

Equipment Design Considerations for Lime and Ion Exchange Treatment of Produced Water in Heavy Oil Extraction

ROBERT HOLLOWAY, Holloway Associates
Etobicoke, Ontario, Canada

GORDON Page, Page Technology Ltd.
Calgary, Alberta, Canada

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INTRODUCTION

“Produced water is commonly treated by lime softening / ion exchange for use as feedwater. Tar sands projects are costly and cost control and sales competition can result in process misapplication or installation of under designed and underperforming equipment. Unplanned shutdowns and production losses can result. The risks can be reduced by good engineering decisions”

Extraction of oil from the tar sands in northern Alberta is accomplished many times by steam injection and recovery of the hydrocarbon along with the condensed steam or produced water. Table 1 shows the quality of typical produced water before and after treatment. After the oil is extracted, the water may be treated for reuse as high pressure steam generator feedwater by treatment with lime, magnesium oxide, supplementary chemicals, filtration and weak acid cation ion exchange.

The Alberta tar sands constitute the second largest oil deposit in the world and there are numerous mega-projects operating, expanding, under construction and in the planning stages. As a result, there are shortages in manpower and materials and fierce competition for available services. The results are delays in completion and startup, cost over-runs and lost revenue for the owners.

There are a large number of projects and the value of orders for treatment system orders makes for fierce competition to obtain contracts. This can lead to utilization of equipment designs in unproven applications, use of higher flow rates and loads in smaller equipment sizes as well as aggressive pricing practices by suppliers anxious to obtain contracts.

All of these factors can contribute to an environment where compromises are made to control project costs. Unproven technologies may be accepted and applied in hopes of eliminating steps in the process based on optimistic

projections of success. Such decisions have in some cases proven to be extremely costly when equipment and system failures curtail production.

At the current price of oil on the world market of approximately US \$60/barrel, a 30000 barrel/day plant loses \$ 1.8 million dollars per day revenue in the event of a shutdown. Obviously, extended plant shutdowns or restricted production of oil because of equipment failures are not a welcome occurrence.

The risks of unplanned shutdowns and production losses can result can be reduced by good planning and engineering decisions based on operating experience and knowledge of the processes and equipment.

Oil Removal

It has long been accepted in the water treatment industry that cold lime softeners could not accept influent containing oil because of flotation of light sludge particles to which the oil becomes attached. It is also accepted that hot lime softeners can remove some oil because the sludge is much more dense with higher solids content; i.e. 13% vs. 5% for cold lime. Claims for the ability of both warm and hot lime to handle oil contamination seem to be anecdotal and little or no solid data has been published to our knowledge. It should also be noted that any ability to adsorb a continuous, low concentration of oil doesn't necessarily impart any ability to cope with major excursions at high concentrations.

We are told the most common cause of excursions is unresolved reverse or micro-emulsions that pass through the deoiling plant untreated due to poor interface control in the oil/water separation vessels. These pass through the process because they are water external emulsions. If these upsets continue, and are not communicated to the water treatment plant operators, the result can be very serious.

Successful water treatment and maintenance of sufficient flow is of primary importance to maintaining steam and oil production. Ultimately, the ability to produce suitable quality generator feedwater at reasonable cost requires that oil contamination of the softening processes be prevented as much as physically possible.

Failure to remove the oil before primary lime softening can, or has, caused:

- Damage to the sludge rake and/or drive mechanism
- Oil contaminated sludge disposed of as hazardous waste
- Gross discharge of oil into the filters and weak acid cations
- Premature bed replacement in filters
- Major failure, and remote replacement, of rubber linings in vessels
- Contamination of resin and hardness leakage to the feedwater
- Short service runs to premature hardness break – greatly increased regeneration costs
- Cost of weak acid cation resin replacement

Increased waste water generation from backwashing and regeneration
Increased neutralization costs
Plant shutdown and oil production loss

It is our opinion that omission of oil removal filters in the separation process is due to uninformed knowledge, or inadequate assessment, of the risks involved. Oil removal filters should definitely be installed in the oil recovery plant following skim tank and induced gas flotation units.

Warm Lime Softening vs. Hot Lime Softening

It isn't possible to cover the differences and similarities of these alternate methods of treatment in this paper. We have studies comparing the two covering many aspects including capital, installation and operating costs. Proponents of each have very definite preferences and support their respective positions strongly. We will attempt to outline aspects of each that require attention in the initial stages of plant design that impact on system performance after start-up.

