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Electrical conductivity as a novel technique for control of lime softening process

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ABSTRACT

Lime softening is a well-established process for partially separating of hardness ions from water. Currently, the lime softening process is adjusted manually based on chemical titration tests aimed at maintaining the simple and total alkalinities in a certain range. Analysis of experimental data from bench and full-scale lime clarifier showed that the current control based on alkalinity is often not correct. It was found in this work that electrical conductivity (EC) can be used as a good indicator for evaluating the performance of lime clarifiers. Therefore, an eco-friendly and very cost effective alternative technique based on EC is introduced in this paper for successful control of lime softening process.

Keywords: Hardness; Lime clarifier; Control; Alkalinity; Electrical conductivity

1. Introduction

1.1. Water softening

The hardness in water causes a cost of millions and even billions of dollars annually due to heat loss and scaling in boilers, and heat exchangers [1,2]. Hardness has also fouling effects on reverse osmosis and other desalination units [1]. Separation of hardness ions from water is called softening. Water softening is almost a common unit operation in many industries and makes the water suitable for using in cooling operation or prepares it for additional purification. Although total or partial removal of hardness ions is possible in various processes such as reverse osmosis, electro dialysis, distillation or freezing, most industrial plants solve their water hardness problem by using two familiar separation processes: sedimentation (lime or lime/soda) and adsorption (ion exchange) [2,3].

Although the high pH associated with excess softening provides alkaline toxicity to bacteria [4] and virus removal and/or deactivation [5,6], pathogen removal is not the main interest for industrial water. Currently, many lime clarifiers use only lime instead of lime-soda as other methods for removing non-carbonate (permanent) hardness are more attractive [3].

Control of softening process is important for a number of reasons. First, consistent quality of the treated water with minimum hardness is most desirable in every industry. Second, optimal control results in minimum solid waste that must be disposed of. Finally, it can reduce the operating costs of water treatment.

It is unanimously accepted that pH has a vital role on the performance of lime softening. However, as the pH does not change in a decisive trend, alkalinities

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are currently controlled as an indicator for optimum operating conditions. This is usually achieved in lime clarifiers by regulating working conditions in such that twice the P-alkalinity of treated water be a little greater than M-alkalinity [2,3,7], i.e. (2*P*-*M*) must be about 5 ppm as $CaCO_3$.

Universal practices indicate that many lime clarifier operators feel that this is not enough reliable condition and they usually check concurrently other operating parameters such as pH and hardness [2,3]. However, in spite of its shortcoming, alkalinity method of control is currently used and a considerable amount of chemical wastewater is generated during various titration tests.

1.2. Electrical conductivity

Electrical conductivity (EC) of water represents solution's ion conductivity and is usually expressed as mhos per centimeter (mho/cm), often called Siemens per centimeter (S/cm).

The utilization of conductivity to oversee the chemical process in liquid phase is itself not a new finding of this work. EC has been utilized in the past as a means of controlling many processes such as, regulating the rate of blow down in power plants or for characterization of colloidal gas aphrons as reported recently by Moshkelani and Amiri [8].

A known lime addition process similar to softening is called alkalinity reduction in scientific literatures. Both processes use lime but for two different targets. The primary purpose in softening process is to achieve minimum hardness in the treated water but the main aim in alkalinity reduction process is to control alkalinity concentration within a certain range. There is no document in scientific literatures to report that these two processes produce precisely the same results.

A number of control systems based on EC have been patented in the past to manage addition of lime for regulating alkalinity, including the following:

(1) Gustafson [9] disclosed in his patent a control system for optimizing the addition of lime for alkalinity reduction based upon the conductivity ratio between raw water and treated water.
(2) Carlson [10] disclosed a control system for optimizing the addition of lime for alkalinity reduction. A pacer unit determines the conductivity of water at optimal treatment. The conductivity of water in the treating unit is also measured. The controller calculates the ratio of the conductivities of the pacer unit and the treating unit. The controller adjusts the rate feed of lime into the treating unit to maintain a predetermined conductivity ratio.
(3) The King system for controlling lime feed for alkalinity control is based on the U-shape conductivity curve [11]. He uses a sample cell to periodically determine the minimum conductivity. A correction signal is then generated to adjust the feed setting to maintain a desired set point based upon the difference between this minimum conductivity and the current conductivity of a sample taken from the treating unit.
(4) Rivers [12] patented methods of analyzing conductive solution. He discovered that the amount of ionized constituent in a liquid phase may be accurately determined by measuring the EC of the liquid phase. This can be done by adding a buffering type reagent capable of reacting with the ionized constituent in this phase, measuring the EC of the reacted stream, and determining the amount of constituent present from a curve of differential EC versus concentration prepared from known concentration of the same constituent.
(5) A proportional control system for alkalinity control using a variable capacity feed pump was disclosed by Zaander et al. [13].
(6) Hawthorne and Herbert [14] disclosed a system for regulating the addition of lime to reduce water alkalinity includes two sensors for measuring the conductivity of the water prior to and after addition of lime, a pump for adding lime to the water, and a controller for regulating the pump. The controller periodically samples the conductivities measured by both sensors and computes the ratio of the conductivities for each sample as well as the slope of the ratio between samples.

