might appear.

The first step towards a resolution is to recognize that there are different degrees of cavitation. The second point is to remember that valves work under cavitation conditions; they just don't work as long as you'd like.

How much cavitation is too much?

Because of their ability to absorb the localized shock waves generated by the cavitation process, rubber lined pinch valves tolerate fairly high levels of cavitation; much higher than metal valves. These limits can be analyzed using basic thermodynamic tools.

These mathematic tools – while not perfect – are more reliable than empirical methods like trying to estimate valve wear based on sound level. There is a disconnect between sound levels and cavitation damage. As soon as the cavitation process is initiated, the characteristic "rumble" can be heard emanating from the valve. (It sounds like gravel is going through the valve.)

However, as cavitation intensifies the sound level remains flat. Also, sound levels are unduly influenced by valve size. There is no auditory change as you cross from acceptable cavitation levels to more destructive cavitation levels. Furthermore, attempt to link the equations used to predict sound levels, to cavitation damage have been fruitless to date.

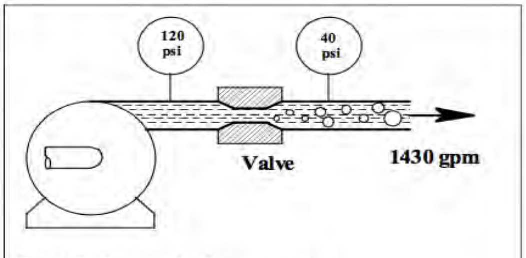


Figure 9: Pump and valve arrangement

To answer this question in a rational manner, think about where the energy driving cavitation comes from: The pump. Let's use the example shown in figure 9. We will make the following assumptions regarding the pump operating conditions:

Assumptions:

- Q (flow) = 1430 gpm
- P1 (pump discharge pressure) = 120 psi
- P2 (pressure downstream of valve) = 40 psi
- ΔP across the valve = P1 – P2 = 80 psi
- ΔPs=50psi
- The motor injects 120 Brake HP into the pump.
- The pump is 83% efficient

Now we have to recall some fundamental concepts we learned in thermodynamics.

1. On the first day of Thermodynamics class the professor goes to the blackboard and draws an amorphous shape with arrows pointing in and out. It looks like a potato stuck with toothpicks. He identifies this 'shape' as an energy boundary and announces: ΣE = 0, or the sum of energy entering and leaving the system = zero, where energy going into the system is positive, and energy flowing out of the system is negative. The border surrounding the picture of our pump and valve is exactly this kind of energy boundary. Electrical energy goes in to the pump motor, and a mixture of liquid horse power, heat, and noise come out
2. Liquid flowing through a pipe contains potential energy that can be extracted to do work. This potential energy is the product of flow and pressure, or:
3. Liquid Horse Power = Flow x Pressure.
4. In US customary-pain-in-the-butt units the equation works out to:

$$HP_{Liquid} = \frac{flow\,(gpm) * pressure\,(psi)}{1714}$$

Equation 3

We can use equation 3 to calculate the power at every point in the pumping system shown in figure 9. If the pump is 83% efficient, then the liquid HP at the pump discharge is:

Liquid HP (discharge) = 120 HP (in) * 0.83 = 100 HP

Or, the pump looses 20 HP due to internal friction losses inside the casing.

We know that ΔPS across the valve = 50 psi, so we can use equation 3 to calculate exactly how much energy is being dissipated here:

$$HP_{Liquid} = \frac{flow\,(gpm) * pressure\,(psi)}{1714}$$
$$= \frac{1{,}430\ gpm * 50\ psi}{1714}$$
$$= 41.6\ HP$$

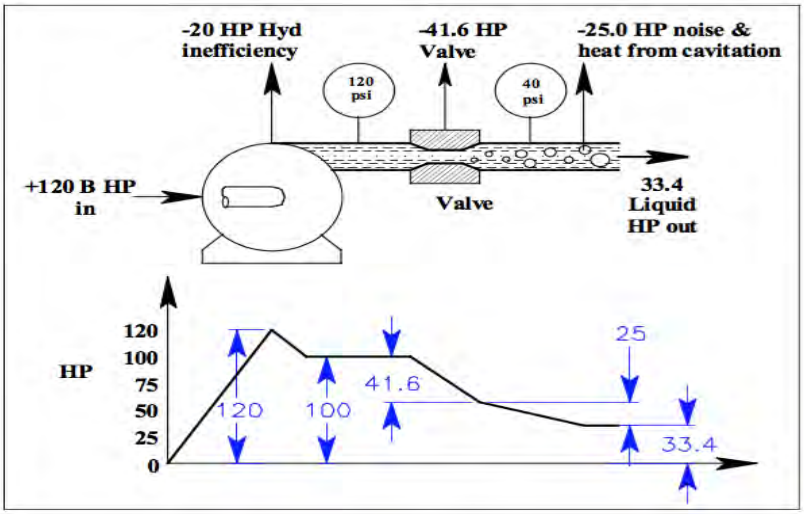
Now, here is the key concept behind our discussion: We know that ΔPS = 50 psi, and ΔP actual = 80 psi, but what does this mean in real physical terms? Between zero and 50 psi the increasing pressure drop causes increasing flow. Once this threshold is reached, further increases in pressure drop do not increase flow; the additional 30-psi of pressure is being used by the system to boil and collapse bubbles!

