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THE CONTROL OF SCALE AND CORROSION IN WATER SYSTEMS USING MAGNETIC FIELDS

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ABSTRACT

A theoretical discussion of the mechanism of applications of magnetic treatment of water to control scale and corrosion is presented. The results of magnetic treatment in actual installations is given. This includes air conditioning and boiler systems, and industrial processes under operating conditions. The efficacy and cost effectiveness of the magnetic treatment is demonstrated.

INTRODUCTION

It is well known that the formation of solid deposits of scale in heat exchanger systems where liquids of different temperatures are in contact with pipes and walls of containment systems is a universal problem. The costs for control of scale and corrosion is very large. Chemical treatment has been the principle method used in treating to prevent and to remove scale, and corrosion. However, it is very expensive in time and money, and in the past few years has fallen into disfavour because of the ecological pollution problems associated with it. In addition, the effectiveness of chemical treatment is questionable as evidenced by the very large costs for the periodic cleaning in systems that are treated chemically, supposedly, to prevent the scale formation; and by the damage that improper chemical treatment often causes. The damage occurs primarily because effective chemical treatment requires continuous accurate monitoring by professional personnel. Whereas, in most cases the treatment is done by personnel with absolutely no training in chemistry, who use the theory that, "if *x* gallons of chemical are prescribed, then twice as much will be twice as good". This philosophy, as one can well imagine, produces disastrous results many times by actually causing scale formation from the chemicals added, such as, in precipitation in the boiler feed line. This is well documented (1).

This philosophy can cause extensive corrosion when strong acids or bases are used for either alkalinity control or cleaning. And even more seriously, the improper use of strong bases can lead to caustic embrittlement of the metal, which in some cases has resulted in boiler failures.

In addition to the above, scale is costly because of the energy losses caused by it. It has been shown (2) that the heat transfer coefficient is reduced 8% by a scale thickness of only 0.01 inch (.0254 cm) and by 38% for a scale thickness of only 0.1 inch (0.254 cm). For silica scale, the heat transfer coefficient is reduced 88% and 95% for these same thicknesses.

Several papers have been published in the past that have been very critical of non-chemical treatments. These papers are characterized by frequent use of the words "fraud", "gadgets", "cure-alls", "devices", etc. in an attempt to discredit the non-chemical treatments. Also, these papers were written by employees of chemical companies selling chemical water treatment or by consultants supported by these companies. A paper by Dromgoole and Forbes (3) is typical, and contains references to earlier papers. The results presented herein refute the allegations in the earlier papers. To substantiate this, the results were obtained independently by plant operating personnel during normal, real-life operating conditions of their equipment. It is a tribute to the personnel because it is very difficult to obtain data under such conditions since their first priority is to provide service and keep the system operating; whether to supply heat or cooling to a building, or keep a process going. To illustrate the universality of using magnetic fields to control scale and corrosion the results obtained on several different types of systems are included.

BACKGROUND. Permanent magnetic type units were used in all cases. The magnetic unit was installed in-line, in the system so that it was as close as possible to the area where the scaling problem was most severe, and so that it treated all of the water going to that area. In some cases a bypass was installed to allow inspection of the magnetic unit without having to shutdown the system. The operating personnel at each facility were thoroughly familiar with the operation of their systems both before and after the installation of the magnetic unit. They supplied all the data given in this report.

THEORY. The following summarizes the proposed mechanism of behavior of the magnetic treatment using this unit. It is based on the principle of magnetohydrodynamics (MHD). The energy put into the solids through the MHD effect increases the surface energy and solubility of solids and decreases the particle size. The water contains charged particles in the form of positive and negative ions (Ca^{+2}, Mg^{+2}, $Na^{+,}$ $CO_3^{--2,}$ HCO_3^{--},, $S0_4^{-2}$, Cl^{--}, etc.) and small solid particles that pick up electrostatic charges. These charged particles are energized by the magnetic field due to their motion. This is analogous to the electrons in a copper wire which are energized when they move through a magnetic field in an electric generator. In electric and conventional MHD generators, highly energized electrons are led into an external circuit where they are utilized as electricity to produce mechanical, thermal or radiative energy. In the case of water treatment, however, the energy is allowed to remain with the particles in the water.