In this work, it was found that a very cost effective technique based on EC of treated water can be developed for controlling the performance of softening process. This aspect of using EC for probing the least hardness in the lime clarifier was not realized in any of the previous works.

1.3. Lime softening reactions

Lime process can decrease only bicarbonate (temporary) hardness. By adding hydrated lime the following reactions (softening) results in precipitation of solid calcium carbonate and magnesium hydroxide [2,15]:

$$2CO_2 + Ca(OH)_2 \rightarrow Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad (1)$$

$$[Ca^{2+} + 2HCO_3^-] + Ca(OH)_2 \rightarrow 2CaCO_3(s) + 2H_2O \quad (2)$$

$$[Mg^{2+} + 2HCO_3^-] + 2Ca(OH)_2 \rightarrow 2CaCO_3 + Mg(OH)_2(s) + 2H_2O \quad (3)$$

Solubility of both calcium carbonate and magnesium hydroxide is highly sensitive to pH, but in different trends. The solubility of magnesium hydroxide sharply decreases in pHs more than 10 but the solubility of calcium carbonate increases at such high pHs. Therefore regulating pH or alkalinity is a decisive factor in controlling the performance of lime clarifier.

Currently for simplicity, alkalinity rather than pH is usually controlled for checking optimum operating conditions. This is accomplished by keeping a positive value for (OH) concentration about 5 ppm as $CaCO_3$. This corresponds to a pH of approximately 10.2–10.5. The concept behind of this working condition is that all of the bicarbonate ions must be converted into carbonate ions for having the least soluble form of calcium; therefore, it is recommended a slight excess of hydroxyl ion should be maintained in the treated water.

However, as softening reactions result in removing hardness ions from the aqueous phase by precipitation, the efficiency of this process can also be checked by total dissolved solids (TDS). EC is a good surrogate measure of TDS. Therefore, reduction in total ions due to removing calcium, magnesium, and bicarbonates can be detected by measuring the conductivity of aqueous phase. It has also been found that the change of conductivity of water with addition of lime has a concave nature. It initially progressively decreases to a minimum value due to precipitation of insoluble products but then increases due to excess lime. Our bench scale (and then full scale) tests demonstrated clearly that EC is a good indicator even better than alkalinity for following the performance of limes clarifiers in view of water softening.

This idea was checked even in full scale and it was found that the workability of EC analysis for lime clarifier was more meaningful than alkalinity tests. Contrary to the current method based on alkalinities, in this new method, no chemical waste is produced and no chemical materials or water is needed for titration.

1.4. Esfahan Steel Company lime clarifier

The Esfahan Steel Company (ESC) is located in the central part of Iran and can currently soften up to 530 m^3/h surface water. ESC utility uses both lime clarifier and ion exchange units for generating soft water. Two parallel lime clarifier (cylindrical building, 12 m in diameter, and 6.1 m total height) are compact upflow softening units that provide a place for chemical reaction of softening, coagulation, flocculation, and sedimentation in the single circular concrete tanks, where the water flows up toward the effluent launders and at the same time the suspended solids settle down. In each "solids-contact" clarifier, the incoming water from the bottom passes through the agitated previously formed flocs that produced by softening reactions. In fact, each clarifier employs scientific principles for enhancing flocculation, sedimentation, and clarification in one single basin.

Operators in ESC perform frequently characterizing tests (usually every 2 hour) on the raw water as well as the treated water for adjusting lime dosage to proper control of softening process. Conscious efforts are made by ESC operators to maintain a caustic alkalinity (twice the phenolphthalein alkalinity minus the total alkalinity) of positive value (greater than zero) in the treatment basin. ESC operators used to vary lime dosage as a tool to maintain *P* and *M* alkalinity ratio in the softened water at a specific level rather than target a specific lime dose.

