CENTER PIVOT UNIFORMITY FOR CHEMIGATION[1]

D. F. Heermann[2]

Modern farming technology advocates the application of many different chemicals for improving production. This includes applying fertilizers for increasing crop growth and crop yields, applying insecticides to control pests, and applying herbicides to control weeds which can significantly reduce production. In general, it is important that chemicals be applied over the entire area as uniformly as possible. Center pivot irrigation systems have been used quite extensively to apply fertilizer and to a more limited extent to apply herbicides and insecticides. This study will analyze the uniformities of center pivot irrigation systems into which chemicals may be injected and applied with the water. Traditionally the uniformity is calculated based on measurements or calculated application depths parallel to the center pivot lateral. The procedure for measuring this radial uniformity with catch cans is detailed in ASAE Standard: ASAE S436. The objective of this study is develop a simulation model to analyze the tangential uniformity in the direction of travel as influenced by the start and stop sequence of each tower. The tower movement is controlled by an alignment mechanism which starts and stops each tower independently, so as to keep the irrigation lateral close to a straight line extending from the pivot.

Simulation models have been used extensively in the design and evaluation of center pivot irrigation systems. Heermann and Hein (1968) developed a simulation program which numerically simulated the application depths under a center pivot sprinkler irrigation system and verified the simulations with catch can data. Kincaid, et al. (1969) expanded the model to simulate the application rate versus time. The intake rates were measured and compared with the application rates to determine the potential runoff under center pivot sprinkler irrigation systems. Solomon, et al. (1978) and von Bernuth (1983) used mathematical simulations to evaluate the angle of operations and nozzle sizes for end guns on center pivot systems. Edling (1979), James (1982), and James (1984) used simulation models to evaluate the effects of pump selection and topography changes on the uniformity of irrigation under center pivot systems. These are examples of the versatility for simulation models which have been used to evaluate and design center pivot irrigation systems.

Hanson and Wallender (1986) used catch cans to measure both the tangential uniformity in the direction of travel and the radial uniformity parallel to the lateral of center pivot and lateral move systems. They found experimentally that considerable nonuniformity exists along the travel path of the center pivot. Ring and Heermann (1978) also observed

---

[1] Contribution from USDA-Agricultural Research Service in cooperation with Colorado State University Agricultural Experiment Station.

[2] Agricultural Engineer, USDA-Agricultural Research Service, Colorado State University, Fort Collins, CO.

nonuniformity in the direction of travel where catch cans were set in adjacent radial lines. Neither of the previous studies were able to quantify the factors causing the nonuniformity but it is assumed that the variability in the start and stop times of each drive tower is a major factor contributing to the nonuniformity. The start and stop time series for each drive tower is required for the simulation of the application depths. For this study, the time series of starts and stops will be simulated for each tower.

DESCRIPTION OF SYSTEMS

Two center pivot sprinkler systems are simulated to determine the effect of start and stop times on uniformity in the direction of travel. The systems were identical in lateral length and tower spacing. Each system had 9 towers; the first seven towers were spaced at approximately 49 m intervals and the last two towers were spaced at approximately 45 m intervals. The distance from the pivot to the last tower was 431 m. Table 1 summarizes other characteristics of the high and low pressure systems. Both systems had pressure regulators at each sprinkler head to provide a high irrigation uniformity in the radial direction parallel to the lateral.

Table 1. Description of center pivot systems for simulation study.

	High Pressure	Low Pressure
Application depth - mm	21	24
Uniformity coefficient - %	98.6	98.9
Irrigated area, ha	64	66
Percent timer setting	60	60
Hours/Rev.	60	60
Discharge - l/s	62	73
Pivot pressure - kPa	760	470
End sprinkler pressure kPa	240	140
Nozzle pressure range - kPa	170-380	140
Nozzle size - mm	3.2-11.1	1.8-8.7
Sprinkler spacing - m	9.1	2.6
Sprinkler type	Impact	Spray

MODEL DESCRIPTION

The stationary application rate patterns for the two sprinkler head types are illustrated in Figure 1. The high pressure system is simulated using a triangular pattern for each of the sprinklers on the system. The low pressure system is simulated using a donut shaped sprinkler pattern (Figure 1). The application rate is assumed to increase linearly from one fifth the peak application rate at the sprinkler head to a maximum rate located at a distance ar from the center. The application rate outside

