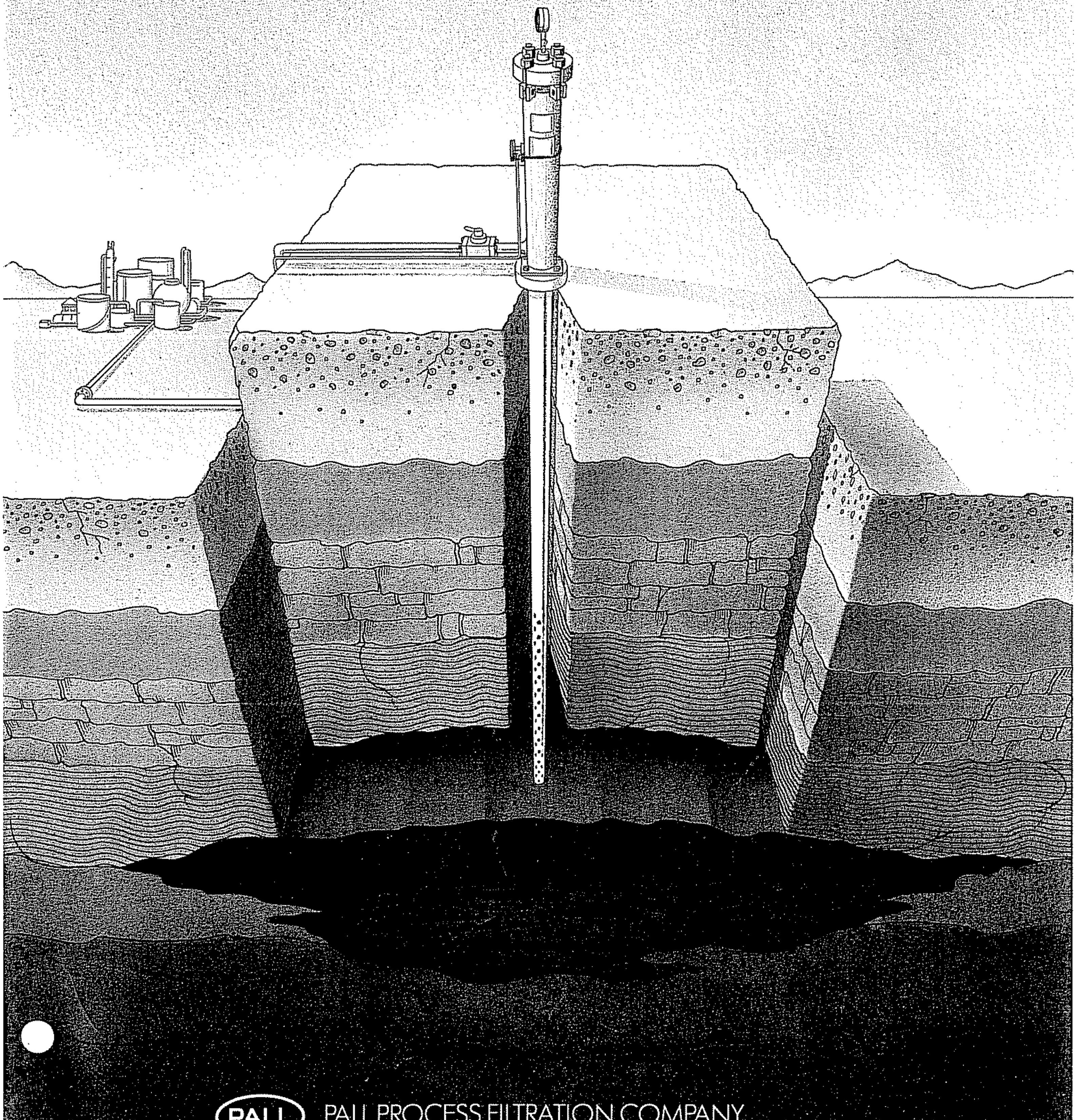
PALL FILTRATION TECHNOLOGY AND PRODUCTS FOR MAXIMUM FORMATION PROTECTION IN WATERFLOOD OPERATIONS

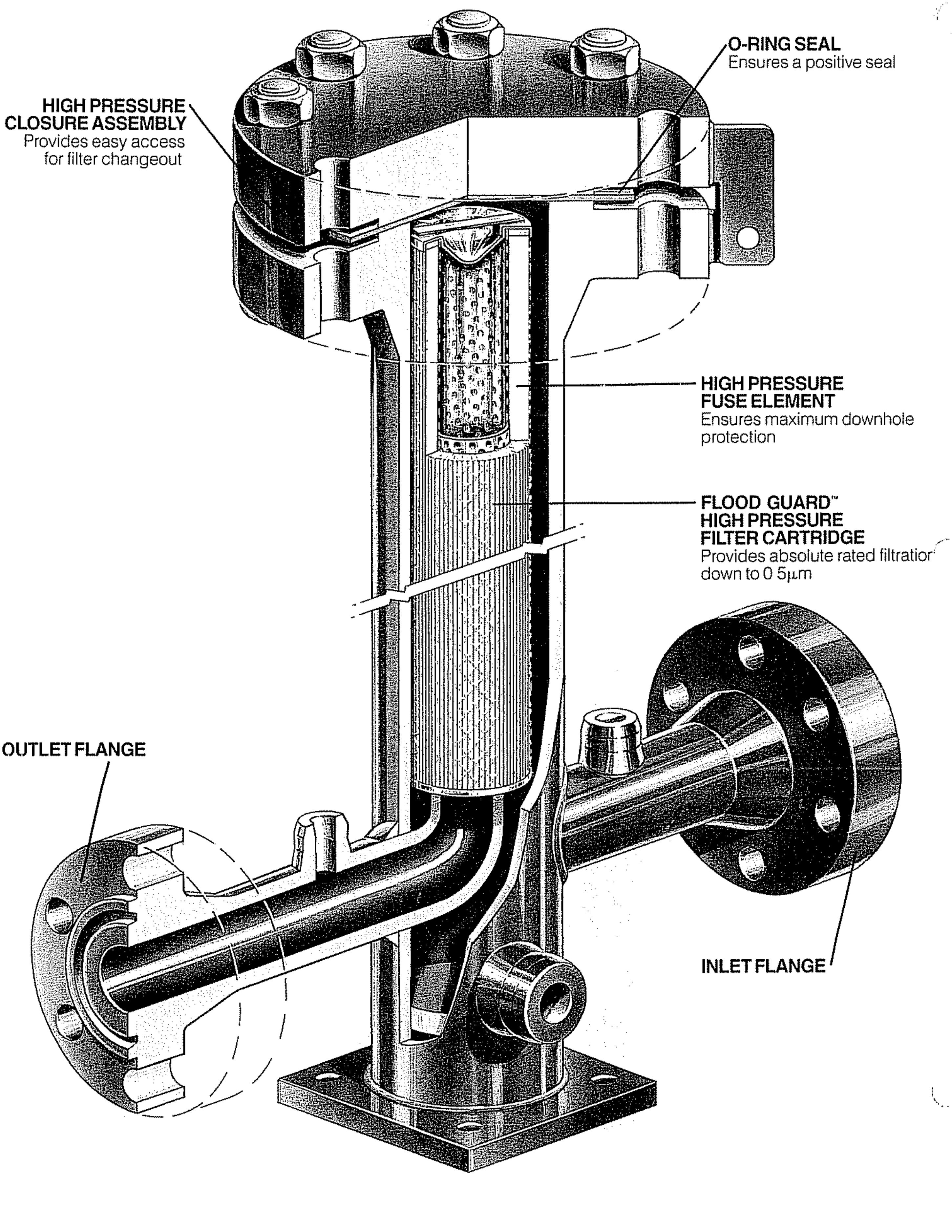


PALL PROCESS FILTRATION COMPANY
HYDROCARBON PROCESSING GROUP

WER 5500-R

High Pressure Waterflood Assembly

Ensures maximum formation protection down to 0 5μm absolute ($\beta_{0\ 5}=5000$)



Pall Filtration
Providing the Ultimate Downhole Formation Protection

Pall Corporation is the world leader in fluid clarification products and technology. Pall products have answered critical filtration needs in the oil, chemical process, hydraulic fluid power, aerospace, and biomedical industries.

Pall Process Filtration Company—Hydrocarbon Processing Group dedicates years of specialized filtration experience to the oil and gas industry. Pall Process has a tradition of innovation that includes the introduction of filtration products to the oil patch. Filtration of completion and workover fluids to 0.5 micron absolute and 0.3 micron absolute filtration of gas streams at gas plants and refineries are several examples. For waterflood, enhanced oil recovery, and other injection operations, Pall Process (HPG) provides clean injection fluids to 0.5 micron absolute. This level of filtration for source water, seawater, or produced water *ensures maximum formation protection resulting in stable injection profiles, less frequent workovers, and maximum production.* Reproducible, high quality injection fluid is guaranteed by Pall's uniquely designed and manufactured filter cartridges.

This reference tool will serve as a guide, explaining reasons why and how to utilize proper filtration in the oil and gas industry.