Daily tests in lime clarifier of ESC showed that changes in lime feed rate would not dramatically affect on the total hardness of finished water. Therefore, for examination of lime clarifier performance, it was decided to change systematically the lime dosage rate. The operators initially were concerned about the effect this would have on turbidity and final hardness (outlet hardness and filter duty) but ESC has sand filters and ion exchange softener in downstream of the lime clarifier to accommodate any dynamic operating changes. Therefore, a short course on softening process was addressed for operators and since the laboratory tests were closely monitoring the situation, worries slowly subsided. The operating results encouraged us to explore a new method, rather than current *P* and *M* monitoring, for controlling the lime clarifier performance.

2. Materials and methods

All physical data or chemicals reported in this paper were obtained either from ESC daily log sheets or local central laboratory, where detailed protocols for the experiments, including titration and calculation methods, are usually based on standard methods [15].

The addition of commercial hydrated lime to the clarifier took place by dosing from a raw material container in the form of a lime silo via a worm conveyor to a slurry tank to dissolve the lime in mixing unit prior to supply to the raw water to be treated. Three dosages of lime were tested by regulating the control valve: normal dosage (170 ppm), less and higher than normal dosage (146 and 202 ppm).

Log sheet data (8-h per shift coverage) of lime clarifier in ESC utility was examined for about four weeks. We have decided to consider all data without any judgment, although only a few data in night shifts seemed incorrect probably due to careless recording.

The characterizing parameters of ESC lime clarifier, collected during this case study, have been included in the appendix spreadsheet. Each of 150 rows, shows details of a series of site data at a given time of sampling as follows: inlet water hardness, treated water hardness, inlet EC, outlet EC, outlet *P* alkalinity, inlet *M* alkalinity, outlet *M* alkalinity, Temperature, *P* and *M* alkalinity ratio, and lime dosage. The "no. column" is a four digit number such as ABCD, where CD is the hour of, and A and B are the week and day of sampling, respectively. For example no. 3208 column represents the sample that was collected at 8 am in the second day of the third week.

The jar tests were executed with the conventional apparatus with six 1-L beakers to determine changes of hardness, EC and alkalinities (*P* and *M*) versus lime dosage. To run each test, an increasing quantity of lime was added to each beaker and stirred at 150 rpm for 10 min. Turning off the mixers and allow the containers to settle for 15 min, then, analyses of the clear supernatants for hardness, calcium, alkalinity, and pH were performed. Ferric chloride as the coagulant in ESC utility is maintained at constant dosage during this period of case study.

3. Results and discussion

The accuracy of the current control method for evaluation of lime process was examined both in bench and in full-scale units.

Changes in hardness and (2*P*-*M*) of a typical softened water generated in a lime treated jar test have been shown in Fig. 1. It can be seen that the current control condition, i.e. 2*P*-*M* = 5 ppm as $CaCO_3$, does not result in minimum hardness of the treated water.

The corresponding results have also been recorded in ESC lime clarifier for various lime dosages (146,170 and 202 ppm) and have been shown in Fig. 2. Inconsistency in hardness readings in Fig. 2 is due to various sources such as changes in temperature, errors in data collection as these data were collected from a large clarifier at different times and by different operators, effect of sludge on hardness process, change in inlet water analysis, effect of residence time, and other minor factors.

It can be seen that a positive value for (2*P*-*M*) is not any assurance for having minimum hardness, since a good control parameter should be satisfied in spite of various operating conditions. Therefore, current control of evaluating the performance of lime clarifier does not anticipate the optimum operation conditions (minimum hardness of treated water).

Some industries such as ESC prefer to observe the current control condition by keeping dimensionless M/P slightly less than two instead of a positive value for (2*P*-*M*). Fig. 3 shows the change of outlet hardness of treated water at various lime dosages versus M/P alkalinity ratio. This operational data clearly demonstrates that the least hardness may be distributed from M/P less than two to more than three. These results are obviously inconsistent with the recommended condition and there is no guarantee for having minimum hardness when M/P is slightly less than two. Fig. 3 also shows that the recommended condition can occur either at high or low lime dosages and there is high chance for ill performance of lime clarifier when lime dosage and simple alkalinity is high. This ill performance of lime clarifier (higher outlet hardness) is possible as a result of increasing in calcium carbonate solubility at higher pH.