Hot Lime Softening

Hot lime softeners are pressure vessels generally designed for rise rates approximately 2.0 gpm/ft^2 of unit cross sectional area and having a treatment detention volume equivalent to one hour. The vessels normally contain an integral deaerator and deaerated water storage compartment. Clean and dirty backwash water storage may also be incorporated inside the vessel. The storage compartments are located in the upper regions of the vessel and are usually formed with conical bottoms grouped around a central cylinder that forms the chemical reaction zone.

At relatively low design flow rates the combination of reaction and settling zones with storage compartments usually results in a vertical cylindrical shaped tank with some length of straight cylinder between a hemispherical head and a partial hemispherical/conical bottom. See Figures 1 and 2. In this configuration, the design rise rate is actually achieved for several minutes within the straight side portion of the vessel shell before internal compartments begin to reduce the area of the settling zone. We cannot specify a maximum vessel diameter where the rise rate remains constant but have worked on units operating at 1100 gpm ($250 \text{ m}^3/\text{h}$) where this configuration provides excellent results.

As the service flow rates increase the required vessel diameter increases until the vessel becomes a "tear drop" shape with little or no straight shell required to provide one hour detention plus the storage volumes required. Units of this configuration have been as large as 42'-0" diameter in produced water service with capacities $> 2500 \text{ gpm}$ ($> 600 \text{ m}^3/\text{h}$). The largest unit of this configuration known to the authors is 52'-0" diameter and is in service treating produced water.

When the “tear drop” shape is achieved, the internal compartments impinge on the cross sectional area available for settling and it is no longer possible to calculate the rise rate based on the vessel diameter. In addition, the minimum rise rate is achieved only for an instant before it begins to decrease as the area is reduced. In some units with an apparent rise rate $< 1.9 \text{ gpm/ft}^2$, the minimum rate at maximum settling area is $> 2.3 \text{ gpm/ft}^2$ minimum. At the sludge bed control taps used by the operators, the rise rate increases to 2.7 gpm/ft^2 and is increasing rapidly above that point. This makes sludge bed level control difficult and increases carryover into the filters. See Figure 3.

The conical bottom of hot lime softeners usually has a contained angle of 76° which is ideal for sludge setting and withdrawal. However, the situation is made worse when a 90° sludge cone is used to reduce vessel cost. The compartments are located lower in the shell and rise rates are even higher at the sludge blanket control tap. See Figure 4.

Integral backwash compartments should provide a minimum of 10 minutes storage for backwash water storage at the rate required for backwash with water at the elevated water temperature. This should be a minimum of $15 - 20 \text{ gpm/ft}^2$ of filter cross sectional area. Some units contain only a dirty backwash water compartment. These compartments are often designed to drain by gravity into the reaction zone through orifices in the compartment wall, which plug easily with sludge. This method should not be accepted because of limits imposed on backwash frequency and volume. Positive transfer should take place in 60 minutes using a transfer pump. The standby pump can be used to reduce transfer time to 30 minutes if required to allow an increase in backwash frequency if necessary.

Warm Lime Softening

Warm lime softeners in produced water service have a sealed roof. See Figure 5. For this service, the design rise rates vary from $0.8 - 1.3 \text{ gpm/ft}^2$. This is usually calculated on the total diameter of the vessel without deducting the area of the rapid and slow mix sections. This is misleading as the rise rate should be calculated on the actual surface area at the outlet launders. For instance, in some designs the diameter of the slow mix hood is 25 -35% of the total tank diameter.

For example, an 85'-0" diameter unit with a 31'-0" diameter slow mix hood, at the water surface, and a design capacity of 4540 gpm has a rise rate of 0.8 gpm/ft^2 when calculated on the tank outside diameter. However, the actual rise rate is 0.93 gpm/ft^2 if calculated on the actual separation surface area. To meet a specified rise rate of $\leq 0.8 \text{ gpm/ft}^2$, the tank would be 90'-0" diameter.

Another important consideration at the plant design stage is provision for increasing treatment capacity. It is not unusual to require increased produced water treatment capacity of 50-60% sometime following initial operation. This

translates to a future rise rate of 1.2 - 1.3 gpm/ft² on the warm lime softener. While it is relatively easy to add filters and weak acid cations to the system, provided space is provided initially, it is difficult and costly to increase the outlet capacity of the warm lime softener. One such case investigated required shutdown of the clarifier to increase the volume of the slow mix zone and to increase the size of the turbine, turbine drive and sludge rake drive.