The energy that the magnetic field adds to the particle actually comes from the momentum of the particle. The interaction of the charged particle with the magnetic field slows the particle. Eliassen (4) erroneously suggested that the energy comes from the magnetic field and depletes it. In actuality, the energy ultimately comes from the pump because it has to work harder to pump the fluid in the presence of the magnetic field. This is analogous to an electric generator, which slows down as the electrical load is increased. The steam turbine (analogous to the pump) has to work harder to produce the electricity to run the load.

Very little total energy is absorbed by the particles because they are present in very low concentrations (ppm), but the effect of this energy is very great because a very large amount of energy per particle is absorbed. It has been shown (5) that small crystals of barium sulfate are about 1000 times more soluble than large crystals and have much higher surface energy. Thus, a great deal of energy is required per particle to solubilize them.

At these low concentration and saturation levels the solutes tend to form precipitates slowly from solution and form large well ordered crystals. That is why scale takes a long time to form and forms large, hard, dense crystals. The large crystals have a low surface energy relative to small particles. The small particles in the water have a higher surface energy and are more soluble than large particles. They normally tend to aggregate and form into large particles, because all systems in nature in accordance with Le Chatelier's principle, tend to seek the lowest energy level, i.e. small particles with high surface energy tend to form large particles with lower energy. However, since the magnetic field increases the surface energy of the small particles and causes them to remain small and highly soluble their tendency to form a precipitate is greatly reduced. If scale already exists in the system, the small energetic particles will give up some of their energy to the scale and cause it to dissolve. This is a slow process because the concentration of the species that carry the energy is low and because it requires more energy to dissolve scale in the presence of a saturated solution.

The magnetic field induces the scale forming species to either remain soluble and be discharged with the bleed or blowdown in the system, or to form small particles which settle in low velocity portions of the system where they can be easily removed. Ryback (6) showed that magnetically treated water precipitated a mixture of 70% aragonite and 30% calcite, while untreated water precipitated 80% calcite and 20% aragonite. Calcite is a dense, rhombohedric crystalline form of calcium carbonate, and aragonite is less dense orthorhomboidal form. The predominant formation of aragonite with the magnetic treatment forms the softer scale. This also demonstrates that adding surface energy to the particles effects their chemical behavior by altering their crystalline structure.

Although this theoretical treatment is very helpful in designing installations, it is not possible to predict the quantitative results in any one system because of the tremendous variability in all the important operating parameters**:** composition of feed water, metal composition, temperature and velocity fluctuations, on-off cycles, etc.

It is interesting to note that Eliassen (4)said that 1,000,000 gauss, which is equivalent to 5000 joules/ml, is needed to dominate the motions of charged particles within atoms, and reported that the magnets used in the water conditioners they tested produced an energy density of "only" 0.5

joules/ml (33 BTU/lb). They concluded that the magnetic field therefore could not have a chemical effect on the scale. Their reasoning is fallacious for several reasons. First of all, the Zeeman effect, in which electron energy levels in an atom are split is demonstrated with only 5000 to 15,000 gauss. Secondly, they assumed that the energy went into 1 ml of water. It actually only goes into the charged particles. This is equivalent to an energy input of 390 joules/ml (17,200 BTU/lb) at 100 ppm concentrations of charged particles, which is certainly enough to effect chemical behavior. Eliassen also said that a claim made by a manufacturer that a permanent magnet will not lose energy as time goes on is false because, according to Eliassen this violates the Second Law of Thermodynamics which, again according to Eliassen, maintains that energy taken up by one body must be given up in like amount by another body**....** the energy cannot come from a permanent nonexpendable source. He then talks about an electromagnet that keeps "leaking" out its magnetic field. He implies that the permanent magnet will lose its strength as it gives up energy to the water. If this were true a permanent magnet type electric generator would not last very long. This analysis is also fallacious, especially as applied to magnetic treatment of water because the energy comes from the pump, which is pushing the charged particles through the magnetic field. It simply has to push a little harder than if no charged particles were present.