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Formation Damage Fundamentals

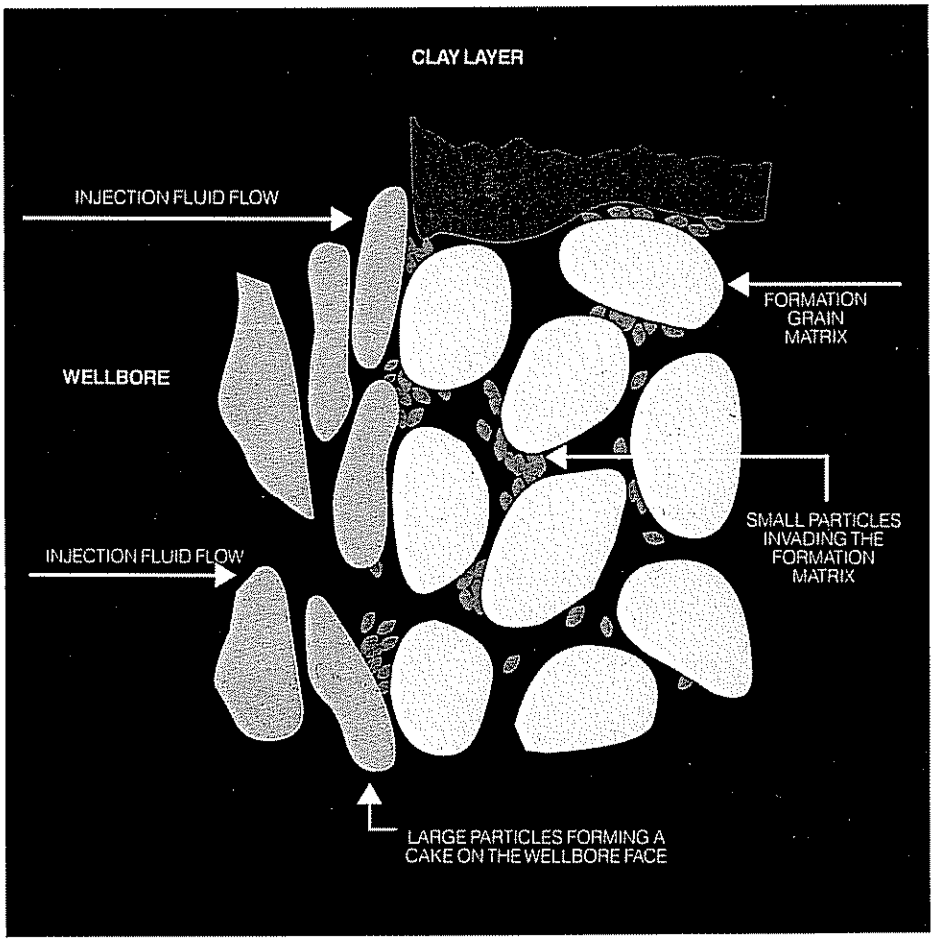
Water Injection Operations
(See page 21 for specification checklist)

Waterflood
Source Water
Sea Water
Produced Water
Polymer Flood

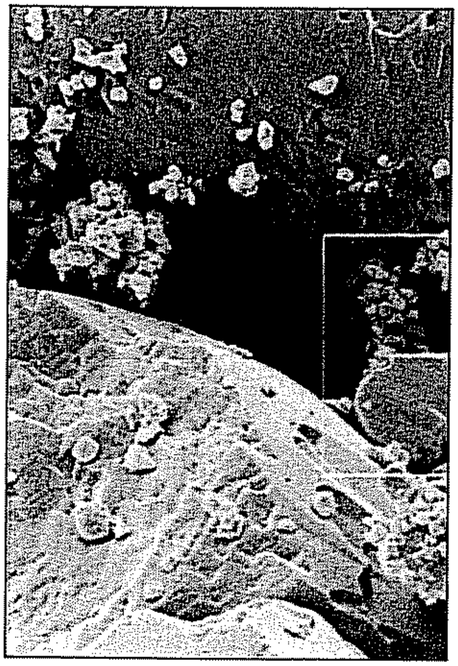
Enhanced Oil Recovery
Steamflood
Chemical Flood
Water-Alternating-Gas (WAG) Flood

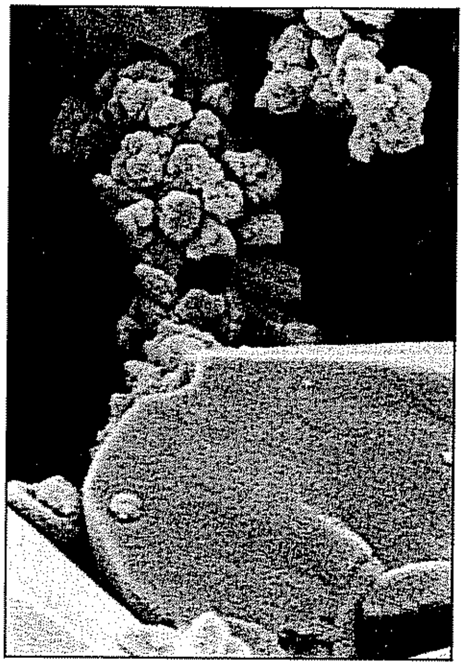
Injection for Disposal
Produced Water
Hazardous Waste
Industrial Fluids
Other Waste Fluids

Water Injection	
Problems	**Solutions**
Suspended Solids	Filtration
Oil	Filtration/Separation
Corrosion, Scale, Bacteria	Chemical Treatment
Formation Fines Migration	Chemical/Velocity



Particles bridging a pore throat*





Permeability = 2012md
Mean pore throat size = 29 5µm
Particle size = 3-5µm

This photomicrograph demonstrates how solid particles, much smaller than pore throats, can bridge and eventually plug the pores

Surface effects from downhole formation damage caused by suspended solids and oil in the injection fluid

Injection Profiles	Increasing injection pressures Decreasing injection rates
Sweep Efficiency	Increasing water production indicating channeling of water and bypassing of oil
Workovers	Increasing frequency of injection well workovers
Injection Pumps	Increasing pump maintenance Increasing energy costs for pumping at higher pressures
Production	Lower production results from project

*SPE 12498 "The Applications of Depth of Formation Damage Measurements in Predicting Water Injectivity Decline" Todd, Somerville and Scott

Evolution of Formation Damage Studies

1970s: Water quality specifications based upon parts per million (ppm) solids

1980s: Water quality specifications based upon particle size using 1/3-1/7 rule-of-thumb

1985: Injectivity modeling specifications of 2μm absolute ($\beta_2 = 5000$) filtration

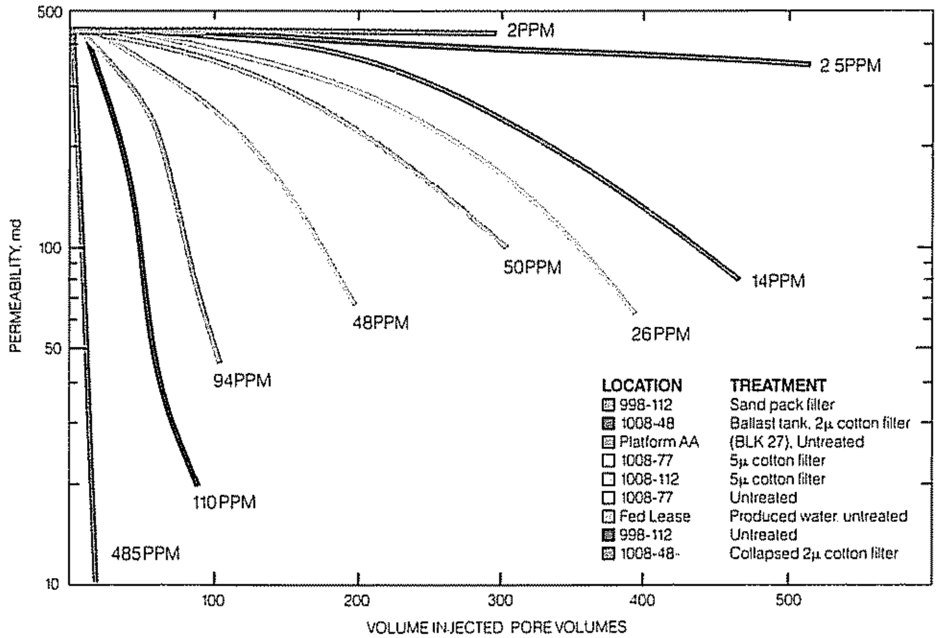
1986 : Maximum formation protection using 0 5μm absolute ($\beta_{0\ 5} = 5000$) filtration

1988: Injection water filtration improves field production

1970s: Water quality specifications based upon parts per million (PPM) solids

450md cypress sandstone core flow test data using various offshore Louisiana Bay waters

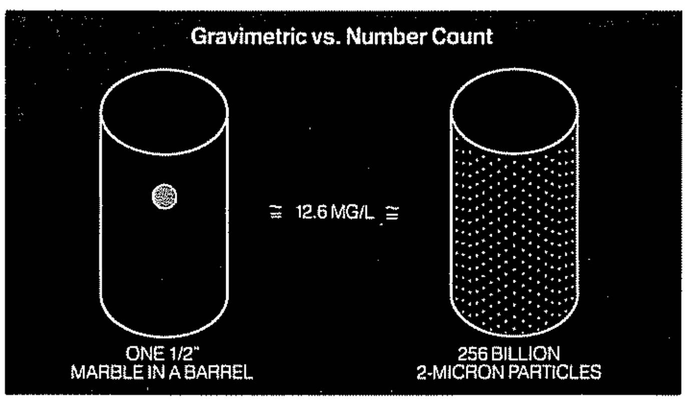
(After Tuttle & Barkman[30] © 1974 SPE-AIME)



Results:
In this study, to maintain original permeability 2ppm injection fluid is required

Hypothesis:
A 2ppm will have different plugging tendencies depending upon the size distribution of the particles in the fluid See diagram below

Conclusion:
Gravimetric specification is misleading Both fluids contain 12 6 mg/l of suspended solids Because of the particle size distribution, they will cause different degrees of downhole formation damage



1980s: Water quality specifications based upon particle sizing using 1/3-1/7 rule-of-thumb

1/3-1/7 rule-of-thumb

X = effective formation permeability (md)

$\sqrt{X}$ = mean pore throat diameter ± 10% (microns)

1/3-1/7 $\sqrt{X}$ = micron level of filtration needed to minimize formation plugging