Therefore, it is prudent to request oversized turbine, turbine drive and slow mix zone at the specification stage. The slow mix detention time should be 20 minutes minimum at the maximum treatment capacity.

It is also important to ensure the turbine is completely level when installed. This should be a specified task of the selected manufacturer.

The sludge rake and drive mechanism must be heavy duty and sized for the maximum future capacity. It must also include protection against the sludge conditions that result when gross oil contamination occurs. The sludge can become thixotropic. In this condition the sludge is gelled, like thick pudding, and can cause considerable damage to the unit.

Some warm lime softeners have been supplied with peripheral effluent launders. This design leads to channeling and short circuiting in the settling zone and the full detention time is not realized. Only radial launders should be accepted and these should be designed for the future capacity. As the unit diameter increases, the number of radial launders provided should also be increased to ensure efficient effluent collection over the complete surface area of the settling zone. For instance, a unit 54'-0" diameter with (6) 8" laterals has 8.5 ft between the laterals at the slow mix hood and 23.7 ft between lateral at the shell periphery. More laterals would increase the efficiency of collection over the full settling area. It is equally important that the launders be leveled at installation.

The side shell height is almost constant regardless of softener capacity and diameter in order that the internal mechanisms and functional zones can be accommodated. As the diameter increases, there is a dramatic increase in the total detention volume and time. For instance, a unit 54'-0" diameter with 21'-0" water depth has a detention time of 2.0 hours while a unit 82'-0" diameter with 21'-6" water depth has a detention time of 3.5 hours at design capacity. The significance of these times is the effect on chemical control when operating.

The lime, magnesium oxide and other chemicals are usually injected into the rapid mix zone while the operating control tests are performed on the effluent as it exits the unit. There is a time lag equal to the detention time between chemical dosage being changed and the time the effect can be seen in the outlet. The response time to dosage changes can be very much reduced, and closer control achieved, if provision is made at the design stage to sample from either the draft tube (two minutes) or the slow mix zone (30 minutes).

Sample connections should be provided to cover the full range of the settling zone at intervals $\leq 2'-0"$ from 2.5' above grade to the low water level. Sample connections should be provided from just above the top of the slow mix zone and just inside the hood as well as from just under the slow mix zone close to the center. At least two sample connections should originate from the wall of the slow mix zone with two additional samples from the top and bottom of the draft tube. Sample valves should be designed and installed with plugged tees rather than elbows so that the pipes can be cleaned.

Warm lime softener performance is adversely affected by rapid changes in flow rates and the system flow, level control and treated water storage systems should be designed to limit such changes as much as possible. We have seen one recommended limit of 10% flow rate change per hour while one plant has set a requirement setting allowable flow rate changes to 2.5% per hour. For the most part, this standard is maintained.

Warm lime softeners are more likely to experience rapid changes in influent water temperature as other streams, such as waste pond supernatant and brackish water are blended with the produced water upstream of the softener. Rapid temperature changes affect the viscosity of the water and can cause major bed upsets and carryover into the downstream processes. The limit for temperature changes is 1°C per hour. All necessary instruments, controls, tanks and procedures should be installed and implemented to maintain this degree of control. A blending tank installed between the oil removal filters and the warm lime softener or use of the deoiled water storage tank can be of help in controlling temperature,

Systems should include external sludge recirculation pumps sized to provide $\geq 15\%$ of full treatment capacity to enhance treatment efficiency and reduce carryover. Flow measurement and flow rate control capabilities should be included.

Sludge inventory control is more difficult in units treating produced water because the units are covered by a roof and in some cases are nitrogen blanketed eliminating access for viewing the rapid mix zone and effluent. The operators are completely dependent on the sludge sample observations and effluent chemical tests in order to adjust control factors. Sludge level instruments for remote indication and monitoring have been successfully applied in cold lime softening and should be investigated for the elevated temperature application. Similarly, sludge density meters should be considered.

After Filters

Over many years we have seen the results of misapplication of unit processes or of exceeding accepted service flow limits in order to reduce equipment size and succeed in a sales negotiation. We can remember no instances where the former proved to be successful. However, in some instances accepted service flow limits

were too conservative and not supported by either theoretical considerations or operating experience. In other cases, misapplication of equipment and exceeding proven flow limits were expensive failures.