CHARACTERISTICS OF THE MAGNETIC UNIT The most important parameters that determine the behavior of the magnetic units used in this study are**:** 1) the strength of magnetic field; 2) the velocity of the charged particles in the magnetic field; 3) the direction of the velocity of the particles relative to the lines of force; 4) the charge on the particles, and 5) their concentration. More energy is imparted to the particles by increasing the field strength, the velocity, and the charge on the particles. It is also increased by having the charged particles cross the magnetic lines of flux at right angles. The concentration is controlled by the bleed in air conditioning systems., or the blowdown in boiler systems. These have all been optimized in the design of this unit.

The magnetic design was chosen because it is most effective and requires the least maintenance. Historically, electromagnets were used (7,8) and are still being used in Soviet Union (9-11). They are expensive to build and run because they need large coils that use a lot of electrical power- to provide the strong magnetic fluxes that are necessary. They need to be water cooled to prevent overheating. They require constant maintenance to make sure the electric power is on and the cooling water is flowing. This can be a serious problem in remote locations because if the power goes off the unit won't function, and if the cooling water goes off the coil will burn out. The voltages used also present a potential shock hazard.

Another type of water treatment uses electrostatic charge. In these units a high voltage is applied to electrodes that are directly in the water flow. They require constant maintenance to make sure that the power supply functions, and that voltage leaks don't occur. The latter represents a serious shock hazard. In normal use a thin film of scale forms on the electrodes. Since scale is an electrical insulator, it must be removed or the unit will stop functioning. Some designs incorporate an ultrasonic generator to keep removing this film. However, this simply makes the system more complex, more costly, and more difficult to maintain. A thin film also forms on the magnets in the magnetic unit, but the film is transparent to the magnetic flux and does not affect the operation of the unit. If magnetic debris gets into a magnetic unit it can short out the magnetic field. Magnetic debris usually comes after work has been done on a system and consists of nuts and bolts and pieces from welding. The magnetic and nonmagnetic portions of debris collected from a magnetic unit in a sugar mill are shown in Figure 1. The debris was pieces 1/8" to 1" in size that were magnetic because the magnetic and non-magnetic components were intimately mixed. The debris can easily be removed if it gets in or it can simply be prevented from getting into the magnetic unit by providing a strainer. The magnetic type does not require any external power source, and the permanent magnets will last indefinitely. As mentioned earlier, very little energy is absorbed because only charged particles, which are present in low concentrations, absorb the energy; and the small amount of energy that is used comes from the pump, not from the magnets.

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TREATMENT IN AN AIR CONDITIONER CONDENSER

A magnetic unit was installed in the condenser inlet line of a 300 ton air conditioner. The measured flow of 1100 gpm was close to the optimum rated flow 1200 gpm for this unit. The following parameters were recorded three times per day: current consumption, temperature differential of the condenser water and the compressor bearing temperature.

