Roscoe Moss Company Memo

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From: George Moss
To: RMC Technical, Marketing, and Sales personnel.

Well Screen Open Area

General Background

Continuous slot screen design originated in the early part of this century to overcome the problems of ground water development from distinctive aquifers characteristic of the north central United States. These aquifers were created from rock picked up, broken, and pulverized by advancing glaciers during the Ice Ages. Although glacial till is not well sorted, occasionally thin layers of fine-grained, uniform sands were washed from the original deposits. Such materials can be high yielding aquifers.

Prior to the advent of rotary well construction and the gravel envelope well design, it was difficult to produce the full capacity of sand free water from these aquifers. A well design, incorporating wire wrap screen, was successfully developed to meet these conditions. The characteristics of' the wire wrap screen are well suited for its original purpose.

The wire wrap screen design differs in many important respects from other types of water well screens. Wire wrap screen manufacturers particularly Johnson Filtration Corporation (Johnson) have for many years asserted a critical importance to wire wrap screen's distinguishing characteristic, high area of opening, using fallacious arguments and statements. This effort resulted in its unnecessary use in well designs other than that for which it was originally intended. This is especially true in the case of gravel envelope wells. Wire wrap screen has no inherent advantages over some other types of screen and some disadvantages.

The following is a discussion of the arguments Johnson has used in their three major publications since 1947 to advance the notion that higher area of opening provides advantages in all water wells. While these arguments and statements are unsupported on a scientific basis their constant repetition has earned them some acceptance in the industry. Regrettably this has resulted in well construction failures, premature well loss, and unnecessary extra cost. In this memorandum these arguments are analyzed scientifically and investigated to determine their real basis if any. The reader will be informed regarding the use of the entrance velocity criteria and its application to water well design.

Ground Water - It's Development, Use and Conservation

Author: E. W. Bennison, Editor, Johnson National Drillers Journal, First Edition, 1947.
Published by: Edward E. Johnson, Inc.

Entrance Velocity As Related To Head Loss

Bennison states:

> *"Our opinion is that sufficient open area should be provided to keep the entrance velocity down to 0.10 to 0.25 feet per/second. A conservative figure would be 0. 10 foot per second after allowance was made for the portion of the open area that would be blocked off by formation particles."*

Apparently this *"opinion"* was not based on any experimental or theoretical work, He cites no references.

Bennison also points out the velocity of flow through well screen is inversely proportional to the well diameter.

> *"In other words, doubling the diameter reduces velocity one-half and friction loss to one-quarter."*

Restated this means friction loss through screens is proportional to the square of the velocity. This is largely true if the flow is turbulent which it will not be with velocities below 2-4 ft/second. Even with turbulent flow the exponent of velocity may not be exactly two.

In a related theory Bennison asserts in cases where,

> *"... The openings are small and their total open area is only a small portion of the screen surface area, then the open area in the screen is less than the open area in the voids of the formation furnishing the water and pressure is required to force water through the formation and screen openings."*

Pressure is always required to force water through the formation and screen openings and the amount of drawdown per quantity produced is a function of aquifer hydraulic conductivity and transmissivity, not porosity. Possibly Bennison means effective porosity. Ground water moves to a well in a streamline (laminar flow) with each individual particle overcoming frictional resistance under a gentle but persistent hydraulic gradient. Approaching the well screen the flow accelerates. In the near well zone and through the well screen turbulent losses may occur but velocities have to exceed 2 to 4 ft/second entering the opening for significant screen losses.

Bennison continues with the statement

> *"...as the sand carrying capacity of water depends entirely on velocity, and once entrance velocity has been reduced sufficiently to prevent sand-carrying further reductions are not necessary. This explains why it is not necessary to make gravel packs more than one foot in thickness".*

This is of course fallacious since in a gravel envelope well the filtering takes place at the interface between the formation and filter pack. Even in most naturally developed wells sand production depends on factors more important than velocity and many high-capacity wells with in place low area of opening perforations have been successfully developed.

