PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE

MSU Is An Affirmative Action/Equal Opportunity Institution
c:\circ\datedue.pm3-p.1

ENERGY SAVINGS AND IRRIGATION PERFORMANCE OF A MODIFIED CENTER PIVOT IRRIGATION SYSTEM

By

Sagar Raj Pandey

THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Agricultural Engineering
Department of Agricultural Engineering

1989

ABSTRACT

ENERGY SAVINGS AND IRRIGATION PERFORMANCE OF A MODIFIED CENTER PIVOT IRRIGATION SYSTEM

By

Sagar Raj Pandey

The goal of any modern irrgation system should be to apply water with the maximum uniformity and minimal labor and energy costs, while increasing both the quality and quantity of food production for maximum economic benefit. Proper irrigation system design is important to achieve maximum possible application uniformity and energy savings.

The demand for energy in center pivot irrigation system changes with the change in the operating point of the pump curve because of the opening and closing of the end gun sprinkler. The primary objective of this research was to determine the possible energy savings of a modified center pivot irrigation system in which the operating point of the pump curve is fixed. Computer programs were written to simulate the design modifications that included auxiliary sprinklers in the system which open with the closing of the end gun sprinkler.

The results showed that there are time and energy savings after the modification in the design of the system. The amount of energy savings was the function of the steepness of the pump curve, with high values

for systems with steep pump curve. In addition, it was found that the capacity of the pump could also be reduced with the modified design.

The application uniformity of irrigation improved significanlty with the modified system. The increase in application uniformity was between 7% and 16% in systems with steep pump curve as compared with the values between 3% and 8% in system with flat pump curves. This increase in application uniformity increased the potential yield of crop by 3% to 17%.

Approved ______________________
Major Professor

Approved ______________________
Department Chairperson

Dedicated

to the Memory of my Grandfather

Sardar Rudra Raj Pandey

ACKNOWLEDGEMENTS

My special thanks to my major professor, Dr. Vincent F. Bralts. I greatly appreciate his support, guidance, and patience in helping me to complete this research. I have very high esteem for him as a teacher, advisor, friend, and individual.

I thank the other members of my committee, Dr. L. J. Segerlind from Agricultural Engineering Department, Dr. David Wiggert from the Civil Engineering Department, and Mr. Austin Miller, P.E., for their helpful comments. Special thanks to Mr. Miller for his thoughts, advise, and encouragement during the analysis of the results. In addition, thanks to the graduate students of the Agricultural Engineering Department for their help and support when things did not look encouraging in those frantic hours.

My special appreciation to Mr. Jerold Bement for allowing me to use his center pivot irrigation system in Dowagaic, MI. Special thanks also to Mr. John Smith, MECP Irrigation Scheduling Technician in Cassapolis, MI, for helping to collect field data.

Special thanks to my wife, Shashi, for her understanding, encouragement, patience, and support because of which this work became possible.

TABLE OF CONTENT

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure | Page

Figure		Page

Figure		Page

Figure **Page**

I INTRODUCTION

Irrigated agriculture has been practiced in various locations around the world for over 4000 years in the world. Most great civilizations started in river valleys of famous rivers such as the Tigris and Euphrates (Middle East), Nile (Egypt), Indus and Ganges (India), Hyuang-Ho (China). Over the years, great wars have been fought for the privilege of using water for irrigation. Worldwide in 1985, over one-third of the world food was grown on only 18% of cropland which was irrigated (Postel, 1985).

The most common form of irrigation worldwide has always been surface irrigation in its various forms (furrow, border, basin). The average irrigation efficiency of the surface (gravity) irrigation system is usually low. Worldwide average irrigation efficiency of surface irrigation is less than 37% (Postel, 1985).

Sprinkler irrigation and drip irrigation were developed in the more industrialized nations with the advent of plastic and aluminum pipes after World War II. These system of irrigation are capital intensive, less labor intensive, and have a greater energy demand than surface irrigation. Sprinkler and drip irrigation systems, however, allow for greater control of water delivery and thus have a greater water use efficiencies than comparable surface irrigation systems. Sprinkler and drip irrigation systems also tend to irrigate more uniformly than gravity systems. Water efficiencies typically average 70% or greater (Postel, 1985).

Irrigation in the United States has experienced unprecedent growth in the last few decades. In most cases the land was brought into irrigation using a variety of high-pressure sprinklers designs. In some areas, farmers have used these systems to irrigate hilly and marginal lands unsuitable for gravity methods. Overall, sprinkler irrigation accounts for virtually all of the net increase in irrigated area in the United States between 1960 and early eighties. In 1980, 32% of irrigated land was under sprinkler irrigation (Jensen, 1982). Today sprinkler irrigation are used on about 35-40 percent of U.S. irrigated land with drip irrigation on only 2-3 percent.

One of most common sprinkler irrigation system is the center pivot system. A single center pivot system irrigates about 150 acres, and is now used in much of the U.S. High Plains. In addition, over 12000 center pivots have been installed in the desert nation of Saudi Arabia over the last several years (Postel, 1985).

The center pivot irrigation system , figure 1, consists of a lateral arm which rotates around the central pivot point. The water is supplied to the lateral under high pressure through the central pivot point. The lateral line sections are usually suspended on towers with the help of simple truss structures and consists of openings for sprinklers, through which water is discharged to the field. The sprinklers are spaced and designed to supply uniform depth of water in

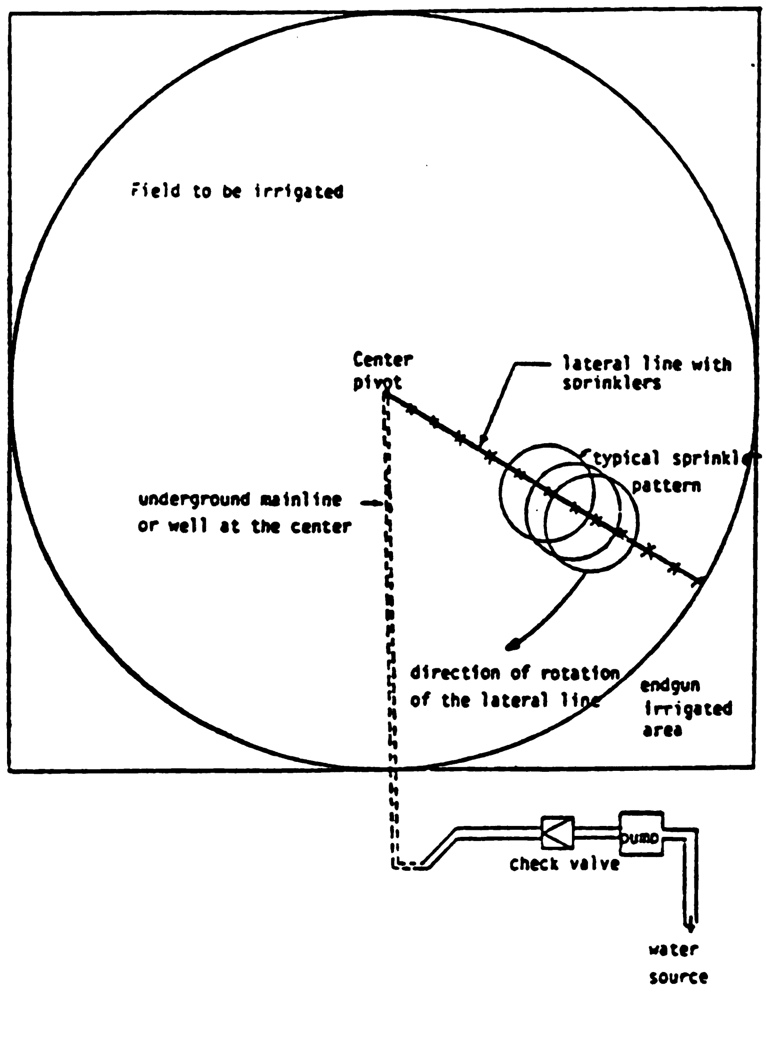


Figure 1. Layout of the Center pivot irriga.ion system.

the field being irrigated.

The most important advantage of the center pivot system when compared with other forms of sprinkler irrigation is that it requires minimal labor. Energy costs, however, are also an important parameter that could determine the viability of a center pivot irrigation system. Rising energy prices, especially when combined with falling water tables, can increase irrigation cost to prohibitive levels. Therefore the need to operate the center pivot system with maximum application and energy efficiency is becoming more and more important for the success of the irrigation systems.

A. SCOPE AND OBJECTIVES

The important factors that determine whether a center pivot irrigation system is properly designed are (1) Energy use, (2) Application rate, (3) Uniformity of application, (4) Instantaneous application rate. Any improvement that can be made in the design of the center pivot irrigation system will require the improvement in one or more of the above mentioned factors, but not at the cost of compromising the other remaining factor(s).

Many researchers (Bermuth, 1982; Solomon and Kodoma, 1978; Heermann and Hein, 1968) studied and developed methods that improved the performance of the center pivot irrigation systems with regard to energy use, application rate, and/or application uniformity. Bermuth (1982), Solomon and Kodoma (1978) pointed out that the operating point of the pump shifts when the end sprinkler of the lateral (end gun) is switched on and off. The switching on of the end gun decreases the

discharge and increases the pressure of the system. This in turn can change the application rate, application uniformity, and energy efficiency in the system. Therefore it is best to keep the discharge and pressure in the system constant such that the system will perform with maximum efficiency throughout the period of irrigation.

Some researchers have suggested using the booster pump which is operated when the end gun is on. Pressure compensating sprinklers can also be used to keep the application rate and uniformity constant. But this does not help in operating the pump with maximum efficiency when the end gun is off.

The possibility of using auxiliary sprinklers to keep the pumping rate and pressure constant throughout the period of irrigation has not been studied by any researcher. The auxiliary sprinklers would operate along the lateral when the end gun is switched off. As soon as the end gun is switched on, the auxiliary sprinklers would stop operating. This method would help to operate the pump with maximum efficiency throughout the irrigation period, thus saving energy.

The overall goal of this research is to investigate the possible conservation of energy by modifying the design of a center pivot irrigation system. The effect on the application rate and application uniformity as a result of the proposed modification will be studied. The specific objectives are

1) Determine the relationship between energy saving and addition of auxiliary sprinklers in the center pivot irrigation system.

2) Make a comparative study of the application uniformity with and

without the introduction of auxiliary sprinklers in the center pivot irrigation system.

3) Study the effect of the introduction of auxiliary sprinklers on the water application rate on the field and the saving of time that is possible.

II. REVIEW OF LITERATURE AND THEORY

Any modification in the design of the center pivot irrigation system such as the introduction of auxillary sprinklers will call for a thorough look at the hydraulics, field uniformity, network analysis, and energy use in the system. Therefore, a literature review of the above aspects of center pivot irrigation system was undertaken. The following is a review of the literature related to the design aspects of a center pivot irrigation system :

A. GENERAL HYDRAULICS

1. General

The hydraulic principles of fluid mechanics are based on the classical equations of continuity and energy. A theoritical development on fluid hydraulics has been given by Garde and Mirajoakar (1977) and others. The continuity equation is based on the conservation of mass principle. Refering to Figure 2, the flow in the pipe is

$$Q = V_1 \ A_1 = V_2 \ A_2 = \text{constant} \qquad [1]$$

where Q = discharge,

V = velocity of flow,

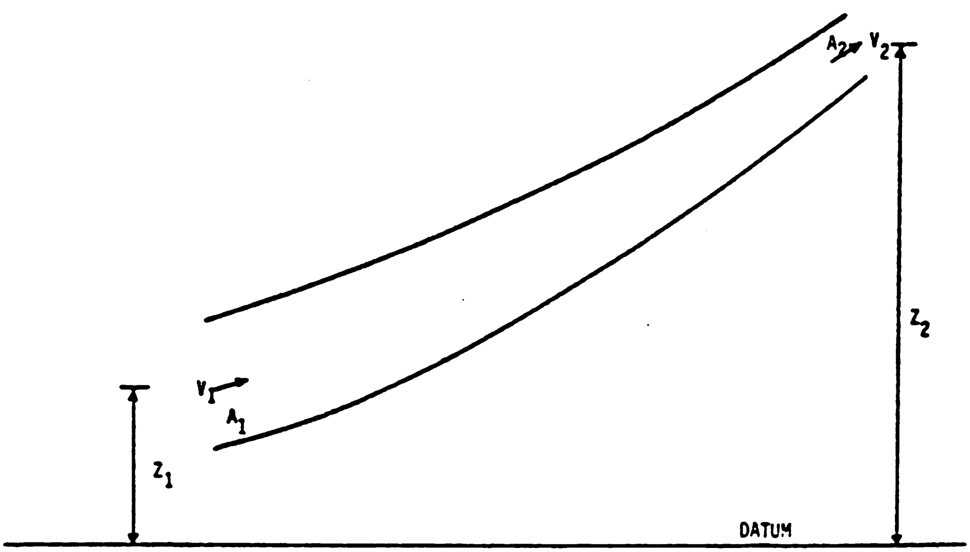


Figure 2. The discharge in the conduit with varying x-sectional area.

A = cross sectional area of the pipe, and
the subscript 1 and 2 are the positions where Q, V, and A are measured.

The energy equation in fluid mechanics is commonly known as Burnoulli's equation. Again refering to Figure 2, the energy balance equation can be written as

$$P_1/\gamma + Z_1 + (V_1)^2/2g = P_2/\gamma + Z_2 + (V_2)^2/2g + \Delta H \qquad [2]$$

or

$$[(P_2-P_1)/\gamma] + (Z_2-Z_1) = [((V_1)^2-(V_2)^2)/ 2g] + \Delta H \qquad [3]$$

where P = pressure in the pipe,

γ = specific density of water,

V = velocity of flow,

ΔH= hydraulic head loss between positios 1 and 2, and

the subscripts again represent the positions where the values are evaluated.

The hydraulic design of sprinkler irrigation systems based upon the above two equations has been presented by several researchers including James (1988), Wood and Charles (1972), Perold (1977).

2. Center pivot system hydraulics

Hydraulics of a Sprinkler: When a fluid is discharged from a conduit into the athmosphere through an opening of any form, the pressure intensity along the issuing jet surface is athmospheric (Garde et al, 1977). In sprinkler irrigation, the opening is a nozzle. Nozzles are employed when a high velocity jet is desired from a pipe. Considering a nozzle as shown in Figure 3 (Garde et al, 1977):

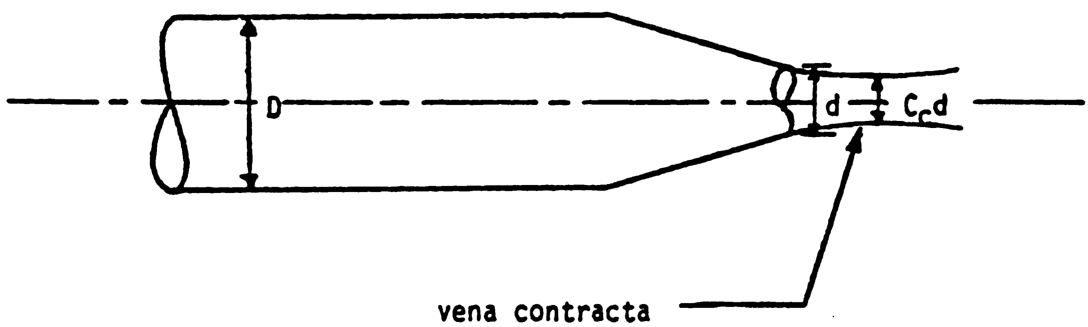


Figure 3. Discharge through the nozzle.

If section 1 is located in the undisturbed flow, while section 2 is located at the vena contracta, Bernoulli's equation gives

$$P_1/\gamma + (V_1)^2/2g = P_2/\gamma + (V_2)^2/2g \qquad [4]$$

The potential head ΔZ has been neglected in the above equation. Solving the above equation with the continuity equation gives

$$Q = [C_c/\sqrt{(1 - (C_c)^2(d/D)^4)}]\ [(\pi d^2/4)(\sqrt{2g})]\ [\sqrt{\Delta P/\gamma}] \qquad [5]$$

or

$$Q = C_d\ (\ \pi d^2/4\ )\ (2g)^{0.5}\ H^{0.5} \qquad [6]$$

where C_d = coefficient of discharge,

H = static head,

C_c = coefficient of contraction,

d = diameter at the mouth of the outlet, and

D = diameter at section 1.

Perrold (1977), Karmeli(1977), and Bralts(1983) have written the equation of flow thru the sprinkler or emitter in the form of

$$q = kh^x \qquad [7]$$

where q = sprinkler or emitter discharge,

k = constant of proportionality,

h = pressure head at the sprinkler or emitter, and

x = sprinkler or emitter discharge exponent.

It can be seen by comparing [6] and [7] that the constant of proportionality, K, contains variables such as the coefficient of contraction, geometry of the nozzle, and gravitaional acceleration.

The exponent x may be assumed to be 0.5 for fully turbulent flow from nozzle or orifice (Perrold, 1977). The nozzle with an x value of less than 0.5 would be pressure compensating in nature. A zero value for x would make the sprinkler fully pressure compensating (Bralts, 1983). All irrigation sprinkler manufacturers give the relation between discharge, q, and head, h, in tabuler form (Table 1).

Lateral line hydraulics: Water flow in a center pivot lateral line is considered to be hydraulically steady, spatially varied pipe flow with the flow being along the streamline. The total flow thru the lateral line decreases every time it passes a sprinkler nozzle. Taking into account the conservation of mass principle,

$$Q = V\ A$$

and the fact that A will remain constant, the velocity then decreases along the lateral line.

A large share of the energy loss is due to the friction in the pipe. In general, head loss due to friction can be written as

$$h_f = RQ^m \qquad [8]$$

where h_f = head loss due to friction,

R = constant depending upon the relation used,

Q = flow thru the pipe, and

m = discharge exponent.

Christensian (1942) used a generalized formula to calculate the

Table 1. Example sprinkler discharge-head relationships given by the manufacturers (Rain Bird; 1986).

104CO/105CO — 23° Trajectory — Ring Nozzle

Nozzle Size	PSI @ Elbow	Diameter	GPM
.870"	60	264	110
	70	275	118
	80	285	127
	90	295	136
	100	305	142
	110	315	150
	120	322	157
.990"	60	284	142
	70	295	154
	80	306	164
	90	315	175
	100	326	185
	110	335	195
	120	344	202
1.100"	60	300	185
	70	314	200
	80	326	213
	90	337	227
	100	348	238
	110	357	250
	120	366	259
1.201"	60	318	226
	70	332	243
	80	345	263
	90	358	278
	100	371	290
	110	382	305
	120	392	323
1.293"	60	335	275
	70	350	295
	80	364	315
	90	378	336
	100	390	352
	110	402	372
	120	412	392
1.380"	60	352	324
	70	367	353
	80	383	374
	90	396	400
	100	409	422
	110	421	441
	120	431	465
1.450"	60	365	385
	70	383	418
	80	398	447
	90	414	475
	100	425	500
	110	438	525
	120	450	550

104CS/105CS — 23° Trajectory — St. Bore Nozzle

Nozzle Size	PSI @ Elbow	Diameter	GPM
0.613"	60	245	86
	70	255	93
	80	265	99
	90	275	105
	100	285	111
	110	295	117
	120	305	122
0.690"	60	269	110
	70	281	118
	80	291	127
	90	300	136
	100	310	142
	110	320	150
	120	330	157
0.790"	60	292	142
	70	304	154
	80	316	164
	90	325	177
	100	334	185
	110	342	195
	120	351	202
0.890"	60	313	185
	70	324	199
	80	336	214
	90	347	227
	100	357	235
	110	365	249
	120	375	262
0.990"	60	329	226
	70	347	245
	80	357	263
	90	367	276
	100	377	290
	110	386	305
	120	395	323
1.090"	60	348	275
	70	363	295
	80	375	315
	90	390	336
	100	400	352
	110	410	372
	120	420	392
1.190"	60	368	331
	70	381	354
	80	395	374
	90	410	400
	100	420	422
	110	430	444
	120	440	465
1.290"	60	385	390
	70	400	418
	80	414	447
	90	427	475
	100	440	500
	110	450	525
	120	460	550

105CS-DC/43° Trajectory — St. Bore Nozzle

Nozzle Size	PSI @ Elbow	Radius (Feet)	V (Feet)	RV (Feet)	Flow (GPM)
0.613"	60	114	46	71	86
	70	118	49	76	93
	80	122	52	81	99
	90	126	54	85	105
	100	129	56	88	111
	110	134	57	90	117
	120	138	58	92	122
0.690"	60	119	47	75	110
	70	125	50	80	118
	80	129	53	84	127
	90	133	56	88	136
	100	136	58	92	142
	110	140	60	95	150
	120	144	61	97	157
0.790"	60	127	49	79	142
	70	131	53	86	154
	80	136	56	91	164
	90	139	59	94	177
	100	144	62	97	185
	110	147	64	101	195
	120	151	65	104	202
0.890"	60	133	50	81	185
	70	137	55	88	199
	80	142	59	95	214
	90	147	62	99	227
	100	149	65	103	235
	110	154	67	108	249
	120	157	69	109	262
0.990"	60	138	51	85	226
	70	145	56	91	245
	80	150	60	96	263
	90	153	64	101	276
	100	156	67	106	290
	110	161	69	110	305
	120	165	71	114	323
1.090"	60	144	52	87	275
	70	151	57	94	295
	80	157	61	99	315
	90	162	65	104	336
	100	167	68	110	352
	110	172	70	115	372
	120	176	72	117	392
1.190"	60	148	53	90	331
	70	155	59	97	354
	80	161	64	105	374
	90	165	68	110	400
	100	169	71	114	422
	110	171	74	117	444
	120	176	77	120	465
1.290"	60	153	54	91	390
	70	160	60	98	418
	80	166	65	105	447
	90	170	70	111	475
	100	175	73	116	500
	110	179	76	120	525
	120	182	79	124	550

head loss due to friction. This relation is commonly used in hydraulic design and analysis (Anon 2,1983; James, 1988)

$$h_f = KLQ^m / D^{2m+n} \qquad [9]$$

where K =coefficient depending upon the formulation and unit used,

m,n = exponents depending upon the formulation used,

L = length of the pipe (m, ft),

D = diameter of the pipe (mm,in), and

Q = flow rate (liters/min, gpm).

Comparing [8] and [9] gives

$$R = KL / D^{2m+n} \qquad [10]$$

Many semi-empirical equations are in use to calculate friction loss (h_f) in the pipe. Some of the more common equations are Darcy-Weisbach, Hazen-William, and Scobey.