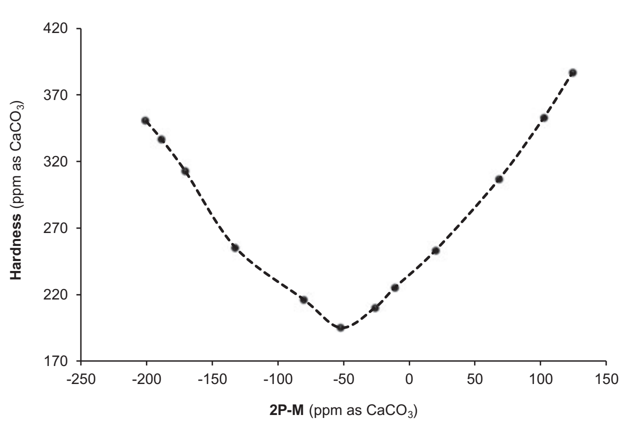

Fig. 1. Changes in hardness and (2*P*-*M*) of a typical softened water in a lime treated jar test.

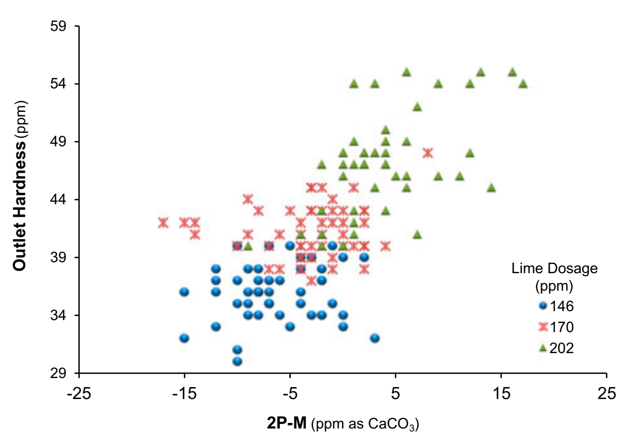

Fig. 2. Change of hardness versus (2*P*-*M*) of treated water at various lime dosages.

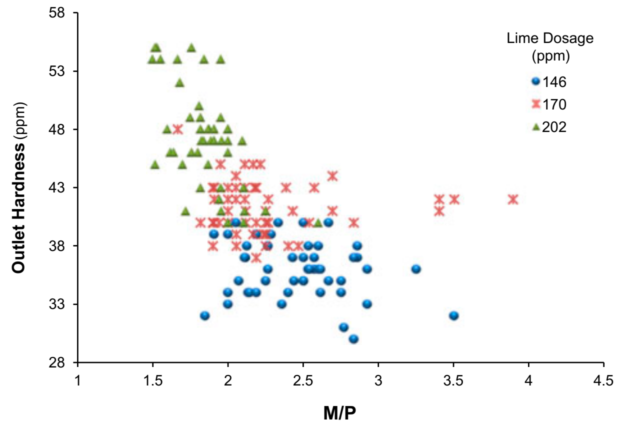

Fig. 3. Change of hardness of treated water at various lime dosages versus M and P alkalinity ratio.

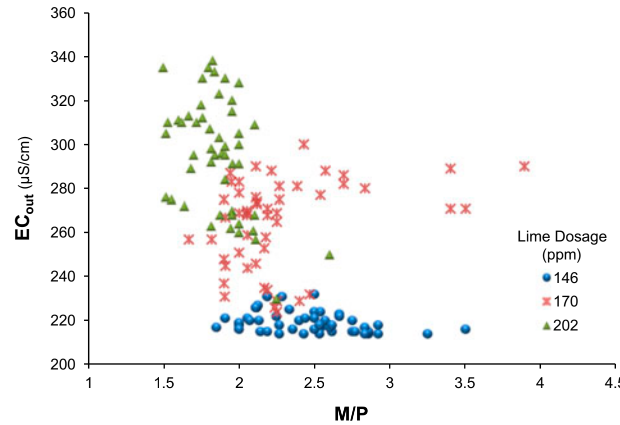

Fig. 5. Outlet EC as a function of M and P alkalinity ratio of the treated water at various lime dosages.

As an overall conclusion, Figs. 1 and 3 illustrate that evaluating the lime clarifier performance based on P and M alkalinities is neither accurate and nor easy. In addition, this current performance criterion may depend on lime dosage.

Fig. 4 shows change of outlet hardness versus lime dosage for all 150 series data. It clearly shows that increase in lime dosage often results in higher hardness. Increase in calcium carbonate solubility at higher pH may explain this ill performance of lime clarifier.