Entrance Velocity As Related To Corrosion

Bennison in his chapter, *Design, Construction, and Use of Well Screens*, he discusses corrosion and encrustation. He develops a theory whereby much encrustation of well screens occurs as a result of reduction of pressure in the water in the formation in the well while pumping. According to Bennison,

> *"Because the pressure head is reduced carbon dioxide gas in the water is released, and the water is unable to carry or rather hold in solution its load of mineral salts. Consequently these mineral salts are precipitated or dropped from the water and deposited where the reduction of pressure has been the greatest. This is in and around the lower end of the well or the well screen."*

He argues that a method of mitigating such encrustation would be to use the screen that will permit water to enter the well with the least resistance at the screen openings. In other words, a high area of opening continuous slot screen. Bennison's theory regarding carbon dioxide is totally incorrect as discussed in the publication *Fundamentals of Metallic Corrosion in Fresh Water*, by J.R. Rossum. No other scientist or engineer has made this claim. If water is originally super saturated with a gas at a given pressure (atmospheric pressure in the case of ground water) it would fizz like soda water when exposed to air. It is frequently true that encrustation occurs near the lower end of the well or the well screen, but this is because water velocity is lower at these points. In pipelines, corrosion is usually least at normal velocities (one to five ft/second).

Bennison also states,

> *"...the rate of corrosion tends to increase with an increase in velocity of the water over the surface of the metal being corroded."*

While the word "tends" is ambiguous, it can be emphatically stated that his statement is incorrect, as also explained in the publication authored by Rossum and many other publications. It is true that many tests have shown that corrosion rates increase with velocity where the environment is very corrosive, for example, iron in dilute sulfuric acid. Under moderately corrosive conditions, velocity may have the reverse effect. Water system operators have known for years that reasonable velocities were essential in mitigating corrosion. Where velocity is low, particularly in dead ends, corrosion is severe. Merril & Sanks (AWWA Handbook on Corrosion Control) state that one of the attributes of a well conditioned water is a velocity of at least 2 ft/sec.

Romeo, Skrinde & Elliassen (ASCE SAN Div., July 1958), in their study on the *Effects of the Mechanics of Flow on Corrosion*, found that corrosion follows an exponential curve and that the corrosion rates for the first two months were greater at velocities of 1 ft/sec. and 2 ft/sec. than the corrosion rate at 0.125 ft/sec. When their curves are extended to long times, it is found that corrosion rates decrease as velocity increases over the range of their investigation of from .125 ft/sec. to 4 ft/sec. Thus the results of the investigation are in accord with general water works experience.

In the Illinois State Water Survey Bulletin No. 59 *Corrosion by Domestic Waters* by T. E. Larson, it is shown that initial corrosion rates are lower at 0.05 ft/second than at 0.34 ft/sec. But after 100 days the effect is reversed in conformance with the results of Romeo et al.

The reasons for these results are easily understood. As the velocity increases the thickness of the laminar layer next to the metal decreases so that oxygen can diffuse to the metal surface more readily. However, high flow rates produce hard durable coatings (McCauly and Abdulah - JAWWA, Vol. 50, page 11419, Nov. 1958) so that after the coatings have formed, corrosion rate decreases at higher velocities.

Bennison's 1966 Book offered much valuable information to the industry. However, as an employee of the Johnson Screen Company, his expositions regarding the advantages of high area of opening continues wire wrap screen were fallacious and self serving. Unfortunately these statements have been repeated through the decades, and their acceptance has frequently led to unnecessary costs and poor results.

Ground Water and Wells

Author: E. E. Johnson Company, 1966
Publisher: Johnson Division UOP, St. Paul, Minnesota

Entrance Velocity As Related To Head Loss

In this publication the statements of Bennison are expanded. The authors state,

> *"Any quantity of water flows more freely through a screen with large open or intake area than through one with limited open area. The entrance velocity through the larger intake area is low, and this means that the head loss for the screen itself is minimum. This, in turn, minimizes drawdown in the well at a given rate of pumping."*

This statement is replete with terms such as *"more freely" "limited open area"*, *"low"* and *"minimum"* These are comparative terms without real meaning and no basis or authority is given.