Using the rule-of-thumb

Permeability = 668md

$\sqrt{668md}$ = 25.8μm = mean pore throat size

1/3 (25.8μm) = 8.6μm

1/7 (25.8μm) = 3.7μm

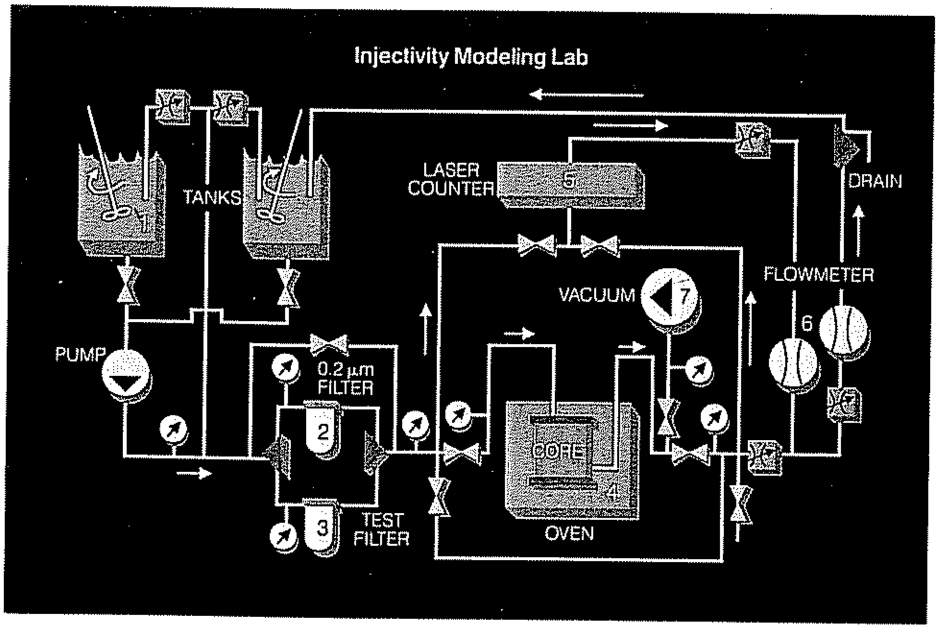
Conclusion:
Filtration of particles between 3-8μm is required to minimize formation damage

1985-Present: Injectivity modeling specifications of 2μm absolute (β_2 = 5000) filtration

Injectivity losses under particle cake build-up and particle invasion

I. Ershaghi. University of Southern California; R Hashemi. Pall Well Technology; S Caothien. Pall Well Technology; SPE 15073

Objective:
1 To determine injectivity losses due to particles in the injection fluid
2 To determine the level of filtration required to minimize formation damage



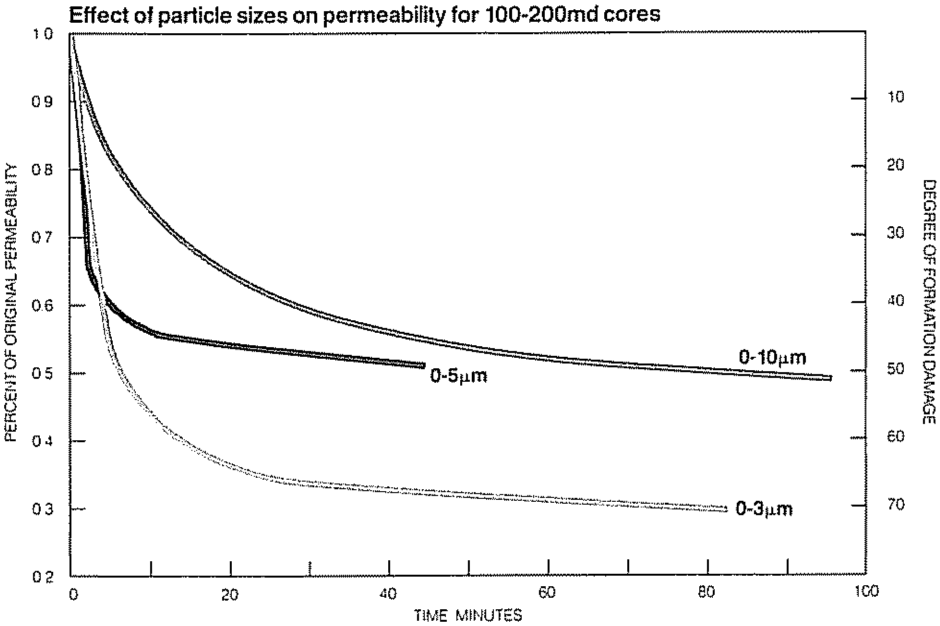
KEY
1 To prepare contaminants in fluid
2 To remove background contaminants from make-up fluid
3 To filter contaminants to distinct particle size cutoff; e g . 2μm absolute (β_2 = 5000)
4 To simulate downhole temperatures
5 To count particles into and out of the core
6 To measure flow decrease through core
7 To remove air from the core prior to saturation with fluid

Evolution of Formation Damage Studies (continued)

1985: Injectivity modeling specification of 2μm absolute (β_2 = 5000) filtration

Typical injectivity losses due to suspended solids

Effect of particle sizes on permeability for 100-200md cores



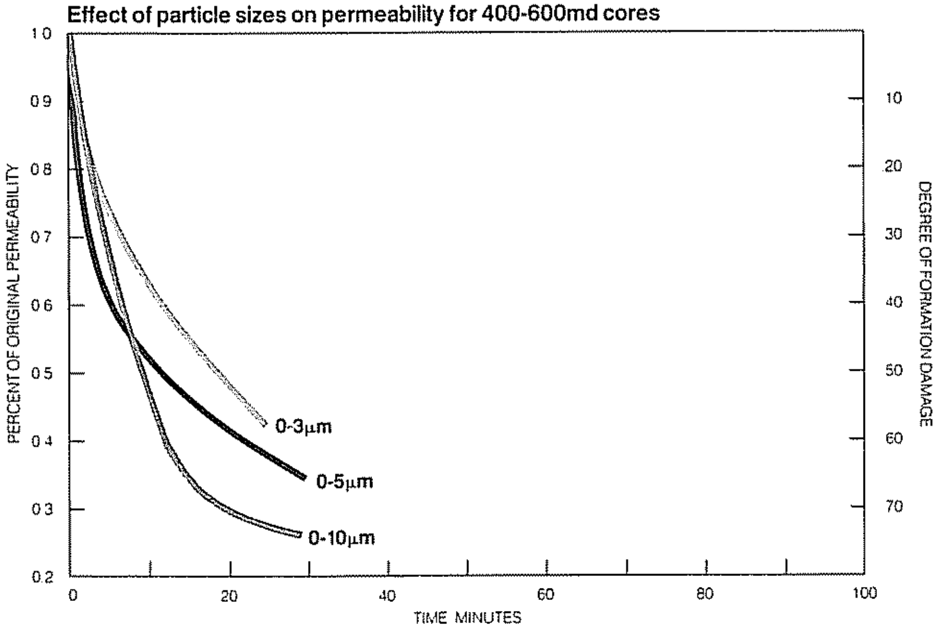
Results:

The greatest reduction in permeability occurs when injecting fluids contain 0-3μm particles; only 30% of the original permeability is retained The predominant mechanism is particle invasion With 0-10μm particles, less damage is observed as large particles are forming a cake on the wellbore face, as shown in the diagram on page 4 While this phenomena occurs in the laboratory study, the nature of water injection systems under actual downhole conditions does not allow controlled cake build-up to minimize formation plugging

Conclusion:

Filtration of 2μm absolute (β_2 = 5000) is required to remove all particles 2μm and larger For example, by installing a 5μm absolute (β_2 = 5000) filter, particles below 5μm will still be injected into the formation

Effect of particle sizes on permeability for 400-600md cores



Results:

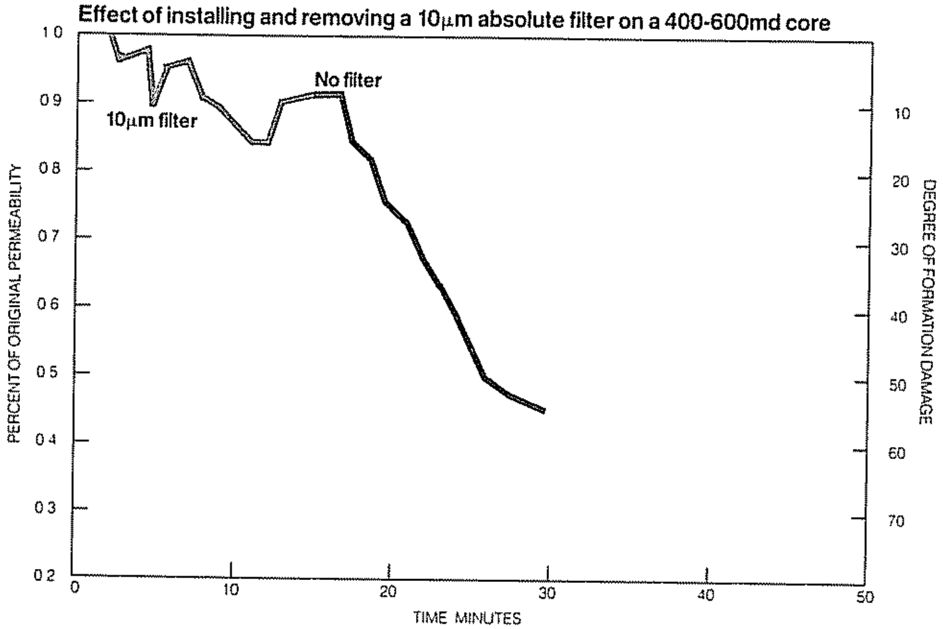
In this case, the greatest reduction in permeability occurs when injecting fluids contain 0-10μm particles The dominant mechanism is once again particle invasion with larger particles creating more serious internal bridging

Conclusion:

Filtration of 2μm absolute (β_2 = 5000) is required to remove all particles 2μm and larger. For example, if a 10μm absolute (β_{10} = 5000) filter is installed, 0-10μm particles will still be injected resulting in a reduction in permeability