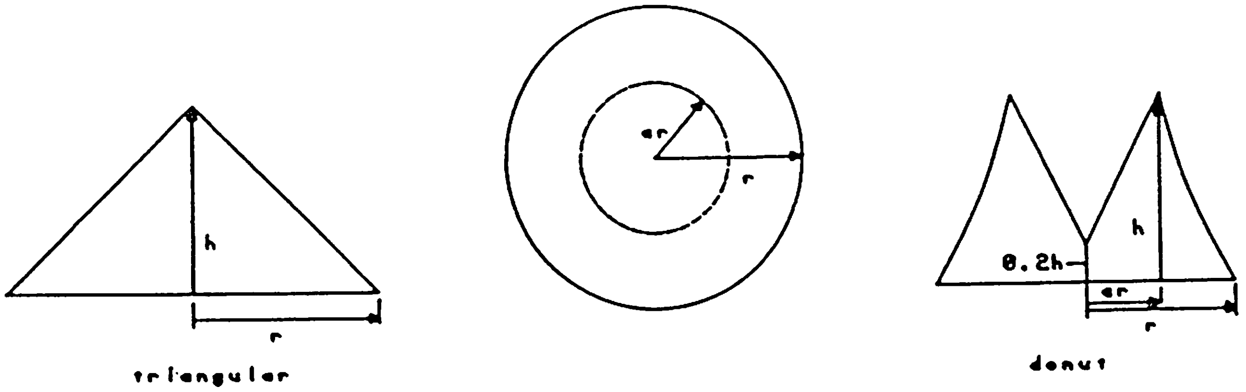

Figure 1. Application rate patterns for a stationary sprinkler head for high (triangular) and low (donut) pressure systems.

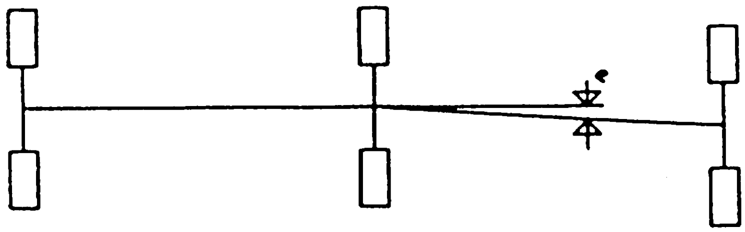

Figure 2. Definition sketch for alignment angle used in generating start-stop sequence for center pivot towers.

the radius ar, is assumed to be parabolic shaped. The donut shaped patterns were estimated from catch can test data courtesy of Valmont Industries[3].

The time series of start-stop times and locations (expressed as an angle) for each of the towers were simulated. Maximum limits on the angle between two adjacent pipes were set at each tower to cause the tower to be started or stopped. It was assumed that when the tower lagged by a $+\epsilon$ angle it would begin travel and continue moving until the angle reached $-\epsilon$ (Figure 2). The ϵ angles simulated were 1/4, 1/2, 1, and 2 degrees. The simulation assumed that all towers were in a straight line initially with the outer tower moving. The speed of each tower, distance to each tower and the percent timer setting for the outer tower were the required input data. At small intervals of time, which was also an input variable, each tower was advanced if it was moving (on). At the end of the time step, the alignment angles (ϵ) were calculated for each tower and the status was changed to either on or off if they were outside the alignment intervals (Figure 2). Each time a tower had a change of status, the angle, time and status were recorded. The tolerance and variability in the switches of the alignment mechanism are assumed to cause as much variability in changing the status of a tower as the simulation time interval. A complete 360 degree circle of start-stop sequences was simulated.

The speed of each sprinkler was determined by linear interpolation of the speed of adjacent towers. The actual speed of each sprinkler could take on four states: 1) stopped, 2) both towers running, 3) the outer tower running with the inner tower stopped, and 4) the inner tower running with the outer tower stopped.

EVALUATION PROCEDURE

The distribution of applied depths parallel to the lateral moving at a continuous and constant speed without tower start and stops is illustrated in Figure 3. The coefficient of uniformity as defined by Heermann and Hein (1968) was used for system evaluation and comparisons. Both high and low pressure systems have a high radial uniformity and this uniformity is the basis for comparison of simulations analyzing the effect of start and stops of the towers. With center pivot systems, a percent timer controls the fraction of time that the outer tower runs and the time to complete an irrigation of a complete circle. The systems simulated in this study started the outer guide tower every minute and run for the percent timer setting which is typical of the control on many center pivot systems. Ten radial lines, spaced 1° apart were simulated with a start-stop time series for $\epsilon = \pm 1^\circ$. The towers running speeds were assumed to be 1.22 m/min. The effect of designing each tower to operate at a different speed was simulated and compared with a system where all towers moved at the same speed. The effect of the change in alignment angle ($\pm\ \epsilon$) was evaluated by generating a start-stop time series for each

---

[3] Mention of a trademark or manufacturer by the U. S. Department of Agriculture does not imply its approval to the exclusion of other products or manufacturers that may also be suitable.