Later it is stated,

> *"Laboratory tests and field experience show that if the screen entrance velocity is equal to or less than 0.1 foot/second the following will result: Friction losses in the screen openings will be negligible. Rate of encrustation will be a minimum. Rate of corrosion will be a minimum."*

We would agree that friction losses in the screen openings will be negligible, but they would also be negligible at an entrance 91 velocity of 2 ft/second. The statement that laboratory tests and field experience demonstrate their argument is absolutely incorrect. No tests were cited. On pages 155 and 156 of this publication reference is made to a laboratory test that reveals that no advantage accrues when screen open area exceeds fifteen to twenty percent. This apparently refers to the work done by G.L. Corey, *Hydraulic Properties of Well Screens*, a master of science thesis published in 1949. The authors castigate the methodology of the test without revealing any other tests substantiating their statements. They also state,

> *"In field practice, experience has shown that the 15 to 20 percent open area limit, which is claimed to be demonstrated by these laboratory tests, is often a false guide in screen selection."*

In reality, field practice Las shown that screens or down--hole perforated casings with open areas as low as 2 percent have demonstrated very high well efficiencies comparable to those of higher area of opening screen wells.

Laboratory tests have been conducted on well screens. A summary of the results of these tests follows this discussion.

Bennison's earlier comment is restated in this publication.

> *"The desirable open area in a well screen is that which is at least equal to the percentage of voids or porosity of the water-bearing sand, or the gravel pack supported by the screen. Simple logic gives us this rule. Suppose that the sand has 30 percent voids or porosity, and the well screen installed in the sand has 10 percent open area. The difference represents a constriction offlow as the water enters the well. This means more draw down because additional head loss occurs in the movement of water through the screen openings."*

This statement is as fallacious as Bennison's original. Note that irrelevant and non-quantitative terms are used.

Entrance Velocity As Related To Sand Production

Unlike Bennison's book, Johnson does not argue that sand production is a function of flow velocities in gravel envelope wells. In fact it is stated that

> *"...a pack thickness of only two or three grain diameters is all that is actually needed to retain the control of formation sand"*

This is correct with a properly selected gravel or filter pack.

Entrance Velocity As Related To Corrosion

Johnson again argues that higher water velocity accelerates corrosion by sweeping away protective films that may otherwise form on the metal surface with,

> *"Movement over the metal surfaces in a well screen supplies the corrosive at a greater rate than if the water were quiet"*, and that *"But the general rule is that corrosion increases with the velocity."*

Nothing is said about the movement of water upward inside the well screen which is a function of the quantity pumped and the inside diameter of the screen and ranges from_____ to____ ft/second. Johnson's "general rule" does not apply to the real world as explained earlier. Johnson again cites "experience" as showing that low entrance velocity through well screen openings tends to reduce corrosive attack on the screen. Experience demonstrates no such thing.

Entrance Velocity As Related To Encrustation

Once again Bennison's earlier argument concerning carbon dioxide in solution is offered to the reader. They go a bit further with the following

> *"...so that the water, with its dissolved mineral salts, is in complete equilibrium with its environment. It is holding in solution exactly the quantity of one or more minerals that the conditions will permit. Any upset in the conditions throws the solution system out of equilibrium and the precipitation of insoluble materials results.*
>
> *Just as the change in pressure can result in the precipitation of calcium carbonate, so a change in velocity could conceivably be enough to provide the necessary upset and result in the formation of insoluble iron and manganese hydroxides."*

These remarks are not affirmative statements but simply suggestive, but even the inferences are wrong.

Ground Water and Wells

Second Edition
Author: Fletcher G. Driscoll
Published by: Johnson Division, St. Paul, Minnesota

The second edition of Ground Water and Wells is a lengthier version of the first edition. It is a useful book to those in the ground water development industry containing a great deal of general information. Nevertheless the old arguments concerning entrance velocity are rehashed.

Entrance Velocity As Related To Head Loss

Driscoll repeats the argument that desirable percentage of open area in a well screen should at least equal the porosity of the water-bearing sand or filter pack. Again, porosity is confused with effective porosity and hydraulic conductivity. They restate

> *"Field experience and laboratory tests show that the average entrance velocity of water moving into the screen should not exceed 0.1 ft/second (0.03 m/second). At this velocity, the friction losses in the screen openings will be negligible and the rates of encrustation and corrosion will be minimal".*

Again we agree that friction losses through the screen will be negligible and they will also be negligible for much higher values.