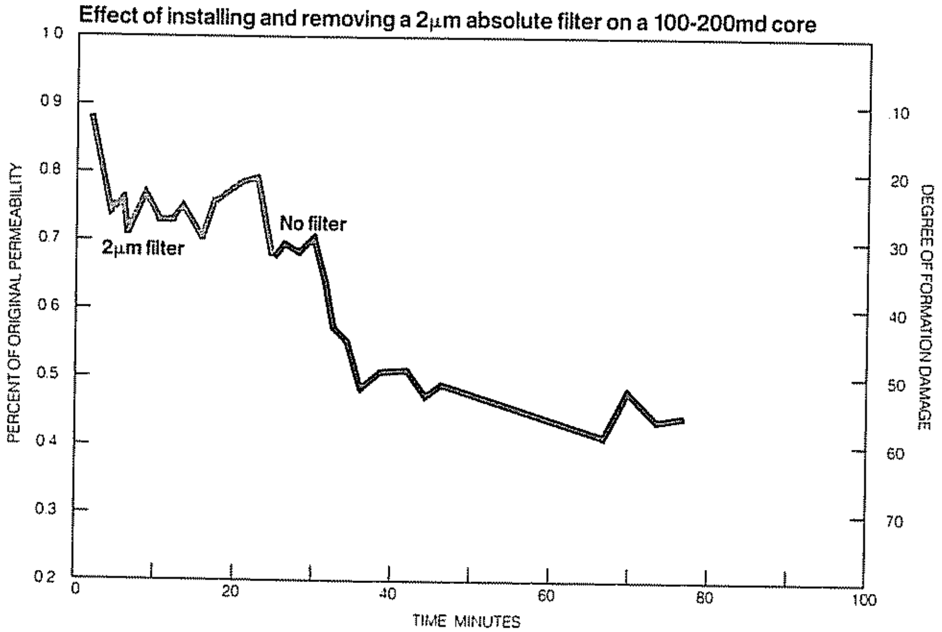
1985: Injectivity modeling specifications of 2μm absolute (β_2 = 5000) filtration

Effect of filtration on damaged formations



Conclusion:

Initially, with the placement of a 10μm absolute filter (β_{10} = 5000) in the line, there was a 20% decrease in the permeability When the filter was removed, a rapid decline in the permeability occurred A 10μm filter, therefore, will only slow the rate of formation damage, but will not prevent the damage from occurring



Conclusion:

Initially, a 20% decrease occurred when injecting fluid contaminated with suspended solids Placement of a 2μm absolute (β_2 = 5000) filter in the line, stabilized and actually improved injectivity Removing the filter results in a similar decline curve

Filtration in a carbonate formation

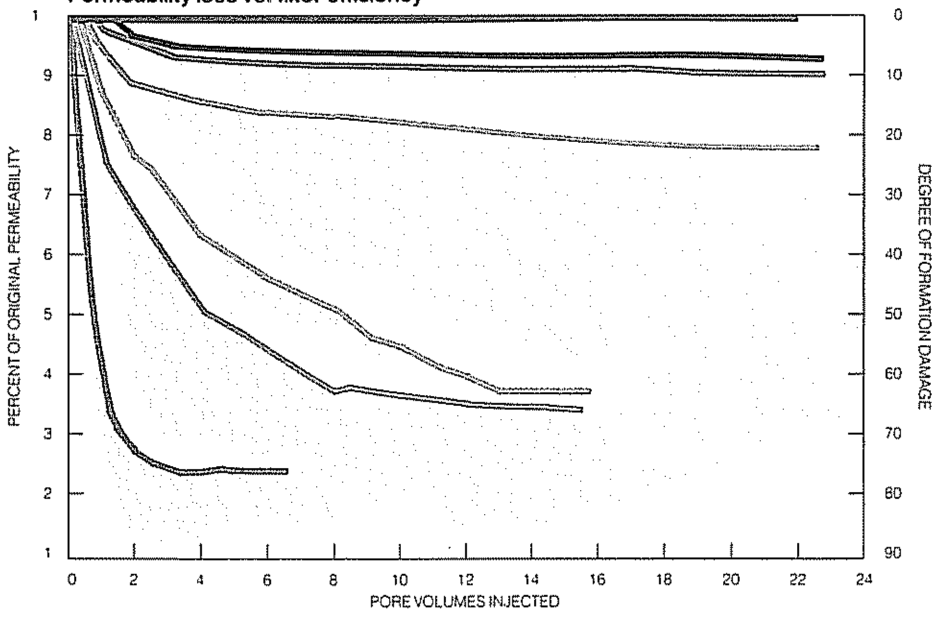
Formation Accepts Water Without Showing Increasing Injection Pressures	
Problem: Water is by-passing oil, channeling to producing well, and showing increased water production.	
Typical solution: acidize injection well • Acid will dissolve carbonate matrix, releasing insoluble fines, resulting in more plugged pores. • Acid may not reach the plugged pores.	**Alternative solution: prevent plugging** Recommendation: 2µm (β_2 = 5000) absolute filtration • Filtration solves pore plugging on the surface rather than downhole.

1986: Maximum formation protection using 0 5µm absolute ($\beta_{0.5}$ = 5000) filtration

Benefits of solids filtration evaluated

R. Hashemi, Pall Well Technology Corp ; S Caothien, Pall Well Technology Corp ; Oil & Gas Journal, January 27, 1986

Permeability loss vs. filter efficiency[1]



Objective:

1 To evaluate pore plugging under different degrees of filtration from 10µm absolute (β_{10} = 5000) to 0 5µm absolute ($\beta_{0\,5}$ = 5000)

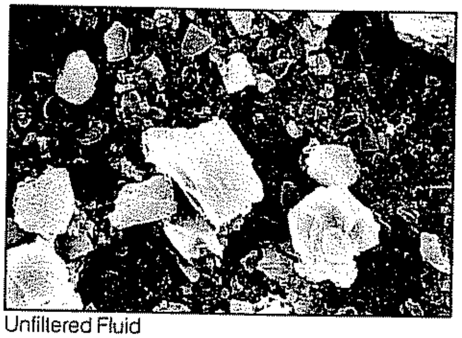
Conclusion:

The Pall 0 5µm absolute provides the maximum formation protection The 1µm nominal filter provides very little formation protection The 0 45µm absolute (β_{45} = 10) provides increased protection but below the 2µm (β_2 = 5000) and 0 5µm ($\beta_{0\,5}$ = 5000) filters

KEY:
- Pall 0 5µm absolute ($\beta_{0\,5}$=5000)
- Pall 2 0µm absolute (β_2=5000)
- Competitive 0 45µm absolute ($\beta_{.45}$= 10)[2]
- Pall 10µm absolute (β_{10}=5000)
- Competitor 1µm nominal
- Competitor 1µm nominal
- No filtration

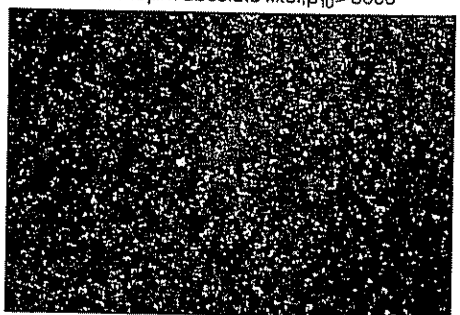
[1] Core permeability = 100md
[2] As reported in their literature, but not confirmed by the OSU F-2 Filter Test

1986 Maximum formation protection using 0 5μm absolute ($\beta_{0\,5} = 5000$) filtration

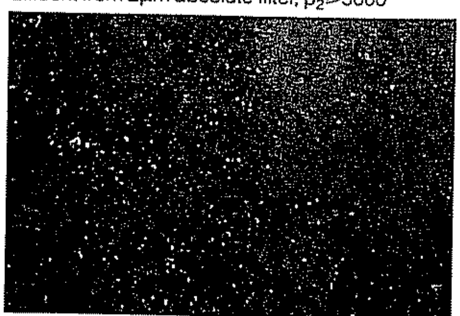


Unfiltered Fluid

Effluent from 10μm absolute filter, $\beta_{10} \geq 5000$



Effluent from 2μm absolute filter, $\beta_2 \geq 5000$



Effluent from 0 5μm absolute filter. $\beta_{0\,5} \geq 5000$

SEM photographs at 2000x magnification illustrate dramatic reduction in particle population of filtrate with increasing degree of filtration fineness

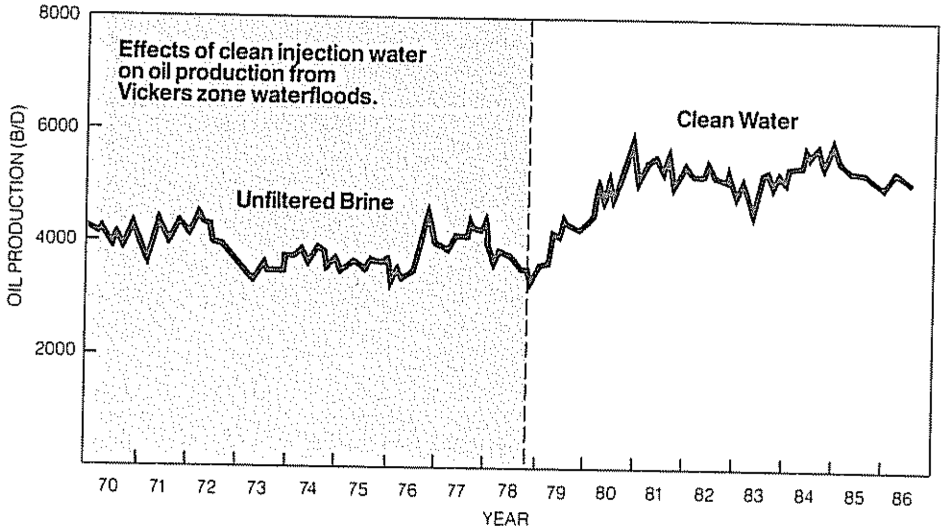
1988: Increase in production due to cleaner fluid injection

Waterflooding a Thick, Heterogeneous Reservoir in Los Angeles Basin—"A Case History"

Parson. Lucidi. Maloney. and Patterson. Chevron U S A Inc

Objective:

To study the effect of injection water quality on the production of Vickers East Pool



Reservoir Properities

Average porosity, %	32	Oil viscosity at 100°F, cp	65
Mean permeability to air, md	500	Water viscosity at 100°F, cp	0 7
Permeability variation	0 6	Reservoir temperature °F	100
Oil gravity, API	18 7	Average current reservoir pressure. psi	225