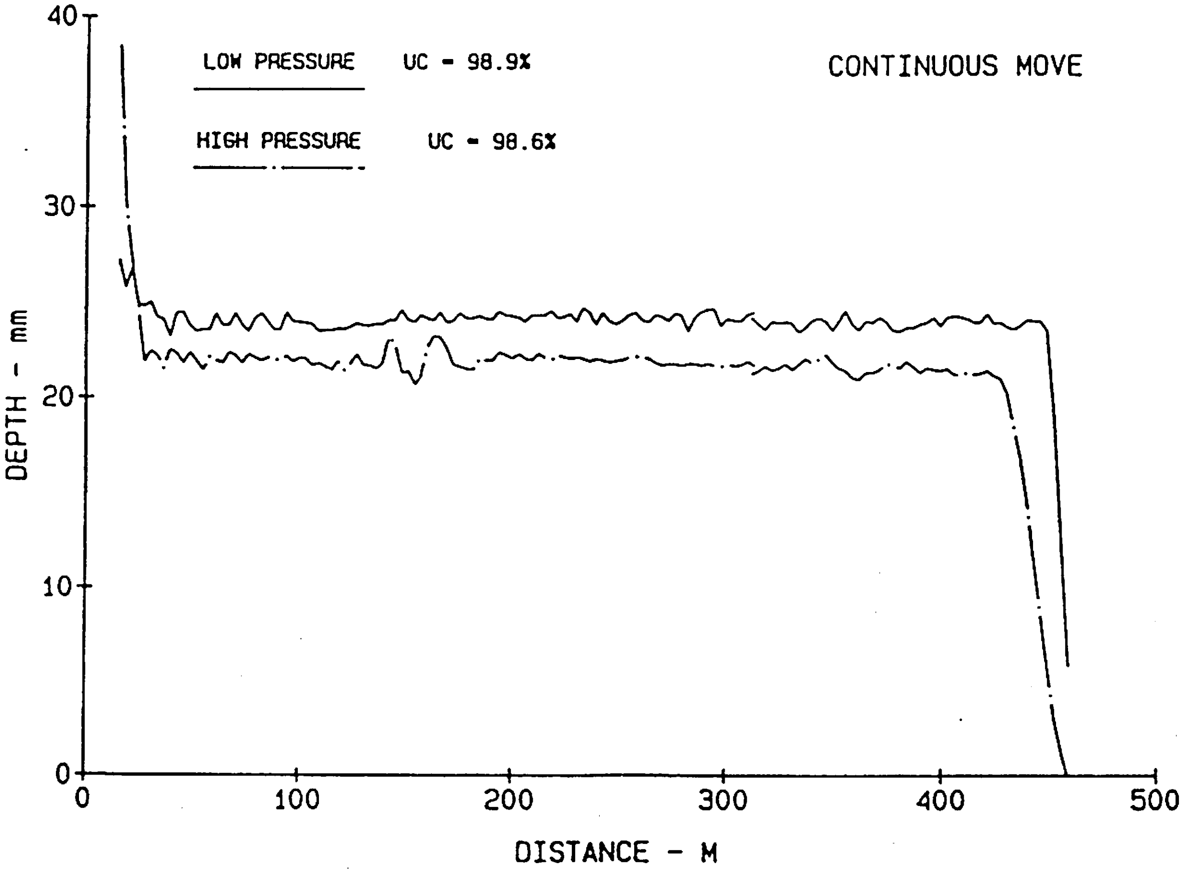

Figure 3. Application depths applied parallel to center pivot lateral for center pivot towers moving continuously at constant speeds.

tower and calculating the application depths in the direction of travel at a radius of 230 m. The effect of operating the system at maximum speed with the outer tower set at 100% was also determined at this constant radius. The effect of changing the time interval in generating the start-stop sequence for each tower was also determined at this constant radius. For this analysis, the system was operated at maximum speed with the outer guide tower set at 100%.

MOVING SYSTEM UNIFORMITY

The application depths for a 10° pie for the high and low pressure systems with the start and stop time series generated with ± 1° deviation were calculated. Application depths were calculated at 1.5 m increments from 30 m to the outer end. These radial simulations were performed at 1° intervals for a total of 10 radial lines. The resulting uniformity coefficients are 97.5% and 89.0% for the high pressure and low pressure systems, respectively. There is very little change in the uniformity coefficient of the 10° pie from that of the constant speed radial uniformity for the high pressure system. However, the uniformity coefficient decreases by 9.9% for the low pressure system from that of a continuous move system. The three dimensional perspective of the application depths for a rectangular area located between 215 and 245 m are illustrated in Figures 4 and 5 for the high pressure and low pressure center pivot systems, respectively. This exhibits significant peaks and valleys for the low pressure system. The vertical scale is approximately the same for the two systems and show the relative change in application depths within the rectangular area. The minimum and maximum application depths are 14 mm and 31 mm for the low pressure system as compared to 20.6 mm and 22.8 mm for the high pressure system.