The Darcy-Weisbach's equation for friction loss is

$$h_f = fLV^2/2gD \qquad [11]$$

and

$$R = 8fL / g\pi^2 d^5$$

where f = friction factor,

L = length of the pipe,

V = velocity of flow, and

D = diameter of the pipe.

The friction factor, f, in [11] depends upon the Reynold's number, R_e, and the relative roughness of the pipe, K = e/D (Garde et al, 1977;

Jeppson, 1982; Swamee and Jain, 1978)

For commercial pipe, the Coolbrook equation can be used to determine the value of f (Garde et al, 1977). This equation is

$$1/\sqrt{f} - 2 \log_{10} R_e/K = 1.74 - 2\log_{10}[1+18.7(R_e/K)/(R_e\sqrt{f})]$$

or

$$1/\sqrt{f} = 1.14 - 2 \log_{10} (e/D + 9.35/(R_e\sqrt{f}) \qquad [12]$$

Equation [12] has to be solved implicitely to determine f. Moody's diagram (Figure 4) is a plot of Equation 12. The drawback of the Moody's diagram is the difficulty of using in computer programming.

Swamee and Jain (1978) developed equations which could be solved for f explicitely. One of their equations is

$$f = 1.325 [\ln(0.27(e/D) + 5.72 (1/R_e)^{0.9}]^{-2} \qquad [13]$$

which is valid for a e/D range of

$$0.01 > e/D > 10$$

and a Reynolds number range of

$$10^{8} > R_e > 5000$$

Equation 13 has been shown to accurately represent the Coolbrook formula (Swamee et al, 1978).

The other popular expressions to determine pipe frictional loss are the Hazen-Williams and Scobey formulas. For the Hazen-Williams formula, $K = (0.285\ C)^{-1.852}$, $m = 1.85$, and $n = 1.17$ in eq. 15. In conventional units,

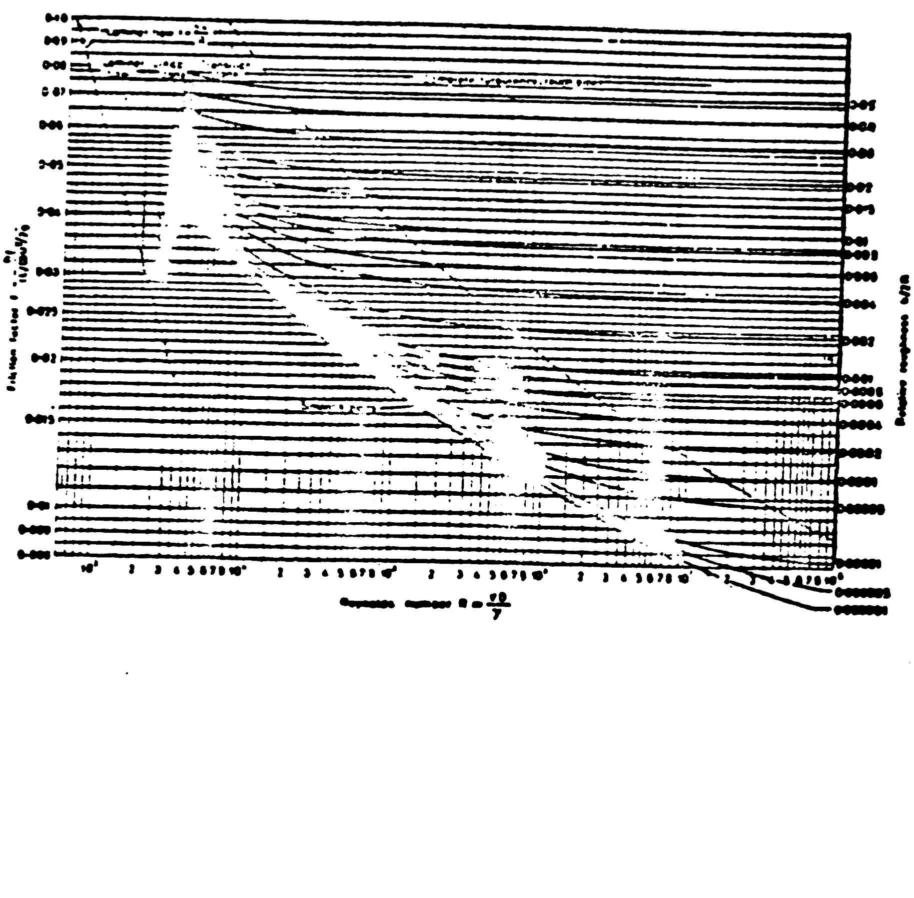


Figure 4. Moody's diagram showing the relationship between friction factor f, relative roughness e/D, and Reynold's number R_e based on the Coolbrook equation for commercial pipes (Garde et al; 1977).

$$h_f = L\,Q^m / (0.285\,C)^{1.852} D^{2m+n} \qquad [14]$$

where C = Hazen-William's constant.

Similarly for Scobey's equation, n=1.10, m=1.90, and $K=K_s/348$. Scobey's equation was given in conventional unit in the following form by Anon 2 (1983)

$$h_f = Ks\, V^{1.9} / D^{1.1} \qquad [15]$$

where Ks = Scobey's constant, and

h_f = head loss per 1000 ft of pipe.

Jeppson (1983) wrote that the values of Hazen-William's C and Scobey's K_s values should clearly be depended upon Reynold number. The limitation of these two equations is that their coefficients are weakly related to the diameter of the pipe. Besides this, they are not functions of the Reynolds number (Wiggert and Potter, 1989).

Since the flow in the lateral line is spatially varied with decreasing discharge, the energy grade line is an exponential curve rather than a straight line (Bralts, 1983).

Component loss: Besides friction, there is energy loss due to the presence of components in the system. This can include tees, connectors, elbows, valves, contraction and expansion joints. Component loss is generally denoted as minor loss and accounts for less than 10% of the total friction loss (James, 1988). It is a general practice to assume that minor losses are 10% of the friction loss in the network (James, 1988; Anon 2, 1983)

Though component losses are generally considered as minor losses, they can have a value more than what would be comfortably called a minor loss. The many outlets on the lateral line can increase the component loss in the system until it is substantial (Villemonte, 1977; Haghighi and Bralts, 1987; Saldivia, Bralts, and Segerlind, 1987)

Component head loss in the lateral line can be given by a generalized equation

$$h_m = K\ (V^2/2g) \qquad [16]$$

where K = loss coefficient, and

h_m = component head loss.

The value of loss coefficient for some components are given in Table 2 as given by James (1988), and Jeppson (1983):

Table 2. Component loss coefficient for a few components.

Standard Components	K
Standard tee; Entrance to minor line	1.8
Gradual contraction	0.04
Abrupt Contraction	0.50

Kincaid and Heermann (1970) reported that with a diameter ratio $d_p/D < 0.2$ and $q / Q < 0.3$, the head loss in feet for the flow into the riser is given approximately by

$$h_r = V^2 / 2g\ e^{(9.2q/Q)} \qquad [17]$$

where h_r = riser entrance head loss,

q = branch discharge,

Q = discharge in upstream mainline section,

d_p = diameter of riser, and

D = diameter of main line.

B. UNIFORMITY AND APPLICATION EFFICIENCY

1. Hydraulic Uniformity

To obtain desired discharge and application patterns from center pivot irrigation, an adequate pressure must be maintained throughout the lateral of the center pivot system.

In the center pivot system, the water is introduced at the pivot point and flows outward thru the line, supplying each of the individual sprinkler heads. Since the water flows outward from the pivot, the pressure at the pivot point is higher than at the outer end of the lateral line. This is not the desired pressure distribution since the larger sprinklers at the outer end normally require higher operating pressures than the smaller sprinkler near the pivot point (Kincaid et al, 1970). To maintain adequate working pressure in the larger sprinkler, the pivot pressure must exceed the outer-end pressure by the amount of pressure drop in the lateral line (Kincaid et al, 1970).

Heermann and Hein (1968) reported that for practical purpose, the uniform distribution of depth of application is achieved by limiting the pressure drop on the lateral line to 20% of the higher pressure. The American Society of Agricultural Engineers (ASAE) also recommends the pressure drop to be no more than 20% of the higher pressure in the system (Anon 1, 1986).

Because of the design of a center pivot system, the discharge of individual sprinkler heads must be increased in proportion to the area each sprinkler irrigates in order to obtain a uniform depth of water distribution over the entire field (Figure 5). If the sizes of the sprinklers are the same, the spacing of the sprinklers farther away from the pivot must be closer than the sprinklers near the pivot(Figure 6).

With approximately constant spacing of the sprinklers, the discharge of the sprinklers farther away from the pivot should be greater than that closer to it. Chu and Moe (1972) showed that

$$Q = Q_o \ (1-r^2/R^2) \qquad [18]$$

where Q = discharge from the sprinkler located at a distance of r from the pivot,

Q_o = total discharge excluding that from the end gun,

r = distance from the pivot to the sprinkler which is under consideration, and

R = distance from the pivot to the end of the system.

Chu et al (1972) showed that the distribution of discharge in the lateral line according to the above equation closely resembles experimental field discharge in the center pivot system (Figure 7a).

They also analytically derived an equation to determine the total pressure head loss in the system as

$$h_o - h_r = h_m \ B(m+1,0.5)/2 \ -(V_o)^2/2g \qquad [19]$$

where h_o = pressure head at the pivot point,

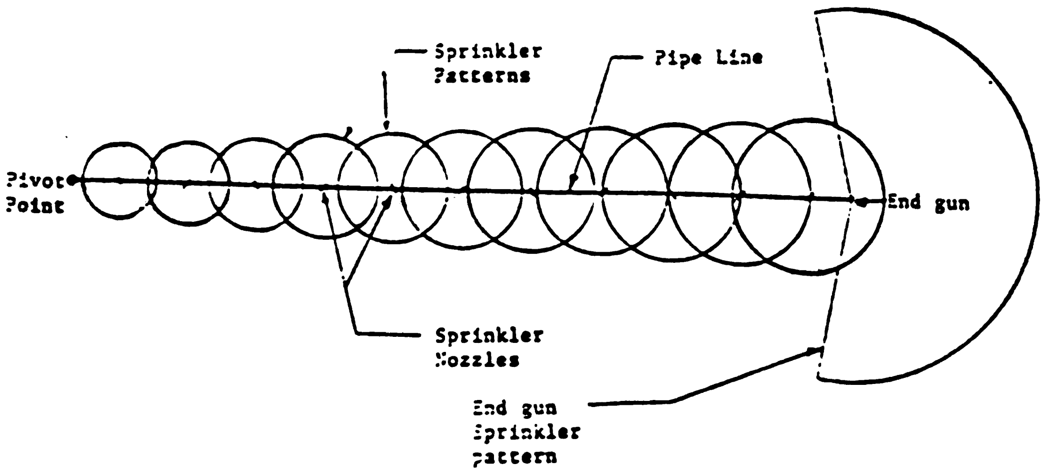


Figure 5. Distribution pattern from the center pivot irrigation system with increasing discharge away from the center pivot.

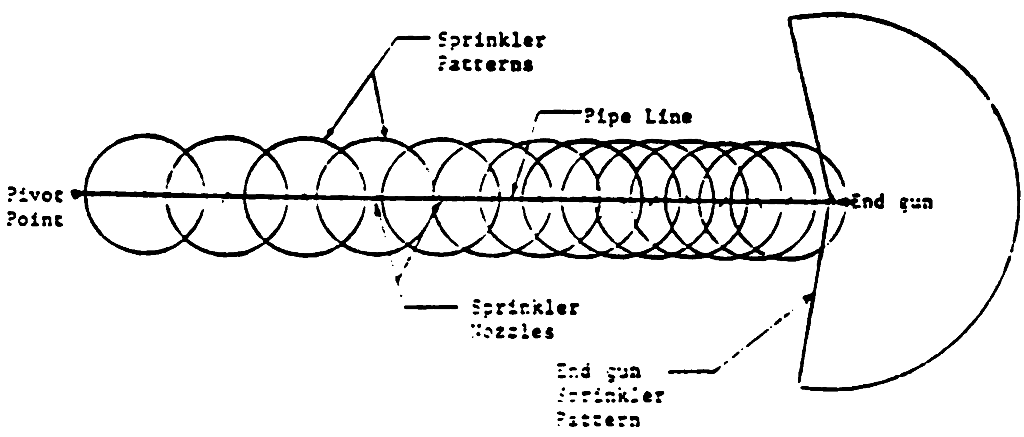


Figure 6. Distribution pattern in the center pivot irrigation system with uniform discharge from all sprinklers.

h_r = pressure head ata distance r from the pivot,

h_m = the friction head loss of the main line operating as a supply line,

B(n+1,0.5) = beta function, and

m,n = exponents from the Christensian general formula for head loss.

The above equation is also written as

$$(h_o - h_r) / h_m = B(m+1,0.5)/2 \qquad [20]$$

The above relation [20] does not include the potential head in the system. Taking into account the potential head in the system, [18] can be written as

$$h_o - h_r = (h_m B(n+1, 0.5)/2) - \Delta Z \qquad [21]$$

where ΔZ = potential head.

Using [20], Chu et al (1972) showed that there is approximately a 50% pressure drop in the first 25% of the lateral line (Figure 7b).

There is a limiting factor as to the acreage that can be covered by a single center pivot system because of the the hydraulic uniformity. The total acreage covered by a system can be increased substantially by increasing the length of the pipe line and the total system discharge to maintain a constant discharge per acre. However, the total head loss will be larger because the extra discharge must be pumped thru the entire lateral. Kincaid et al (1970) showed that the 30% increase in area (from 140 acres to 180 acres) and discharge increased losses nearly 100%. This relatively high head loss may cause higher than necessary pumping costs and it also provides higher pressures than required for the

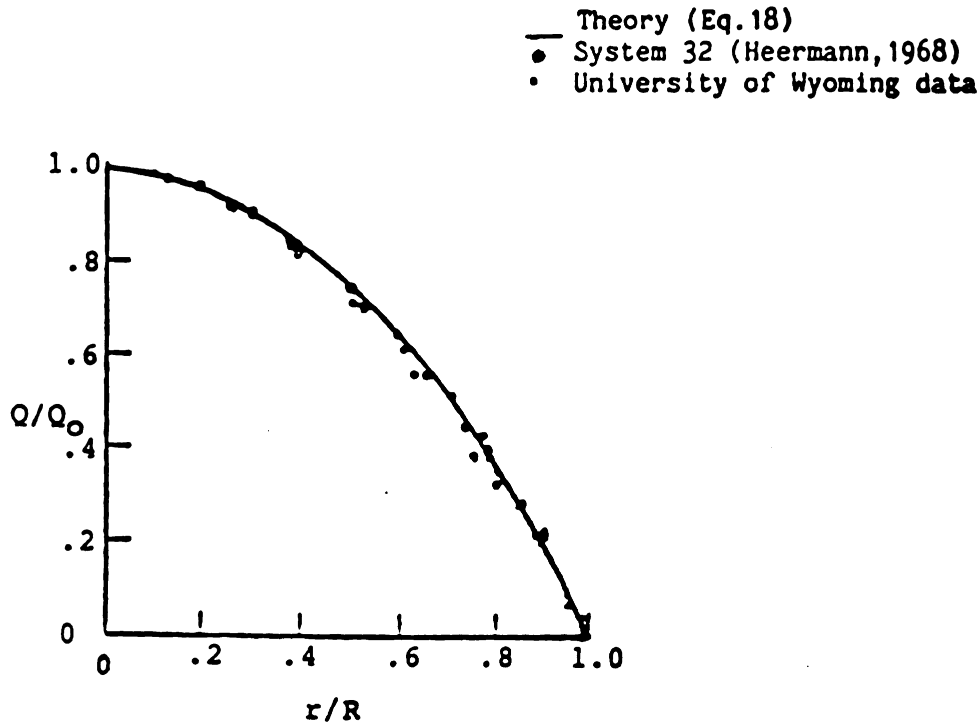


Figure 7a. Distribution of discharge in the lateral line.

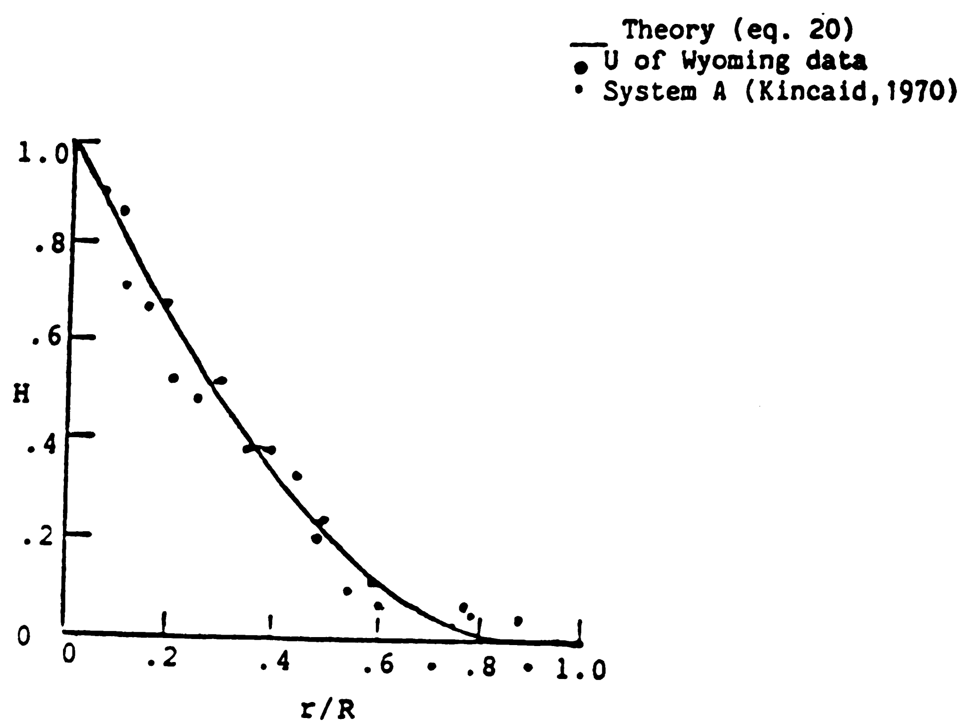


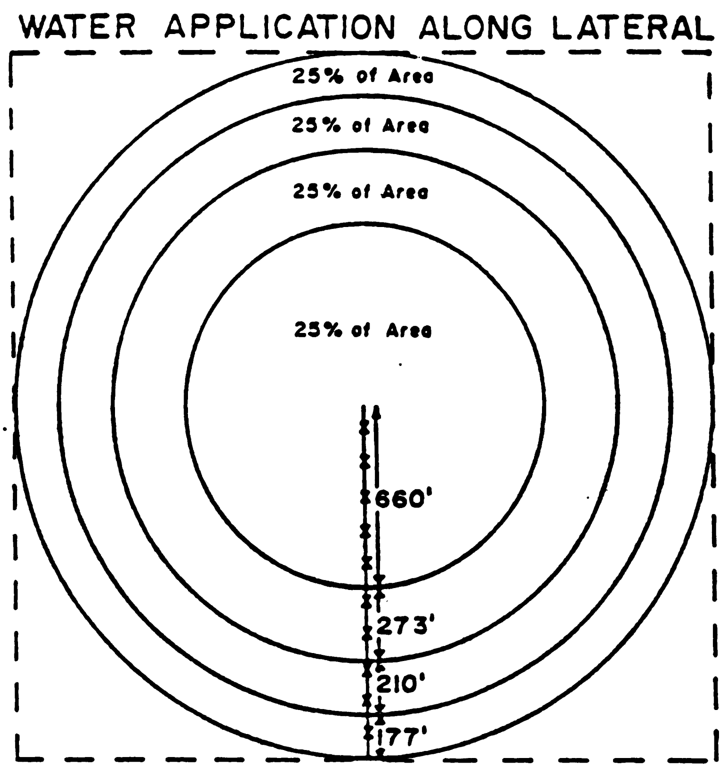
Figure 7b. Distribution factor of pressure head loss.

smaller sprinklers and lower than required for larger sprinklers. Besides this, the application uniformity can be drastically effected because of the high pressure loss in the lateral line (Kincaid et al,1970) .

2. APPLICATION EFFICIENCY

The water application rate to a point on the soil surface varies continuously with time during application by any moving sprinkler system (Kincaid, Heermann, and Kruse; 1969). In the center pivot system, the application rate must vary along the lateral length from a low value near the pivot to higher values at the outer end. Figure 8 illustrates why the application rate must increase toward the outer end of the lateral. The discharge and linear rate of travel of the sprinkler heads must increase in proportion to the area irrigated.

The water is thought to be applied in an elliptical or triangular pattern from the sprinkler to the field. Bittenger and Longenbaugh (1962) found that the triangular pattern with a spacing equal to the radius of the pattern itself will produce a more uniform distribution of water than the elliptical pattern when moved at a constant speed. But Kincaid et al (1969) conducted experiments and found that the assumption of elliptical rather than triangular-pattern sprinklers produced the accumulated application curve that agreed more closely with the experimentally determined curve. This means that the elliptical pattern has to be considered in obtaining the application rate and application depth in a center pivot system. Bittenger et al (1962) found that the most even distribution for the elliptical pattern exists at a spacing of about 1.4 times the radius of the pattern (r).



PER CENT OF AREA	LATERAL LENGTH	ACRES
100	1320'	125.66
75	1143'	94.24
50	933'	62.83
25	660'	31.42

Figure 8. The relationship between the area of the field and the lateral line distance that irrigates it for a 125 acres field.

The water distribution pattern from individual sprinklers greatly depends upon the pressure available at the nozzle. The distribution of water can vary a lot when the pressure is greater or less than the design pressure (Anon 2, 1983). When the end gun is switched off, the pressure in the lateral rises as a result of which the water distribution from a sprinkler can change to give a different application pattern in the field (Figure 9).

Heermann et al (1968) showed that the total depth D_s of water at a distance s from the pivot for one pass of the system for the elliptical pattern is

$$D_s = (4/w)\sum_{i=1}^{N} h_i(1-m_i)^{1/2} \int_0^{wT_i/2} [1- \{4n_i(n_i+m_i)\sin^2\phi / (1-m_i{}^2)\}]^{.5}\, d\phi \quad [22]$$

where D_s = total depth of application from a sprinkler at a distance s from the center of rotation,

w = angular velocity of sprinkler lateral,

h = rate of application at center of sprinkler pattern,

m = ratio of distance from sprinkler to point P, measured along sprinkler lineto pattern radius (s-R)/r,

T = time required for one-half a single sprinkler pattern to pass point P,

n = ratio of radius of rotation to pattern radius, R/r,

ϕ = angle of integration, equal to $(\pi/2 - \alpha/2)$,

α = angle of rotation about pivot,

s = distance from pivot to point P,

R = distance from pivot to sprinkler,

r = radius of sprinkler pattern, and

i = subscript referring to the i^{th} sprinkler on the system.