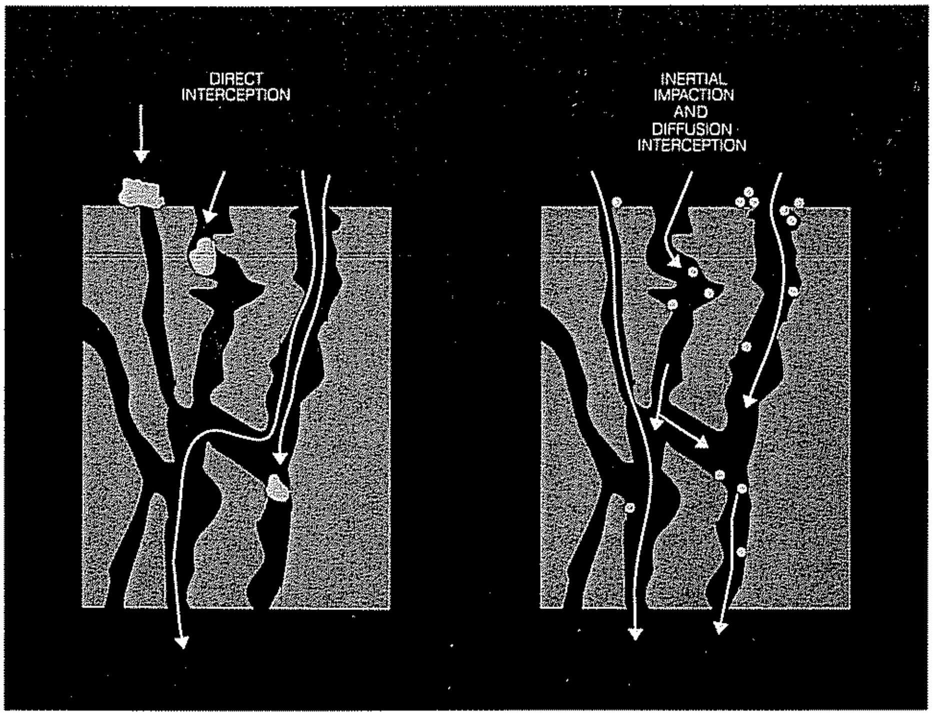
Conclusions:

- The Vickers East Pool, despite its large thickness, high degree of heterogeneity, complex faulting, and thin-bedded sand bodies, could be waterflooded successfully.
- Benefits of clean water injection include improved vertical coverage, reduced water cycling, reduced need for well workovers to remove perforation/formation plugging, and longer job life for required stimulation work
- Control of vertical profiles of water injection wells was essential Perforation size and density, downhole equipment, and stimulation techniques were emphasized to control, and, when necessary, to modify injection coverage throughout the Vickers East zone
- Air flotation units and sand filters were installed to clean the injection water Oil production increased 3500 to 5500 barrels/day. About 70% of the gain is attributed to improved water quality and an expanded workover program; the remainder resulted from drilling new injector and producer wells

Principles of Filtration to Reach Water Quality Specifications

Filtration: Removal of solid or liquid contaminants from a liquid stream by means of a porous medium

Mechanisms of filtration



Filter rating systems:

Nominal: National Fluid Power Association: An arbitrary value assigned by the manufacturer, based upon weight percent removal, which varies widely. It is not reproducible and has no real meaning

Absolute Filtration Ratio: The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. This is an indication of the largest opening in the filter element

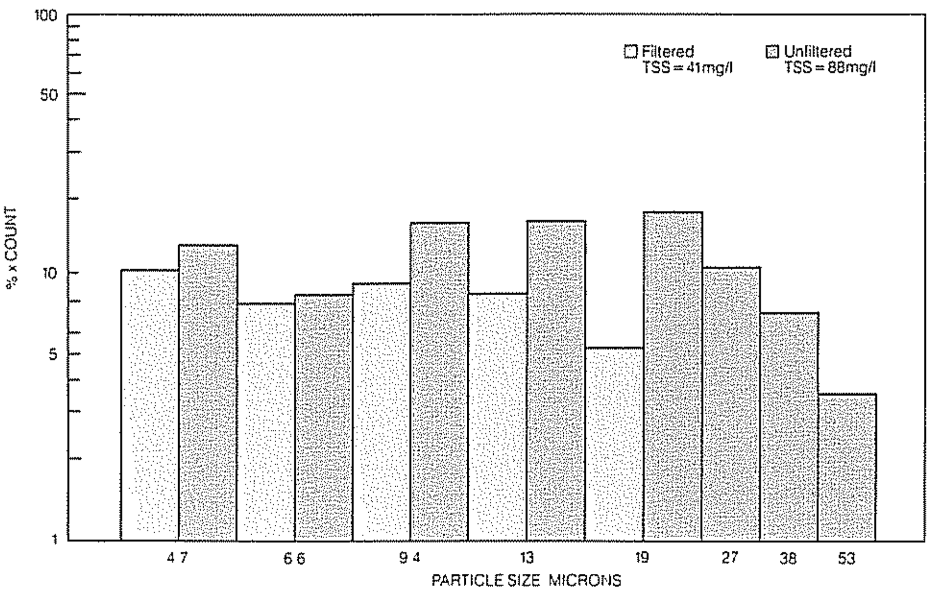
Beta Value (β): β is the ratio of the number of particles equal and greater than a given size in the influent compared to those of the same size or larger in the effluent

$$\beta_x = \frac{\text{no. of particles IN at X micron and larger}}{\text{no. of particles OUT at X micron and larger}}$$

$$\text{\% removal efficiency} = \frac{\beta_x - 1}{\beta_x} \times 100$$

Nominal rating explanation

(McLeod & Crawford. SPE 11008)

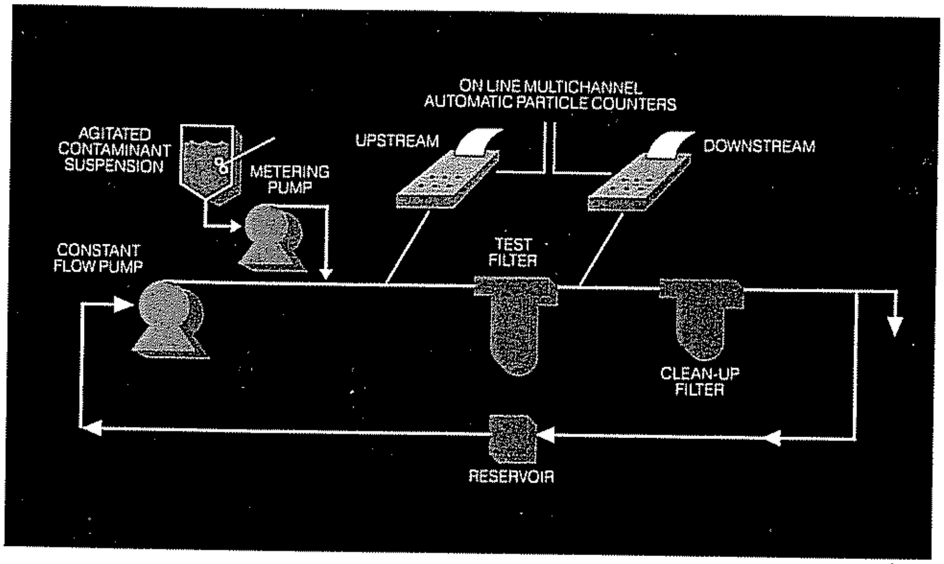


Conclusion:

A 2-5μm nominal filter cartridge was used to filter 9.6 lbs/gal brine. The clear bars indicate the particle size distribution in the influent, while the blue bars show the distribution in the effluent stream. The 2-5μm nominal filter removed 53% by weight of the particles. The filter, however, passed particles up to 19μm in size. This performance follows directly from the nominal rating definition of an arbitrary value assigned by the manufacturer based upon weight percent removal. A nominal filter does not provide a distinct particle size cutoff and, therefore, does not provide maximum formation protection

Filtration ratio test: beta test stand

(OSU F-2, ISO 4572, ANSI B 93 31-1973)



Test Procedure:

The modified OSU test system is equipped with two particle counters with a range of 0 5 to 100 microns One counter, upstream of the filter, records the influent particle counts, and the other, downstream, records the effluent levels Each counter can be preset to count particles greater than each of five or more particle diameters These counts are used to determine the efficiencies at the respective particle sizes By taking the ratio of the counts above a given particle size in the influent to the respective count in the effluent, absolute and beta values or removal efficiency at each particle size can be calculated

Beta rating explanation

Typical beta test results for a 2μm absolute ($\beta_2 = 5000$) filter

# of Particles per ml IN	# of Particles per ml OUT	Beta Ratio β_x	% Removal Efficiency
100,000≥ 2μm	2≥ 2μm	$\beta_{2\,0}=5000$	99.98%
120,000≥1 5μm	120≥1 5μm	$\beta_{1\,5}=1000$	99.9%
150,000≥1 0μm	1500≥1 0μm	$\beta_{1\,0}=100$	99%
200,000≥0 5μm	20,000≥0 5μm	$\beta_{0\,5}=10$	90%

Using beta values to compare filters

Filter	# of Particles per ml ≥2μm		Beta Ratio β_2	% Removal Efficiency
	Influent	Effluent		
Filter A	10,000	5,000	2	50%
Filter B	10,000	100	100	99%
Filter C	10,000	10	1000	99.9%
Filter D	10,000	2	5000	99.98%

Conclusion:

Percent removal efficiency can be misleading Filter A is 50% efficient, while Filter D is 99 98% efficient It would appear that Filter D is two times more efficient However, Filter A allows 2,500 times more particles downstream than Filter D Filter D is, therefore, 2,500 times more efficient Beta values compare performance directly. The filter with the highest beta value will have the lowest downstream particle count and offer the maximum degree of formation protection

$$\beta_x = \frac{\text{no of particles IN at size X and larger}}{\text{no of particles OUT at size X and larger}}$$

$$\text{\% removal efficiency} = \frac{\beta_x - 1 \times 100}{\beta_x}$$

Principles of Filtration to Reach Water Quality Specifications (continued)

Beta rating explanation

Significance of beta values for minimizing formation damage

Typical source water

Particle Size µm	No. of Particles
⩾0.5	150,000
⩾1.0	20,000
⩾2.0	8,000
⩾4.0	2,000

Particle Size µm	No. of Particles
⩾10	800
⩾25	300
⩾50	100

Contamination Level 4 0 mg/liter

Particle size distribution (PSD) = Total number of particles per milliliter larger than shown micron size

Filtration results:

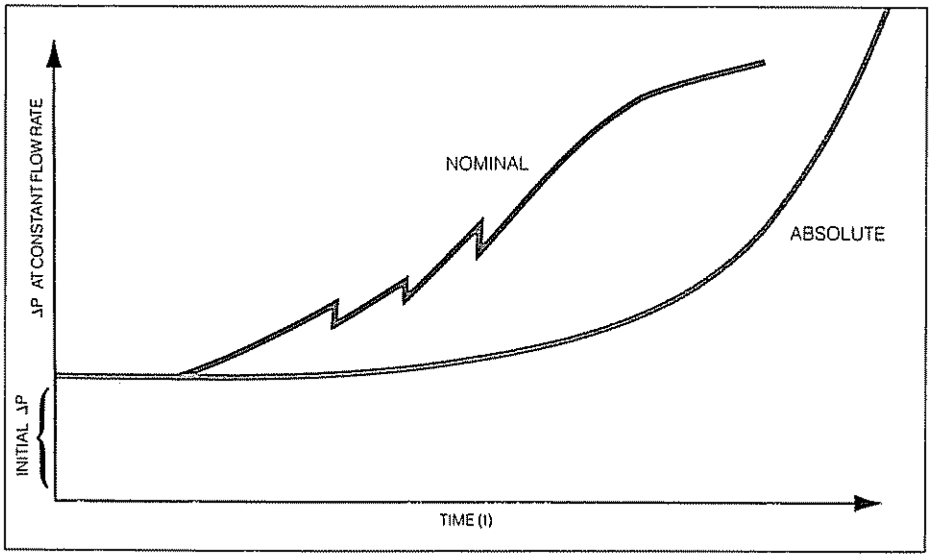
Filter Brand	$\beta_x = \beta_{0.5}$[1]	Removal Efficiency[2]	Number of Particles/ ML⩾0.5µm	
			Influent	Effluent
A	2	50%	150,000	75,000
B	100	99%	150,000	1,500
C	1000	99.9%	150,000	150
D	5000	99.98%	150,000	30

[1]Beta value: $\beta_{0.5}$ is the ratio of the number of particles equal and greater than 0 5µm in size in the influent to the number of particles 0 5µm and larger in size in the effluent

[2]β_x is related to the removal efficiency as follows:

Efficiency (%) $\frac{\beta_x - 1}{\beta_x} \times 100$

Typical filter response to increasing differential pressure

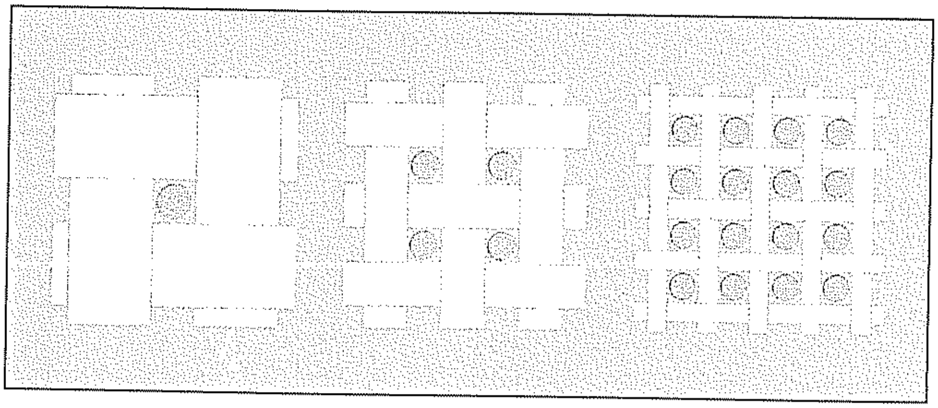


Conclusion:

An absolute filter, because of its fixed-pore construction, will maintain its pore structure and media integrity as differential pressure increases. A nominal filter behaves differently. As pressure drop increases, pore sizes may change such that previously caught particles are released and passed downstream (unloading). Further, the media itself may detach and also be passed downstream (media migration). The results are fluctuating differential pressure readings (cycles of increasing ΔP followed by a sharp decrease), deceptive filter life and loss of formation protection

The importance of fiber diameter for void volume and dirt capacity

(Constant pore size)



Conclusion:

The three examples are of equal areas and pore sizes The only variance is fiber diameter Using smaller diameter fibers, there is more void volume (i e , open space) and, therefore, higher dirt capacity, resulting in longer filter life

Types of filter media fixed pore versus non-fixed pore construction

Fixed pore media are constructed such that the fibers cannot distort and the pores do not increase in size at increased pressure or dirt loading In non-fixed construction, pore dimensions may change as pressure drop increases The result is unloading (passing previously trapped particles) and media migration (filter medium detaching and passing downstream) Comparison of fixed pore and non-fixed pore type media is inappropriate because of the differences in their filter ratings and the occurrence of unloading and media migration

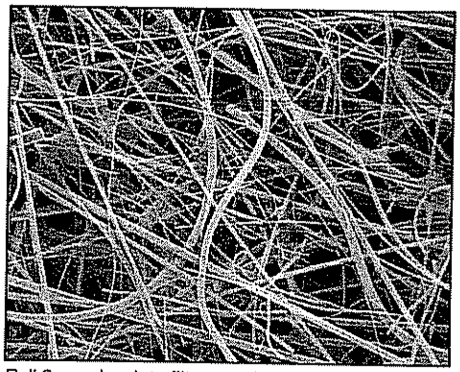
Fixed pore: absolute rating

- Resin impregnated cellulose
- Resin bonded glass fiber
- Continuous polypropylene pleated
- Continuous polypropylene depth

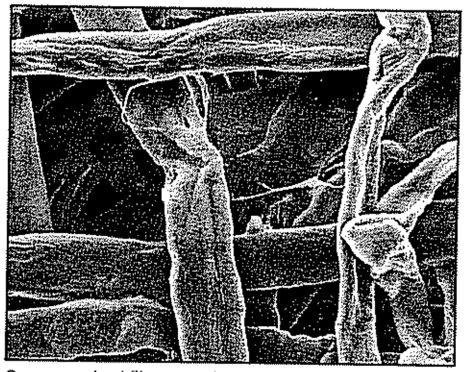
Non-fixed pore: nominal rating

- Unbonded fiberglass
- Cotton wound
- Molded cellulose
- Spun wound polypropylene
- Cotton sock
- Sand beds
- Other media beds
- Diatomaceous earth

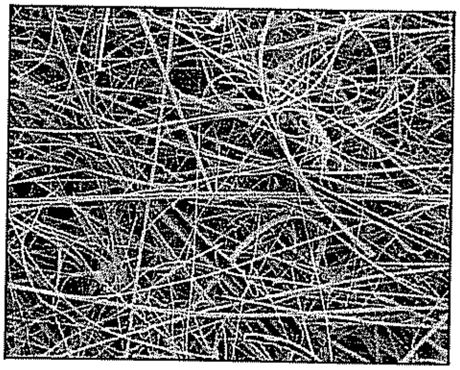
Photomicrographs of absolute and nominal rated media



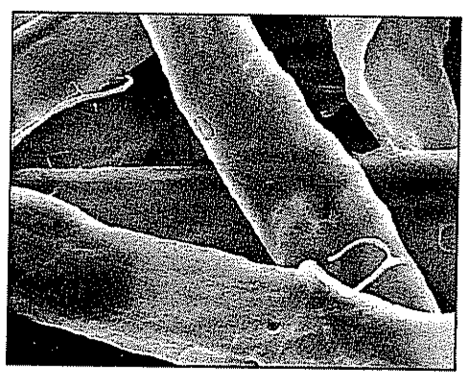
Pall 2μm absolute filter medium magnification—500X



3μm nominal filter medium magnification—500X



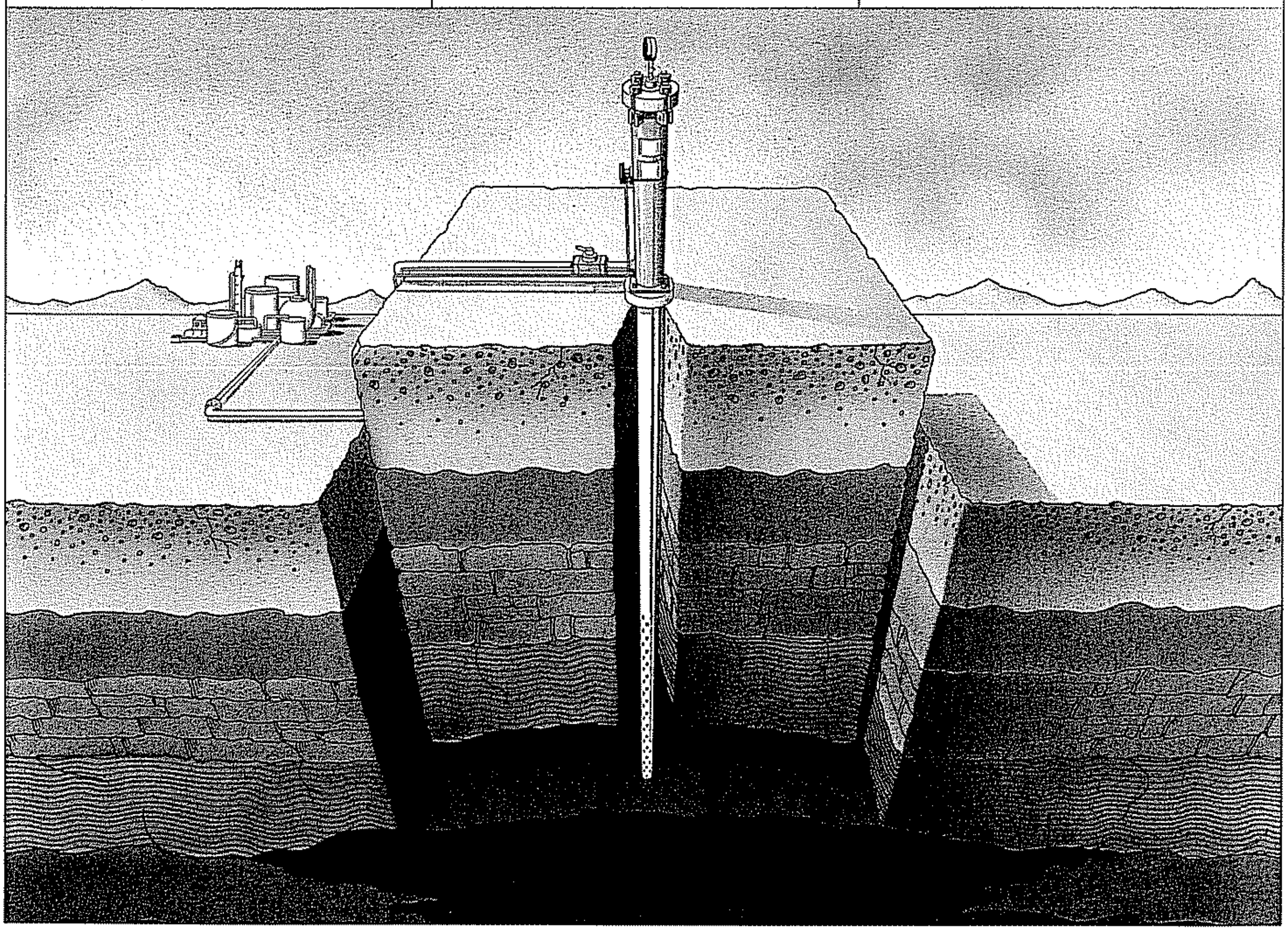
Pall 2μm absolute filter medium magnification—1000X