VARIABLE TOWER SPEEDS

The first simulations were for systems that had each tower with a speed of 1.22 m/min when moving. The towers successively closer to the pivot run a smaller fraction of the total time. A second simulation was run with slower tower speeds toward the pivot (Table 2). The start-stop time sequence was generated with variable tower speeds with an alignment deviation of ± 1°. Again, the application depths were calculated for the 10° pie for the low pressure system. The coefficient of uniformity for the variable speed system is 89.5% as compared to 89% for the constant speed towers. The maximum, minimum, and average of 10 application depths calculated at 3 m intervals are shown in Figure 6 for both constant and variable speed towers. The range of calculated depths is larger for the system with the constant speed towers than that for the variable speed towers. The average depth is less near the pivot for the constant speed system which is probably caused by the large nonuniformity and the chance that there are more valleys than peaks in the 10° arc simulated as compared to the variable speed system. The range between maximum and minimum depths for the variable speed system is approximately two thirds of that for the constant speed system at the midpoint of the system (230 m). There is a slight improvement in system performance when the towers are designed to travel at slower speeds toward the pivot. The generation of

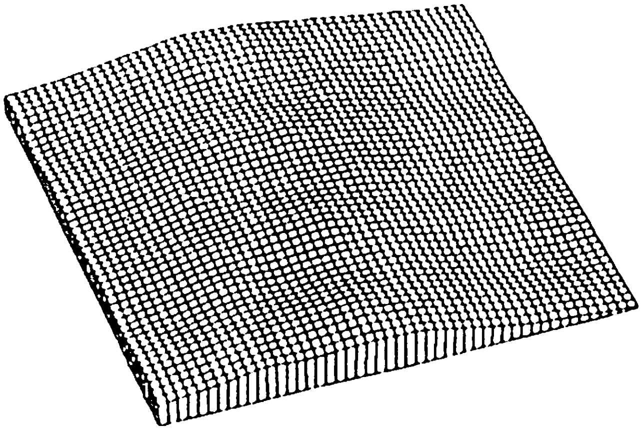

Figure 4. Application depths for a rectangular area 37 m wide from a radius of 215 m to 245 m for a high pressure center pivot system.

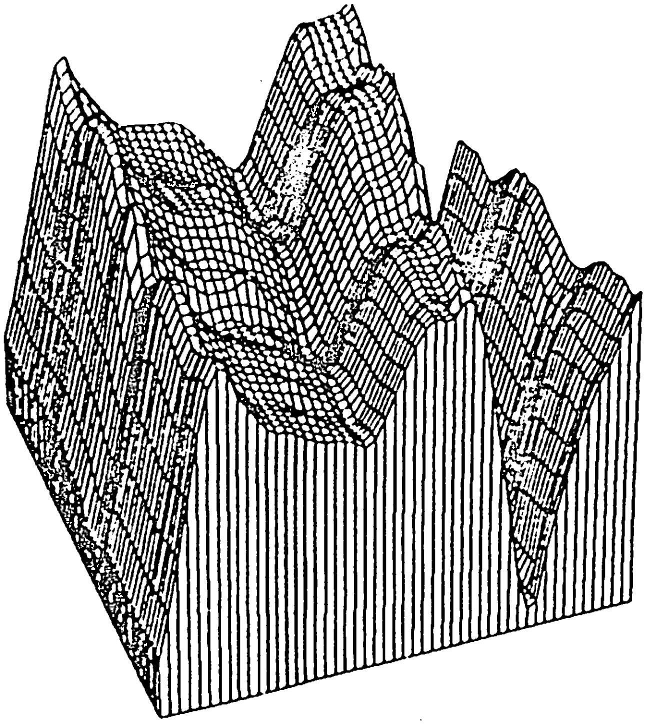

Figure 5. Application depths for a rectangular area 37 m wide from a radius of 215 m to 245 m for a low pressure center pivot system.