Anthracite filter medium following lime precipitation processes becomes heavily coated and fouled with the sticky precipitate. It can be very difficult to remove by simple hydraulic backwash. Gas injected before, or as part of, hydraulic backwash has proven to be of great assistance in increasing filtration efficiency and maintaining cleaner beds. In warm or hot applications, air cannot be used because of corrosion concerns. Process gas cannot be used in the water treatment plant where the filters are installed because of area classification regarding safety hazards. However, nitrogen could be used and is available on many plant sites. Extreme care must be exercised to vent the gas safely to atmosphere as nitrogen will not support life. Nitrogen scour valves and piping should be installed for special, manual scouring when needed.

In our opinion, the use of oil removal filters as devices to remove both oil and lime precipitates following either hot or warm lime softening is a bad decision. If the surfaces of the medium are coated with lime, it will be incapable of adsorbing oil. The purpose of the after filters is to protect the weak acid cation resin from lime carryover as much as possible so that very low hardness water can be produced for generator feedwater. The oil removal function should not be combined with the lime precipitate removal function.

Backwashing of filter beds used in warm and hot water service requires the use of higher cross-sectional flow rates than used in cold water service. The use of higher flow rates increases the costs of valves, piping, pumps and tanks necessary to store and dispose of clean and dirty water. Therefore, it is not uncommon to encounter equipment systems designed for backwash rates as low as 12 gpm/ft² of filter area for hot and warm water service. Some manufacturers offer equipment designed for 15 gpm/ft² of filter area.

The American Water Works Association (AWWA) generates a great deal of technical data on filtration every year concerning every aspect of filter operations including recommendations for backwash rates. Figure 6 shows the AWWA standard for rates as related to water temperature. The graph is self explanatory and shows the need to provide for adequate backwash rates to successfully clean the media.

In addition to applying the correct backwash rates to clean the bed, filters following lime softening operations, regardless of temperature, should each be backwashed every 24 hours based on time in service and not just on differential pressure. If high bed ΔP develops in less than 24 hours, that should initiate backwash but otherwise the time interval should apply.

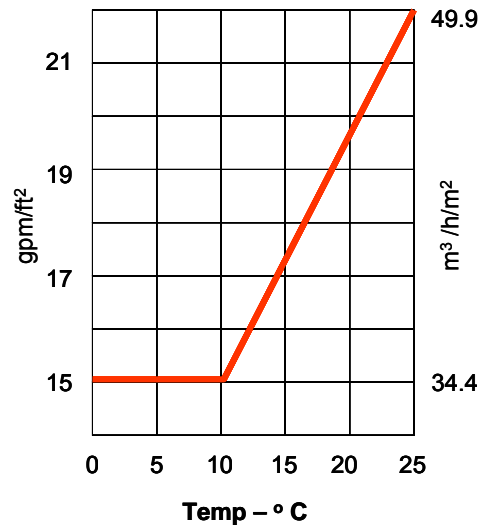


Figure 6 – Filter backwash Rate vs. Temperature

WAC Softeners

Very early in the plant design stages, a decision is required regarding the source of suitable regenerant dilution water for the plant start-up stage. Soft water must be available for generator feed purposes so steam injection can commence and produced water isn't returned for treatment for some time after start of steaming.

The WAC resin is supplied in the hydrogen form and cannot soften water to the required hardness concentration in that form. It must be converted to the sodium form by regeneration with caustic soda. If hard water is used to dilute the caustic soda, calcium and magnesium hydroxide precipitation will occur in the piping, units and resin and cause hardness leakage

If the system uses external regeneration, soft water is needed for the initial transfer stages as well as for regeneration prior to transfer. The use of rented sodium cycle cation units may be one solution but they must be on site and in service providing water to the treated water tank by the time of commissioning the filters and WAC systems. Alternately, obtaining one charge of WAC resin in the sodium form might be possible and would probably allow production of enough soft water to allow loading, transfer and regeneration of the balance of resin.

Particularly with external regeneration, it is beneficial to monitor resin bed level in the various forms in which the resin is found. This is necessary to monitor success of resin transfers and to maintain similar resin volumes in all vessels. 6" sight glasses must be located exactly and the use of 4" X 12" sight glasses would be beneficial with increased depth visible by use of overlapping locations.