The numerical solution of [22] requires a considerable amount of

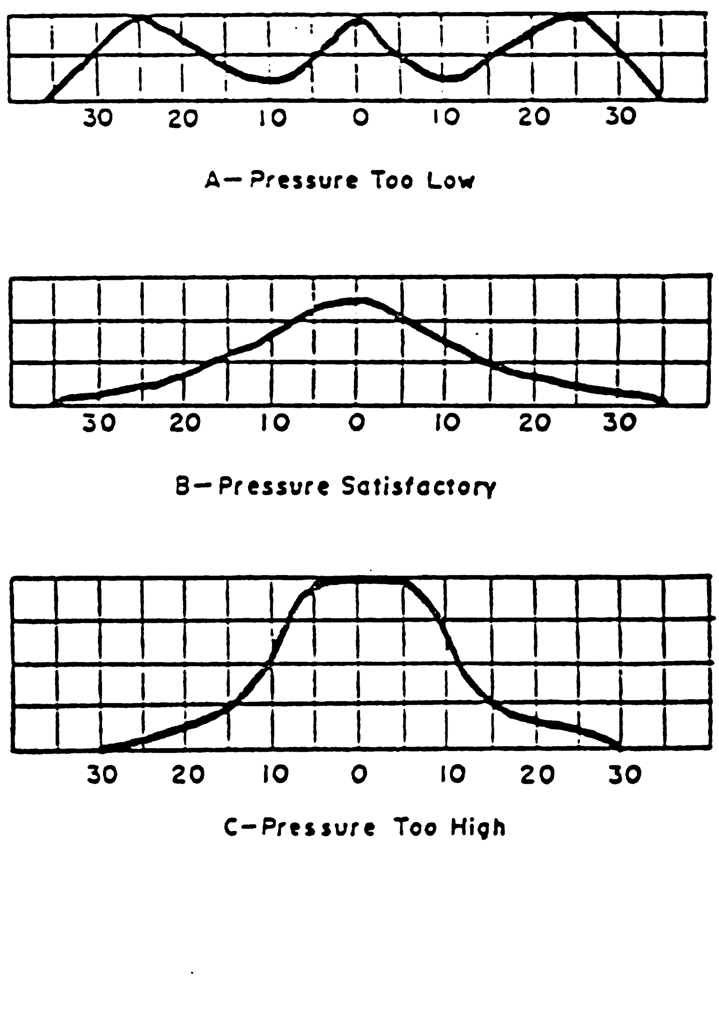


Figure 9. A typical application pattern from a single sprinkler with the change in pressure.

computer time. Heermann et al (1968) and Bittenger et al (1972) reported that the skewness for the circular path was less than 0.01 inches of water from the inner to the outer radius for a sprinkler at a radius of more than 650 feet. Therefore, when the radius of circular sprinkler motion is greater than 650 feet, the application pattern are essentially equivalent to those of linear motion and the depth of application can be found from

$$D_s = \pi / 2w \sum_{i=1}^{N} (h_i \; r_i)/Ri * (1-m_i) \qquad [23]$$

The maximum application rate which occurs at the center of the pattern was given by Dillon,Hilel,and Vittetoe (1972) as

$$h_l = 2 \; q_l \; / \; \pi r_l \qquad [24]$$

where h_l = peak application rate at the center of the elliptical path,

q_l = flow per one foot wide band in gpm, and

r_l = distance along the center line of the band from the center of the pattern.

Dillon, et al (1972) also gave the relation between the distribution of water by a sprinkler along the lateral and the percent of area covered. The water applied to a one foot band of land which encircles the pivot is proportional to the area of the band divided by the total area irrigated by the system. This was expressed as

$$q_l = 2 \; L \; Q \; / \; R^2 \qquad [25]$$

where L = distance from the pivot to the middle of the foot wide band in feet,

Q = flow at the pivot in gpm, and

R = radius of coverage of the system in feet

By substituting [24] into [25] and correcting for units, the following expression was obtained

$$h_l = 122.5\ QL\ /\ R^2 r_l \qquad [26]$$

Since the maximum application rate occurs at the end of the system, Dillon, et al (1972) approximated the maximum application rate in the system as a whole from the following relation

$$h = 122.5\ Q\ /\ R\ r \qquad [27]$$

where h = maximum application rate at the last few sprinklers, and

r = radius of coverage of the last few sprinklers on the system excluding the end gun-type sprinklers.

The intake rate and the storage capacity of the soil are important parameters that determines the maximum application rate that is possible without runoff from the soil. It is possible to use one center-pivot system to irrigate two fields if the intake rate of the soil is relatively high, provided the discharge and the pressure in the lateral line is sufficient.

Potential runoff begins when the surface storage of the soil is satisfied. The surface storage is equal to the amount of water applied faster then the soil intake rate which eventually infiltrates into the soil. If surface storage is not considered, the feasibility of center pivot systems is limited (Dillon et al (1972).

The minimum speed of travel of the end tower v ,such that there is no runoff from the field , in feet per minute, is determined from the expression

$$v = r / 30t \qquad [28]$$

where v = minimum speed of travel of the end gun,

r = the radius of coverage of the last few sprinklers on the system excluding the radius of the end gun-type sprinklers, and

t = maximum time in hours for an elliptical pattern to pass a point before the surface storage is exceeded.

Dillon, et al (1972) determined the surface storage curves for 0.5 and 0.3 intake family soils (Figures 10 and 11). The value of t in [28] can be determined from these curves based on the surface storage and intake characteristic of the soil.

3. FIELD UNIFORMITY:

Karmeli (1978) estimated the sprinkler distribution pattern using linear regression. He noted that the use of linear regression, based upon the dimensionless cumulative frequency curve of the infiltration depth Y and the fraction of area (X) represented by $Y = A + Bx$, is an accurate method for describing sprinkler distribution pattern. This approximation proved to produce good estimates for both high and low quality distributions.

Christensian was the first to introduce a uniformity coefficient (U_c) to a sprinkler system (Karmeli, 1978).

$$U_c = [1 - (\Sigma \mid Y_i - \bar{Y} \mid) / N \bar{Y}]100 \qquad [29]$$

or

$$U_c = [1 - \Delta Y / \bar{Y}]100$$

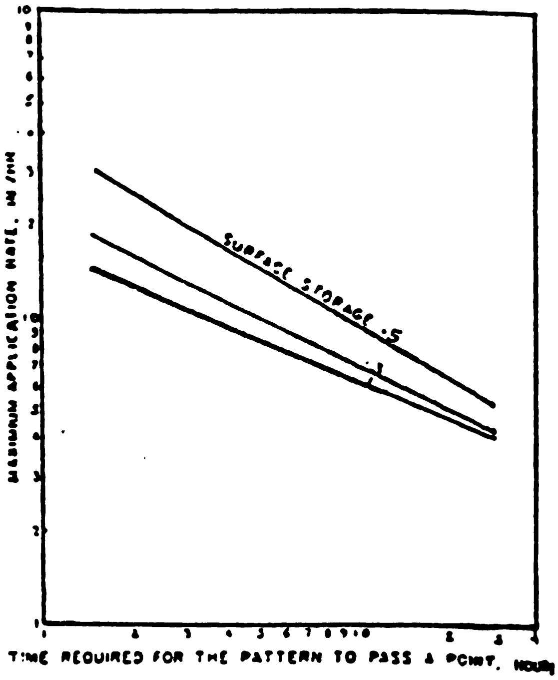


Figure 10. Surface storage curve for 0.3 intake family soil.

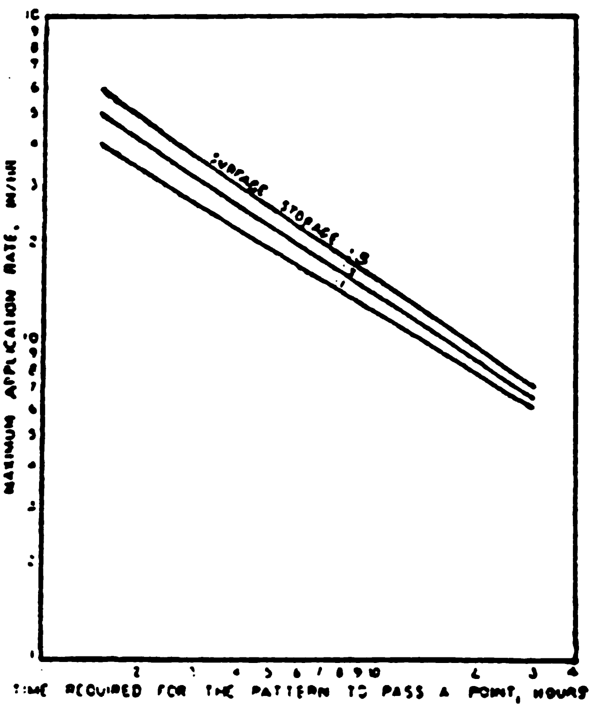


Figure 11. Surface storage curve for 0.5 intake family soil and Pullman soil.

where $\Delta \overline{Y}$ = mean deviation about the mean.

Hart(1961) and Hart and Reynold (1965) developed a uniformity coefficient (U_h) with the assumption that water distribution from commonly used sprinklers, under regular spacing conditions, may be described and approximated by the Gaussian distribution

$$U_h = [1 - (s\sqrt{2\pi} / \overline{Y}]100 \qquad [30]$$

where s = standard deviation, and

$\overline{Y}$ = mean of the sample.

Karmeli (1978) pointed out that, with a normal distribution, the mean of the absolute values of deviation equal 0.789s, and the uniformity coefficient can be written as

$$U_h = [1 - 0.789s / \overline{Y}]100 \qquad [31]$$

Wilcox and Swailes (1947) first presented the statistical concept for the evaluation of sprinkler irrigation systems (Bralts, 1983). This statistical uniformity coefficient was based on the coefficient of variation, Vy, and is defined by the equation

$$U_w = 1 - V_y$$

or

$$U_w = [1-(S / \overline{Y})]100 \qquad [32]$$

where U_w = coefficient of uniformity,

V_y = coefficient of variation,

S = standard deviation, and

$\overline{Y}$ = mean of the sample.

Heermann and Hein (1968) have developed a method to calculate the uniformity coefficient for center pivot system based on the "coefficient of uniformity " concept proposed by Christensian.

This uniformity concept considers the ratio of a summation of the absolute deviation of the mean volume from observed volumes for sub areas to the total volume applied and is expressed as

$$U_c = 100 \left[1 - \frac{\{\Sigma S_s \, |D_s - (\Sigma D_s S_s \, / \, \Sigma S_s)|\}}{\{\Sigma D_s S_s\}} \right] \qquad [33]$$

where U_c = Heermann and Hein uniformity coefficient,

D_s = Total depth at a distance S from the center,

S = Distance from the pivot to the collector,

s = subscript denoting a point at a distance S from the center, and

Σ = summation of the total number of catch containers.

The ASAE standard (Anon 1, 1986)) on the test procedure for determining the uniformity of water distribution of center pivot uses the above Heermann and Hein uniformity equation. The above equation is more commonly known as the Heermann and Hein modified equation.

E. NETWORK ANALYSIS:

The solution of the energy gradient in the irrigation lateral can be determined by approximation method or by iterative procedures.

1. Hardy-Cross Method:

One of the first and probably the most widely used method of analysis is the Hardy-Cross technique (Wood and Charles, 1972). This method was popular in the pre-computer days as a hand worked solution. This method has been incorporated into numerous computer algorithms for the solution of hydraulic network problem (Wood, 1972). The method analyses the network by using the (i) head balance technique in the loops and (ii)flow balance technique at the nodes.

The energy equation of flow is used to write the head balance equation in each loop of the network, and it is written as

$$\Sigma h_f = \Sigma RQ^m = 0 \qquad [34]$$

The continuity equation is used in the flow balance technique. In equation form, the relation at each node can be written as

$$\Sigma Q_{in} = \Sigma Q_{out} = 0 \qquad [35]$$

The Hardy Cross method uses the combination of an assumed flow (Q_o) and a corrective flow (ΔQ) to solve the loop equations. The head loss equation around a loop that includes corrective flow is

$$\Sigma h_f = \Sigma R\ (\ Q_i + \Delta Q)^m \qquad [36]$$

Once the corrective flow is established, a new assumed flow is determined by using

$$Q_{i+1} = Q_i + \Delta Q_i \qquad [37]$$

where i = iteration number.

The use of the Hardy Cross method was also described by Chenoweth and Crawford (1974) and Jeppson (1982). Using [8] to write discharge in terms of head loss, [35] is written as

$$\Sigma(h_f/R)^{1/m}{}_{in} - \Sigma(h_f/R)^{1/m}{}_{out} = 0 \quad [38]$$

Jeppson (1978) reported that the number of simultaneous equation that must be solved is greatly reduced by using [38] instead of [35].

After substituting the junction pressure,

$$\Sigma[(H_{j-1} - H_j) / R]^{1/m}{}_{in} = \Sigma[(H_j - H_{j+1}) / R]^{1/m}{}_{out} \quad [39]$$

where H_{j-1} = junction pressure at the upstream node,

H_j = junction pressure as the present node, and

H_{j+1} = junction pressure as the downstream node.

The Hardy Cross solution for the corrective pressure ΔH at a node can be determined by using [8] and [36] to yield

$$\Delta H = [\{(h_f / R)^{1/m}\} / \{ (1/m)(h_f/R)^{1/m - 1}\}] \quad [40]$$

Equation 40 is non-linear and iterative. As the calculation of ΔH procced over the network, the value of ΔH should be calculated at each node and correction should then be applied to the energy and hydraulic grade line elevetion (Chenoweth et al , 1974).

The number of iterations required in the Hardy Cross method is dependent upon the accuracy of the initial guess. In some cases, Wood (1972) found that convergence was very slow and not at all.

2. <u>Newton-Raphson Method:</u>

This method overcomes the drawback of the Hardy Cross method by quadratic convergence. The development of the equation below is based

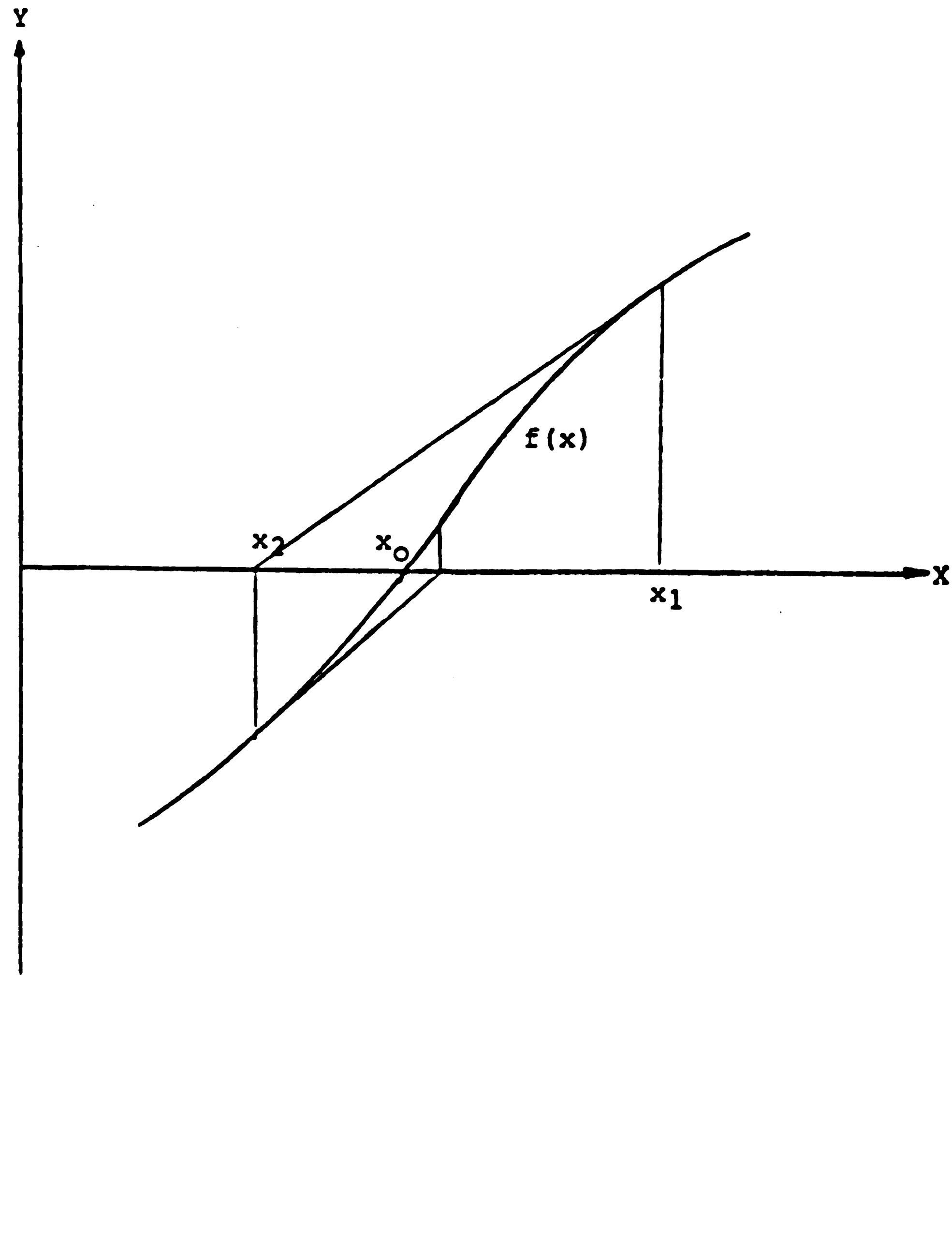


Figure 12. Illustration of solutions using the Newton Raphson Method

upon the method given by Shamir and Howard (1968).

Referring to Figure 12, the value X_o is sought for the solution such that

$$f(X_o) = 0$$

At the k^{th} iteration, the approximation for X_o is denoted by X_k. The next approximation is given by

$$X_{k+1} = X_k + \Delta X_k = X_k - f(X_k) / [df(X_k) / dx] \qquad [41]$$

The equation for the K^{th} improvement ΔX_k can be written as

$$\Delta X_k = f(X) + (\partial f/\partial X)\Delta X = 0 \qquad [42]$$

in which both $f(X)$ and $\partial f/\partial X$ are evaluated using the present value of X.

Because this method adjusts the flow rates in all the loops simultaneously, convergence using the Newton-Raphson approach is much quicker than using the Hardy Cross approach. However, both methods of analysis require initial guesses for the flow distribution and a very bad estimate of these values can lead to slow convergence or no convergence at all.

3. <u>The Linear Theory Method:</u>

This method was first proposed by Wood and Charles in 1972. Some of the special features of this method are that it is not necessary to estimate initial flow rates, convergence is extremely fast, programming is easier, and it can be used for optimization analysis.

The basic principle of this method is to transfer the loop equations into linear equations by approximating head loss by using the following equation:

$$h_{li} = R_i Q_i^m = R_i Q_{io}^{m-1} Q_i = R_i' Q_i \quad [43]$$

where Q_{io} = approximate discharge in line i, and

R_i' = modified pipeline constant.

Reasonably accurate initial flow rate is calculated by assuming that the modified pipe line constant is independent of flow rate and, as a first approximation, is given by

$$R_i' = R_i \quad [44]$$

The solution of nodal equations obtained by applying this theory was highly accurate with fast convergence (Wood and Rayes, 1981). But in some cases convergence was never obtained.

The linear theory method was used by Wood et al (1972) to solve network consisting of 58 pipes. The comparision of this method with Hardy Cross and Newton-Raphson methods showed that the number of iterations in this method is the least (Table 3).

Table 3. Numerical methods and the number of iterations required for convergence.

Method	No of iterations
Hardy-Cross	635
Newton-Raphson	24
Linear Theory	4

4. Finite Element Method:

Bralts and Segerlind (1985) reported that the finite element method could be used for hydraulic network analysis if the head loss equation can be written in a linear form. Considering the pipe segment shown in Figure 13,

$$Z_i + H_i = Z_j + H_j + RQ^m \qquad [45]$$

where Z = elevation,

H = static pressure head,

RQ^m = head loss due to friction, and

i and j are subscripts denoting upstream and downstream end of the pipe element.

Equation 45 can be rearranged to give

$$R^{1/m} = [(Z_i + H_i) - (Z_j + H_j)]^{1/m} \qquad [46]$$

or

$$Q = C_p\,[(H_i - H_j) + (Z_i - Z_j)] \qquad [47]$$

where $C_p = [(Z_i + H_i) - (Z_j + H_j)] / R^{1/m}$ is known as the pipe coefficient.

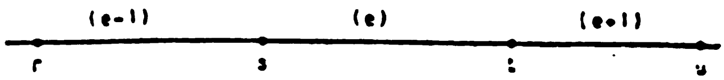
For the simple network in Figure 13, the nodal equations for element (e) can be written as

$$-Q_s(e-1) + Q_s(e) = 0 \qquad [48]$$

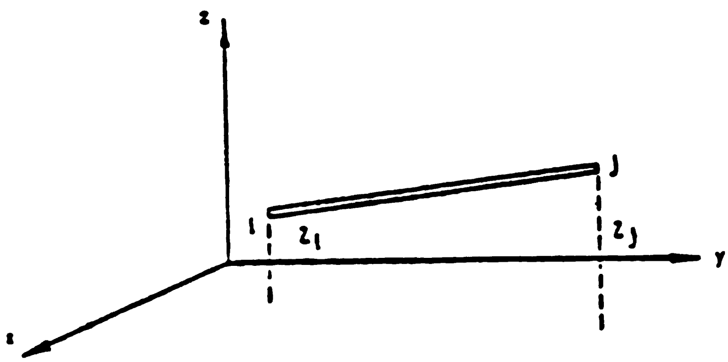
and $$-Q_t(e) + Q_t(e+1) = 0 \qquad [49]$$

where Q_s = flow to node s, and

Q_t = flow to node t.



a. Straight pipe element



b. Simple one branch element

Figure 13. Element considered in the finite element method.