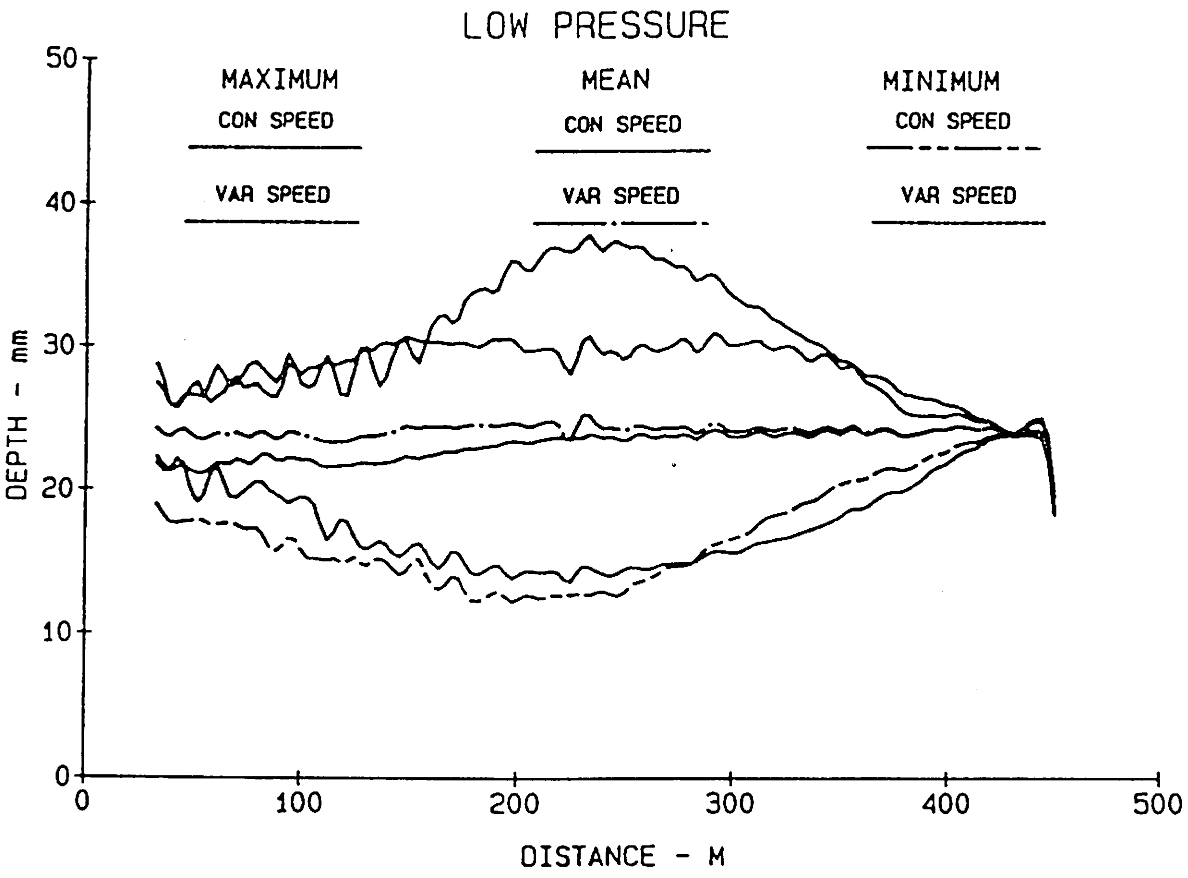

Figure 6. The average and range of application depths for a low pressure center pivot system with variable and constant tower speeds.

the start-stop sequence required the speed changes to consecutive towers be kept small or the alignment could not be maintained.

Table 2. Tower speeds for simulated variable speed system.

Tower	1	2	3	4	5	6	7	8	9
Speed m/min	0.61	0.69	0.76	0.84	0.91	0.99	1.07	1.14	1.22

UNIFORMITY IN THE TRAVEL DIRECTION

The application depths were calculated at a constant radius of 230 m for a more detailed study of the effects on start and stops on the uniformity of water application in the direction of travel. On each of these simulations the application depth was calculated at 1/2° increments from 30° to 330°. Thus, the application depths were calculated at approximate 2 m intervals. The mean, standard deviation, and coefficient of uniformity for the simulations in the travel direction are given in Table 3. Note that the coefficients of uniformity for the high pressure systems are nearly the same or higher than that for a single radial for a continuous move system line. However, if the angle of the tower deviation is 2°, there can be significant differences in application depths (Figure 7). The peak application is approximately 1/3 above the average application depth and the minimum application is approximately 2/3 of the average application depth. If the alignment tolerance angle is less than ± 1°, the travel direction uniformity is quite good.

The low pressure system exhibits significantly lower uniformity in the direction of travel. Even with the alignment tower deviation equal to 1/4°, the maximum application depths are 10% above the average application depth (Figure 8). The coefficient of uniformity in the travel direction for the 1/4° alignment angle is still less than the radial uniformity for the continuous move system.

The start-stop tower move time series were simulated using 1.2 sec intervals at which time the alignment angle was compared to its tolerance for changing the status of the tower drive motor. This appears to be a reasonable selection when considering the expected variability or repeatability of an alignment switch. The time interval was reduced to 0.6 sec and a new start-stop tower time sequence was generated for the ± 1° alignment deviation. The simulation was repeated for the low pressure system and resulted with coefficient of uniformities equal to 82.0% and 84.2% for the 1.2 and 0.6 sec time intervals, respectively. The comparison of distribution of application depths in the travel direction for the simulations are shown in Figure 9. The time intervals of 1.2 and 0.6 seconds for generating the start-stop sequence had very little effect on the coefficient of uniformity (82.0% and 84.2%, respectively).