In the chapter on water well design the reader is referred to appendix 13.1 entitled, *Discussion of appropriate Screen Entrance Velocities*. Unlike Johnson's earlier publications, references are given in this appendix. However none of them consider any laboratory testing, surprising in view of Driscoll's earlier comment. The first reference is C.F. Tolman in his 1937 publication, *Ground Water*, referring to entrance velocities of 0.1 to 0.2 ft/second in discussing the entrainment of sand into a screen. Tolman's work while a milestone in the science of ground water development contains errors. The movement of sand through perforations in a naturally developed well depends on many factors other than entrance velocity. In a gravel envelope well, velocity will not be an influence with a correctly selected filter pack. The second reference is T. P. Ahrens (1957) who is quoted

> *"Selection of screen length and diameter is based on average entrance velocities between 0.1 and 0.25 ft/second"*

This is clearly derived from Bennison's original statement.

Robert C. Smith (American Water Works Association, 1963) refers to experience of drillers completing wells in silty formations and that the safe entrance velocity would be about 0.06 ft/second. Our earlier comment about transport of sands by water through filter packs applies. In the next reference, *Water Well Construction Practices* (1975c), Driscoll claims the Unites States EPA recommends entrance velocities from 0.03 to 0.1 ft/second based upon the hydraulic conductivity of the aquifer. Examination of this source reveals that this statement was supported by two references. One is Water Well Technology (see below) and the other *Bulletin 49* from the Illinois State water survey. The Illinois State water survey reference incorporates work done by Walton, 1962. This has to do with migration of fine materials toward the well and clogging of the openings. It is applied only to naturally developed wells. There is no mention of friction losses or corrosion and encrustation.

The next reference is Hunter Blair (1970). Blair's paper is entitled *Well Screens and Gravel Packs*. In the abstract he states

> *"The use of correctly designed equipment is important and this paper represents a review of the diverse types available, but does not set out to make any recommendations,"* and also, *"It is evident from the variety of claims made for well screens and gravel packs that further research is necessary. It is suggested that the following points need further investigation:*
>
> - *Improved design of non-blocking opening.*
> - *Design consideration of screen resistance to chemical attack.*
> - *Best type of gravel and optimum thickness of the pack.*
> - *Head Loss Through The Screen And Pack."*

As the author acknowledges his paper is a compilation of material from other sources. There is no original research involved. He does include high area of opening and low entrance velocity in the overall screen selection criteria.

With respect to corrosion Blair does not refer to entrance velocity. With respect to encrustation he suggests that blockage of screens is more likely formed as a result of chemical interactions rather than from a pressure drop across the openings. The work of Smith (1963) is mentioned with reference to the movement of sand into the well. Regarding frictional losses the work of Peterson et al., (1955) is discussed. They state that for minimum screen losses CL/D should be greater then six where C = 11.31 CcAp a dimensionless relationship, L = screen length and D = screen diameter. As Mazir and Ahmad pointed out in a discussion of the Peterson et Al., papers in almost all practical cases the value of CL/D will be greater than 6.

Three other references are given. One of them, the *American Water Works Association (Manual M21 (1973)* which contains much information contributed by Johnson is cited) has changed their recommended entrance velocity to a range of 0.1 to 1.5 ft/second as shown in AWWA A 100-84. In this specification they offer this special notice.

> *"Experience, practice, and physical conditions of various aquifers vary between well sites and geographic regions. Committee deliberations during preparation of this standard revealed that many designers have, for various technical reasons, limited well screen entrance velocities so that they do not exceed 0. 1 fps. Others have used and demonstrated successful well designs and installations with velocities exceeding 0.1 fps, in some cases up to 2.5fps.*
>
> *The upper limit of entrance velocity of 1.5 fps included in this standard is a compromise upper limit for entrance velocity based on the judgement and consensus of the committee. The user of this standard is cautioned to thoroughly examine the issue of well-screen entrance velocity and to establish upper limits of entrance velocity if aquifer conditions and experience so dictate (Sec. 5.2)."*

This change was made in 1984 and the Driscoll book was published in 1985.