To search for finding a decisive parameter for evaluating the performance of lime clarifier, other parameters were also checked. Fig. 5 shows EC of treated water as a function of P and M alkalinity ratio at various lime dosage. It shows that there is no coherent correlation between these two parameters. Rivers' patent about alkalinity regulation [12] had already found that there is no linear relationship between EC and ($2P$-M). Fig. 5 indicates that lower lime dosage that means lower pH, results in lower range of EC of treated water. This result can be expected as a result of lower calcium carbonate solubility at lower pHs ≃8.5–9.5. It also can be seen that lower M/P that means higher pH and lime dosage, enhances higher EC of treated water. This result is possible due to increase in calcium carbonate solubility at higher pH.

The results of our bench scale tests always showed that minimum EC conform minimum hardness in lime process. Changes in hardness and EC of a typical softened water in a lime treated jar test have been shown in Fig. 6. This finding encouraged us to follow these changes in ESC lime softening clarifier for various lime dosages as shown in Fig. 7. It can be seen that three discrete sections corresponding to three lime dosages could be detected well in this figure. It shows that when hardness of treated water is high (poor performance), ECs are high in magnitude and scattering of data but when the treated water hardness is low, both the magnitude and also the range of changes in EC are small.

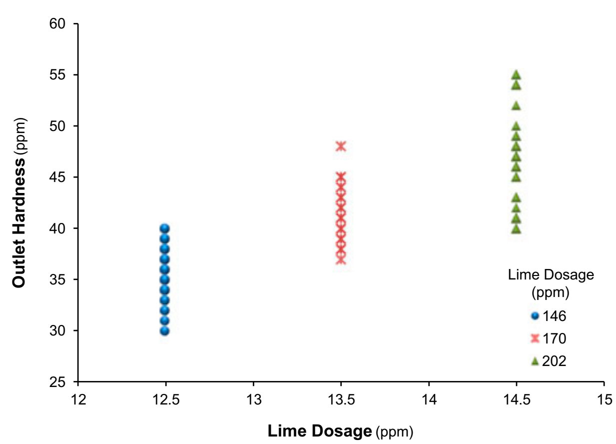

Fig. 4. Change of outlet hardness versus lime dosage.

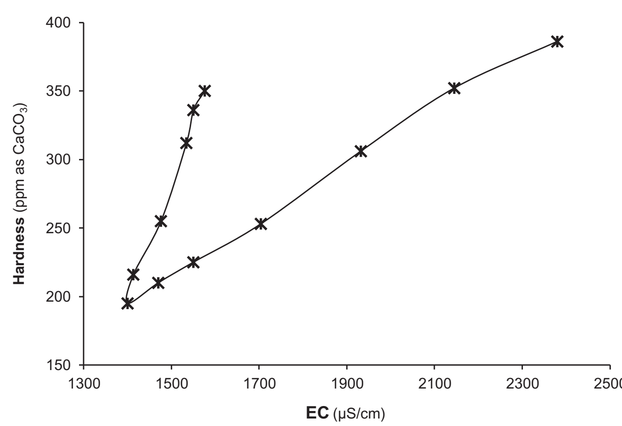

Fig. 6. Changes in hardness as a function of EC for a typical water in a lime treated jar test.

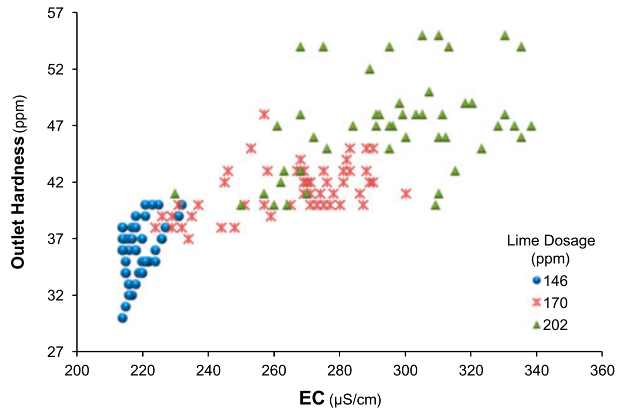

Fig. 7. Outlet hardness as a function of EC of treated water in ESP lime softening clarifier.

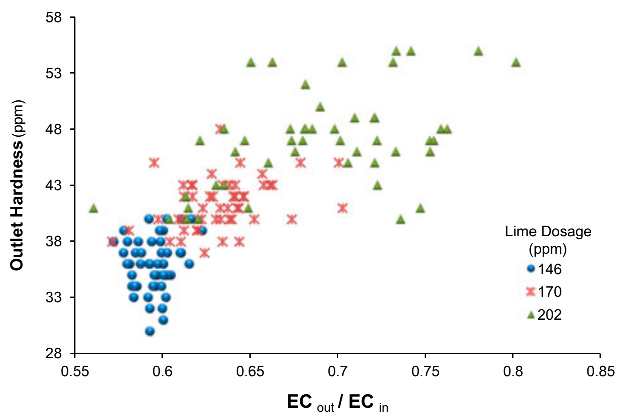

Fig. 8. Changes in outlet hardness as a function of the ratio of the ECs of outlet and inlet water in various lime dosages in ESP lime softening clarifier.