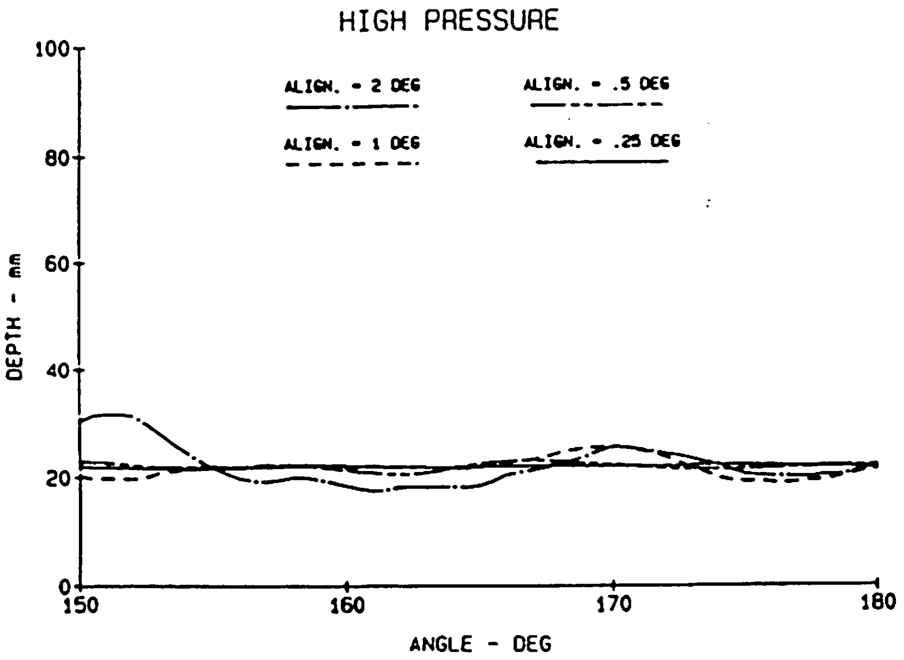

Figure 7. Application depth in travel direction at a radius of 230 m from a high pressure system.

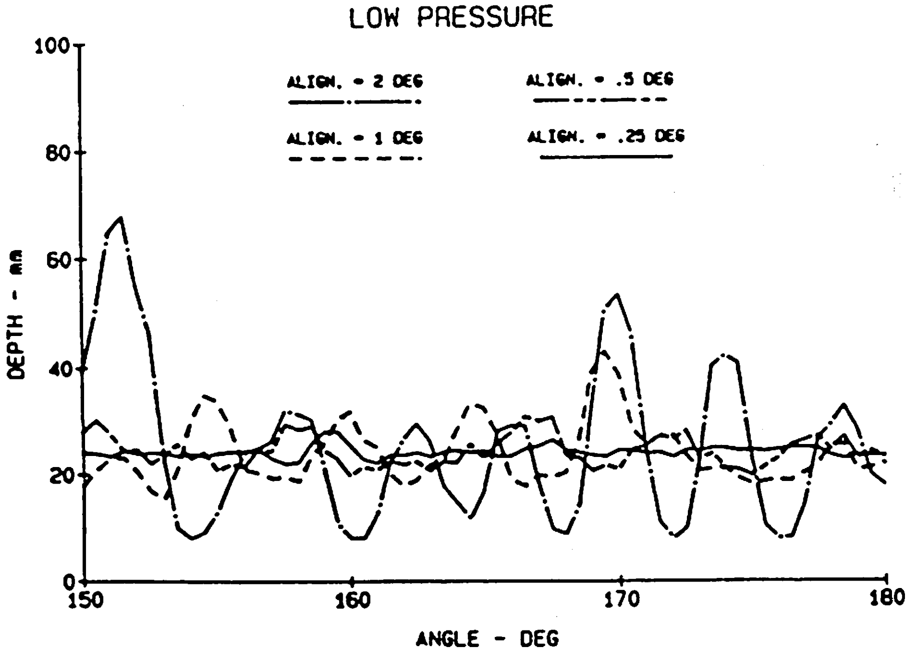

Figure 8. Application depth in travel direction at a radius of 230 m from a low pressure system.