An important reference is Water Well Technology written by Campbell and Lehr. Driscoll states Campbell and Lehr indicate that

> *"Desirable entrance velocity is usually considered to be 0.1 to 0. 2.5 ft/second based on the open area of the screen"*

Once again we have Bennison's much earlier number. *Water Well Technology* is a compendium and represents many sources and authors. It is interesting to review the context in which the citation appears. It appears immediately preceding two paragraphs which were extracted from *Ground Water and Wells*. In other words Driscoll is using Johnson as a reference through Campbell and Lehr. On the page preceding appears a statement by Rorabaugh that

> *"...head loss through a screen is only a small percentage of the total loss, most of which occurs within the aquifer."*

This comment was not referenced by Driscoll. Also in *Water Well Technology* is Walton's work for the Illinois State Water survey.

The final reference, Mabillot (1979) is quoted, *"Numerous observations indicate the best value of the entrance velocity through the well screen is (3 cm/second) 0 12 ft/second At this velocity the head loss for the flow of water through the openings is negligible."*

This is a repetition of Johnson's published statements. Of course the head loss is negligible at this level. The *"numerous observations"* seem to equate with *"laboratory tests and field experience"* and they are not explained further.

Following this last reference it is stated

"The collective experience of the Johnson division's worldwide technical staff suggests that the authorities cited above are correct in recommending low screen entrance velocities."

That is no surprise.

Convergence Losses

A novel statement concerning convergence losses appears in this edition. It asserts,

"Poor distribution of screen openings cause excessive convergence of flow near the individual openings and may produce twice as much draw down as necessary."

No basis for this is given and the argument is easily refuted.

Boulton showed that for long vertical slots spaced equally around the circumference of the well, the convergence head loss is closely given by

hl = (52 8Q/NLK)log(2/(l - cos a 3.14))

where:

hL = head loss due to convergence (ft),
Q = discharge rate [gpm],
N = number of vertical slots around the circumference of the screen.
L = Length of screen [ft],
A = slot/width ratio (width of slot divided by distance between centers)

Under any practical circumstances convergence losses are insignificant for this type of screen and are even less for most other types.

Most of Appendix 13I is devoted to the relationship between entrance velocity and corrosion. The majority of this is an expansive presentation on the theory of corrosion, but part on a corrosion study undertaken by Johnson. According to them this study shows

"For low carbon steel screens the corrosion rate increases linearly as velocity increases. At a velocity of 2.5 ft/second the corrosion rate is nearly five times the rate at 0.1 .f/lsecond. Thus for low carbon steel screens the data indicate that entrance velocities should be kept at about 0.1 ft/second to minimize corrosion. Higher velocities enhance the corrosion rates significantly."

Other tests were conducted on stainless steel.

We have two comments to make. First, while this work represented research on the part of Johnson this is one time they should have looked at field experience first. In the real world corrosion on well casing, screens, pipe lines, tanks, etc., does not increase linearly as velocity increases. The second comment is that according to Johnson's own test the corrosion rate of low carbon steel was virtually nil even at much higher entrance velocities than 0.1 ft/second. At 0.1 ft/second the corrosion rate is only .0005 inch/year and at 2.5 ft/second is about .0025 inch/year. If this were the case we would never have to use stainless steel. Their data is worthless for all practical purposes and confirms the well-known difficulty of practical laboratory corrosion testing. Never at a loss for ambiguity Johnson handles this with the following curious sentence.

> *"Because water chemistry varies greatly, the actual corrosion rates determined in the tests are less important than the general trends noted between velocity and corrosion."*

Nothing more needs to be said.

Entrance Velocity As Related To Encrustation

Johnson repeats their statement that at an entrance velocity of 0.1 ft/second encrustation and corrosion will be minimal. Their ridiculous theory concerning the precipitation of carbon dioxide due to pressure differences induced when pumping a well is downplayed and covered in a section in their chapter <u>*Ground Water Chemistry*</u>. They state

> *"However, the pressure near a well is usually reduced by pumping and the carbon dioxide then comes out of solution as bubbles qf gas. When chemical equilibrium is disturbed, calcium carbonate may precipitate until the solution is again in equilibrium. These chemical adjustments take place each time a well is pumped in areas where carbon dioxide occurs in waters high in calcium carbonate.*
>
> *To minimize deposition of calcium carbonate when a well is pumped, head losses (pressure reduction) must be kept as low as possible. Low entrance velocity through well screen openings help greatly. Minimal entrance velocity is obtained by using well screens that provide maximum inlet area."*

Johnson's earlier statements in this regard have been modified somewhat. We now see *"<u>When</u> chemical equilibrium is disturbed, calcium carbonate <u>may</u> precipitate."* Their theory is fallacious as explained earlier, but by careful use of words the appearance of making a statement is preserved.