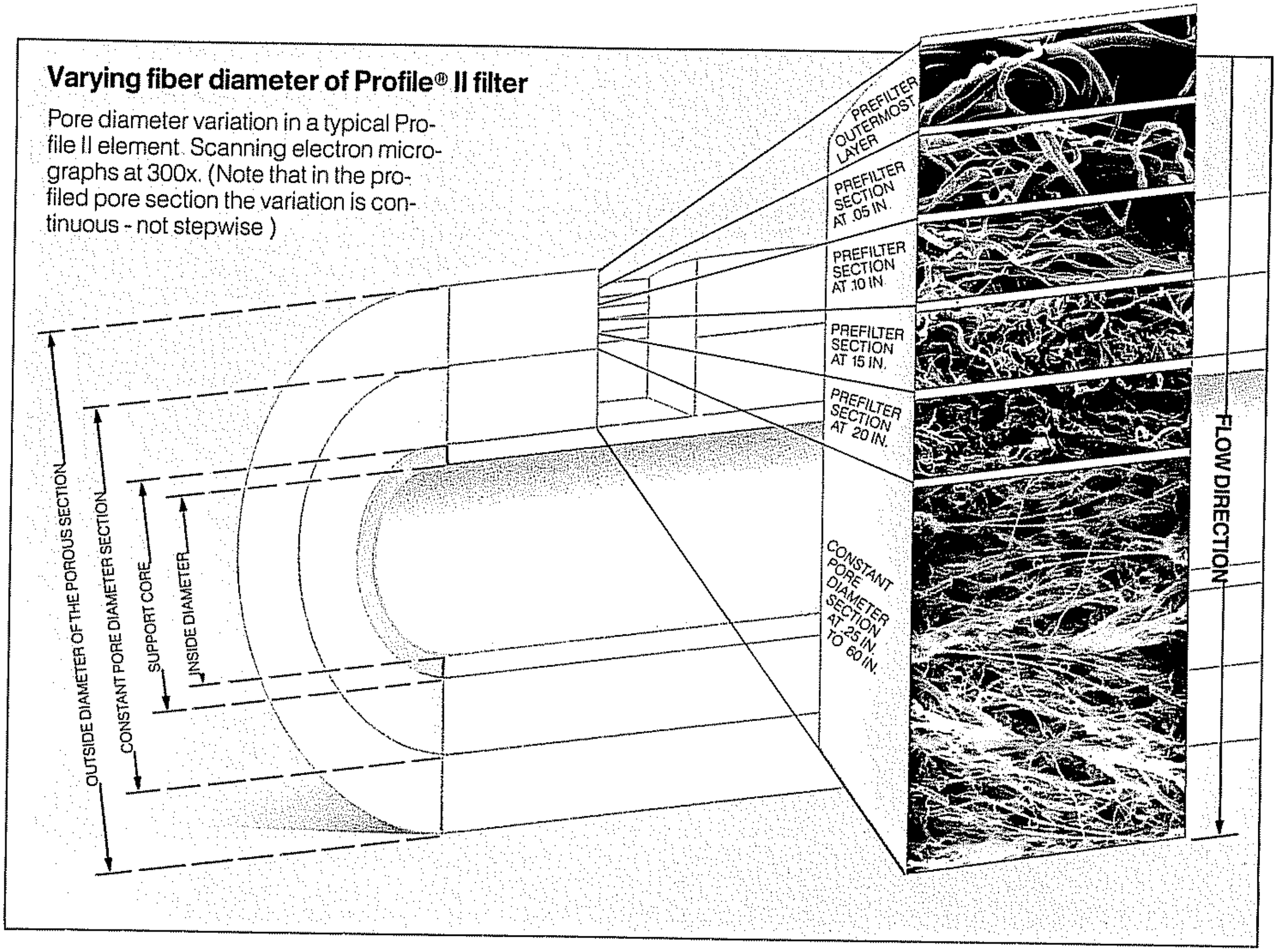
3μm nominal filter medium magnification—1000X

Setting Water Quality Specifications

Preliminary steps:	Setting specifications:	Filtration suppliers should:
Characterize formation and permeability	Base specifications on particle size	Conduct on-site filterability studies and provide a fluid quality assessment thereof
Provide information on current and future injection plans	Downhole particle plugging is *not* reflected by PPM or mg/l	Recommend the most appropriate filtration means in accordance to capability with central lines and the wellhead system
Measure present condition of water quality on-site	For *adequate* formation protection, specify 2μm absolute ($\beta_2 = 5000$) filtration	Assist in the installation of the filtration unit and troubleshooting
	For *maximum* formation protection, specify 0.5μm absolute ($\beta_2 = 5000$) filtration	



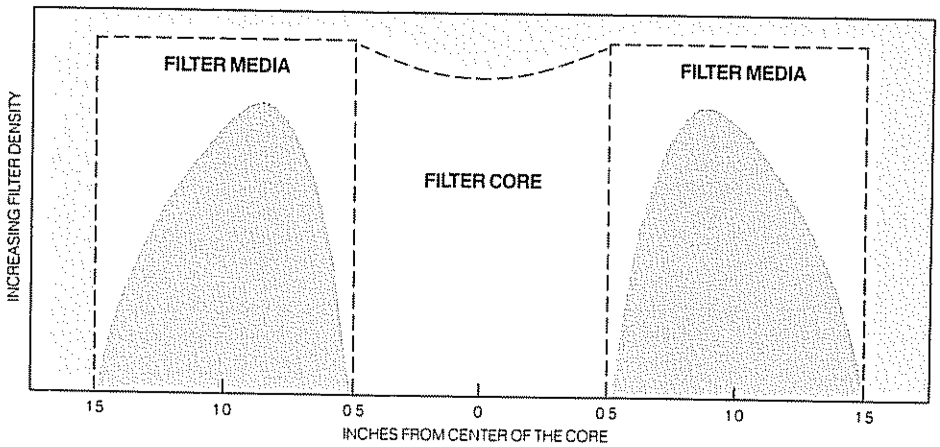
Products for Waterflood Application to Reach Water Quality Specifications



Varying fiber diameter of Profile® II filter

Pore diameter variation in a typical Profile II element. Scanning electron micrographs at 300x. (Note that in the profiled pore section the variation is continuous - not stepwise)

Varying filter density of typical depth filters

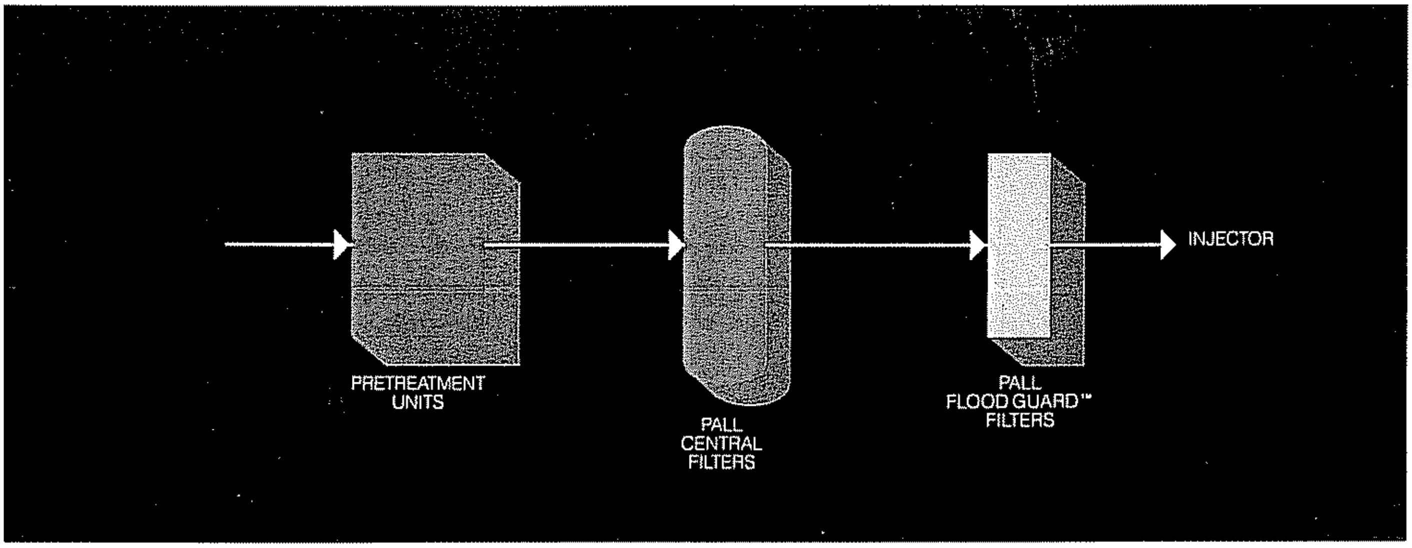


Conclusion:

This diagram shows the change in media density as described by a manufacturer of nominal rated cartridges The dotted lines depict a front view cutaway of the filter The filter density increases towards the core Increasing filter density leads to lower void volume, less dirt capacity, and shorter filter life

Systems Approach to Meeting Water Quality Standards Economically

Systematic approach to inline filtration in waterflood applications



Filtration system technical specifications
Typical Pall filter cartridge specifications

Grade [1]	Removal Ratings, µm Percent Efficiency				$\beta_x = 5000$	Media Description [2]
	90%	99%	99.9%	99.98%	x = µm	
WF4P005	<0.5	<0.5	<0.5	0.5	0.5	Profile® II
WF4P020	<0.5	<1.0	<1.5	2	2	Profile II
WF4P100	6.5	7.5	9	10	10	Profile II
MCC1401U2-20	0.3	0.8	1.3	2	2	Ultipor®
MCC1401E100	<2.0	5.0	7.5	10	10	Epocel®

[1]WF styles are 40" length, a 2½" outside diameter with 0-ring seal; MCC style is a 40" length with 3½" outside diameter.
[2]Profile® II filters are polypropylene; Ultipor GF® filters are resin impregnated glass fiber; Epocel® filters are resin bonded cellulose.