As high efficient operation of lime clarifier is certainly corresponding to the least hardness of outlet treated water, this situation is well correlated with changes in EC (both in magnitude and in scattering) of treated water as Fig. 7 demonstrates it. This is the main finding of this work and based on this finding, a scheme was patented for daily evaluating the performance of lime softening clarifiers [16]. No chemical waste is generated in this method.

Fig. 8 shows changes in outlet hardness as a function of the ratio of the conductivities of treated water and raw water in various lime dosages. Contrary to the patented methods for alkalinity reduction process [9–14], the ratio of the conductivities (in comparison to outlet conductivity in Fig. 7) is not a good indicator for probing lime clarifier as it enhances the data scattering.

4. Conclusions

The current method for evaluating the lime clarifier performance based on *P* and *M* alkalinities measurement could be cumbersome and it was found that this method is not often quite accurate. In addition, the current practice usually depends on lime dosage.

It was found that EC, an intensive property that can be measured easily for characterization of water, is a good indicator for following the performance of lime clarifier in view of water softening. It is an eco-friendly technique for routine tests without using any chemicals. The proposed method is a very cost effective alternative technique for optimizing the performance of lime clarifier without producing any chemical waste.

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Appendix

Number	Dosage	T	$2P$-M	M/P	M out	P	EC out	EC in	H out	H in
1,108	13.5	31.7	−4	2.25	36	16	229	374	39	128
1,110	13.5	34.1	2	1.904762	40	21	231	378	40	127
1,112	13.5	34.5	2	1.9	38	20	237	382	40	131
1,114	13.5	34.5	−3	2.166667	39	18	235	379	39	130
1,116	13.5	34.7	−4	2.235294	38	17	226	389	39	136
1,118	13.5	40.4	−4	2.25	36	16	224	392	38	132
1,120	13.5	42.7	4	1.818182	40	22	257	394	40	132
1,122	13.5	40.6	2	1.9	38	20	248	391	38	133
1,124	13.5	39.1	−1	2.055556	37	18	244	379	38	132
1,210	13.5	37	−3	2.1875	35	16	234	375	37	134
1,212	13.5	31	−6	2.4	36	15	229	379	38	136
1,214	13.5	32.4	−7	2.466667	37	15	232	380	38	135
1,222	13.5	30.4	2	1.909091	42	22	245	397	42	136
1,302	13.5	41	−3	2.166667	39	18	253	425	45	137
1,308	13.5	42	−3	2.1875	35	16	268	420	43	137
1,314	13.5	39	−3	2.176471	37	17	258	418	43	138
1,316	13.5	37.7	1	1.95	39	20	283	417	45	141
1,318	13.5	32.7	2	1.9	38	20	275	415	43	141
1,402	13.5	34.5	8	1.666667	40	24	257	406	48	138
1,404	13.5	34.4	−2	2.111111	38	18	246	402	43	141
1,406	13.5	38.8	−2	2.111111	38	18	290	414	45	140
1,408	13.5	39.4	−1	2.052632	39	19	268	408	44	129
1,410	13.5	42	−1	2.052632	39	19	269	409	43	134
1,412	13.5	43	0	2	40	20	251	420	40	145
1,414	13.5	41	−1	2.052632	39	19	270	441	42	143
1,420	13.5	39.9	−4	2.25	36	16	265	435	40	142
1,422	13.5	34.4	−1	2.055556	37	18	259	418	39	142
1,424	13.5	34.4	0	2	40	20	283	428	43	147
1,502	13.5	35.5	0	2	38	19	269	429	42	143
1,504	13.5	35.2	0	2	40	20	278	432	41	141
1,506	13.5	37.8	−2	2.111111	38	18	276	431	42	145
1,508	13.5	33.8	−4	2.25	36	16	269	425	41	146
1,510	13.5	35	2	1.909091	42	22	267	433	43	146
1,512	13.5	37.4	−15	3.5	35	10	271	431	42	147
1,514	13.5	38.4	−14	3.4	34	10	271	435	41	145
1,516	13.5	40	−10	2.833333	34	12	280	450	40	141
1,524	13.5	37.5	−2	2.117647	36	17	273	433	40	140
1,602	13.5	33.8	−2	2.117647	36	17	274	430	41	138
1,604	13.5	33.2	−3	2.1875	35	16	271	428	40	142
1,606	13.5	32.8	−4	2.266667	34	15	275	430	40	141
1,608	13.5	39	−7	2.538462	33	13	277	434	40	142
1,610	13.5	40	−6	2.428571	34	14	300	427	41	140
1,612	13.5	37	1	1.941176	33	17	287	426	40	141
1,618	13.5	40.5	−5	2.384615	31	13	281	443	43	145
1,620	13.5	35	−9	2.692308	35	13	282	449	44	143
1,622	13.5	34	−8	2.571429	36	14	288	449	43	141
1,702	13.5	37.7	−9	2.692308	35	13	286	445	41	140
1,704	13.5	39.6	−3	2.214286	31	14	288	447	45	143