Thus far, the simulations were made with center pivot systems having the outer guide tower operating with the percent timer set at 60%. The effect of changing the timer setting to 100%, which is often the case in applying chemicals, also was investigated. The results of this simulation for the entire 30° to 330° simulation at 230 m is shown in Figure 10. The coefficient of uniformity in the travel direction increases to 95.6% with the system operating at 100% as compared to 82.0% when the system is operating at 60%. The two curves in Figure 10 compare the application depths where the start-stop time series are generated with 1.2 and 0.6 sec intervals. The nonuniformity is much more random but we do see significant deviations at infrequent intervals. The time interval used in generating the start-stop tower move sequence does have an effect. However, the magnitude of deviations from the average depth is not reduced with the smaller time interval as one might expect. An observation of the tower move time sequence indicates the cause for the nonuniformity. The uniform application depths in the travel direction occur when no tower runs unless all towers outward from any given tower are running. Thus no

Table 3. Performance characteristics for simulated center pivot systems at a radius of 230 m.

Alignment Angle Degrees	High Pressure Mean Depth mm	Standard Deviation mm	CU %	Low Pressure Mean Depth mm	Standard Deviation mm	CU %
2	22.1	2.6	90.6	24.4	12.4	58.4
1	22.1	1.2	95.9	24.4	5.4	82.0
1/2	22.1	0.7	97.6	24.4	2.6	91.6
1/4	22.1	0.2	99.4	24.4	1.0	96.8
1[1]				24.0	4.5	85.1
1[2]				15.0	1.0	95.6
1[3]				15.0	0.8	96.7

[1] Variable speeds for each tower.

[2] Outer guide tower at 100 percent timer setting with 1.2 second time interval for generating start-stop sequence.

[3] Outer guide tower at 100 percent timer setting with 0.6 second time interval for generating start-stop sequence.

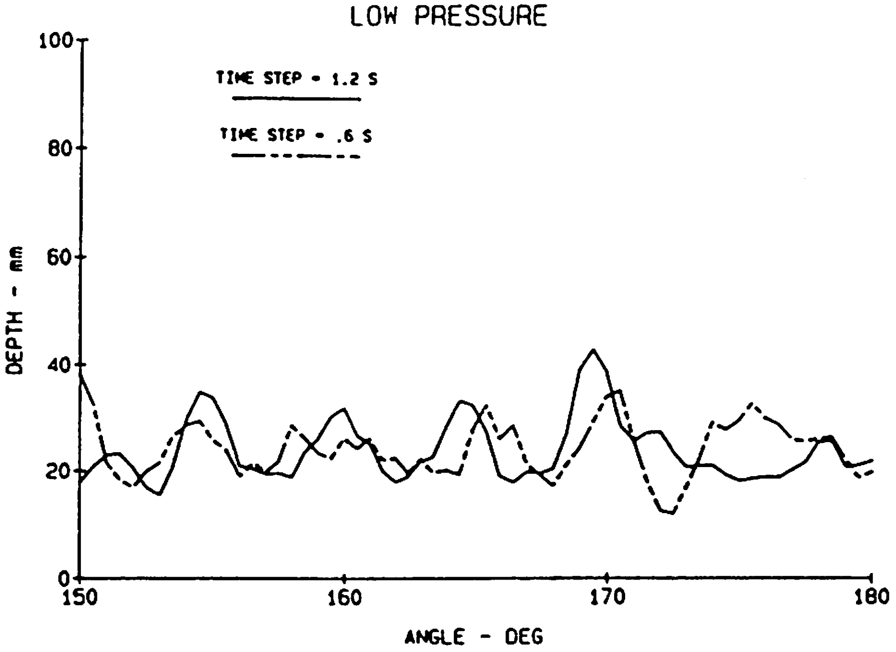

Figure 9. Application depth in travel direction at a radius of 230 m from a low pressure system with time intervals of 1.2 and 0.6 sec for generating the start-stop sequence of the towers.