Pall Customer Support Services

Pall offers unique scientific and laboratory services

Technical assistance with difficult problems is provided by Pall's Scientific and Laboratory Services Department (SLS) The Department's main headquarters are in the U S , Great Britain, and Japan, with support laboratories located in Canada, Germany, France, and Italy These laboratories are staffed with skilled engineers and scientists trained in disciplines associated with fluid clarification and are equipped with the most sophisticated analytical instruments available They are prepared to conduct performance feasibility and design optimization studies in support of solids separation applications using Pall's specially designed laboratory core injectivity test apparatus Field test equipment for in-process side stream evaluations can be arranged by contacting Pall Pall's scientists and engineers help analyze requirements, help determine fluid compatibilities, and solve complex solids separation problems Their efforts help Pall customers find practical, prompt, reliable, and cost-effective solutions

Scanning Electron Microscope located at Pall SLS facilities

Definitions of on-site water quality analysis conducted for the customer by Pall SLS

Total Suspended Solids (Gravimetric Analysis):
The gravimetric measurement is reported in milligrams/liter. By measuring the influent and effluent levels of the filter, the efficiency of the filters with respect to the specific fluid and contaminant can be determined. From the gravimetric analysis, the amount of solids going downhole can be calculated.

Particle Size Distribution:
Particle size distribution is reported as the percent of particles with a given diameter in specific micron ranges. Filters with absolute ratings have effluents with distinct particle size cutoffs at their absolute rating. From the analysis, the potential for well impairment can be examined.

Turbidity:
Turbidity is reported in nephelometric turbidity units (NTU). NTU measurements show the relative reduction of contaminant and the consistency of fluid quality with no bypass, media migration, or particle unloading.

Hydrocarbon Content:
Hydrocarbon content is reported in milligrams/liter. Oil and solids levels will affect filter life, as well as the degree of well impairment and injectivity.

Filterability:
For waterflood and EOR applications, the filterability analysis provides information to determine the effectiveness of a filter with a given fluid and contaminant.

Field Test Report

Project: On-site evaluation of injection brine
Company: Oil exploration and production
Location: Texas
Plant: Water treatment plant
Contact: John Smith

Date: 5/1/89
Report No.: W333
Date Sampled: 4/26/89

Objective: To determine the fluid quality of the injection brine filtered by Pall 2μm absolute filters (P/N MCC1401 U2-20)

System description

1 System flow: 500 BPD

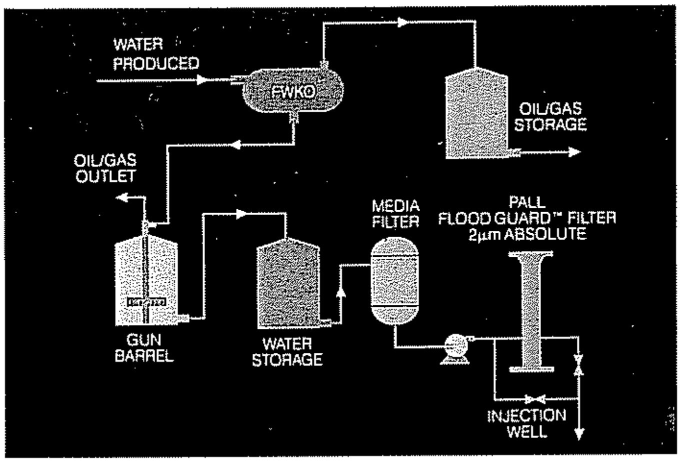
2 Operating pressure: 400 psi

3 Fluid type: Produced water

4 Fluid temperature: 70°F

5 Chemical treatment:

6 Filtration system: Pall Flood Guard 2μm absolute filters



Analytical test results

Fluid Sample	Gravimetric (mg/1)	Turbidity (NTU)	Hydrocarbon cont. (mg/1)	Viscosity (cPs)	Comments
Influent media	32 5	45	27		
Effluent media	11 3	9	6		
Effluent Pall					
2μm absolute	0 4	0 5	2		

Particle size distribution

Fluid sample	1-5μm	5-15μm	15-25μm	25-50μm	>50μm
Influent media	44 6%	28 3%	22 4%	3 5%	1 2%
Effluent media	67 6	18 3	10 7	2 5	0 9
Effluent Pall					
2μm absolute	100	—	—	—	—

Pall Filter Specification Checklist for Waterflood Applications

Operating conditions

Type of fluid to be filtered: ______

Fluid flow rate:

Central: ______

Each injector: ______

Operating pressure:

Central: ______

Wellhead: ______

Operating temperature: ______

Formation permeability: ______

Porosity: ______

Design specifications

Existing filtration: primary: ______

New project: secondary: ______

Housings (if existing): ______

Cartridges (if existing): ______

Water quality requirement: ______

Frequency of well workover (existing): ______

Pall Filtration Assembly Recommendation

Housing Diameter	Number of Cartridges	Overall Height	Dry Weight lbs.	Inlet/Outlet Connection	Flow Rate (BPD) Recommended*	Flow Rate (BPD) Max.

*Recommended flow rate for optimum cartridge life

Filter cartridge recommendation

Filter media: ______

Inner core: ______

Endcaps: ______

Filter area: ______

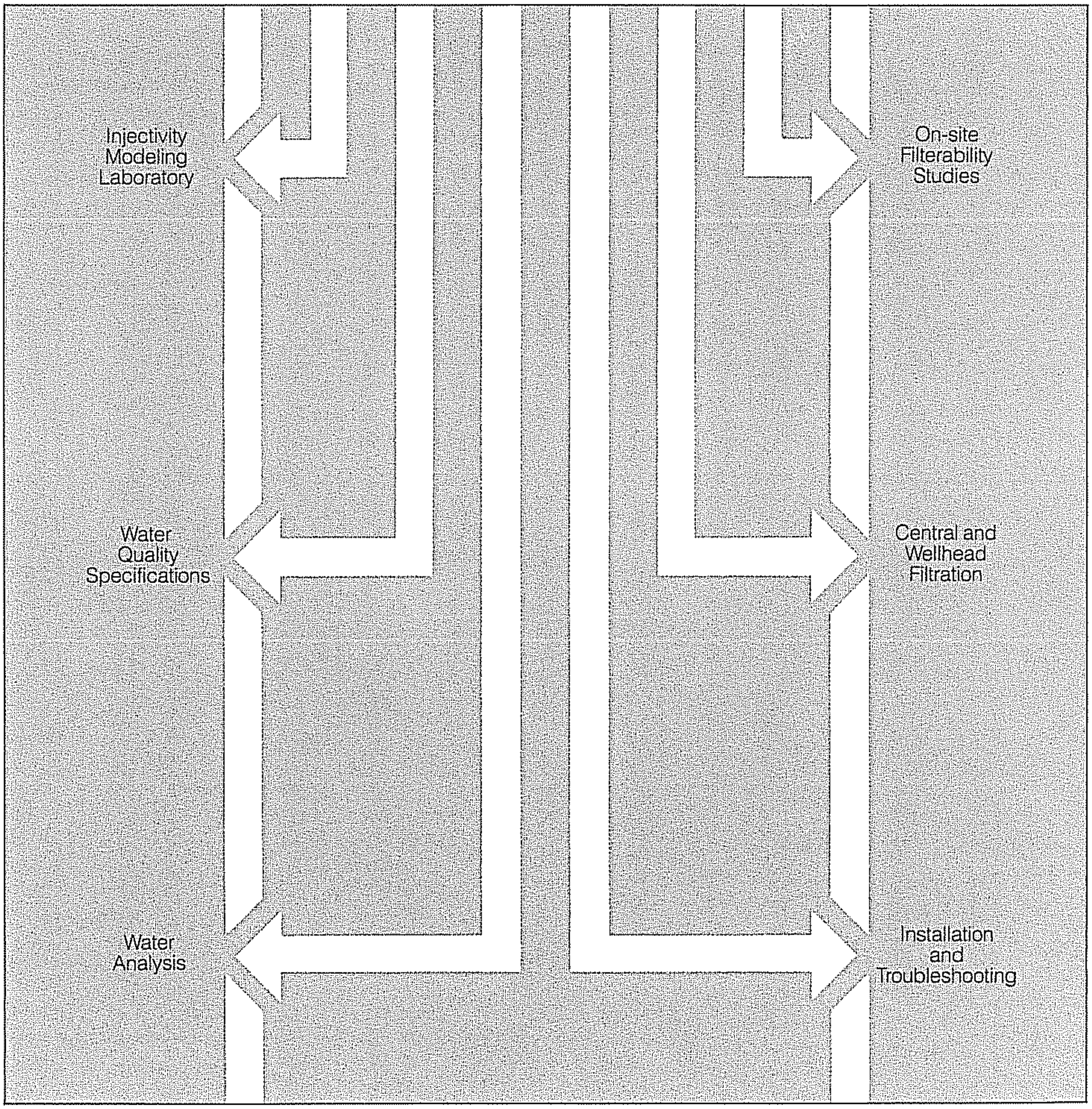
Performance removal test method: ______

Gasket material: ______

Recommended flow density (GPM/ft ^{2}): ______

Summary

A systems approach to better enhanced recovery



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