Based on the definition given by Segerlind (1984), the contribution of element (e) to equations to the global stiffness matrix are simply Q_s and Q_t where

$$Q_t(e) = -C_p(P_s - P_t) - C_p(Z_s - Z_t) \qquad [50]$$

where H_s = static pressure head at node s,

H_t = static pressure head at node t,

Z_s = elevation at node s, and

Z_t = elevation at node t.

Equations 49 and 50 can be written in the finite element form as

$$\begin{Bmatrix} Q_s(e) \\ Q_t(e) \end{Bmatrix} = \begin{bmatrix} C_p & -C_p \\ -C_p & C_p \end{bmatrix} \begin{Bmatrix} P_s \\ P_t \end{Bmatrix} + \begin{Bmatrix} C_p\ \Delta Z \\ -C_p\ \Delta Z \end{Bmatrix} \qquad [51]$$

where $\Delta Z = Z_t - Z_s$.

Equation 51 has the standard finite element form

$$\{R^{(e)}\} = [\ K^{(e)}]\ \{P^{(e)}\} - \{f^{(e)}\} \qquad [52]$$

where $[K^{(e)}]$ = element stiffness matrix,

$\{f^{(e)}\}$ = element force vector,

$\{R^{(e)}\}$ = residual vector, and

$\{H^{(e)}\}$ = pressure head vector.

Haghighi and Bralts (1987) extended the above concept to include the component loss as a result of an elbow, a knee joint, a valve joint, an expansion/contraction joint, and a booster pump in the network. Saldivia, Bralts, and Segerlind (1987) showed that the hydraulic design of the sprinkler irrigation system could be done using the finite element approach. The sprinkler element and a pump was also considered in their analysis. The sequence of nodes and elements at the riser was considered as shown in Figure 14.

The major advantage of the finite element approach for the analysis of pipe network is that the matrix is banded and symetric which minimizes the computer storage requirement (Segerlind, 1984).

F. ENERGY USE

Irrigation is a major energy user in production agricultural, accounting fo 13% of all energy used on farms (USDA-ERS, 1977). In the Southern Plains of the U.S., irrigation pumping account for about 50% of the energy used on irrigated farm (Clark and Schneider, 1980)

Energy used in irrigation depends upon the method of irrigation. Keller and Bliesner (1983) have shown that center pivot irrigation system consumes less energy than the handmove sprinkler and traditional surface irrigation system when the water is pumped from a well of 500 ft deep. The main factor that makes the center pivot system compete with other methods of irrigation is that it requires minimal labour energy. The demand for the center pivot system increases with the increase in the cost of labor energy (Heermann and Hein, 1968).

Massey, Skaggs, and Sneed (1983) suggested that the energy requirements for irrigation may be reduced by (i) improving pumping plant efficiency, (ii) increasing irrigation efficiency so that less water is required, and (iii) lowering the pressure head of the system.

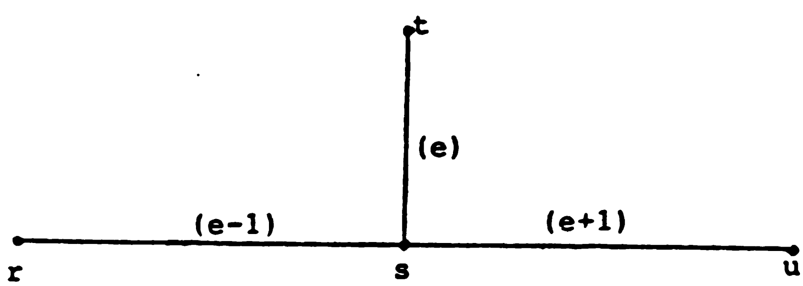


Figure 14. Sequence of the nodes and elements of a riser element.

Energy in irrigation is used to lift water from one elevation to a higher level, to overcome friction loss during conveyance, and to provide pressure for sprinkler operation. Energy requirement in center pivot irrigation is normally supplied by a pump that either runs with electricity, diesel, or gas.

Capacity, head, power, efficiency, required net positive suction head, and specific speed are parameters that describe the performance of a pump. The power imparted to the water by the pump is called water power. Water power is (James, 1988)

$$WHP = QH / K \qquad [53]$$

where WHP = water horse power (hp, KW),

Q = discharge (gpm, m^3/sec),

H = head (ft, m), and

K = constant depending upon the unit used (K = 3960 for conventional unit; K = 0.102 for SI unit).

Pump efficiency (η_p) is the ratio of the energy delivered by the pump to the energy supplied to the pump shaft; that is, the ratio of the water horsepower to the brake horsepower(BHP), or,

$$\eta_p = WHP / BHP \qquad [54]$$

Overall efficiency (η_o) is the ratio of the energy delivered by the pump to the energy supplied to the input side of the pump driver; for example, the overall efficiency of a motor driven pump is the ratio of the liquid horsepower to the electrical horsepower (EHP) (Anon 3,1987), or,

$$\eta_o = WHP / EHP \qquad [55]$$

Anon 2 (1983) gave the nomograph developed by Kenneth Frost that shows power requierments with other factors known (Figure 15).

The required net positive suction head ($NPSH_a$) is the amount of energy required to prevent the formation of vapor-filled cavities of fluid within the eye of the single-and-first stage impellers. Continued cavition can severely damage pumps.

James (1988) wrote that the net positive suction head required to prevent cavitation is a function of pump design and is usually determined experimentally for each type of pump. Cavitation is prevented when heads within the eye of single-and-first stage impellers wxceeds the required NPSH ($NPSH_r$) values published by manufacturers.

A well designed irrigation system have pumps that operate with maximum efficiency for the design discharge and head. This pump efficiency is constant when the discharge and head are constant.

Curves relating head, efficiency, power, required net positive suction head to pump capacity are utilized to describe the operating properties (characteristic) of the pump. This set of four curves is known as the pump characteristic curves (Figure 16).

An operating irrigation system has water flowing thru the pipes. The head under which the system operates is dynamic. The dynamic head is made up of several heads and is given by James (1988) as

$$H_s = SL + DL + DD + H_l + M_l + H_o + VH \qquad [56]$$

where H_s = dynamic head,

SL = suction side lift,

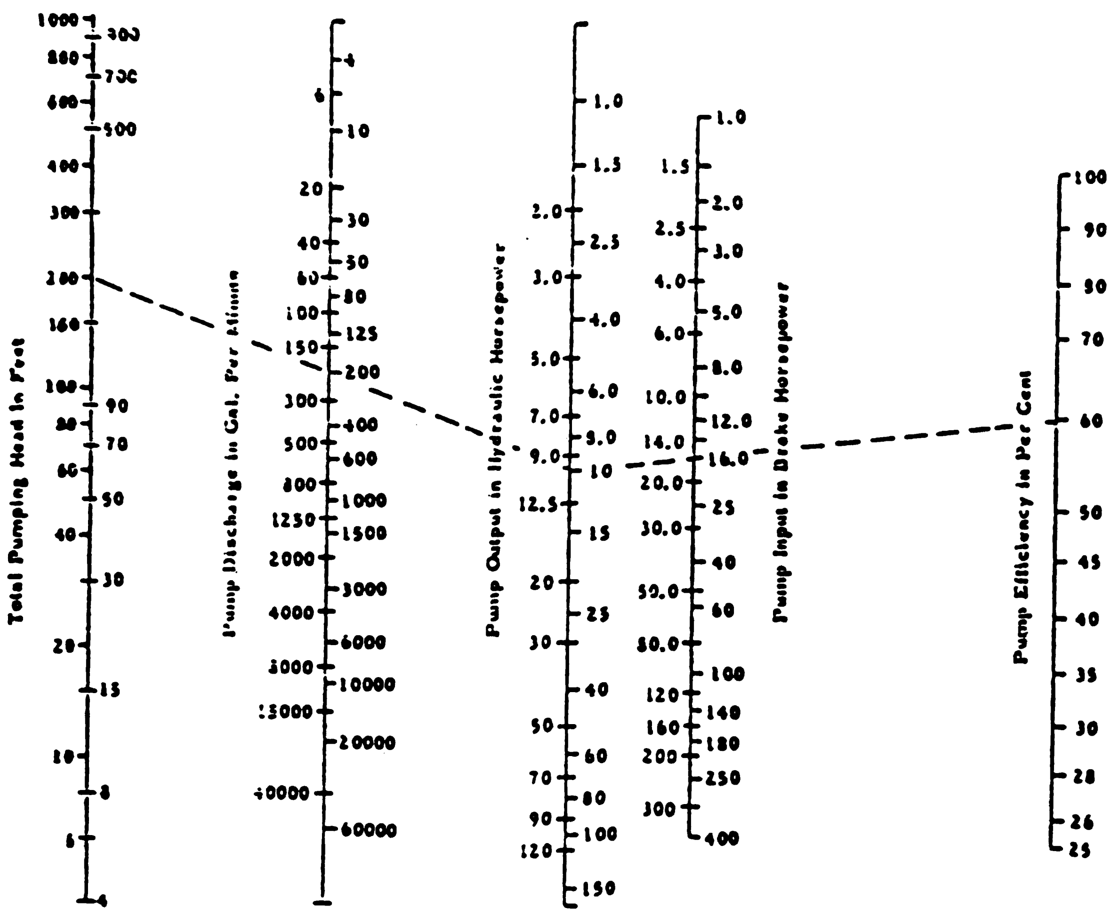


Figure 15 A power nomograph to be used to determine the horsepower required to pump water when the total head, discharge, and pump efficiency are known (Anon 2, 1983).

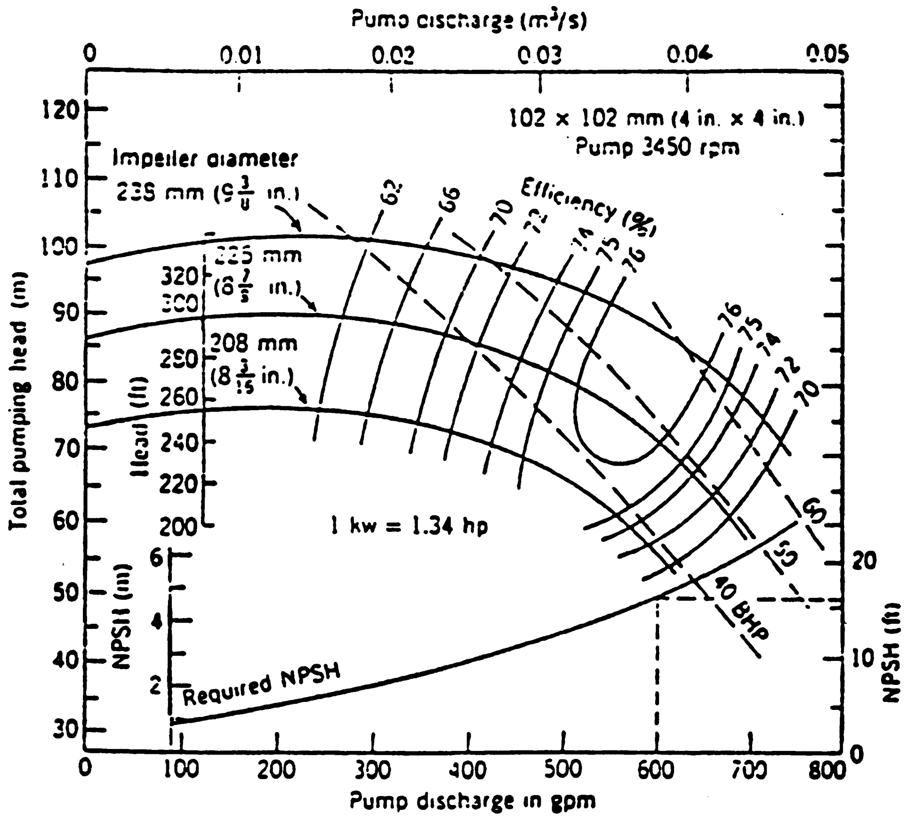


Figure 16. Pump characteristic curve.

DL = discharge side lift,

DD = water source drawdown,

H_l = Head loss due to pipe friction,

M_l = component head loss,

H_o = operating head, and

VH = velocity head.

Except for the suction side lift and the dynamic side lift, all the other heads are dependent upon the Q-H value in the system (James, 1988). Therefore any change in Q-H value will change the prevented when heads within the eye of single-and first stage impellers exceeds the required NPSH ($NPSH_r$) values published by manufacturers.

A well designed irrigation system will have pumps that operate at the optimum point of the pump curve. An example of the optimum operating point of the pump is shown in Figure 17.

Changing the diameter and/or speed of an impeller alters its characteristic curve (Anon 3, 1987). The changes in impeller performance resulting from changes in pump speed can be estimated using the following equations

$$Q_2 = Q_1 \, (N_2/N_1) \qquad [57]$$

$$H_2 = H_1 \, (N_2/N_1)^2 \qquad [58]$$

$$BP_2 = BP_1 \, (N_2/N_1)^3 \qquad [59]$$

where 1 and 2 are the subscripts denoting two different pump conditions.

There are two center pivot irrigation design philosophies (a)

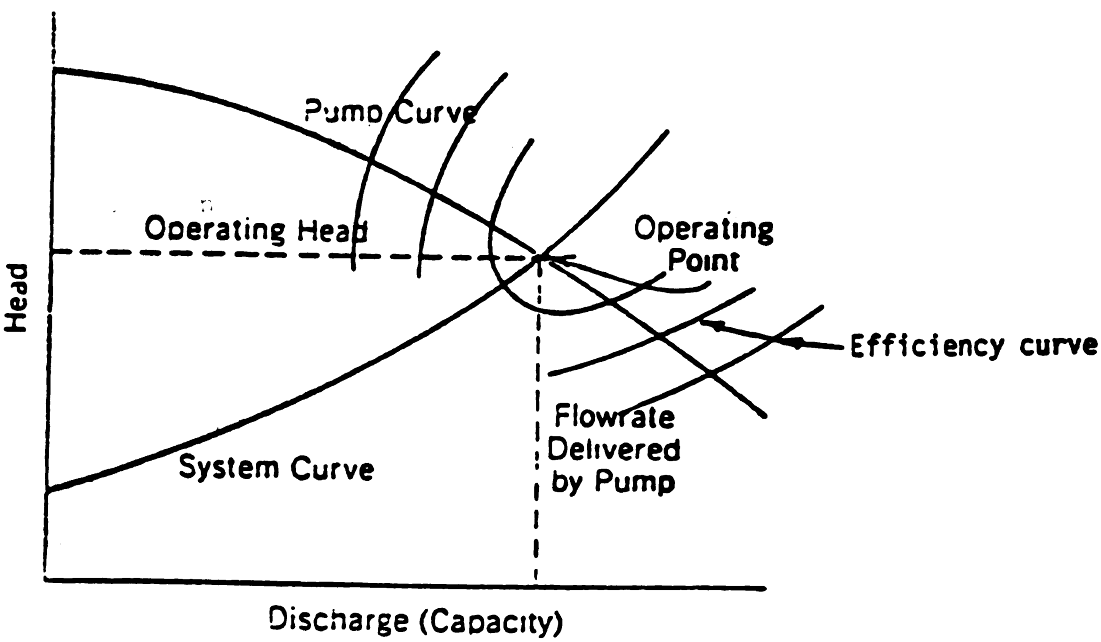


Figure 17. The plot of the operating point of the pump.

design assuming that the end gun is in operation and (b) design assuming that the end gun is not in operation. Bermuth (1982) used a field verified computer computational technique and studied the effect of cycling an end gun on and off for a typical center pivot condition for consideration in selecting sprinkler nozzles for flow uniformity. Based on the flow uniformity concept, he found that the superior nozzling philosophy was to nozzle interior sprinklers assuming that the big gun is not in operation. But the difference between the flow uniformities for the two philosophies was extremely small. Besides this, the error induced as a result of the second philosophy was toward under irrigation. Bermuth did not consider the change in the performance characteristic of the pump in his study.

Most design engineers use the second design philosophy when considering the pump that is to be installed. The main reason for using the second philosophy is to make sure that there is no cavitation when the converse fashion of operation is used.

The end gun in the center pivot system is turned on when the corners of the field are irrigated. This will increase the discharge and decrease the head in the pump according to the performance curve (characteristics) of the pump. This means that the operating point of the pump will change. The change in operating point means a possible change in the efficiency of the pump (Figure 18).

Many researchers (Bermuth, 1983; Solomon and Kodoma, 1978) have written about the change in operating point in the pump curve as a result of turning the end gun on and off during irrigation. But no one has looked at the possibility of using auxillary sprinklers that

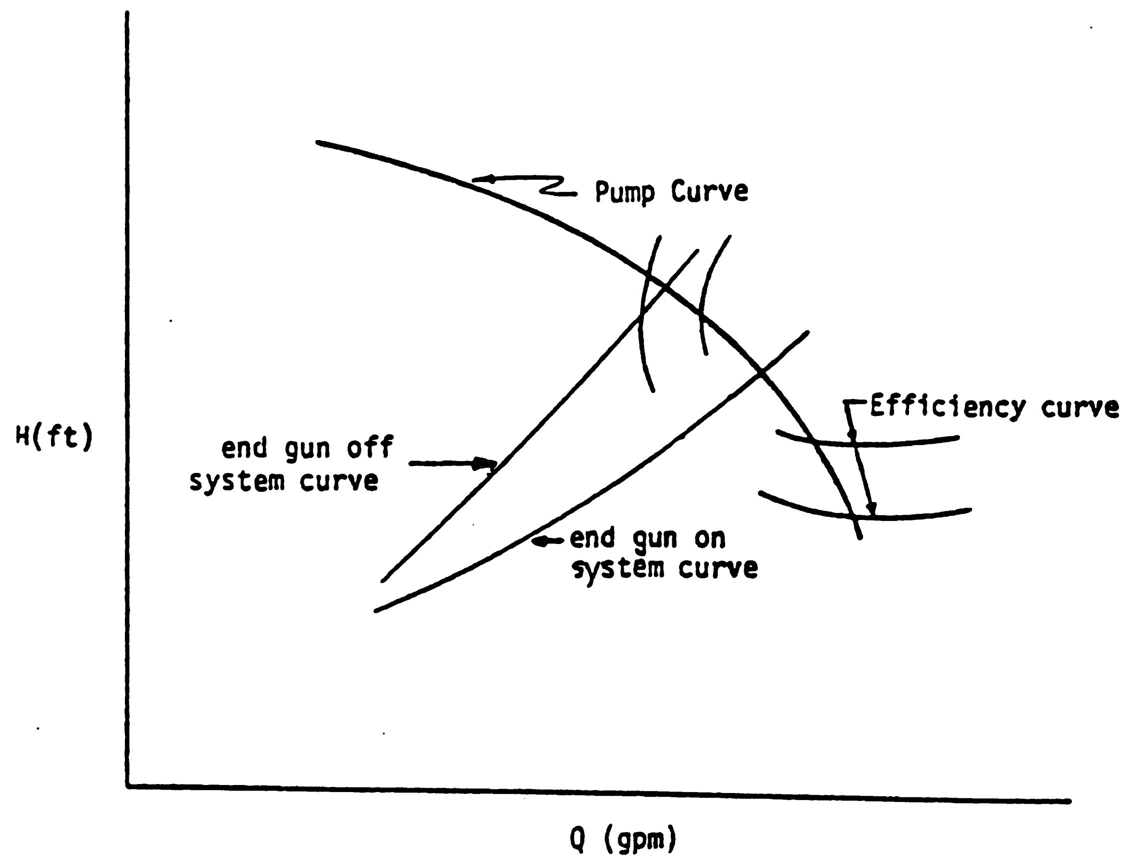


Figure 18. The change in the operating point of the pump with the change in the operating head.

turn on when the end gun is off end gun discharge. The sizing of these auxillary sprinklers can be such that their total discharge is equal to the end gun discharge. The use of auxillary sprinklers can keep the operating point of the pump constant so as to operate it with maximum efficiency throughout the irrigation period.

SUMMARY AND DISCUSSION:

The review of the literature related to hydraulics indicates that the Hazen-William and Scobey equations are widely used to calculate the friction head loss in a pipe even though it is known that the Hazen-William constant C and Scobey constant K_s does not accurately represent the friction factor in the pipe. The main reason for using these equations instead of the Darcy-Weisbach equation is because of the requirement to solve friction factor f implicitely for the later equation. This difficulty in solving for f can be overcome by using the Swamee-Jain equation that can be solved for f explicitely. The Swamee-Jain equation also contains the relative roughness, e/D, and the Reynolds number terms.

The review of the literature on hydraulics also provides the theoritical framework for the analysis of the center pivot system hydraulics.

The need to calculate the component head loss instead of assuming its value to be 10% of the total friction head loss is reflected in this section of the review.

The review of literature related to hydraulic uniformity indicates the difficulty and importance of achieving uniformity of pressure in the center pivot lateral line. Though the best pressure distribution is to have higher pressure at the end of the lateral line, this can not be achieved. Therefore a standard has been set by the American Society of Agricultural Engineers (ASAE) limit the pressure drop in the lateral line to no more than 20% of the pressure at the pivot. This limitation in the pressure drop will allow a better water uniformity in the field. It will also limit the pumping cost per field area to a reasonable value.

The main focus of any irrigation system is the application of water to the field. Since the elliptical application pattern from the sprinkler produced the accumulated application curve that agreed more closely with experimental values, it is relevent to consider elliptical application pattern from the sprinkler.

The intake rate and the storage capacity of the soil determine the maximum application rate of water in the field. It is possible to use one center pivot system to irrigate two fields if the intake rate of the soil is relatively high. The addition of auxillary sprinklers, which operate when the end gun is shutoff, and the increase in the angular speed of the lateral line can increase the application rate as a result of which the total time required to irrigate the field is reduced.

The literature review of field uniformity was motivated by the need to know which field uniformity coefficient equation was the most valid for the center pivot irrigation system.

Heermann and Hein (1968) uniformity coefficient concept was developed from the basis Christensian uniformity concept. It takes into account the fact that the application rate in the center pivot irrigation system increases farther away from the pivot. Any change in the system design concept should not reduce the field uniformity significantly or below the minimum appraved level.

The literature review on the network analysis was required to incorporate the most efficient and accurate network analysis method in the development of the model. The linear theory model is an excellent tool for the analysis of pressure drop in a loop. But this method does not always give convergence in the flow calculation at a node. The Newton Raphson method is also a good technique to analysis networks. The Hardy Cross method requires the most iterations to solve the equations, though this does not necessary mean that it requires maximum computer time for the analysis.

The finite element method for network analysis is gaining in popularity. Basic research for its use in sprinkler irrigation has been completed by researchers. The major advantage of this method is in computer network analysis. This method cannot be used easily for analysis with the hand calculator.