(*Continued*)

Appendix (*Continued*)

Number	Dosage	*T*	2*P*-*M*	*M*/*P*	*M* out	*P*	EC out	EC in	*H* out	*H* in
1,706	13.5	40.5	−4	2.27	34	15	281	438	42	142
1,708	13.5	42.2	−17	3.89	35	9	290	449	42	145
1,710	13.5	39.2	−14	3.4	34	10	289	447	42	145
2,116	12.5	35.4	−5	2.33	35	15	225	365	40	139
2,118	12.5	35.8	2	1.91	42	22	221	368	39	140
2,120	12.5	31.2	0	2	40	20	218	377	39	138
2,204	12.5	35.8	−8	2.61	34	13	215	369	34	137
2,210	12.5	40	−2	2.12	36	17	226	377	37	131
2,212	12.5	38	−8	2.57	36	14	218	363	36	127
2,214	12.5	42	−4	2.25	36	16	222	381	35	128
2,216	12.5	44.6	−2	2.12	34	16	227	379	38	135
2,218	12.5	43.1	−3	2.19	35	16	231	371	39	131
2,220	12.5	42.5	−1	2.05	37	18	221	373	40	136
2,302	12.5	30.1	−15	3.25	39	12	214	368	36	132
2,304	12.5	37.8	−12	2.86	40	14	214	374	38	128
2,306	12.5	39.8	−10	2.67	40	15	223	365	40	128
2,308	12.5	41.4	−10	2.67	40	15	222	367	35	129
2,310	12.5	39.9	−12	2.86	40	14	215	372	37	130
2,312	12.5	39.3	−9	2.6	39	15	218	371	36	129
2,314	12.5	42.3	−9	2.6	39	15	217	374	38	132
2,322	12.5	37	−6	2.4	36	15	220	369	34	132
2,324	12.5	37	−7	2.5	35	14	224	372	35	136
2,402	12.5	39	−4	2.27	34	15	218	368	36	134
2,404	12.5	36	−7	2.5	35	14	221	370	35	131
2,410	12.5	39.5	−2	2.13	32	15	220	367	34	133
2,412	12.5	42.3	−1	2.07	29	14	220	365	35	132
2,414	12.5	45	0	2	30	15	219	374	34	133
2,416	12.5	39.1	−2	2.14	30	14	215	368	34	128
2,502	12.5	36	−3	2.19	35	16	215	368	34	128
2,504	12.5	35.7	3	1.85	37	20	217	366	32	130
2,506	12.5	36.1	0	2	38	19	216	370	33	131
2,508	12.5	35.8	−8	2.53	38	15	216	351	36	132
2,510	12.5	38.5	−12	2.92	38	13	214	369	36	132
2,518	12.5	34.9	−8	2.57	36	14	220	365	37	130
2,520	12.5	35.5	−6	2.42	34	14	214	366	37	130
2,522	12.5	36	−8	2.61	34	13	218	363	36	130
2,524	12.5	36.8	−2	2.11	38	18	226	370	37	125
2,602	12.5	39.4	−7	2.44	39	16	221	368	35	126
2,608	12.5	30.5	−8	2.53	38	15	214	361	36	125
2,610	12.5	32.1	−7	2.5	35	14	216	354	37	127
2,614	12.5	35.6	−8	2.53	38	15	218	367	38	125
2,616	12.5	36	−4	2.27	34	15	214	365	38	128
2,618	12.5	37.3	−10	2.83	34	12	217	369	37	129
2,622	12.5	36.5	−9	2.75	33	12	215	361	35	130
2,624	12.5	38.7	−5	2.36	33	14	216	365	33	128
2,706	12.5	39.7	−12	2.92	38	13	218	362	33	123
2,708	12.5	34.4	−10	2.77	36	13	215	358	31	120
2,710	12.5	33.2	−15	3.5	35	10	216	360	32	122
2,712	12.5	32.8	−10	2.83	34	12	214	361	30	119