Searching for a new justification to bolster the low entrance velocity virtue, Johnson earlier discusses reduction of water pressure in a well due to increased near well velocities, according to the Bernoulli equation. This in turn leads to the release of carbon dioxide gas. The claim that a higher velocity will create a Bernoulli pressure drop sufficient to release carbon dioxide gas is absurd. Any Bernoulli equation induced pressure drop is insignificant with the velocities of water approaching water wells in all practical cases.

Encrustation is also mentioned in appendix 13I. It is stated that

"...Johnson Division initiated research programs to test the effect of entrance velocity on both corrosion and incrustation rates of well screens. The incrustation study is in progress as this book goes to press."

To date (1992) we have no knowledge of this study or its results.

Open Area As Related To Development

It is noted that in this edition continued emphasis is made to water jetting as a superior method of development. It is safe to use in continuous wire wrap screens which could be damaged by more effective methods of development such as swabbing.

Driscoll states

> *"All development methods work best in wells equipped with screens having both maximum open area... "* and *"Screens with high open area can be developed more effectively because more of' the development energy can reach the formation."*

There is no scientific foundation for these statements. The publication *Mathematical Analysis of Preliminary Development Methods for Gravel Envelope Wells* by E.John List, PhD., deals in a scientific way with various methods of well development.

The Bureau of Reclamation, United States Department of the Interior conducted a number of tests with their aquifer/well model on the efficacy of jetting as a development tool. The results were published in a report *Gravel Pack Thickness for Ground-Water Wells Report No. 1, June 1986*. Their tests revealed several limitations and potential problems with this method. The argument that screens with high open area can be developed more effectively is clearly refuted. In fact the physical effects of the jet energy on a gravel envelope and aquifer are entirely different than the Johnson conception as confirmed by both the List and Bureau of Reclamation Tests.

Laboratory Tests On Flow Through Well Screens

The relationship between well yield and transmitting capacity through well screens has been studied since the early 1900's. These studies include both theoretical and experimental aspects. The following represents a summary of those experiments which explore the aspect of head losses.

Corey, G. L. *Hydraulic Properties of Well Screens*; Master of Science Thesis, Colorado Agriculture and Mechanical College, Fort Collins, Colorado, 1949.

Corey built an experimental tank consisting of a 2 ft section of well screen surrounded by a 2-1/2 ft gravel envelope encased in a 6 ft diameter tank. The well screen was 12" in diameter. Corey made a significant contribution with his statement that above a certain perforated open area (approximately 15%) head losses through well screen are minimal for constant discharge.

Peterson, J. S., Rohwer, C., Albertson, M.L. *Effect of Well Screens on Flow into Wells:* Transactions, American Society of Civil Engineers; Paper 2755, Volume 120, 1955.

The authors developed theoretical relationships based on continuity, momentum, and energy equations. Assuming that viscous forces are much smaller than inertial forces, the Reynolds number is not significant. They also assume that drag in the well screen is almost entirely the result of the influence of the jets of water issuing from the screen openings, and that the roughness coefficient of screen itself can be neglected. Based on these assumptions, they proceed to derive their basic relationship involving the loss coefficient, which is defined as the head loss across the screen:

$$(Ahpz)/(Q^2/A^2 g) = (COSH(CL/D) + 1)/(COSH(CL/D)-1)$$

where: $(Ahpz)/(Q^2/A^2 g)$ = loss coefficient
hpz = difference in piezometric head between the inside and outside of the screen.
C = 11.31 Ap Cs
Ap = Percent open area of screen
A = Cross sectional area of screen
Cs = Screen coefficient
L = Length of screen
D = Diameter of screen

The screen coefficient Cs is obtained from the plot of CL/D versus the loss coefficient. This plot also shows that for CL/D values greater than 6, the loss coefficient asymptotically approaches a minimum value of 2. The reason for this is obvious. When CL/D increases, the value of +1 compared to the value of the hyperbolic cosine term becomes insignificant.