The literature review on energy use is an important aspect in the development of the objectives that is to follow. Though many researchers have noted the fact that there is a change in the operating point of the pump with the switching of the end gun on and off, no one has looked into the possibility of providing auxillary sprinklers in the lateral line such that thes sprinklers operate only when the end gun is off.

This can keep the operating point of the pump constant so that it is possible to have maximum pump efficiency throughout the irrigation period. The energy saving with this design concept of the center pivot system may be substantial, especially if the pump characteristic curve is steep.

III. METHODOLOGY

The review of the literature on the center pivot system in the previous chapter revealed that no one has looked into the possibility of energy conservation in the center pivot irrigation system by modifying its design to include auxillary sprinklers. There is a possibility of energy conservation by keeping the pump operating point constant throughout the period of irrigation. The application depth and application rate are also important parameters that are to be considered in any modification of the center pivot system. The following is a summary of the research approach to be followed in this study.

A. Research approach

The research approach that will be followed to achieve the major research objectives is proposed to be the following:

Objective 1. To determine the relationship between energy savings and the addition of auxillary sprinklers in the center pivot irrigation system.

The approach to be followed to achieve the above objective will be the development of computer simulation models. The hydraulic network analysis model will be based on the finite element approach. This model will be used to simulate the best positions and specifications of the auxillary sprinklers in the modified design of the center pivot system. This simulation will be done to get the constant discharge and pressure head throughout the period of irrigation so as to operate the pump with constant maximum efficiency. Simulation will also be done to determine the water power (WP) for varying amount of end gun discharge that will be passed thru the auxillary sprinklers when the end gun is off. Some model results will be compared to field data collected on existing modified center pivot system.

Objective 2. To make a comparative study of the application uniformity and depth with and without the addition of auxillary sprinklers in the center pivot system.

It is proposed that the above objective will be achieved by using the Heermann and Hein theoritical concept on the depth of application on the field. The application depth for the following conditions will be studied (i) the end gun is on (ii) the end gun is off, and (iii) the end gun is off with the modification in the design to include auxillary sprinklers. The study of the application uniformity will be based on this simulated total application depth of water.

Objective 3. To study the effect of the introduction of auxillary sprinklers on the water application depth in the field and the speed of the lateral arm movement.

The approach to be followed to achieve objective 3 will be to the relationship between the addition of the sprinklers and the application rate for different speed of the lateral in the model. The model will simulate the condition when the application rate after the design modification will be the same as without the change in the design. The calculation of the irrigation time that can be saved with the modification of the design will be studied with the help of the model.

B. Theoritical Development

The theoritical development section covers the (a) hydraulic analysis and irrigation performance evaluation section, (b) energy evaluation section, and (c) an example implementation section.

The hydraulic network analysis of the center pivot irrigation system network is based on the finite element approach. The pressure head difference between two sections of the network is the result of the friction head loss, the components head loss, and sprinkler head loss. Applying the energy balance between two points in the network, figure 19, gives

$$(Z_i+H_i) - (Z_j+h_j) = \Delta H \qquad [60]$$

where the subscripts i and j denote the upstream and downstream conditions respectively and all the other variables are as previously defined.

The head loss term, ΔH, of [60] can be further divided into three equations

$$\Delta H = RQ^m \qquad \text{pipe head loss} \qquad [61]$$

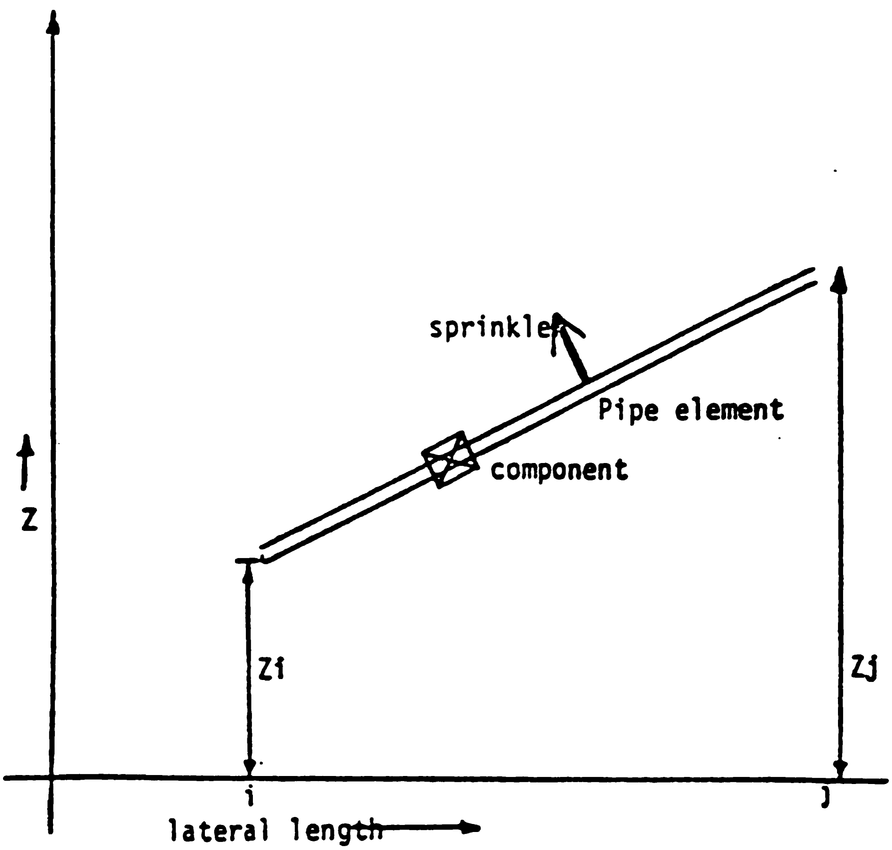


Figure 19. Network cosisting of a pipe, a component, and a sprinkler.

$\Delta H = K_c Q^2 / 2gA^2$ component head loss [62]

$\Delta H = K_{sp} Q^a$ sprinkler head loss [63]

Equation [61] can also be written as

$$Q = C_p (H_i + Z_i) - C_p (H_j + Z_j) \quad [64]$$

where $C_p = \{ [(H_i+Z_i) - (H_j+Z_j)]^{1-m/m} \} / R^{1/m}$.

Similary [62] and [63] can be rearranged to give

$$Q = C_{pc}(H_i - H_j) + C_{pc}(Z_i - Z_j) \quad [65]$$

where $C_{pc} = \pi^2 g D^4 / 8K_{ij}Q$,

D = diameter of the pipe,

K_{ij} = component loss for the ij element, and

$$Q = C_{sp} (H_i - H_j) \quad [66]$$

where $C_{sp} = (H_i-H_j)^{(a-1)} * K_{sp}$.

The elevation differences in the sprinkler element and the component element are neglected in [65] and [66].

The calculation of the head loss due to friction will be based on the Darcy Weisbach equation. The friction factor f will be calculated using the Swamee-Jain equation, [13], which has been explained in the literature review section.

The sprinkler head loss depends upon the sprinkler coefficient k and the exponent 'x' which is given by [7] as

$$q = kh^x$$

The values of q and h in [7] are given in the pressure-discharge chart provided by the sprinkler manufacturer (e.g. Table 1). The value of the exponent, x, is usually taken as 0.5 for a non pressure compensating sprinkler. The exponential value, x, and the coefficient, k, of [7] can be determined by linear regression of the known discharge-pressure relationship between q and h.

The pressure along the length of the pipe line of the center pivot irrigation system will be initialized using the model developed by Chu and Moe (1972). The initialized estimated pressure along the center pivot system pipe length using the Chu and Moe model is determined by using the beta function and is written as

$$h_o - h_r = (h_m B(m+1,0.5)/2) - \Delta Z \qquad [67]$$

where the variables are as explained in the literature review section. The distribution factor H is given by

$$H = (h_r - h_R)/(h_o - H_R)$$

or

$$H = 1 - B_x(m+1,0.5)/B(m+1,0.5) \qquad [68]$$

where x = r/R, and

$B_x(m+1,0.05)$ = the incomplete gamma function.

The value of m in [68] is 2 when using the Darcy Waisbach's equation to determine the head loss in the pipe line. Therefore the distribution factor H in [68] can be estimated using the following equation (Cho and Moe, 1972)

$$H = 1 - (15/8)(x - 2x^3/3 + x^5/5) \qquad [69]$$

where $x = r/R$

Considering [60], [61], and [62], the discharge thru any element is

$$Q = (C_p + C_{sp} + C_{cp})[\Delta H] - C_p \Delta Z \qquad [70]$$

The global stiffness matrix can be built for the network of the center pivot system to solve the pressure head loss at the nodes on the basis of [70].

The Gaussian Elimination method will be used to determine the solution to the global stiffness matrix.

The irrigation depth in the field will be determined using the Heermann et al (1968) equations [22] and [23]. The irrigation application uniformity is estimated using equation [33] developed by Heermann et al (1968). The American Society of Agricultural Engineers (ASAE) also recommends using equation [33] to estimate the irriagtion application uniformity for the center pivot irrigation system.

A part or whole of the end gun discharge will pass thru the auxillary sprinklers when the end gun is turned off. This distributed discharge required at different segments of the lateral line will be calculated using the Cho et al (1972) relationship given as

$$q = Q(1-(r^2/R^2)) \qquad [71]$$

where q = extra discharge in the lateral line at a distance r from the pivot point,

Q = discharge from the end gun that is to be distributed along the lateral line, and

R = the distance from the pivot point to the radius of coverage of the system.

The auxillary sprinklers sizes and spacings will be determined based on the discharge required to pass thru it for the expected pressure in it. Once the auxillary sprinklers are included in the model, the pressure distribution along the pipe line will be calculated for the modified system.

Field performance evaluation will be done for cases when 33%, 50%, and 66% of the circle is covered with the end gun on.

The calculation of the power imparted to the water by the pump, i.e. water power (WP), is done using the following relation

$$WP = QH/K$$

where the variables are as defined in [52]. The total discharge, Q, and the total pressure head, H, in [52] are the values calculated by hydraulic analysis. The discharge and the pressure at the pump will be determined by plotting the system curve and the pump curve. The point of intersection of the system curve and pump curve is the operating point of the pump.

The pump efficiency η_p is determined using the pump curve (e.g. Figure 20).The pump efficiency is determined by plotting the efficiency curve. The efficiency curve that passes thru the operating point of the pump gives the efficiency of the pump. It is possible to determine the brake power of the pump by using equation [53] once the pump efficiency and water power are determined. The total energy required will be given by

$$\text{Total energy required} = (BP/\eta)*\text{time of operation of the system}$$

where η = electrical efficiency.

The field data is obtained for the verification of the model from Mr. Jerry Bemeant's farm in Cass county of Michigan. This farm has the option of operating the system with the auxillary sprinklers attached to the pipe line so a part of the the end gun discharge is passed thru these sprinklers when the end gun is turned off. This system is 787 feet long from the pivot point to the end gun sprinkler. It has 28 primary sprinklers manufactured by Nelson Irrigation Corporation. The pivot pressure and the spacing of the sprinklers are noted. The lateral speed of the end tower is also noted. The system is set up as shown in figure 20.

The model will be run to determine energy savings for three different pumps (i.e. three different types of pump curves). The two extreme cases will have horizontal and vertical pump curves as shown in figure 21 and figure 22. The pump with horizonatl pump curve as shown in figure 21 will have the operating pressure head always constant. The pump with vertical pump as shown in figure 22 will always give almost a constant discharge. The pump with the pump curve as shown in figure 23 was being used in Mr. Bemeant's farm in Cass county of Michigan.

Pumps with horizontal and vertical pump curves are included in the study to show the maximum possible energy and time savings that is possible for different type of pumps. The comparision of the results obtained for these three different pumps will give the range of energy savings that may be possible.

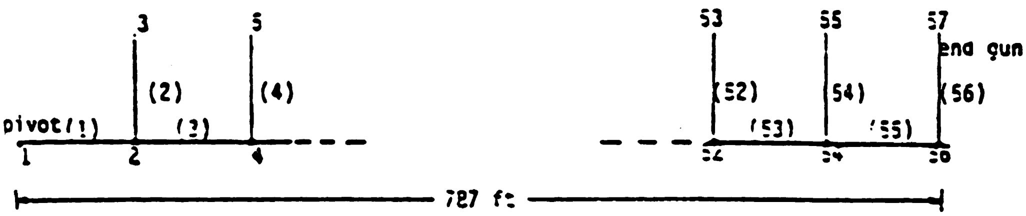


Figure 20a. Sequence of nodes and elements for the center pivot simulated model.

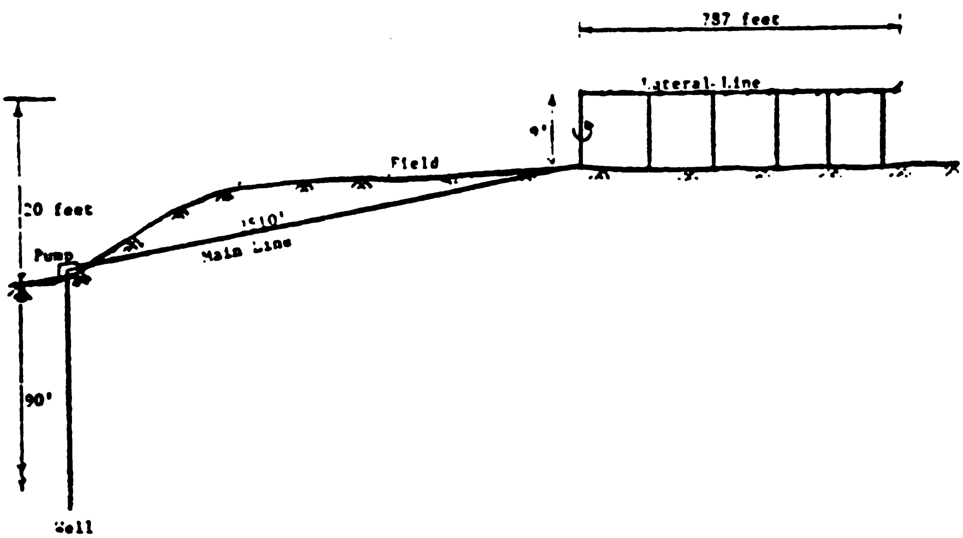


Figure 20b. The experimental network of a center pivot irrigation system.

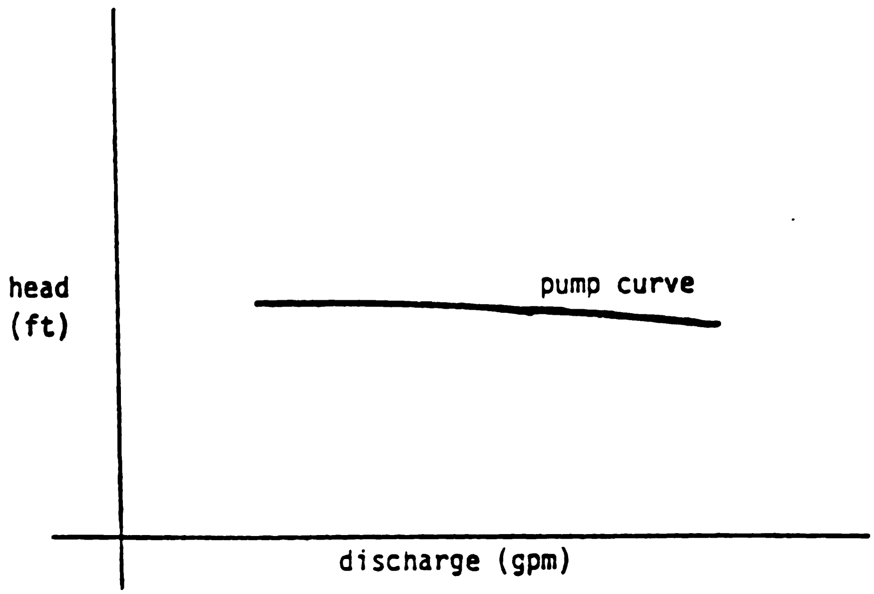


Figure 21. Pump curve to operate the pump at constant pressure.

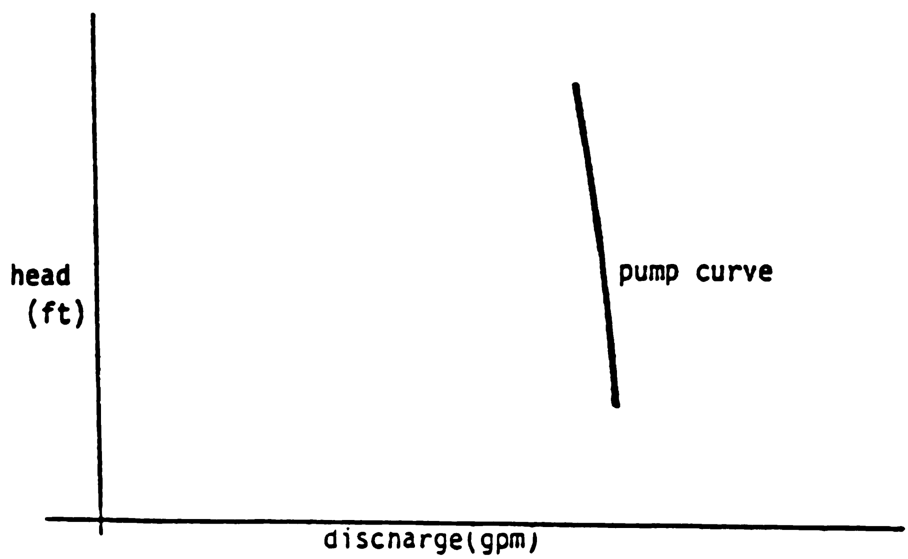


Figure 22. Pump curve to give a constant discharge for all pressures.

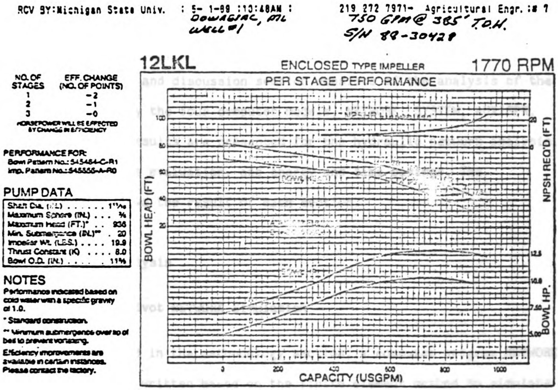


Figure 23. Pump curve for the pump used in the field.

IV RESULTS AND DISCUSSION

The results and discussion section consists of the analysis of the data generated by the four computer models, NETWORK, SYSTEM, AUXISPR, and FIELD. The results are presented for the hydraulic network analysis, field performance evaluation, and energy and time savings. The discussion follows the result of each section.

A. Hydraulic Analysis

1. Center Pivot NETWORK Simulation

As presented in the methodology section, a computer program NETWORK (Appendix A) was written based on the finite element method to simulate the discharge from the center pivot system when the end gun is on and when the end gun is off. The input data for the example system is given in Figure 24. In general, the center pivot system has a 787 feet long lateral line on which there are 28 sprinklers. The distance from the center pivot point to the last tower (not the end of lateral line) is 765 feet (Figure 20). The discharge-head equations for the sprinklers were obtained by regression analysis of the discharge-head relationship given by the manufacturer (Anon 4, 1986). Twenty five of the sprinklers have the exponent of pressure head between 0.49 and 0.51 which compares

DATA AND RESULTS

No of sprinklers in the system= 28
Total length of lateral= 787 ft
Distance to last tower= 765 ft
Maximum Allowable error in calculating pressure head= .5 ft

SPR NO	SPACING (ft)	DISTANCE FROM PIVOT (ft)	CALCULATED KC	CALCULATED a	REGRESSION EQUATION
1	28.0	28.0	0.2882	0.5094	Q= 0.29(H**0.51)
2	28.5	56.5	0.3863	0.4902	Q= 0.39(H**0.49)
3	28.5	85.0	0.4563	0.5031	Q= 0.46(H**0.50)
4	28.5	113.5	0.9148	0.4568	Q= 0.91(H**0.46)
5	32.5	146.0	1.2006	0.4428	Q= 1.20(H**0.44)
6	28.5	174.5	1.0171	0.5007	Q= 1.02(H**0.50)
7	28.5	203.0	1.0171	0.5007	Q= 1.02(H**0.50)
8	28.5	231.5	1.4853	0.4975	Q= 1.49(H**0.50)
9	28.5	260.0	1.6195	0.5014	Q= 1.62(H**0.50)
10	28.5	288.5	1.3012	0.5003	Q= 1.30(H**0.50)
11	32.5	321.0	1.6318	0.4887	Q= 1.63(H**0.49)
12	28.5	349.5	1.6195	0.5014	Q= 1.62(H**0.50)
13	28.5	378.0	1.6195	0.5014	Q= 1.62(H**0.50)
14	28.5	406.5	1.6380	0.5009	Q= 1.64(H**0.50)
15	28.5	435.0	1.9721	0.5014	Q= 1.97(H**0.50)
16	32.5	467.5	2.1261	0.5039	Q= 2.13(H**0.50)
17	28.5	496.0	2.1261	0.5039	Q= 2.13(H**0.50)
18	28.5	524.5	2.1261	0.5039	Q= 2.13(H**0.50)
19	28.5	553.0	2.4629	0.4895	Q= 2.46(H**0.49)
20	28.5	581.5	2.6199	0.4912	Q= 2.62(H**0.49)
21	32.5	614.0	2.8755	0.4995	Q= 2.88(H**0.50)
22	28.5	642.5	2.2352	0.5187	Q= 2.24(H**0.52)
23	28.5	671.0	2.8755	0.4995	Q= 2.88(H**0.50)
24	28.5	699.5	2.8755	0.4995	Q= 2.88(H**0.50)
25	28.5	728.0	3.1986	0.4971	Q= 3.20(H**0.50)
26	28.5	756.5	3.1986	0.4971	Q= 3.20(H**0.50)
27	26.8	763.3	3.0516	0.5064	Q= 3.05(H**0.51)
28	23.7	787.0	13.9973	0.4990	Q= 14.00(H**0.50)

DIAMETER (inches)	DISTANCE FROM PIVOT (ft) FROM	TO
2.79	0	765.0
2.78	765.0	787.0

PIPE ROUGHNESS=0.000600 inches
SLOPE OF THE FIELD IS NEGLIGIBLE
RISER DIAMETER = 1.0000 inches
END GUN RISER DIAMETER = 2.0000 inches
K FOR TEE AND ELBOW COMPONENTS = 1.00

Figure 24. Data for the hydraulic network analysis of the center pivot irrigation system network.