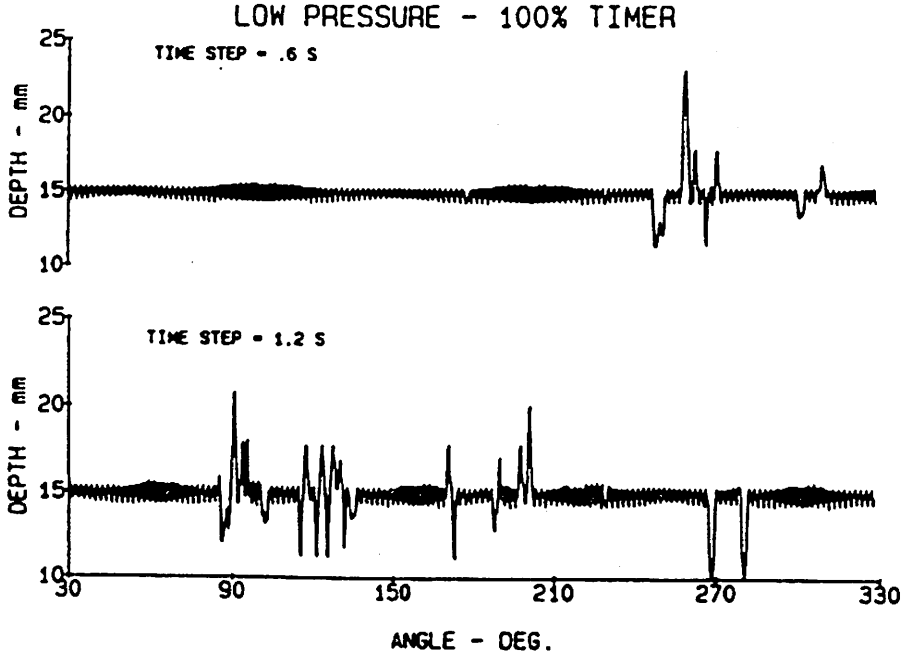

Figure 10. Application depth in travel direction at a radius of 230 m from a low pressure system with the outer guide tower running at a 100 percent timer setting.

tower will stop unless all towers towards the pivot are stopped. The nonuniformity begins to occur whenever a tower is running and any tower further out from the pivot is stopped. The standard deviation of move times for the arcs of uniform water application was 0.13 min as compared to 2.0 min for the arcs of nonuniform water application.

DISCUSSION

The application depth at the 230 m radius resulted from the integration of water applied from five sprinklers from both the high pressure and low pressure systems. The sprinkler number, pattern radius, and arc length through each of the individual sprinkler heads is given in Table 4. Even though the spacing is 3.5 times as large for the high pressure system, the increased pattern radius results with the same number of sprinklers applying water at the constant radius.

Table 4. Arc lengths for integration path for the sprinklers overlapping at 230 m.

	Sprinkler No.	Pattern Radius	Arc Length
High Pressure		m	m
	23	20.1	17.6
	24	20.1	36.6
	25	20.6	41.2
	26	20.6	36.2
	27	21.0	19.9
Low Pressure			
	86	6.2	4.2
	87	6.2	10.6
	88	6.3	12.6
	89	6.3	11.9
	90	6.3	8.6

IMPLICATIONS FOR CHEMIGATION

The uniformity parallel to the center pivot lateral is sufficiently high for both the high and low pressure systems to provide for very accurate application of chemicals. The uniformity in the direction of travel is significantly higher in general for the high pressure system than that of the low pressure system. Low pressure systems that are designed and installed with alignment angles of 1/2° or less have coefficients of uniformity above 90% in the direction of travel. A system with the outer control tower operating at 100% timer setting resulted with high uniformities. However, it is doubtful that the high uniformity would occur in the field because of the observed synchronization of tower operation that contributed to the uniformity. The nonuniformity simulated is similar to the experimental data of Hanson and Wallender, 1986 where they measured segments with large variance followed by segments of nearly constant application depth. The simulation results also demonstrated that installation of different tower speeds could slightly improve the uniformity of application.

CONCLUSION

The mathematical simulation model provides an excellent tool for evaluating the various factors affecting the uniformity of water application in the direction of travel. The uniformities and system performance appears to be similar to that reported from an analysis of experimental data by Hanson and Wallender, 1986.

It is concluded that the center pivot system, when properly designed and operated, can apply chemicals with a high degree of uniformity. The coefficient of uniformity is more a function of the sprinkler pattern radius and arc lengths than the magnitude of the alignment angle.

REFERENCES

1. Edling, R. J. 1979. Variation of center pivot operation with field slope. Transactions of the ASAE 22(5):1039-1043.

2. Hanson, B. R. and W. W. Wallender. 1986. Bidirectional uniformity of water applied by continuous-move sprinkler machines. Transactions of the ASAE 29(4):1047-1053.

3. Heermann, D. F. and P. R. Hein. 1968. Performance characteristics of the self-propelled center pivot sprinkler irrigation system. Trans. of the ASAE 11:1115.

4. James, L. G. 1982. Modeling the performance of center pivot irrigation systems operating on variable topography. Transactions of the ASAE 25(1):143-149.

5. James. L. G. 1984. Effects of pump selection and terrain on center pivot performance. Transactions of the ASAE 27(1):64-68, 72.

6. Kincaid, D. C., D. F. Heermann and E. G. Kruse. 1969. Application rates and runoff in center pivot sprinkler irrigation. Trans. of the ASAE 12:790-794, 797.

7. Ring, L. and D. F. Heermann. 1978. Determining center pivot sprinkler uniformities. ASAE paper 78-2001, ASAE, St. Joseph, MI 49085.

8. Solomon, K. and M. Kodoma. 1978. Center pivot end sprinkler pattern analysis and selection. Transactions of the ASAE 21(4):706-712.

9. vonBernuth, R. D. 1983. Nozzling considerations for center pivots