Initial inspection of the condenser prior to installation of the magnetic unit revealed 1 mm coating of very hard calcium carbonate scale. This condenser had been running many years without any chemical treatment. Representative range of analyses of the feed water and tower water are shown in Table 1. After three months operation with the magnetic unit, the condenser was opened again. The scale in the tubes was noticeably thinner and softer. The condenser was closed and mild steel corrosion coupons were put in the condenser water of this air conditioner and in an identical one nearby that was using untreated water. After three more months the condenser was opened again. The character of the scale had altered significantly. The most important change was in its hardness. The scale was considerably softened. This is shown in Figure 2. The close up photo of the condenser tubes shows two tubes where the scale was wiped out with a finger. These tubes are defined by the intersection of the horizontal and vertical arrows on the figure. The scale could have easily been wiped out of all the tubes with a soft brush. The inside of the magnetic unit is also shown in Figure 2 to show that some scale normally forms in the unit, and that the scale is soft enough to wipe easily with a finger. The corrosion rates are expected to be high because of the high chloride concentrations (Table 1). It is actually like a dilute sea water. However, the treated tower showed a corrosion rate of 0.206 mm/year (8.1 mpy), which is well within the customary accepted limits of .076 to 0.254 mm/year (3 to 10 mpy). On the other hand, the corrosion in the untreated tower was .4 37 m m / year (17.2 mpy) which is almost twice as high as the acceptable limit. This reduced corrosion in the treated tower is shown in Figure 3. The corrosion coupon on the top was in the untreated water and shows much more corrosion visually. The reduction in corrosion was also evident by the color of the scale, which changed from rust color to white, due to reduction in formation of the iron oxide.

During the first six months of operations, the current decreased from 145 to 125 amperes, the bearing temperature decreased from 142 to 132^{O}F (61.1 to 55.7^{O}C), and the condenser water temperature differential increased from a range of 2 to 4^{O}F (1.1 to 2.2^{O}C), to a range of 4 to 6^{O}F (2.2 to 3.3^{O}C). These improvements in performance are even more significant when it is realized that the test started in December, and that the cooling load actually increased from its annual minimum to near its maximum.

The annual savings in electrical power were estimated to be about $7,000. The cycles of concentration was increased from 1.8 to 12 cycles which resulted in an estimated annual savings of $5,376 in water and sewer charges. The total measurable annual savings were $12,376. The lower current consumption and lower bearing temperatures indicate that there will be less wear on the compressor. This results in additional savings though it is not possible to estimate the amount.

It is interesting to note that the tower had been running at 1.1 to 1.8 cycles concentration for five months prior to the installation of the magnetic unit. It is a commonly accepted notion that the scale should have dissolved during that time, but it was still thick and hard as concrete. On the other hand, after three months with the magnetic treatment at the similarly low cycles, the scale was much softer and thinner. In addition, the air conditioner was run at higher cycles (from 5 to 33) for the next three months with the magnetic treatment. Again, it is commonly accepted that more scale should have formed during this period, while actually it continued to be removed. Towards the end of the test period in June the magnetic unit was operating very close to its optimum conditions. It was operating at 1100 gpm and 2855 ppm TDS, while optimum is 1200 gpm and 2500 ppm TDS.

TREATMENT IN A SUGAR MILL

A series of sequential steps are followed in processing sugar cane into raw sugar. The sugar cane is pressed to remove the juices. The solid material (bagasse) is discarded or used as a byproduct. The juices are treated with lime and heated to precipitate impurities. Flocculants are added and the juice is filtered. This clarified juice is fed into a series of vacuum evaporators (called bodies) where the water is removed. The incoming juice is concentrated from about 15% solids to about 65% solids. During the evaporation residual inorganic solids from the soil and from the lime treatment precipitate on the tubes of the evaporators.

Evaporators must be shut down every few days to clean the tubes. The scale is removed by treatment with boiling caustic and acid. In this plant the boil-outs took 10 to 12 hours. It is very costly in terms of chemicals used, time wasted, lost production, and damage to the system by the harsh chemicals.

Any reduction in the scale formation would be extremely beneficial. Hugot (12) reported the use of a magnetic unit and an electric unit in sugar mills to reduce the scale formation. Meade and Chen (13) reported on the use of an ultrasonic descaler. They compared two identical evaporators running in parallel; one with the treatment and one without it as a control. After 14 days operations, the treated evaporator had about 1/3 as much scale as the untreated evaporator (85g vs 189g scale per tube, and .26 mm vs .65 mm scale thickness respectively).