DATA AND RESULTS

No of sprinklers in the system= 28
Total length of lateral= 787 ft
Distance to last tower= 765 ft
Maximum Allowable error in calculating pressure head= .5 ft

SPR NO	SPACING (ft)	DISTANCE FROM PIVOT (ft)	CALCULATED KC	CALCULATED a	REGRESSION EQUATION
1	28.0	28.0	0.2882	0.5094	Q= 0.29(H**0.51)
2	28.5	56.5	0.3863	0.4902	Q= 0.39(H**0.49)
3	28.5	85.0	0.4563	0.5031	Q= 0.46(H**0.50)
4	28.5	113.5	0.9148	0.4568	Q= 0.91(H**0.46)
5	32.5	146.0	1.2006	0.4428	Q= 1.20(H**0.44)
6	28.5	174.5	1.0171	0.5007	Q= 1.02(H**0.50)
7	28.5	203.0	1.0171	0.5007	Q= 1.02(H**0.50)
8	28.5	231.5	1.4853	0.4973	Q= 1.49(H**0.50)
9	28.5	260.0	1.6195	0.5014	Q= 1.62(H**0.50)
10	28.5	288.5	1.3012	0.5003	Q= 1.30(H**0.50)
11	32.5	321.0	1.6318	0.4987	Q= 1.63(H**0.49)
12	28.5	349.5	1.6195	0.5014	Q= 1.62(H**0.50)
13	28.5	378.0	1.6195	0.5014	Q= 1.62(H**0.50)
14	28.5	406.5	1.6380	0.5009	Q= 1.64(H**0.50)
15	28.5	435.0	1.9721	0.5014	Q= 1.97(H**0.50)
16	32.5	467.5	2.1261	0.5039	Q= 2.13(H**0.50)
17	28.5	496.0	2.1261	0.5039	Q= 2.13(H**0.50)
18	28.5	524.5	2.1261	0.5039	Q= 2.13(H**0.50)
19	28.5	553.0	2.4629	0.4895	Q= 2.46(H**0.49)
20	28.5	581.5	2.6199	0.4912	Q= 2.62(H**0.49)
21	32.5	614.0	2.8755	0.4995	Q= 2.88(H**0.50)
22	28.5	642.5	2.2352	0.5187	Q= 2.24(H**0.52)
23	28.5	671.0	2.8755	0.4995	Q= 2.88(H**0.50)
24	28.5	699.5	2.8755	0.4995	Q= 2.88(H**0.50)
25	28.5	728.0	3.1986	0.4971	Q= 3.20(H**0.50)
26	28.5	756.5	3.1986	0.4971	Q= 3.20(H**0.50)
27	26.8	783.3	3.0516	0.5064	Q= 3.05(H**0.51)
28	3.7	787.0	13.9973	0.4990	Q= 14.00(H**0.50)

DIAMETER (inches)	DISTANCE FROM PIVOT (ft) FROM	TO
2.79	0	765.0
2.78	765.0	787.0

PIPE ROUGHNESS=0.000600inches
SLOPE OF THE FIELD IS NEGLIGIBLE
RISER DIAMETER = 1.0000 inches
END GUN RISER DIAMETER = 2.0000 inches
K FOR TEE AND ELBOW COMPONENTS = 1.00

Figure 24. Data for the hydraulic network analysis of the center pivot irrigation system network.

well with the usual turbulent flow equation

$$Q = kH^{0.5} \qquad [7]$$

As a preliminary test, the program NETWORK was run ten times each with given center pivot pressure. This pressure was increased from 80 psi to 125 psi in 5 psi increments with the end gun on, end gun off, and the modified center pivot system conditions. Figures 25a and 25b are the output from these runs for the end gun on and end gun off conditions. The reason for these preliminary runs was to establish the discharge-head relationship of the system at the center pivot point, making it possible to determine the pivot pressure for any given discharge thru the system.

The allowable error for the runs were 0.5 feet of head. The pressure drop along the lateral line with the end gun off is about half of what it is when the end gun is on. These results indicate that the pressure along the line increases when the end gun is off. It can also be seen that regardless of the pressure at the pivot point, the percentage of total flow passing thru the end sprinkler (end gun) when the end gun is on is constant (22.42%) for all the runs. In addition, the discharge ,Q , and the pressure head , H, at the pivot point illustrated a very strong association (R^2=0.99999) as shown in Figure 26. Thus it can be shown that the total of all flows passing thru the sprinklers (Q) (discharge thru the pivot) is related to the pivot pressure (H) by

$$Q = 57.007\ H^{0.502798} \qquad [72]$$

The Q-H relationship equation for the end gun off condition was

END GUN ON

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	69.4	160.5	10.56	24.62	786.7	176.5	22.42	6
2	85.00	196.47	73.8	170.5	11.22	25.94	810.9	181.9	22.42	6
3	90.00	208.03	78.2	180.7	11.84	27.37	834.6	187.2	22.42	6
4	95.00	219.58	82.5	190.8	12.46	28.81	857.6	192.4	22.42	6
5	100.00	231.14	86.8	200.7	13.18	30.45	879.9	197.3	22.42	7
6	105.00	242.70	91.2	210.8	13.80	31.89	901.8	202.2	22.42	7
7	110.00	254.25	95.6	220.9	14.41	33.32	923.2	207.0	22.42	7
8	115.00	265.81	100.0	231.1	15.03	34.75	944.0	211.7	22.42	7
9	120.00	277.37	104.3	241.2	15.63	36.18	964.5	216.2	22.42	7
10	125.00	288.92	108.7	251.3	16.27	37.61	984.8	220.7	22.42	7

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 37.007(H**0.502798)

END GUN OFF

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	74.6	172.4	5.42	12.52	622.2	0.0	0.00	4
2	85.00	196.47	79.4	183.4	5.63	13.03	641.6	0.0	0.00	3
3	90.00	208.03	84.1	194.3	5.94	13.73	660.4	0.0	0.00	3
4	95.00	219.58	88.8	205.2	6.21	14.36	678.8	0.0	0.00	4
5	100.00	231.14	93.5	216.1	6.51	15.05	696.8	0.0	0.00	4
6	105.00	242.70	98.2	226.9	6.82	15.76	713.7	0.0	0.00	4
7	110.00	254.25	102.9	237.8	7.12	16.45	730.6	0.0	0.00	4
8	115.00	265.81	107.6	248.7	7.42	17.15	747.1	0.0	0.00	4
9	120.00	277.37	112.3	259.6	7.71	17.81	763.3	0.0	0.00	3
10	125.00	288.92	117.0	270.4	8.01	18.50	779.2	0.0	0.00	3

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 44.890(H**0.503703)

Modified end gun off

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	72.0	166.4	8.03	18.56	774.2	0.0	0.00	3
2	85.00	196.47	76.6	177.0	8.44	19.51	798.4	0.0	0.00	3
3	90.00	208.03	81.1	187.5	8.90	20.56	821.7	0.0	0.00	3
4	95.00	219.58	85.6	198.0	9.36	21.63	844.4	0.0	0.00	3
5	100.00	231.14	90.2	208.5	9.78	22.62	866.6	0.0	3.00	4
6	105.00	242.70	94.8	219.0	10.25	23.69	888.1	0.0	0.00	4
7	110.00	254.25	99.3	229.5	10.70	24.74	909.1	0.0	0.00	4
8	115.00	265.81	103.8	240.0	11.16	25.80	929.7	0.0	0.00	4
9	120.00	277.37	108.4	250.5	11.62	26.87	949.8	0.0	0.00	4
10	125.00	288.92	112.9	261.0	12.07	27.90	969.5	0.0	3.30	4

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 55.855(H**0.503705)

Figure 25a, b, and c. Results obtained from the computer simulation model 'NETWORK' for the end gun on, end gun off, and modified end gun off conditions.

END GUN ON

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	69.4	160.3	10.56	24.62	786.7	176.3	22.42	6
2	85.00	196.47	73.8	170.3	11.22	25.96	810.9	181.9	22.42	6
3	90.00	208.03	78.2	180.7	11.84	27.37	834.6	187.2	22.42	6
4	95.00	219.58	82.5	190.8	12.46	28.81	857.6	192.4	22.42	6
5	100.00	231.14	86.8	200.7	13.18	30.45	879.9	197.3	22.42	7
6	105.00	242.70	91.2	210.8	13.80	31.89	901.8	202.2	22.42	7
7	110.00	254.25	95.6	220.9	14.41	33.32	923.2	207.0	22.42	7
8	115.00	265.81	100.0	231.1	15.03	34.75	944.0	211.7	22.42	7
9	120.00	277.37	104.3	241.2	15.65	36.18	964.5	216.2	22.42	7
10	125.00	288.92	108.7	251.3	16.27	37.61	984.8	220.7	22.42	7

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 57.007(H**0.502798)

END GUN OFF

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	74.6	172.4	5.42	12.52	622.2	0.0	0.00	4
2	85.00	196.47	79.4	183.4	5.65	13.05	641.6	0.0	0.00	3
3	90.00	208.03	84.1	194.3	5.94	13.73	660.4	0.0	0.00	3
4	95.00	219.58	88.8	205.2	6.21	14.36	678.8	0.0	0.00	4
5	100.00	231.14	93.5	216.1	6.51	15.05	696.8	0.0	0.00	4
6	105.00	242.70	98.2	226.9	6.82	15.76	713.7	0.0	0.00	4
7	110.00	254.25	102.9	237.8	7.12	16.45	730.6	0.0	0.00	4
8	115.00	265.81	107.6	248.7	7.42	17.15	747.1	0.0	0.00	4
9	120.00	277.37	112.3	259.6	7.71	17.81	763.3	0.0	0.00	5
10	125.00	288.92	117.0	270.4	8.01	18.50	779.2	0.0	0.00	5

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 44.890(H**0.503708)

Modified end gun off

RUN NO	Ppivot (PSI)	Hpivot (FT)	Pend (PSI)	Hend (FT)	Pdrop (PSI)	Hdrop (FT)	Qpivot (GPM)	Qend (GPM)	Qend (% of Qpivot)	ITER NO
1	80.00	184.91	72.0	166.4	8.03	18.56	774.2	0.0	0.00	3
2	85.00	196.47	76.6	177.0	8.44	19.51	798.4	0.0	0.00	3
3	90.00	208.03	81.1	187.5	8.90	20.56	821.7	0.0	0.00	3
4	95.00	219.58	85.6	198.0	9.36	21.63	844.4	0.0	0.00	3
5	100.00	231.14	90.2	208.5	9.78	22.62	866.6	0.0	0.00	4
6	105.00	242.70	94.8	219.0	10.25	23.69	888.1	0.0	0.00	4
7	110.00	254.25	99.3	229.5	10.70	24.74	909.1	0.0	0.00	4
8	115.00	265.81	103.8	240.0	11.16	25.80	929.7	0.0	0.00	4
9	120.00	277.37	108.4	250.5	11.62	26.87	949.8	0.0	0.00	4
10	125.00	288.92	112.9	261.0	12.07	27.90	969.5	0.0	0.00	4

THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY
Q= 55.855(H**0.503705)

Figure 25a, b, and c. Results obtained from the computer simulation model 'NETWORK' for the end gun on, end gun off, and modified end gun off conditions.

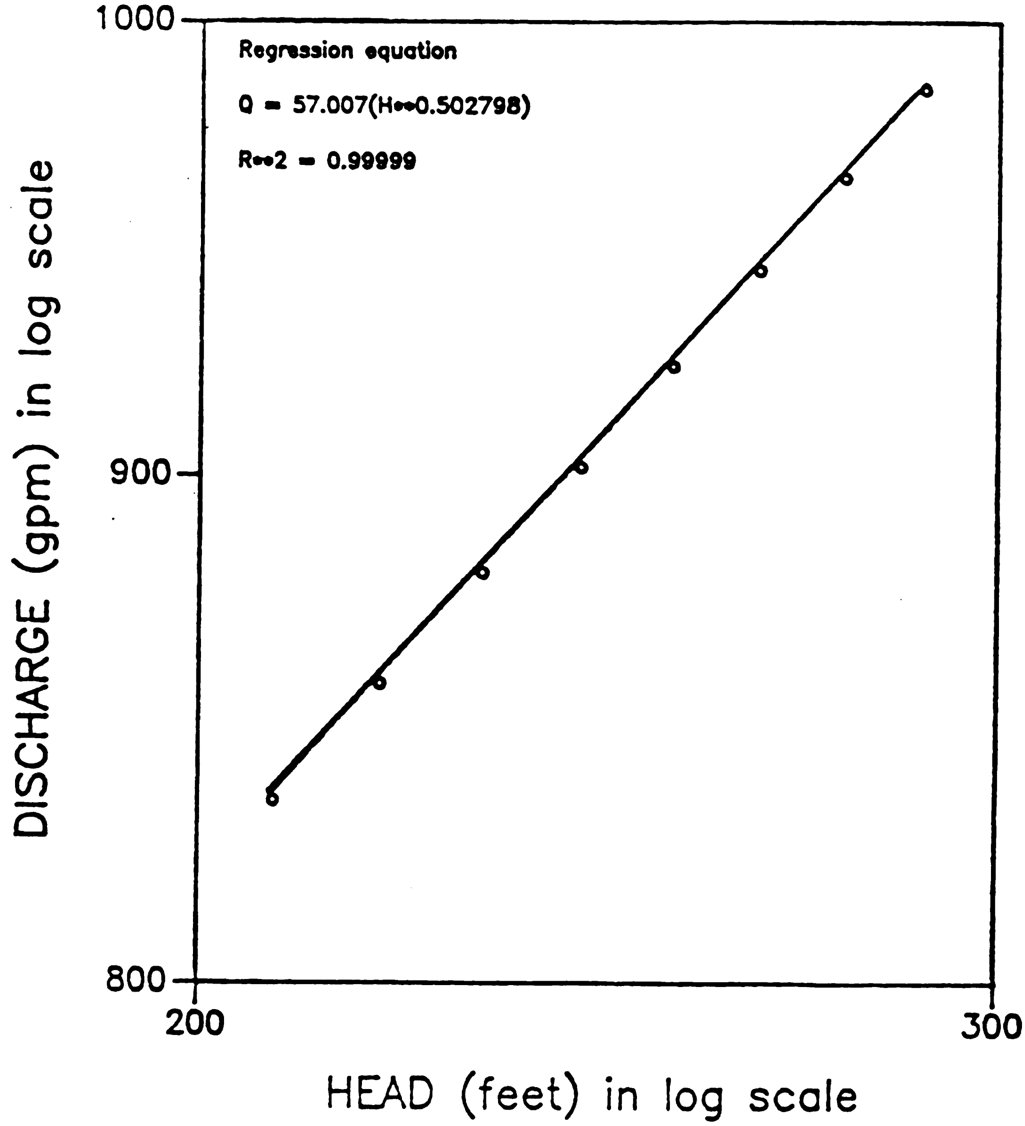


Figure 26. Graph showing the discharge-pressure relationship at the center pivot point for the end gun on condition.

similarly determined with a coefficient of determination (R^2) of 0.99996 (Figure 27). The regression equation for this condition is

$$Q = 44.890\ H^{0.503705} \qquad [73]$$

2. **System Curve Simulation**

Equations [72] and [73] were used to determine the system curve at the pump for the given elevation head (20 feet), lift from water level to the pump (90 feet), diameter of the main line (8 inches), and the length of the main line (3510 feet) (Figure 20). Program "SYSTEM" (Appendix C) was used to determine the Q-H relationship at the pump for the given data. The system curve based on the output results from "SYSTEM" (Figures 28a and 28b) were used to determine the Q-H relationship at the pump (Figure 29). These are the system curves for the system.

The energy savings and field performance evaluation were done for three different pumps : pump 'H' with the horizontal pump curve, positive displacement pump 'V' with the vertical pump curve, and the pump used in the field pump 'J'. Pump curves for pumps H and V are hypothetical. These are the two extreme cases for pump curves. They are included in the study to show the range of energy and time savings depending upon the type of the pump used. Figures 30, 31, and 32 show the pump curves for the pumps 'V', 'H', and 'J' and the system curves for the end gun on, end gun off, and the modified end gun off conditions. The intersection of the pump curve and the system curve is the operating point of the pump.

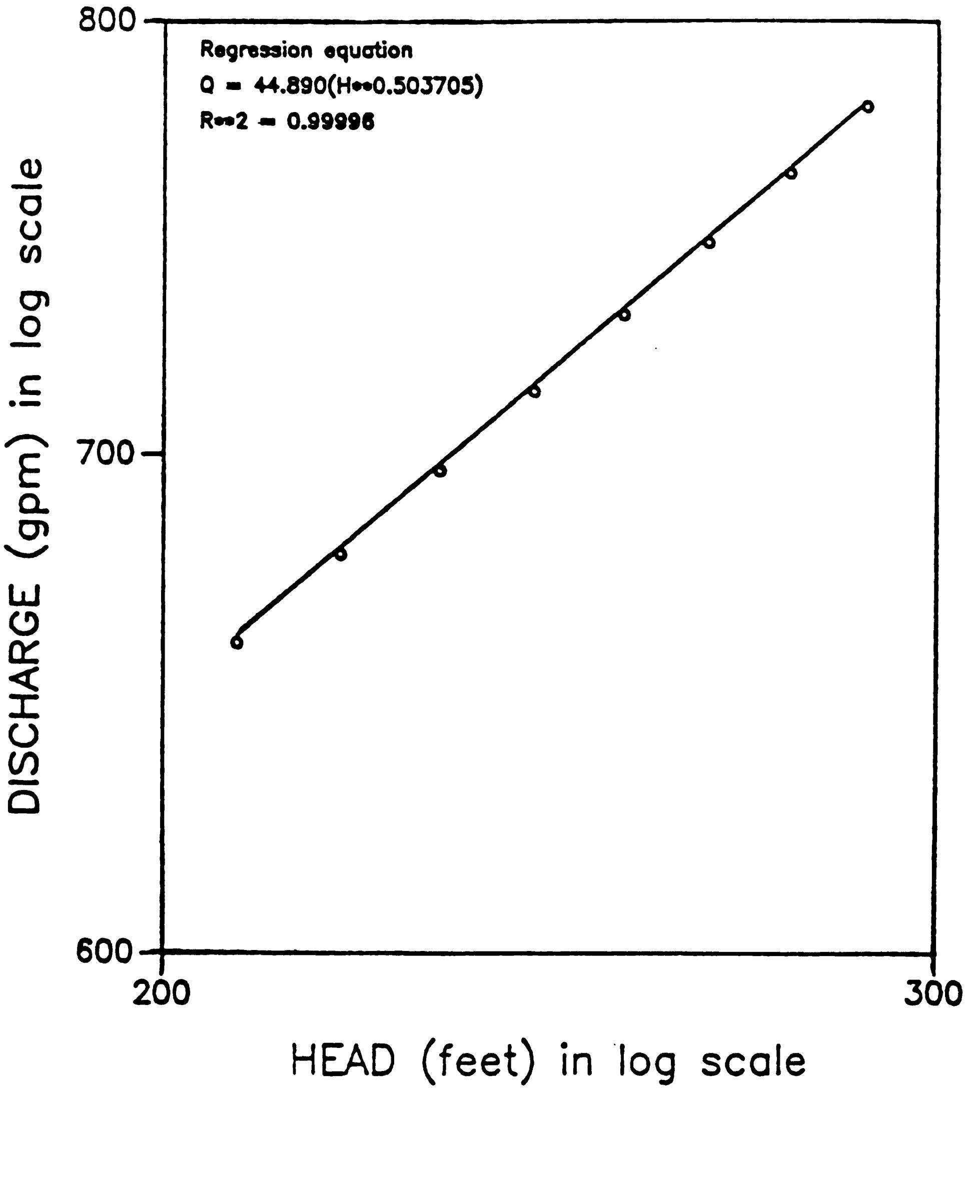


Figure 27. Graph showing the discharge-pressure relationship at the center pivot point for the end gun off condition.

END GUN ON

DELIVERY HEAD (FT)= 20.0
LIFT HEAD (FT)= 90.0
ROUGHNESS OF THE PIPE (INCHES)=0.000600
DIAMETER OF THE PIPE (INCHES)= 8.0000
DIAMETER OF THE SUCTION PIPE=12.0000
LENGTH OF THE DELIVERY PIPE (FEET)=1310.0
COEFFICIENT OF THE SYSTEM AT THE PIVOT= 57.0070
EXPONENT OF THE SYSTEM AT THE PIVOT=0.5036

QSUM GPM	FIXED H FT	FRIC HEAD DEL(FT)	FRIC HEAD SUCT(FT)	VEL HEAD FT	OPR HEAD FT	TOTAL HEAD FT
500	110.00	14.8016	0.0520	0.1582	75.890	200.0499
550	110.00	17.6349	0.0617	0.1914	90.762	218.5800
600	110.00	20.6990	0.0721	0.2278	107.810	238.8368
650	110.00	23.9922	0.0833	0.2673	126.531	260.7900
700	110.00	27.5130	0.0953	0.3100	146.625	284.4404
750	110.00	31.2602	0.1079	0.3559	168.191	309.0066
800	110.00	35.2324	0.1212	0.4049	191.226	336.0633
850	110.00	39.4286	0.1352	0.4571	215.731	365.6163
900	110.00	43.8479	0.1500	0.5124	241.703	396.0636
950	110.00	48.4095	0.1654	0.5710	269.143	428.2035
1000	110.00	53.2526	0.1815	0.6327	298.049	463.0343

END GUN OFF

DELIVERY HEAD (FT)= 20.0
LIFT HEAD (FT)= 90.0
ROUGHNESS OF THE PIPE (INCHES)=0.000600
DIAMETER OF THE PIPE (INCHES)= 8.0000
DIAMETER OF THE SUCTION PIPE=12.0000
LENGTH OF THE DELIVERY PIPE (FEET)=1310.0
COEFFICIENT OF THE SYSTEM AT THE PIVOT= 44.8900
EXPONENT OF THE SYSTEM AT THE PIVOT=0.5037

QSUM GPM	FIXED H FT	FRIC HEAD DEL(FT)	FRIC HEAD SUCT(FT)	VEL HEAD FT	OPR HEAD FT	TOTAL HEAD FT
500	110.00	14.8016	0.0520	0.1582	119.746	244.7060
550	110.00	17.6349	0.0617	0.1914	144.690	272.5184
600	110.00	20.6990	0.0721	0.2278	171.873	302.8999
650	110.00	23.9922	0.0833	0.2673	201.552	335.8520
700	110.00	27.5130	0.0953	0.3100	233.365	371.3682
750	110.00	31.2602	0.1079	0.3559	267.829	409.6467
800	110.00	35.2324	0.1212	0.4049	304.441	450.0780
850	110.00	39.4286	0.1352	0.4571	343.379	493.2860
900	110.00	43.8479	0.1500	0.5124	384.642	539.0021
950	110.00	48.4095	0.1654	0.5710	428.227	587.2870
1000	110.00	53.2526	0.1815	0.6327	474.132	638.1170

END GUN OFF (MODIFIED SYSTEM)

DELIVERY HEAD (FT)= 20.0
LIFT HEAD (FT)= 90.0
ROUGHNESS OF THE PIPE (INCHES)=0.000600
DIAMETER OF THE PIPE (INCHES)= 8.0000
DIAMETER OF THE SUCTION PIPE=12.0000
LENGTH OF THE DELIVERY PIPE (INCHES)=1310.0
COEFFICIENT OF THE SYSTEM AT THE PIVOT= 55.8550
EXPONENT OF THE SYSTEM AT THE PIVOT=0.5037

QSUM GPM	FIXED H FT	FRIC HEAD DEL(FT)	FRIC HEAD SUCT(FT)	VEL HEAD FT	OPR HEAD FT	TOTAL HEAD FT
500	110.00	14.8016	0.0520	0.1582	77.599	202.5563
550	110.00	17.6349	0.0617	0.1914	93.758	221.5842
600	110.00	20.6990	0.0721	0.2278	111.437	242.3640
650	110.00	23.9922	0.0833	0.2673	129.633	264.0090
700	110.00	27.5130	0.0953	0.3100	151.335	289.1580
750	110.00	31.2602	0.1079	0.3559	173.551	315.1660
800	110.00	35.2324	0.1212	0.4049	197.275	342.9136
850	110.00	39.4286	0.1352	0.4571	222.537	372.3925
900	110.00	43.8479	0.1500	0.5124	249.265	403.6350
950	110.00	48.4095	0.1654	0.5710	277.407	436.5478
1000	110.00	53.2526	0.1815	0.6327	307.383	471.2180

Figure 28a, b, and c. Discharge pressure relationship of the center pivot system at the pump for the end gun on, end gun off, and modified end gun off condition.