Hydrogen – as furnished and after acid regeneration – smallest volume
 Calcium and magnesium – exhausted – 15% larger volume than hydrogen

Sodium – after caustic soda regeneration – 60% larger volume than hydrogen

External regeneration is beneficial to concentrate the need for high temperature, oil resistant rubber linings and Hastelloy internals to the external regeneration tank. In theory, because normal backwashing will not occur in the service vessels the freeboard can be reduced in the service vessels to reduce the tank costs. In fact, some freeboard is required for bed decompaction backwash prior to transfer and regeneration and after return transfer to level the bed. Therefore, freeboard must accommodate backwashing the resin in the swollen sodium form.

Incorporation of external regeneration requires careful study of important design considerations in the system chosen:

Completeness of resin transfer – it is well understood in the production of very high purity water for steam generation that the regenerated state of the resin at the outlet of the unit establishes the equilibrium that causes leakage of impurities into the effluent. Counter-current regeneration is employed to ensure the resin in contact with the water at the effluent is in a most highly regenerated state.

For the same reason, it is important to remove all exhausted resin from the bottom of externally regenerated working units. Exhausted resin left in the bottom and not regenerated causes high hardness leakage and this has been confirmed in working plants.

Underdrain design is of vital importance if the resin is to be transferred completely. Designs that use flat bottoms with header lateral systems may have features, such as header boxes, which inhibit resin movement. Multiple resin outlet points do not always solve this problem. Dished bottoms with bottom centre resin outlets may be more successful but resin can hold up on the sloped bottom particularly if contaminated with oil or lime precipitate carryover. See Figure 7.

Resin sluicing should include water flow from above the bed as well as significant fluidization flow through the underdrain. In addition, the regeneration cycle should include a settle step following transfer followed by an additional transfer step with high rate fluidization flow through the underdrain to move resin traces.

Because the resin regeneration vessel is usually of smaller diameter than the working columns the top and bottom sluicing flow rates required are higher for the working columns. In addition, the system should provide flow monitoring and control capabilities so that the rates can be varied to optimize complete resin transfer. Different rates should be settable for different diameter vessels. The additional, or second, transfer step should provide for different flow rate settings than the initial transfer step.

High fluidization flow rates may be necessary to sweep the resin off the bottom of the tanks and the resin transfer piping must be sized to accommodate the resin slurry transfer rates required at acceptable velocities. These rates must be sufficiently high to prevent resin settling out in the transfer piping but low enough to prevent damage to the resin. We recommend slurry flow rates be ≥ 5 ft/sec and ≤ 8 ft/sec.

6" piping has been successfully used to move almost a complete resin charge in 5-6 minutes but high sluicing flows are used. 2"-3" piping will also transfer resin successfully with lower sluicing rates and longer transfer durations but this may be insufficient to remove all of the resin. Slower transfer does give the operator an opportunity to confirm transfer is occurring to the appropriate receiving vessel and that resin is not being lost to the lagoon due to valve malfunction as happened in one facility. Piping and valve interlocks should be designed to prevent such an occurrence in automatic transfer systems.

The sluice water source is commonly the treated water tank and the treated water used is discharged to the waste pond from where it is reclaimed as part of the supernatant stream. This requires complete retreatment of a substantial amount of otherwise clean water. It might be reclaimed more advantageously upstream of the filters as long as flow rate upsets are avoided in the lime softener.

Resin transfer system – our experience with resin transfer for external regeneration or elution began with the uranium extraction plants installed in Elliott Lake, Ontario in the 1950's. That early and successful experience predates the use in condensate polishing systems in utility high pressure steam generation plants.

Many readers will know from experience that fluidized resin will escape rapidly through a broken underdrain strainer. The reverse is true if the resin is allowed to settle, compress and lose fluidization. It then becomes extremely difficult to refluidise in a hose or pipe and reinitiate movement.

Successful transfer without resin damage requires the application of certain standards, the first of which is "eliminate all possible impediments to free slurry movement". The second standard is "don't allow the resin to stop moving or settle out in dead spots" while the last is "do not use valves that close on resin or block the transfer in any way".

Resin transfer piping must never use right angle bends, tees or short radius elbows or bends. Long radius fittings are a minimal requirement and curved pipes with > 24 " radius of bend are much better. Where slurry leaves or enters a movement header, "Y" type connection should be used and piping should be continuous without flanges as far as is practicable. Resin transfer should employ only full bore ball valves.