In view of this, magnetic units were installed in a sugar mill in Louisiana. It was installed to treat the juice entering the first body. The flow rate of the juice varied from 500 to 700 gpm. After eleven days running the amount of scale was less than normal, and it was soft. The scale was removed more easily with caustic, but some acid treatment was needed to clean all the scale. In the next run, of ten days duration, the amount of scale was again lower than normal and it was soft. This time a short treatment with acid removed the scale, and the caustic treatment was eliminated. However, even though the amount of scale in the fifth body was reduced it was more than was desirable.

Another magnetic unit was therefore installed to treat the syrup as it entered the fifth body. The next run lasted $2^{1}/_{2}$ weeks. It should be noted that before installation of the magnetic unit, the runs usually lasted 3 to 4 days before shutdown due to scaling. The tubes after this run are shown in Figures 4A to 4G. Figures 4A and 4F show the tubes in the first and fifth bodies respectively, before a run, and just after being cleaned with caustic and acid. They are clean but the harsh affect of the acid was evident by green copper corrosion product in the tubes. The remaining Figures 4B to 4F show the tubes in bodies 1 to 5 after running $2^{1}/_{2}$ weeks. The tubes in the first body (Figure 4B) appear to be greatly scaled, but this is actually a small amount compared to run without the treatment. And even more importantly, the scale is soft and easily removed. To show the softness, the tube shown in the middle of Figure 4B was scratched with a fingernail. All the scale in the evaporators was removed by a 45 minute treatment with acid. This is a great savings in time and money from normal cleaning which was two hours with muriatic acid and six hours with caustic, which took ten to twelve hours including several filling, heating, emptying and rinsing cycles. Very little scale formed in the second body (Figure 4C) and no scale formed in the third, fourth and fifth bodies (Figures 4D, 4E and 4F). In fact, the fourth and fifth bodies looked better after the run than before it because the corrosion was removed, and no new corrosion formed.

In this particular sugar mill, without the magnetic treatment, the deposits in the first bodies were calcium scale, and usually a silica scale formed in the last body. The scale in the fifth body was the biggest problem. It was very tenacious and difficult to remove. However, with the magnetic treatment this scale did not even form. The reduction in scale in the system manifested itself in the improved economic performance of the mill. The production figures for that season are shown in Figure 5. The season usually lasts from about 35 to 65 days.

The curves in Figure 5 show the variation in the Brix* of the syrup production from the fifth evaporator during three consecutive seasons. The top curve shows the. significant increase in output after the magnetic unit was installed. This resulted in a savings of $1^{1}/_{2}$ times the cost of the magnetic units in one season. The unit functioned just as well the next season.

* Brix represents the percent of solids in the solution.

The first season was very short---38 days compared to 52 and 62 days for the two previous season. The cost savings would have been about $2^1/_2$ times the cost of the units if the season had been longer.

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LARGE SCALE CHEMICAL PROCESS COOLING SYSTEM TRIAL

This chemical plant has several hundred large water cooled shell and finned tube condensers with surface areas ranging from 37 to 1300 sq m (400 to 14,000 sq ft). Maintaining a high efficiency of heat transfer is extremely important because the cooling capacity limits the production of the plant. The plant used raw Ohio River water clarified with a flocculant. The cooling system water was treated with chromate, and the pH was maintained slightly acidic. Even with this treatment the condensers became fouled with calcium carbonate scale. They were cleaned by a sand slurry procedure that: is effective but expensive .

The flow rate was measured with a 10-point pilot traverse, and the inlet and outlet temperatures of the water and the refrigerant were measured with calibrated platinum RLDS. The operating conditions during the test were similar to those immediately before the installation of the magnetic unit. The flow rate was 2.8 fps (240 gpm).

A badly fouled condenser, 218 sq m (2350 sq ft area) that was part of the system of condensers was chosen for the test. This condenser had been running several years and had not been previously cleaned. There was considerable scaling in the two-pass head and some of the tubes were blocked.