HEAD (feet)

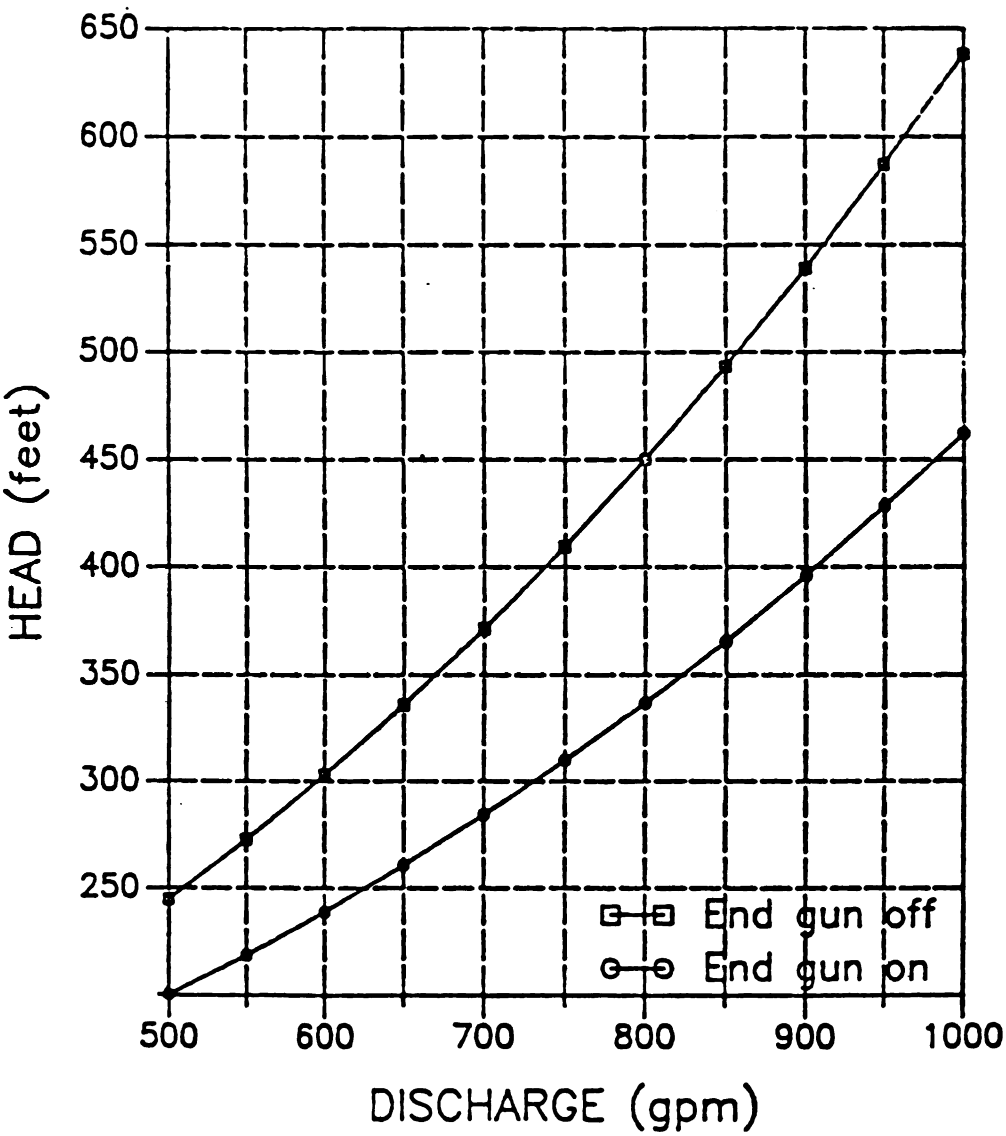


Figure 29. System curves of the center pivot irrigation system for the end gun on and end gun off conditions.

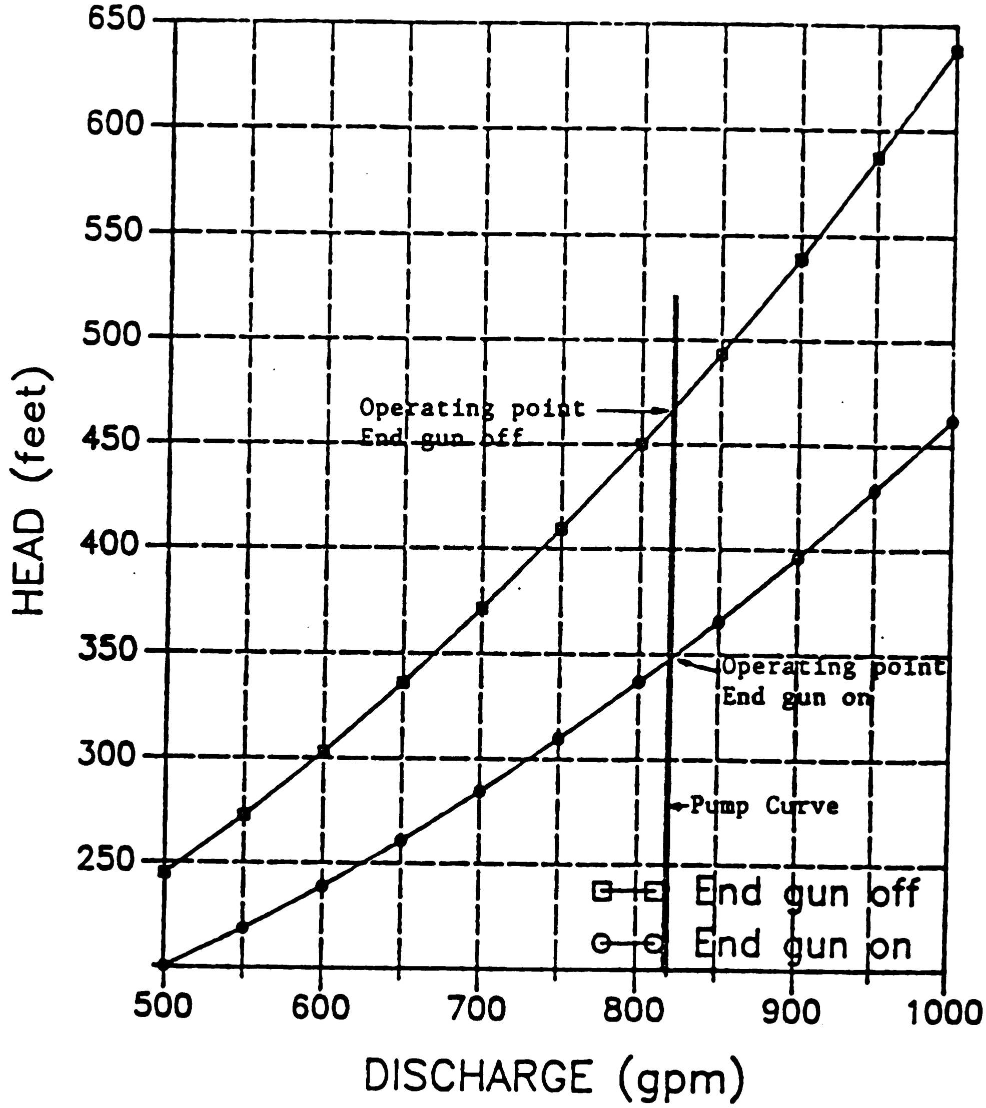


Figure 30. Pump curve for pump 'V' plotted with the system curves to determine the operating points of the pump.

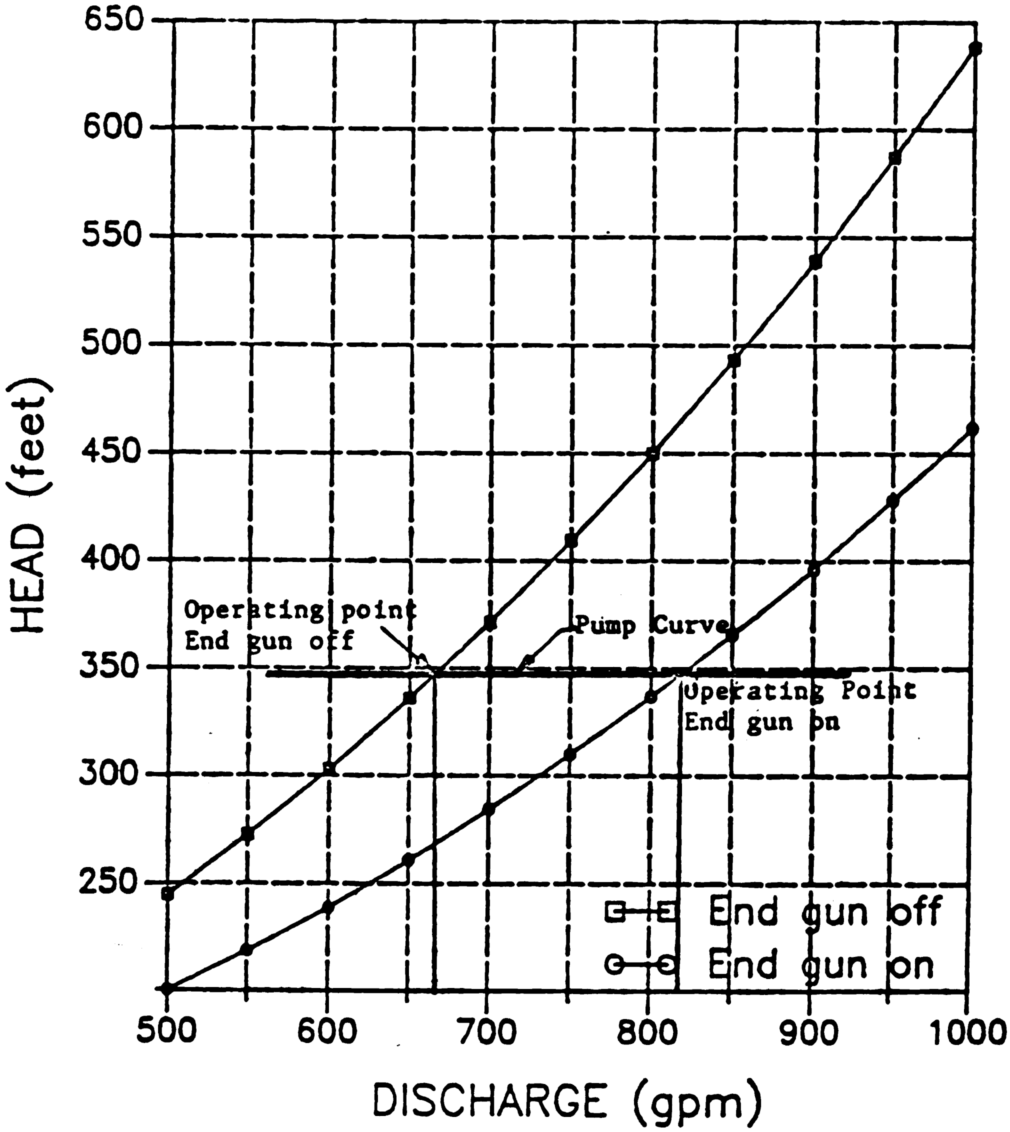


Figure 31. Pump curve for pump 'H' plotted with the system curves to determine the operating points of the pump.

HEAD (feet)

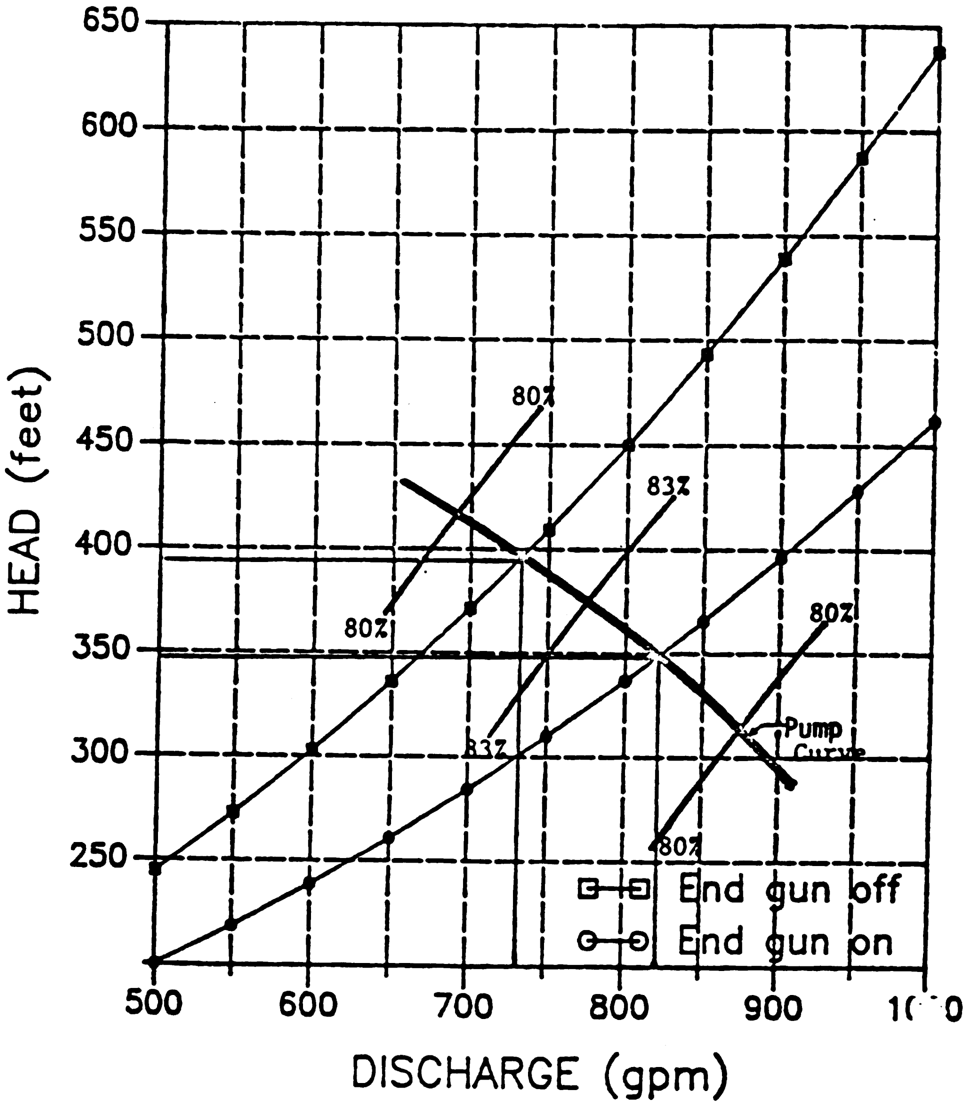


Figure 32. Pump curve for pump 'J' plotted with the system curves to determine the operating points of the pump.

The data collected from Mr. Jerry Bement's field (Appendix G) showed the operating head and discharge to be 349 feet (151 psi) and 830 gpm respectively for the end gun on condition. The simulated model discharge is 825 gpm for a head of 349 feet when the end gun is on [Figure 28], which is 0.602% different from the field observation value.

The discharge and head at the pumps when the end gun is turned off are obtained from Figures 30, 31, and 32 for pumps H, V, and J respectively. The pressure head at the pump for a given discharge can also be determined Figure 28. Table 4 gives the discharge from different pumps for the end gun off conditions as obtained from the Figures 30, 31, 32. It also gives the operating pressure at the pumps.

Table 4. Discharge from example pumps when the end gun is turned off.

Pump	Discharge (gpm)	Pressure (psi)
H	670.5	92.84
V	825.0	140.00
J	730.5	110.00

From Figure 30 for the vertical pump curve, it is evident that if the discharge is constant, the pressure will increase when the end gun is shut off. This means more power will be required to operate the pump when the end gun is off. In this case, the time required to apply a certain depth of water will be less.

With the discharge of 825 gpm when the end gun is on, the pressure head at center pivot point using [72] is 88 psi. The hydraulic analysis of the system from the pivot to the end end gun gave an end gun discharge of 185.2 gpm. This is 22.42% of the total discharge. Figure 25 gives the same percentage of discharge as passing thru the end gun. This shows that a constant percentage of total discharge passes thru the end gun sprinkler irrespective of the pivot pressure.

The design of the center pivot irrigation system is modified to distribute this end gun discharge of 185.2 gpm along the lateral line with the addition of sprinklers which are automatically turned on when the end gun is turned off. This will keep the total flow passing thru the system constant when the end gun is on or off.

3. Auxiliary sprinkler simulation

Program "AUXISPR" (Appendix C) was written and used to simulate the positions of and discharge from these auxiliary sprinklers so as to distribute the water with maximum uniformity. Figure 33 is the output obtained from AUXISPR. A total of nine auxiliary sprinklers are required to discharge a minimum of 164.4 gpm to irrigate the field upto the point of the last auxiliary sprinkler. When the radius of coverage of the sprinklers are considered, the actual total discharge passing thru the auxiliary sprinklers will be more than 164.5 gpm. Figure 33 also shows the auxiliary sprinklers models and nozzle diameter that will be used as auxiliary sprinklers at the distances shown. The spacings and discharge of the auxiliary sprinklers are based on their uniform spacing and the locations of the plugs in the existing system. Figure 34 shows the characteristic of the regular sprinklers and the auxiliary sprinklers. The Nelson Agricultural Impact Sprinklers chart (June 1986) was used to

DESIGN DATA :

SYSTEM LENGTH = 783.3 FT
DISCHARGE THRU THE END GUN = 185.2 GPM
MINIMUM DISCHARGE THRU THE AUXILLARY SPRINKLERS = 7 GPM

NO	PLUG NO	DISTANCE FROM PIVOT (FT)	DISCHARGE (GPM)	SPRINKLER MODEL	NOZZLE SIZE	EXPECTED PRES (PSI)	ACTUAL GPM
1	11	155.5	7.31	F33APV	11/64"	84.7	8.1
2	16	222.0	7.59	F33APV	11/64"	83.7	8.1
3	21	302.0	12.67	F43APV	7/32"	82.2	12.5
4	26	368.5	13.48	F43APV	15/64"	81.3	14.2
5	31	444.5	18.68	F43A	15/64 x 1/8"	80.2	18.3
6	36	515.0	20.45	F43A	13/64" x 1/8"	79.6	22.0
7	41	591.0	25.41	F43AV	14/64" x 1/8"	78.9	26.1
8	46	661.5	26.70	F43AV	5/16" x 1/8"	78.5	29.2
9	51	737.5	32.15	F43APV	3/8"	78.2	34.4

CALCULATED DISCHARGE DISTRIBUTED ALONG THE LATERAL LINE = 164.4 GPM
EXPECTEDD DISCHARGE DISTRIBUTED ALONG THE LATERAL LINE = 172.0 GPM

Figure 33. Auxiliary sprinklers models and nozzle sizes used for the modification of the center pivot irrigation system.

determine the auxillary sprinkler type. Figure 35 gives the Q-H relationship of the sprinklers by linear regression and also their spacings after the modification in the design of the center pivot system.

The Q-H relationship at the pivot for the modified system is shown in Figure 36. It has the coefficient of determination of 0.99999. The system curve at the pump for the modified system is shown in Figure 37.