Reliability of Regeneration - Most in-situ regenerated plants have multiple primary and polishing units. If one or more units fail for any reason, or must be taken out of service for maintenance, feedwater can continue to be produced with steaming maintained without difficulty.

If an externally regenerated system has only a single regeneration vessel, and a major problem is encountered that takes the regenerator out of service, production of feedwater stops once the feedwater tank is emptied. The system cannot function without a regeneration vessel. Externally regenerated systems should have two regeneration vessels plus a spare charge of resin.

This arrangement means regeneration should always be possible. Resin transfer takes approximately 5-15 minutes while regeneration takes ≈ 4 hours. With a single regenerator, a working column is out of service for ≈ 5 hours if regeneration proceeds without problems. With a second regenerator and a spare resin charge, a working unit can be emptied and returned to service in \approx one hour.

Use of a regenerated resin storage tank with a spare resin charge also will reduce the out of service time for a working unit but does not allow regeneration in the event of a regenerator tank failure.

Gas Scour of WAC Units

If the working units become fouled by lime carryover or oil, the gas scour would be very beneficial but nitrogen used at this point is subject to the same safety measures described for the filters. Nitrogen scour is a definite benefit in the regenerator vessel(s) where more complete resin cleaning can be accomplished.

Cost of Oil Fouling of Resin

The WAC units are typically 13'-0" diameter containing ≈ 330 cubic feet of resin in the hydrogen form. The cost of one regeneration is \approx \$1000 for hydrochloric acid and \$1500 for caustic soda. The number of regenerations varies with water analysis and effectiveness of lime softening but one unit regeneration a day with clean resin represents an annual cost of \approx \$900000. Premature hardness break because of oil fouling may reduce treated water volume by $\geq 40\%$ increasing the annual cost by a substantial amount.

In addition, a typical external regeneration produces $\approx 2 \times 10^6$ gallons of waste, including resin sluicing water, in a single working unit plus $\approx 2 \times 10^6$ gallons of regeneration waste. At one regeneration per day, the annual volume is $\approx 1400 \times 10^6$ gallons from an oil free system. Any increase in regenerations because of oil fouling of resin causes a proportionate increase in waste water production.

Most of this water, having been treated in the lime softener, must be captured and retreated again increasing the cost of operation.

Conclusion

The risks of equipment operating problems and plant shut downs can be reduced by reasoned decisions at the beginning of a project. Many desirable requirements can be incorporated at reasonable cost provided they are identified, negotiated and included before a contract is awarded. After contract award, changes and additions become more difficult and expensive.

Proposals should be evaluated very carefully to ensure all design and specification requirements are included. It should not be assumed that every supplier's offering is in compliance with the specifications.

If new technology is considered for use, or employment at higher rates of service than currently demonstrated, the supplier should be required to post a performance bond in the amount of 50% of the contract value. In the event a system does not produce the specified results, the supplier is given the opportunity to make modifications and improvements. If all attempts fail to produce the guaranteed results, the amount of the performance bond is passed to the purchaser or owner. We have had personal experience in providing such a bond and know it to be an effectual procedure in reducing the risk of employing new or improved technology.

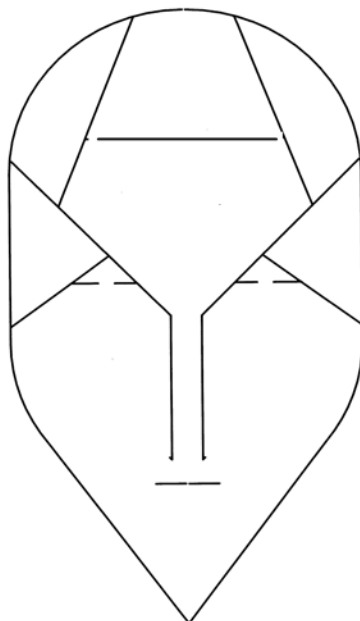
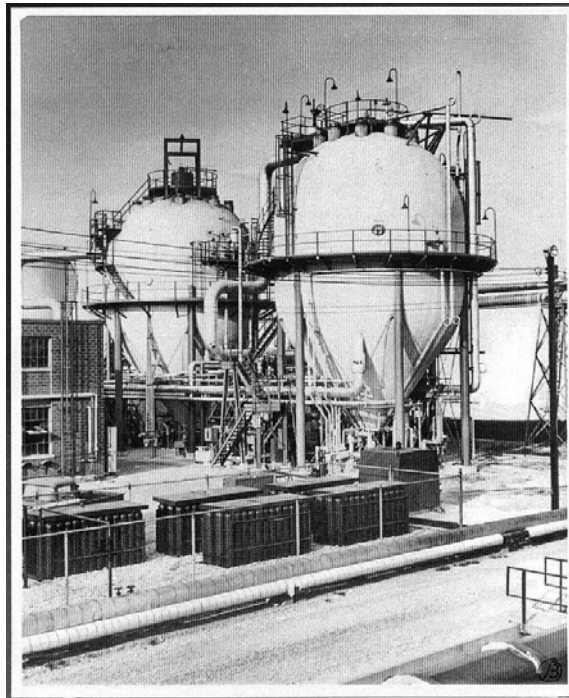
Table 1 – Produced Water – Raw & Treated