Their test apparatus consisted of a circular tank 6 ft high and 7.5 ft in diameter. The 12" well screen was surrounded by a 2.5 ft gravel pack. The remaining area was surrounded by water. Discharge through their model ranged from 56 gallons per minute to almost 900 gallons per minute.

Their main conclusions are summarized as follows:

1. CL/D must be greater than 6 for minimum well screen loss.
2. If CL/D>6, loss through the well screen is independent of gravel size, and therefore the pack can be selected on the basis of sand control.
3. When CL/D>6, actual head loss for a given discharge depends only on the diameter of the screen. An increase in the diameter may reduce the value of CL/D below 6 and in this case the loss will no longer be a minimum. When this occurs, CL/D can be increased by using a longer screen.
4. The greater part of the flow in a well takes place over the length of screen, measured from the discharging end of the well, that is required to obtain a value of CL/D = 6. The quality of this section of screen is therefore of greater importance than that of the remainder of the screen.

This ASCE paper included a review by several noted ground water scientists. Nazir and Ahmad as noted earlier stated that in all practical cases the factor (CL/D) will always be greater than 6 and the loss will be minimum regardless of the water pumped out. Rorabaugh commented that *"the data demonstrates that losses in most commercial screens are small... "* Other comments were that the authors results are a function of the geometry of their particular model and the material used in the testing. Also the authors ignore the effect of the convergence of flow lines in associating increasing head loss due to partial penetration effects. Field studies which would have been helpful in evaluating their work were never conducted.

Williams, D. E., *The Well/Aquifer Model Initial Test Results;* Roscoe Moss Company, 1981.

Williams' study represents the most extensive experimental work on flows through well screens. A wedge-shaped model five feet high and twelve feet long was built which represents a typical section of an aquifer having pure radial flow into a well. The sides of the prism represent those of an equilateral triangle with the internal angles being 60 degrees or $1/6^{th}$ the circumference of a well. With a 10" diameter scrteen and a stand pipe providing 60 feet of head (or draw down) on the aquifer, a maximum amount of flow of 300 gallons per minute was obtained using typical aquifer materials. This flow is equivalent to 1800 gallons per minute for a similar well in the field representing a five foot section of the same aquifer materials. Forty-four 1/4" piezometer tubes were placed in the aquifer and gravel pack in four horizontal planes arranged logarithmetically from the well bore. A 45th piezometer was located in the well. A particle counter measured sand production, and pressure readings were taken under control of a computer.

Six different well screens were chosen for testing. Their parentage open area ranged from 1.74% to 34%. A number of conclusions were reached during tests conducted with this model.

Among them are:

1. In a properly designed and developed gravel envelope well entrance velocity is not a factor in controlling production of sand. Velocities of about 9 ft/sec were achieved in model tests with sand concentrations of less than one ppm.
2. Frictional head loss across the screen varies with the square of the entrance velocity in accordance with $K = v^2/2g$. Accordingly with screen open area percentages above 3% to 5%, and entrance velocities less than 2.5 ft/sec, screen losses were minimal.
3. Above a minimum percentage of screen open area (3% to 5%), and entrance velocities less than 2.5 ft/sec, well efficiency approaches a maximum and no significant increase in efficiency is achieved with an increase in percentage of open area.

Jackson, P. A., Bikis, E. A., and Ahmad, M. U. *Laboratory and Field.Studies of Well Design and Efficiency*

This laboratory study was to examine:

1. Valid methods of well efficiency determination.
2. Permanent formation damage due to drilling mud.
3. Screen open area and well losses.
4. Entrance velocity and particulate movement.

Laboratory models and data from the Sarir production production in Libya were used to observe the effect of screen open area on screen losses. In each scenario screens with lower open areas performed as well as screens with greater open area. The percentage open area of screens tested was from six to 38%. In an experimental water well located at Ohio University it was found that well losses were less than 2% of the total losses for the well. Other turbulent losses occurred outside the well.

In their conclusions the following is stated.