(*Continued*)

Appendix (*Continued*)

Number	Dosage	*T*	2*P*-*M*	*M*/*P*	*M* out	*P*	EC out	EC in	*H* out	*H* in
2,802	12.5	35.2	−9	2.75	33	12	220	370	34	130
2,804	12.5	38	−7	2.54	33	13	224	375	36	129
2,806	12.5	39	−4	2.28	32	14	231	386	39	128
2,808	12.5	37.8	−7	2.5	35	14	232	385	40	127
3,116	14.5	37.3	−4	2.25	36	16	230	410	41	138
3,118	14.5	39.5	−9	2.6	39	15	250	414	40	140
3,120	14.5	36.7	−2	2.11	38	18	257	418	41	139
3,122	14.5	38	0	2	40	20	260	419	40	142
3,208	14.5	43.6	0	2	40	20	264	430	40	140
3,216	14.5	33.2	1	1.94	35	18	262	427	42	143
3,218	14.5	34.6	−2	2.1	40	19	268	425	43	145
3,220	14.5	35.8	1	1.95	45	23	270	416	41	144
3,222	14.5	36.1	3	1.87	45	24	268	422	48	148
3,304	14.5	32.2	4	1.82	40	22	263	414	43	136
3,306	14.5	36	7	1.72	43	25	310	415	41	140
3,308	14.5	30.1	−2	2.1	40	19	309	420	40	140
3,310	14.5	23.3	12	1.6	48	30	311	408	48	130
3,312	14.5	26.4	11	1.62	47	29	310	412	46	135
3,320	14.5	33.4	3	1.84	35	19	295	420	54	163
3,322	14.5	29.3	7	1.68	37	22	289	424	52	170
3,404	14.5	34	14	1.52	44	29	276	418	45	138
3,406	14.5	41.1	17	1.5	51	34	335	418	54	142
3,408	14.5	39.9	16	1.53	52	34	310	418	55	145
3,410	14.5	35.5	13	1.52	41	27	305	416	55	143
3,412	14.5	37.4	12	1.55	42	27	275	415	54	146
3,414	14.5	36.7	1	1.95	43	22	268	412	54	145
3,416	14.5	32.6	−2	2.09	44	21	261	420	47	145
3,418	14.5	35.2	9	1.64	41	25	272	424	46	146
3,420	14.5	35.9	1	1.96	47	24	291	428	47	140
3,502	14.5	35.6	4	1.82	40	22	298	420	49	140
3,504	14.5	33.6	6	1.7	34	20	295	418	45	139
3,506	14.5	33.4	2	1.89	34	18	296	422	47	141
3,508	14.5	36.7	0	2	40	20	300	444	46	140
3,510	14.5	33.3	2	1.91	42	22	299	439	48	141
3,512	14.5	36.6	2	1.91	42	22	284	439	47	140
3,514	14.5	29.3	0	2	40	20	291	427	48	142
3,520	14.5	34.6	3	1.87	43	23	303	434	48	139
3,522	14.5	32.8	0	2	40	20	305	445	48	138
3,524	14.5	33.4	2	1.91	42	22	295	438	47	142
3,602	14.5	34.2	4	1.82	40	22	292	434	48	140
3,604	14.5	37.6	6	1.76	44	25	312	439	46	136
3,606	14.5	39.1	6	1.75	42	24	318	441	49	142
3,616	14.5	25.2	9	1.67	45	27	313	428	54	140
3,618	14.5	22.8	6	1.76	44	25	330	423	55	141
3,620	14.5	27	0	2	40	20	328	436	47	142
3,624	14.5	25	2	1.91	42	22	330	435	48	143
3,706	14.5	21.3	1	1.95	43	22	320	444	49	142
3,708	14.5	20.5	4	1.81	38	21	307	445	50	145
3,716	14.5	21.3	1	1.95	43	22	315	436	43	145

(*Continued*)

Appendix (*Continued*)

Number	Dosage	*T*	2*P*-*M*	*M*/*P*	*M* out	*P*	EC out	EC in	*H* out	*H* in
3,718	14.5	21.6	3	1.87	43	23	323	448	45	139
3,720	14.5	28	4	1.83	42	23	338	448	47	145
3,722	14.5	26.2	5	1.8	45	25	335	457	46	143
3,724	14.5	27.2	4	1.84	46	25	333	461	47	145