Constituent	Raw	WLS
Calcium	70	24
Magnesium	16	70
Sodium	4142	3924
Potassium	186	179
Lithium	8	8
Total Cations	4422	4205
Bicarbonate	476	44
Carbonate	0	406
Hydroxyl	0	0
Chloride	3384	3666
Sulphate	146	140
Total Anions	4006	4256
P Alk'y	0	203
M Alk'y	476	450
Carbon Dioxide	10.9	0.28
Silica reactive	330	40
Turbidity	6.9	8.9
Dissolved Solids	5528	5106
Conductivity	8505	7855

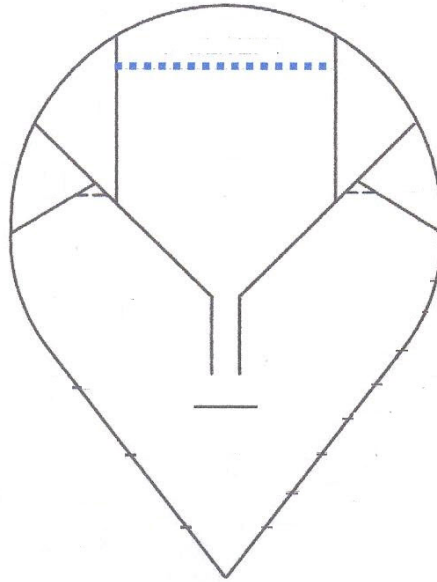
pH	7.9	9.5
TOC	180	148