There was a noticeable improvement in the heat transfer performance during the seven month trial period (See Table 2). The heat transfer coefficient increased by 13.6%; (from 71.2 to 80.9 BTU/hr-ft ^{O}F) and the tube side fouling factor decreased by 23.7% (from .00196 to .00150 hr-ft ^{O}F/BTU). Visual inspection showed that the amount of deposits in the head boxes was reduced and some of the tubes that had been plugged at the beginning of the test were opened.

TREATMENT IN A BOILER

A magnetic unit was installed in a water tube boiler. The boiler was rated at 5357 kg/hr (6 T/hr). The magnetic unit was mounted in the outlet of the feed pump. During the test no chemical treatment was used. The efficiency of the boiler was calculated every day. The monthly averages of the efficiency is shown in Figure 6. The efficiency increased continuously from 85.93 to 87.53% over a four month period from July 25 to November 25. The increase in efficiency of 1.6% represents a substantial savings in fuel costs. Samples of the feedline pipe were removed each month. They are shown in photograph in Figure 7. The internal diameter of the pipe was measured and the scale thickness and heat loss due to the scale were calculated. The results are shown in Table 3. The I.D. of the new pipe was 53.2 mm. Before the test, the pipe had 3.37mm of scale in it (its I.D. was 46.47mm).

After 123 days of treatment the pipe I.D. increased to 51.3mm, the scale thickness decreased to 0.95 mm.

These are very significant improvements. Although, this occurred in the feedline pipe, similar scale removal and improvement in heat transfer obviously took place in the boiler tubes resulting in the increase in efficiency. The quantitative effect of increasing heat transfer on the increase in efficiency depends on the system. However, the 1.6% increase in heat transfer is reasonable, and well within the ranges reported in various installations (14). It is also significant to note that the operating engineer of this boiler reported that the boiler had not shown an 87% efficiency at least within the previous three years.

TREATMENT IN A STEAM GENERATOR

A magnetic unit was installed in a steam generator in a railroad car. The steam, generators are used to heat the railroad cars in the winter. The steam generator was a Model OK-4740 manufactured by the Vapor Corporation, Chicago, Illinois, Figure 8. The capacity of the boiler is 2180 kg/hr (160 HP). It has a beating surface of 22.7 sq m contained within five coils connected in series. Its rated operating pressure is 280 to 1925 Kpa (40 to 275 psi). The test period covered 3 months and 25 days from November 16 to March 11. Untreated city water was used for the makeup. The steam generator had new coils at the beginning of the test. The coils were not cleaned during the 115 days of this test period. whereas, the coils in the other steam generators had to be cleaned every 15 days in order to function. The five copper coils are shown in Figure 8D to 8H as they appeared after the test. They had a small amount of deposit in them, 2.85, 1.75, 0.25, 0.25, and 0.25 mm in coils 1 to 5 respectively. The deposit was a soft sludge that could have been easily removed by blowdown. By contrast, the scale in the coils in the untreated steam generators was hard and could only be removed by severe chemical treatment. In addition, no corrosion was evident in the treated steam generator. (The deposits were white, rather than red). The steam generator that had no magnetic treatment showed evidence of corrosion from the usage and from the chemical cleaning treatment.

It was concluded that the elimination of chemical treatment, and reduction in coil cleaning and corrosion represented substantial cost savings over the winter heating period, in addition to the improved convenience of having less downtime on the railroad cars.

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CONCLUSIONS

It was concluded that the magnetic unit used in these tests was very effective in controlling scale and corrosion in water systems, in such diverse applications as, a large air conditioner condenser, syrup evaporators in a sugar mill. cooling exchangers in a large chemical processing plant, in a boiler and a steam generator. Significant savings in time, cost and equipment were effected in all cases.