$$\Delta P_{cavitation} = \Delta P_{actual} - \Delta P_S$$

Since we know exactly what fraction of our pressure energy is driving the cavitation process and we know the flow rate, we can calculate the power involved in the cavitation transformation. This is important because this power is being used just to grind away the discharge of the valve.

$$HP_{Cavitation} = \frac{flow\,(gpm) * \ (\Delta P - \Delta P_S)\ psi}{1714}$$
$$= \frac{1{,}430\ gpm * (80 - 50)\ psi}{1714}$$
$$= 25.0\ HP$$

In our example, we can see that 25 HP is simply generating the destructive power of cavitation. Now we can account for all of the energy entering and leaving our system.



If we know the destructive power going into cavitation and we have some idea of the surface area inside the valve that has to absorb this, we can write an equation to distributed destructive power over surface area. We need to quantify ‘cavity impacts per square inch’.

The question arises concerning the length over which cavitation occurs. As you saw in figure 7, cavitation damage occurs in a narrow hand, forming a ‘bath tub’ ring in the exit of the valve.

The width of this hand is fairly consistent regardless of valve size, so we can distribute cavitation power over circumference of the valve, treating the width of this band as a constant. We have used this technique for several years and empirical results correlate with predictions fairly well.

(The choice of ‘G’ as the dependent variable was strictly arbitrary.) The decimal point in the denominator was shifted two places to yield more convenient units, so the final equation is:

$$G = \frac{Q, gpm * (\Delta P_{actual} - \Delta P_S)}{17.14 * d}$$

Where:

P = pressure in psi

D = pipe size in inches

In our example if the valve size is 8 inches then:

$$G = \frac{1{,}430 \ \ gpm \ * \ (80 \ \ psi \ - \ 50 \ \ psi\ )}{17.14 \ * \ 8}$$

$$= 312$$

Interpreting the Results

This "G" number provides a means of comparing different valves, or operation of the same valve in different locations. On the basis of our experience with rubber lined pinch valves, we have developed the following 'rules of thumb' for rubber valves operating beyond choked flow conditions. Higher 'G' numbers indicate faster erosion.

G	Conditions:
$0 \le G \le 100$	Cavitation damage will be undetectable
$100 \le G \le 250$	Some damage will be observable after 1 year of operation
$250 \le G \le 500$	Sleeve damage will be observable in 6 months unless you modify the piping as described in the following paragraphs.
$500 \le G \le 750$	Frequent maintenance and sleeve replacement unless you modify the piping as described in the following paragraphs.
$750 \le G$	Consult factory

Minimize Damage from Cavitation

When dealing with fluids like slurries, abrasives, or pigments that preclude conventional cavitation trim such as strainers it is possible to delay the initiation of cavitation by other means.

One method is to use an orifice plate downstream of the valve. This builds up backpressure on the valve so that AP is below the cavitation threshold. For orifice plates:

$$\Delta P = CQ^2$$

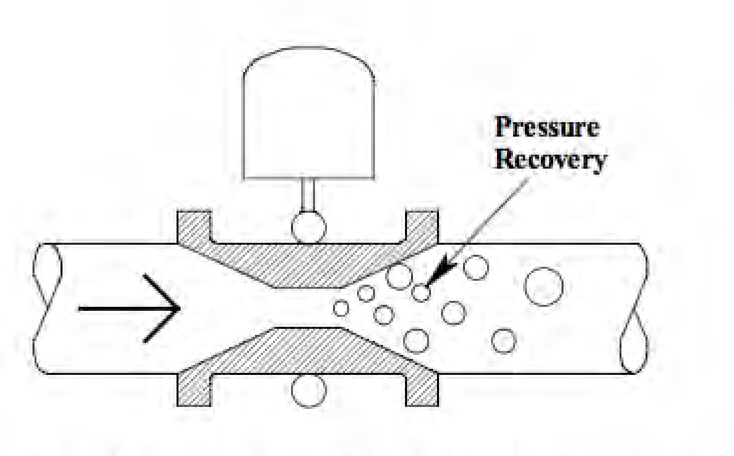
Where Q is flow and “C” is a constant associated with the orifice and depends on the shape and size of the opening in the orifice.

Dropping 250 psi of pressure on a tar sand slurry in Alberta Canada

These devices are non linear. Reducing the flow by 1/2 reduces the pressure drop to 1⁄4 of its original value. Orifice plates are useful in processes with fairly constant flow, with no more than a 2: 1 turn down.

Another alternative: Brute force!

Install two (or more) valves in series and take half the pressure drop across each valve. This is a highly effective, albeit expensive solution.