Treatment consists of lime, magnesium oxide, flocculant and coagulant

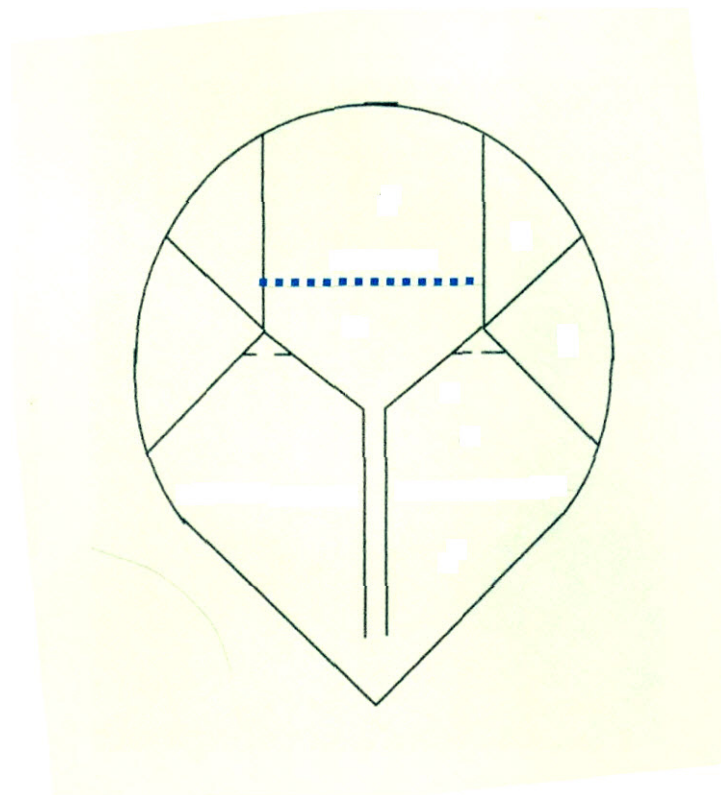
Figure 1 – Hot Lime Softener



**Figure 2 – Hot Lime Softener
with Straight Shell**



**Figure 3 – Hot Lime Softener (Tear Drop)
with 76° Sludge Cone**



**Figure 4 – Hot Lime Softener (Tear Drop)
with 90° Sludge Cone**

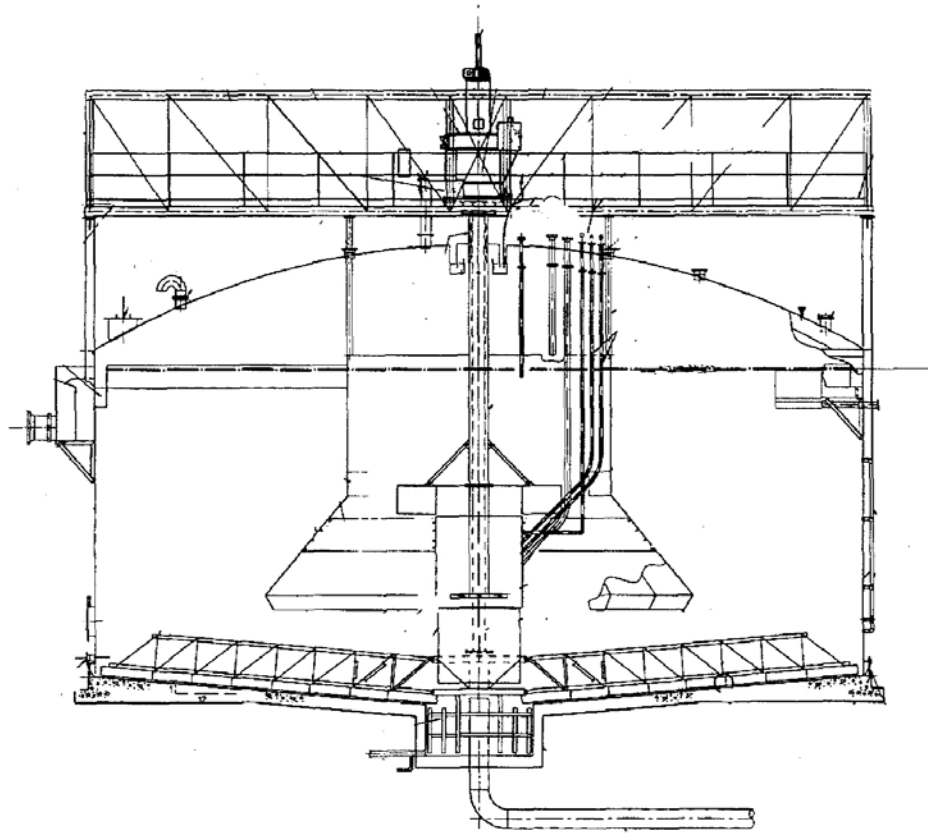


Figure 5 – Warm Lime Softener

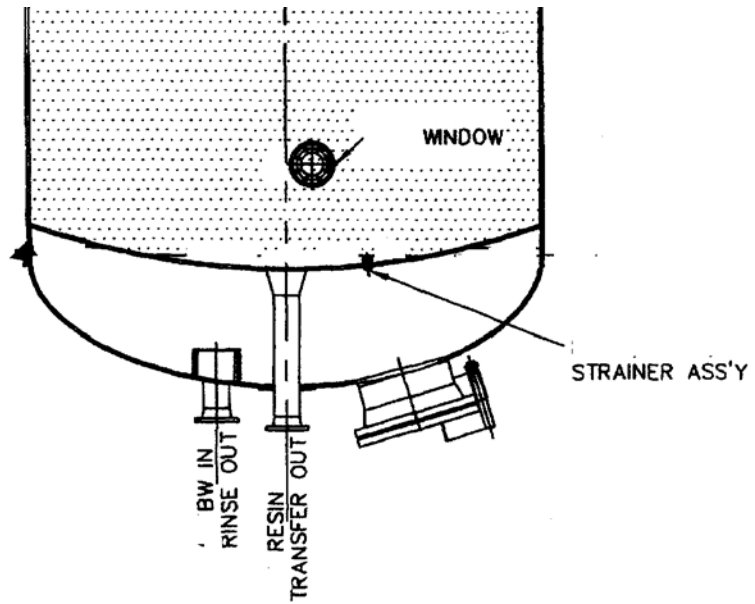


Figure 6 – Dished Bottom Underdrain WAC