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TABLE 1: REPRESENTATIVE RANGE OF ANALYSIS OF FEED AND TOWER WATER

		Feb. 13		June 8	
		Makeup Water	Tower Water	Makeup Water	Tower Water
Phenolphthalein Alkalinity	P	14	0	12	24
Total Alkalinity	M	32	44	48	164
Hydroxide Alkalinity	OH	0	0	0	0
Carbonate Alkalinity	CO_3^{-2}			24	48
Chloride	Cl^-	108	172	120	1792
Total Dissolved Solids	TDS	202	284	218	2855
Total Hardness	$CaCO_3$	68	100	108	848
pH		8.4	7.5	8.8	8.5
Cycles of Concentration			1.5		14.9

ALL UNITS EXCEPT "pH" AND "CYCLES OF CONCENTRATION" ARE IN PPM.
Alkalinity and Total Hardness expressed as $CaCO_3$

TABLE 2: RESULTS OF COOLANT CONDENSER PERFORMANCE TESTS WITH MAGNETIC WATER TREATMENT

Heat Trans. Coeff. U(BTU/hr-ft^2-F)	Tube-Side Fouling Factor (hr-ft^2-F/BTU)
71.2	0.00196
73.6	0.00191
75.4	0.00174
72.2	0.00180
72.4	0.00182
78.9	0.00154
81.0	0.00148
76.2	0.00172
76.6	0.00168
80.9	0.00150

Table 3.   Removal of Scale in Feed Line Pipes , and Increase in Heat Transfer.

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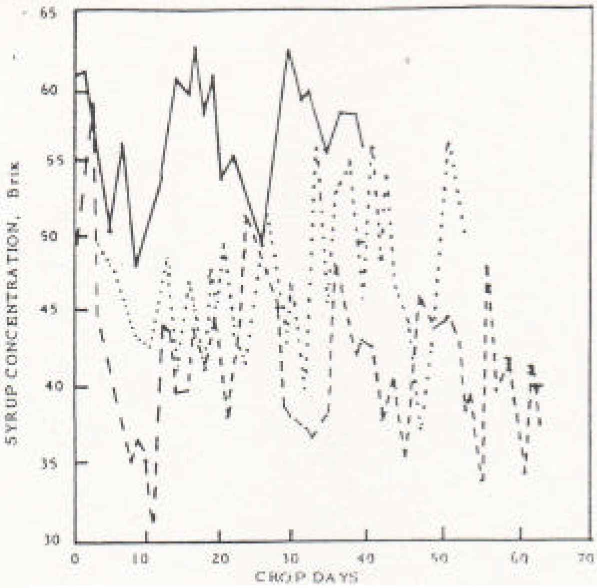
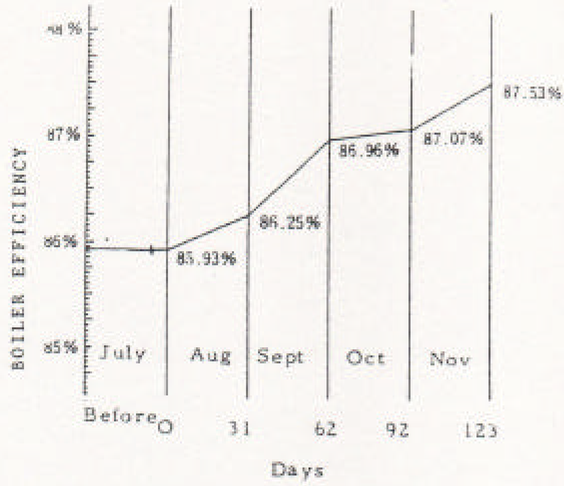
Days	Pipe I. D. mm	Scale Thickness Difference mm	Heat Loss %	Flow Rate l/hr
New Pipe	53.2	0	0	170
Before	46.5	6.7	39	130
31	48.2	5.5	28	139
62	49.6	3.6	22	148
92	50.2	3.0	19	160
123	51.3	1.9	17	164



5. Sugar Mill Production With and Without Magnetic Treatment.



6. Boiler Efficiency During the Test Period With Magnetic Treatment.