> *"There is no relationship between the velocity of the water as it passes through the screen and the amount o fparticulates entering the well. Water well design should not depend on limiting screen entrance velocities to less than 0.1 FPS. The factorv which due influence the movement include the discharge, the hydraulic gradient in the formation and the velocity of the formation near the well. Other studies support these findings (Lockman, 1954), (D. Williams, 1981) (E. Williams, 1981), (Clark and Turner, 1983)."* And also *"Screens with as low as 6% open area performed comparably with screens of much higher open areas in terms of screens losses (both laboratory models and the Sarir production project). This conclusion of negligible screen losses agrees with the works of Lehr (1926), Corey (1949), Bikis (1978), D. Williams (1981), Clark and Turner (1983), and Jackson (1983). There is a trend of increased screen losses with decreased open area, agreeing with Nazir and Ahmad (1954), Bikis (1978), and Jackson (I 983), but the increased screen losses due to reduction in the screen open area are still not significant enough to warrant concern."*

Park, L., and Turner, P. A., Experiments to Access the Hydraulic Efficiency of Well Screens Ground Water, Volume 26 No. 3, May - June 1983.

Clark and Turner investigated the hydraulic properties of commercial well screens to determine which screen design features affected head loss. The test program began with laboratory experiments and continued with the installation of well field in the Thames valley gravel aquifer at Medmenham, England. The laboratory experiments carried out between 1976 and 1980 involved measuring well losses across small sections of test screen in both segmental and full diameter models of wells. Open area of the screens tested ranged from 5% to 40%. The field experiments were conducted during 1980.

In discussion of the results the authors report.

> *"The laboratory experiments show the relationship between the well screen head losses and the flow rate through the well screen to of the form: $H = CV^2$ which is in accord with both the theoretical and experimental findings of previous work which was performed on perforated well casings as distinct from purpose built well screens (Vaadia and Scott, 1958)."*

The authors made an attempt to rank the screens tested according to head losses. In order to obtain any ranking it was necessary to operate at an extremely high intake velocities for all types of well screen.

> *".. where intake velocities were more realistic in terms of a field situation (less than 30 cm/sec), then the head loss across all screens was very small (less than 5 mm of water), and for all practical purposes may be considered negligible."*

This result agrees with previous work by Turner (1978), and other workers using models incorporating screen aquifer and gravel packs. The authors concluded

"For all practical purposes, the head loss attributed to well screens was negligible."

With respect to the field experiments among other conclusions the authors state

"A maximum entrance velocity of 0. 1 to 0.25 ft/sec has been suggested as a basis of well design. The present suggest that this is a sound, but conservative, criterion. Entrance velocities of 0.5 ft/sec (15 cm/sec) were tolerated hydraulically at Medmenham for the period of the experiments."

In the same issue of *Ground Water* was an accompanying article *Commentaries on "Experiments to Assess the Hydraulic Efficiency of Well Screens"* by Moid U. Ahmad, E. B. Williams, and Latif Hamdan. Ahmad first considers the work done by Bikis (1978, 1979) in the testing of performance of nine well screens. Open area of the screens ranged from 8 - 38%. Bikis found that the screen losses were negligible. Ahmad also states

"Clark and Turner reported that the head loss attributed to the well screen is negligeble; this is confirmed by Bikis, Williams, and Jackson".

Ahmad also discusses the south and north Sarir well fields in Libya, which he designed. Bikis examined 157 production wells out of which 48 were fiberglass-slotted screens with 7% open area and 109 Johnson screens with 17-39% open area. He concluded that the fiberglass screen wells performed as well as the Johnson screen wells.

In E. B. Williams' commentary he states

"Their results confirm the opinion of many investigators, including myself (1981), that there is a minimal head loss across most well screens of even moderate open areas, and that the screen entrance velocity is therefore of little significance", and also *"The authors have corrected demonstrated the overemphasis of screen entrance velocity as a design criteria."*

The commentary by Latif Hamdan deals principally with the possible changing value of C in the equation $H = CV^2$ and the development of the test wells at Medmenham.

The preceding accounts for all the relevant laboratory testing found in the literature. One is at a loss to explain Driscoll's statement (1985)

"Field experience and laboratory tests show that average entrance velocity of water moving into the screen should not exceed 0.1 ft/sec (0. 03 m/sec)"

as well as the earlier similar statement in the first edition of *Ground Water and Wells*.

All the tests reviewed in this summary were conducted prior to 1984.