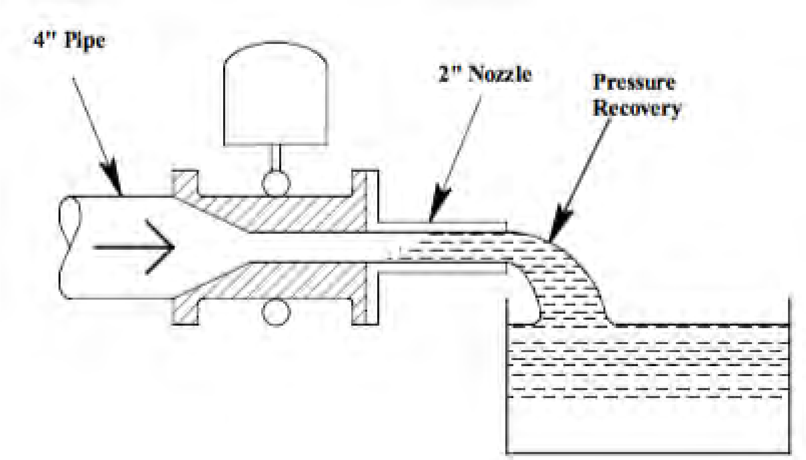


Typical modulating pinch valve with standard reduced port sleeve.

A better way to deal with severe cavitation is to export it from the piping completely. Cavitation does not start at the throat of the valve. As mentioned earlier it develops past the throat where pressure begins to recover.

As a result, cavitation damage occurs downstream of the valve throat. Cavitation damage in pinch valves destroys the sleeve between the pinch point and the valve exit. Modulating pinch valves are usually supplied with a reduced port sleeve. The sleeve is molded with a Venturri shape that tapers down to a small diameter in the center of the valve. The sleeve is normally symmetric, tapered on both inlet and outlet so the valve can be installed with flow going in either direction. This design is vulnerable to cavitation damage.

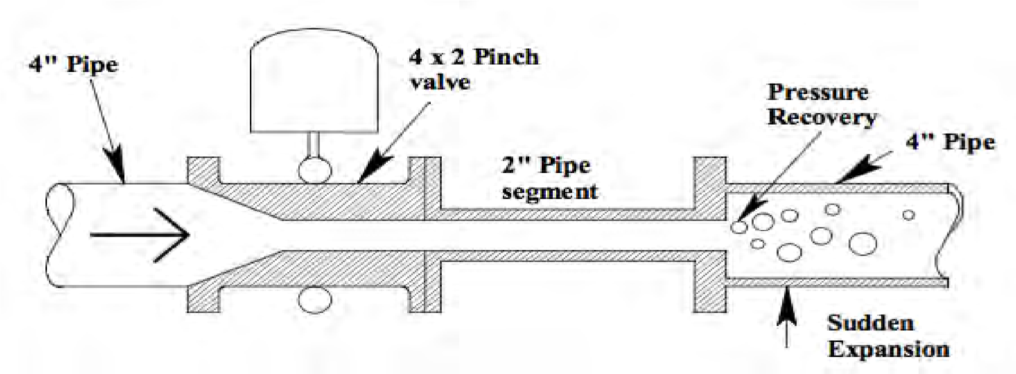
Revising the sleeve design to an asymmetric shape enables the valve to withstand high levels of cavitation. This is called a “trumpet mouth” design or a “cone sleeve”. The thicker rubber at the valve outlet absorbs the pounding from the cavities. There are several ways to exploit this feature to tolerate even higher levels of cavitation with minimum sleeve damage.



Example showing a 4" valve. Installing the valve at the end of the piping run exports cavitation from the system.

One method is to install the valve at or near the end of the piping run allowing the pressure to recover as the fluid emerges from the piping system. Here the cavities form after they have emerged from the piping system, where they cascade harmlessly into the open tank. In our example we have a 4" x 2" pinch valve installed in a 4" pipeline. Notice that we have added a short section of 2" pipe with a reducer flange at the valve exit in order to delay the pressure recovery until the end of the run.

If it is not practical to install the valve at the end of the pipe run, there is another variation to this approach that is very effective. This approach again starts with a trumpet mouth design sleeve. Our example uses a 4" x 2" valve but it works equally well with any size valve and sleeve port. This approach uses a short spool piece of pipe equal to the valve port size, 2" diameter in the example. A reducer flange is used to attach the 2" pipe to the 4" valve. The minimum spool piece length is typically 10 times nominal diameter or 20 inches. This connects to the remainder of the 4" pipe run with a second reducer flange creating a sudden expansion at the inlet to the 4" pipe. Do not use a tapered expander here; you want a sharp sudden expansion.



This design pushes the pressure recovery and its accompanying cavitation out of the valve. The obvious question is “what about the 4” pipe at the sudden expansion?” Well, yes, this is going to

take a certain amount of pounding, but first of all this can be a rubber pipe joint to absorb the noise and wear, and secondly it is easier and less expensive to replace a section of 4” hose once or twice a year than to have to service the valve.

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