The modified end gun off system curve shows that the Q-H relationship after the modification of the system is very close to the end gun on system curve. This can also be understood by comparing the regression equation of the modified end gun off system

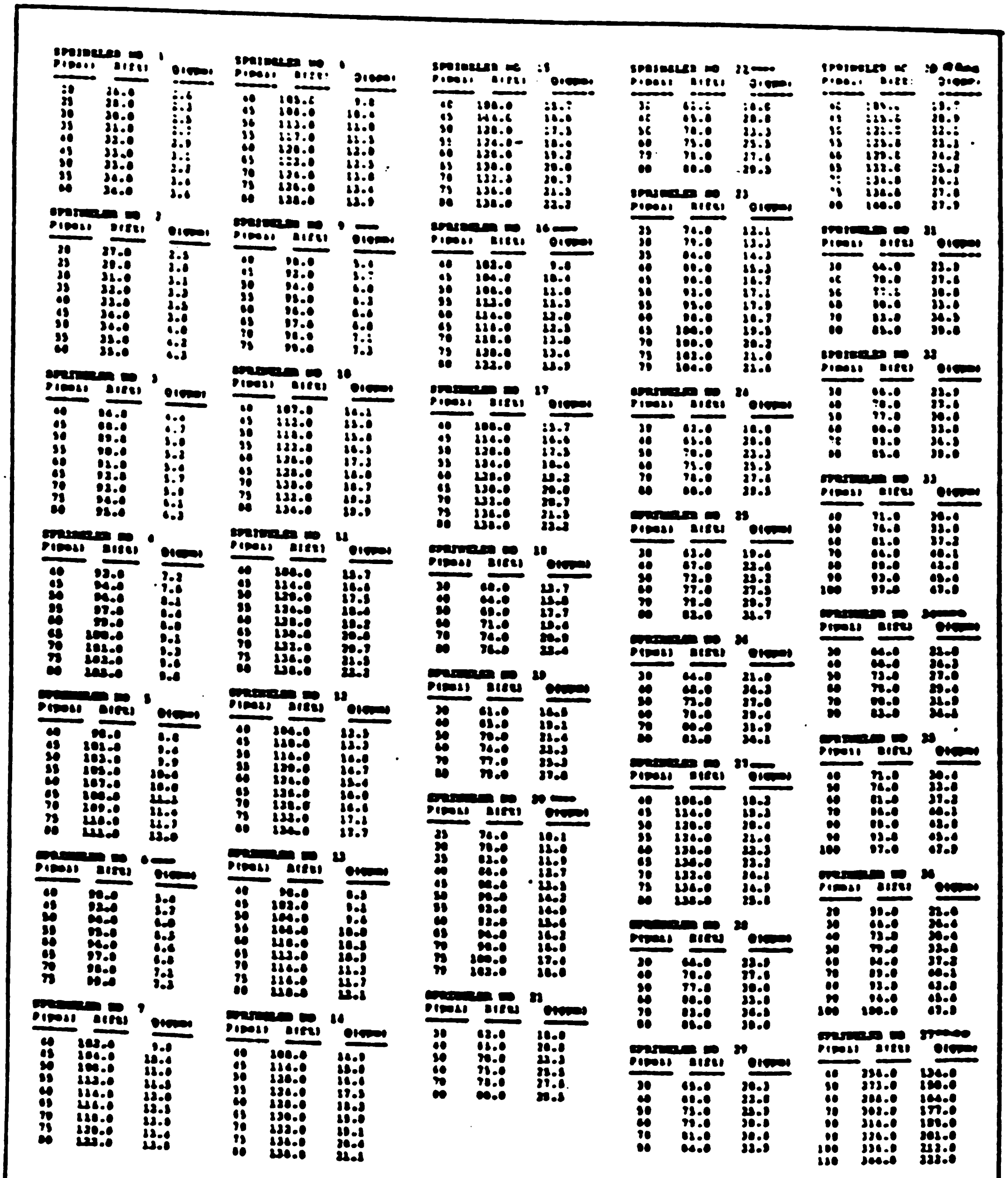
$$Q = 55.855(H^{0.503705}) \qquad [74]$$

equation [72].

Figure 38 shows the intersection of the pump curves (pumps H, V, and J) and the system curves for the condition when the end gun is on, end gun is off, and the end gun is on with the modification of the center pivot system.

B. Field performance evaluation

The flow and radius of coverage from the sprinklers and their spacings are required for the field performance evaluation of the center pivot irrigation system. The evaluation of the system was done for the following cases :



**** denotes auxillary sprinklers

Figure 34. Sprinkler characteristics showing the pressure (P), radius of coverage (R), and discharge (Q) for the regular and auxillary sprinklers (Nelson Agricultural Impact Sprinklers, 1986).

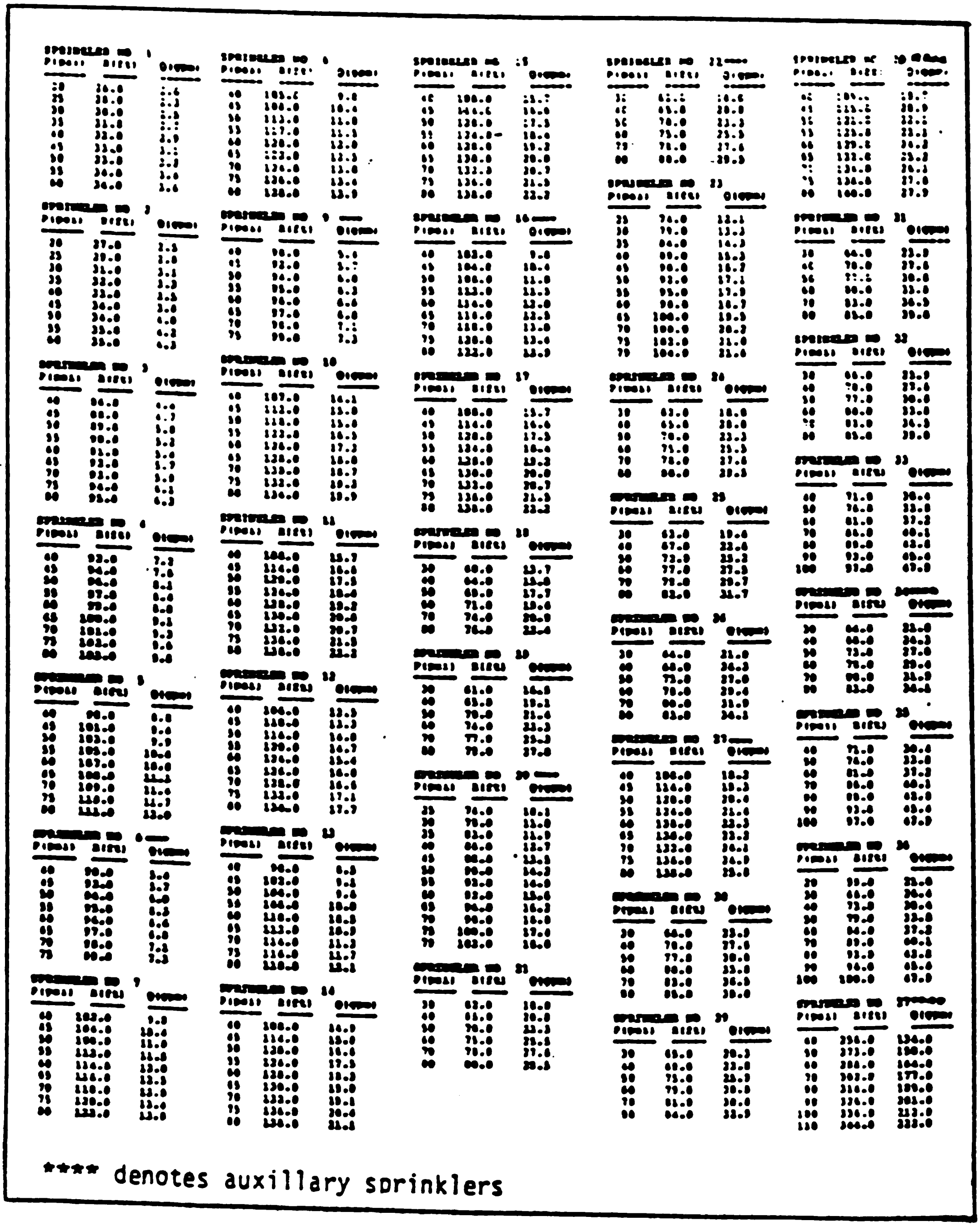
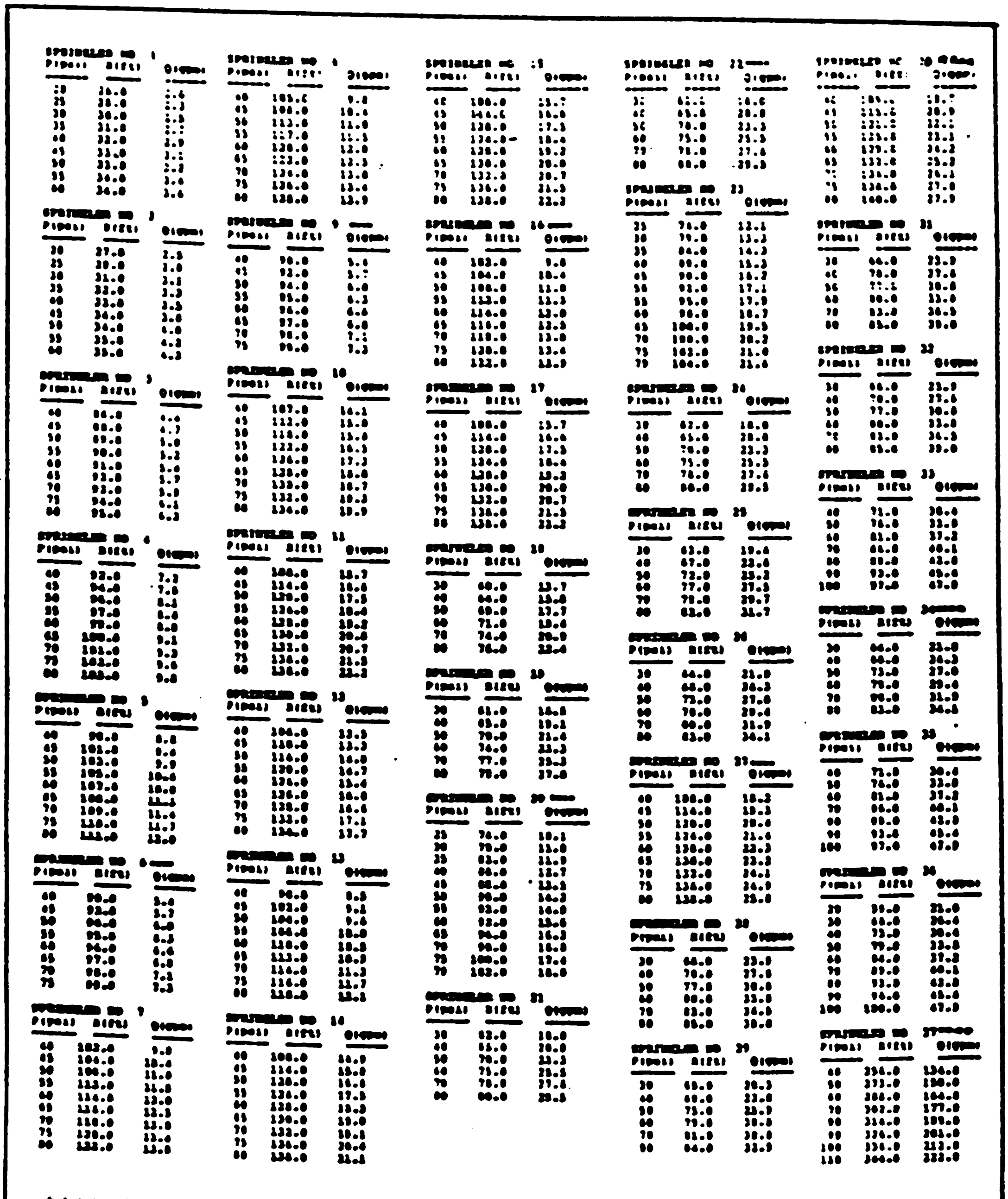


Figure 34. Sprinkler characteristics showing the pressure (P), radius of coverage (R), and discharge (Q) for the regular and auxiliary sprinklers (Nelson Agricultural Impact Sprinklers, 1986).



**** denotes auxillary sprinklers

Figure 34. Sprinkler characteristics showing the pressure (P), radius of coverage (R), and discharge (Q) for the regular and auxiliary sprinklers (Nelson Agricultural Impact Sprinklers, 1986).

DATA AND RESULTS

No of sprinklers in the system= 37
Total length of lateral= 787 ft
Distance to last tower= 765 ft
Maximum Allowable error in calculating pressure head= .5 ft

SPR NO	SPACING (ft)	DISTANCE FROM PIVOT (ft)	CALCULATED XC	CALCULATED a	REGRESSION EQUATION
1	28.0	28.0	0.2882	0.5094	Q= 0.29(H**0.51)
2	28.5	56.5	0.3863	0.4902	Q= 0.39(H**0.49)
3	28.5	85.0	0.4563	0.5031	Q= 0.46(H**0.50)
4	28.5	113.5	0.9148	0.4568	Q= 0.91(H**0.46)
*5	32.5	146.0	1.2006	0.4428	Q= 1.20(H**0.44)
6	9.5	155.5	0.5715	0.4951	Q= 0.57(H**0.50)
7	19.0	174.5	1.0171	0.5007	Q= 1.02(H**0.50)
8	28.5	203.0	1.0171	0.5007	Q= 1.02(H**0.50)
*9	19.0	222.0	0.5715	0.4951	Q= 0.57(H**0.50)
10	9.5	231.5	1.4853	0.4975	Q= 1.49(H**0.50)
11	28.5	260.0	1.6195	0.5014	Q= 1.62(H**0.50)
12	28.5	288.5	1.3012	0.5003	Q= 1.30(H**0.50)
*13	13.5	302.0	0.8931	0.4988	Q= 0.89(H**0.50)
14	19.0	321.0	1.6318	0.4887	Q= 1.63(H**0.49)
15	28.5	349.5	1.6195	0.5014	Q= 1.62(H**0.50)
*16	19.0	368.5	1.0171	0.5007	Q= 1.02(H**0.50)
17	9.5	378.0	1.6195	0.5014	Q= 1.62(H**0.50)
18	28.5	406.5	1.6380	0.5009	Q= 1.64(H**0.50)
19	28.5	435.0	1.9721	0.5014	Q= 1.97(H**0.50)
*20	9.5	444.5	1.3228	0.5001	Q= 1.32(H**0.50)
21	23.0	467.5	2.1261	0.5039	Q= 2.13(H**0.50)
22	28.5	496.0	2.1261	0.5039	Q= 2.13(H**0.50)
*23	19.0	515.0	1.5910	0.5001	Q= 1.59(H**0.50)
24	9.5	524.5	2.1261	0.5039	Q= 2.13(H**0.50)
25	28.5	553.0	2.4629	0.4895	Q= 2.46(H**0.49)
26	28.5	581.5	2.6199	0.4912	Q= 2.62(H**0.49)
*27	9.5	591.0	1.8905	0.5004	Q= 1.89(H**0.50)
28	23.0	614.0	2.8755	0.4995	Q= 2.88(H**0.50)
29	28.5	642.5	2.2352	0.5187	Q= 2.24(H**0.52)
*30	19.0	661.5	2.0346	0.5017	Q= 2.03(H**0.50)
31	9.5	671.0	2.8755	0.4995	Q= 2.88(H**0.50)
32	28.5	699.5	2.8755	0.4995	Q= 2.88(H**0.50)
33	28.5	728.0	3.1986	0.4971	Q= 3.20(H**0.50)
*34	9.5	737.5	2.6199	0.4912	Q= 2.62(H**0.49)
35	19.0	756.5	3.1986	0.4971	Q= 3.20(H**0.50)
36	26.8	783.3	3.0516	0.5064	Q= 3.05(H**0.51)
37	3.7	787.0	13.9973	0.4990	Q= 14.00(H**0.50)

* auxillary sprinklers

DIAMETER (inches)	DISTANCE FROM PIVOT(ft) FROM	TO
5.79	0	765.0
2.78	765.0	787.0

PIPE ROUGHNESS=0.000600inches
SLOPE OF THE FIELD IS NEGLIGIBLE
RISER DIAMETER = 1.0000 inches
END GUN RISER DIAMETER = 2.0000 inches
K FOR TEE AND ELBOW COMPONENTS = 1.80

Figure 35. Design data for the hydraulic network analysis of the modified center pivot irrigation system.

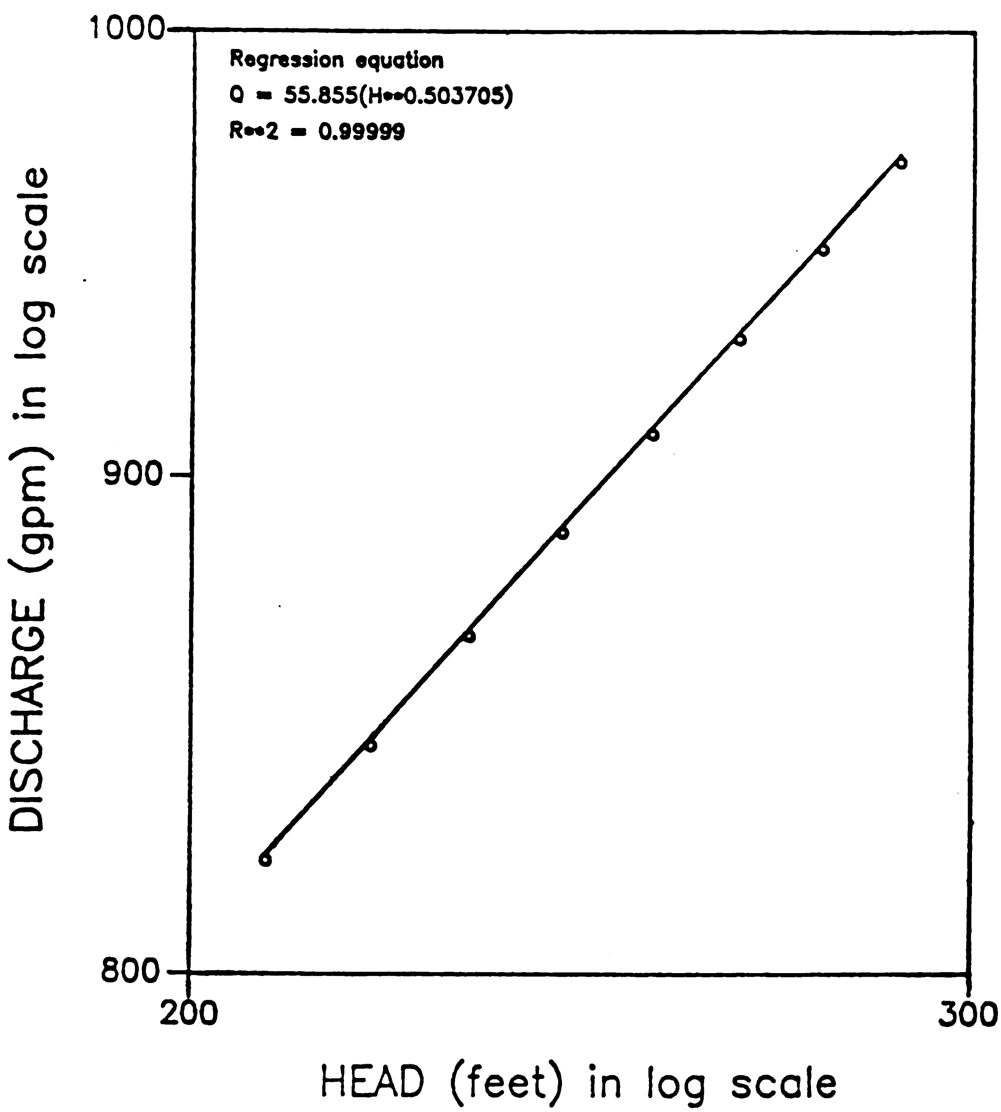


Figure 36. Graph showing the discharge-pressure relationship at the center pivot point for the modified end gun off condition.

HEAD (feet)

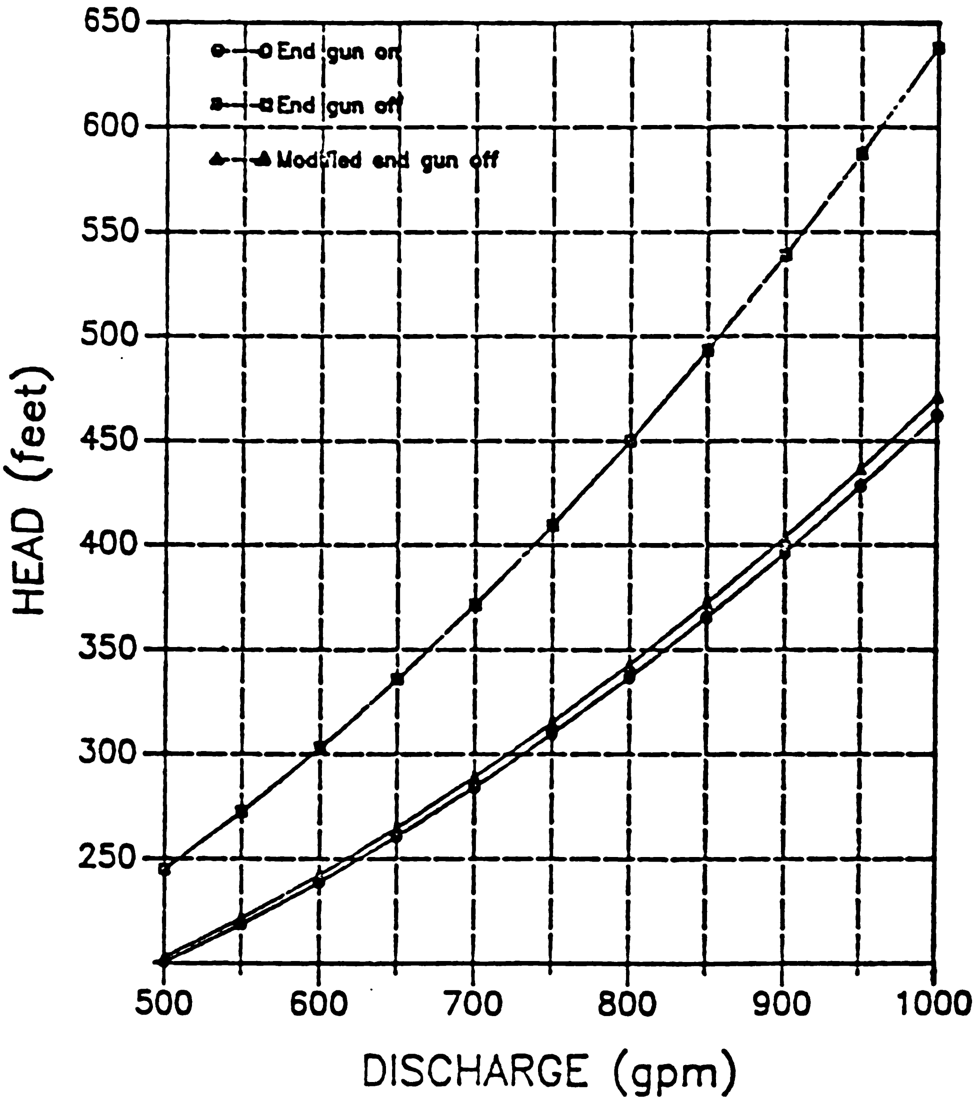


Figure 37. System curves for the modified end gun off condition with respect to the end gun on and end gun off conditions.

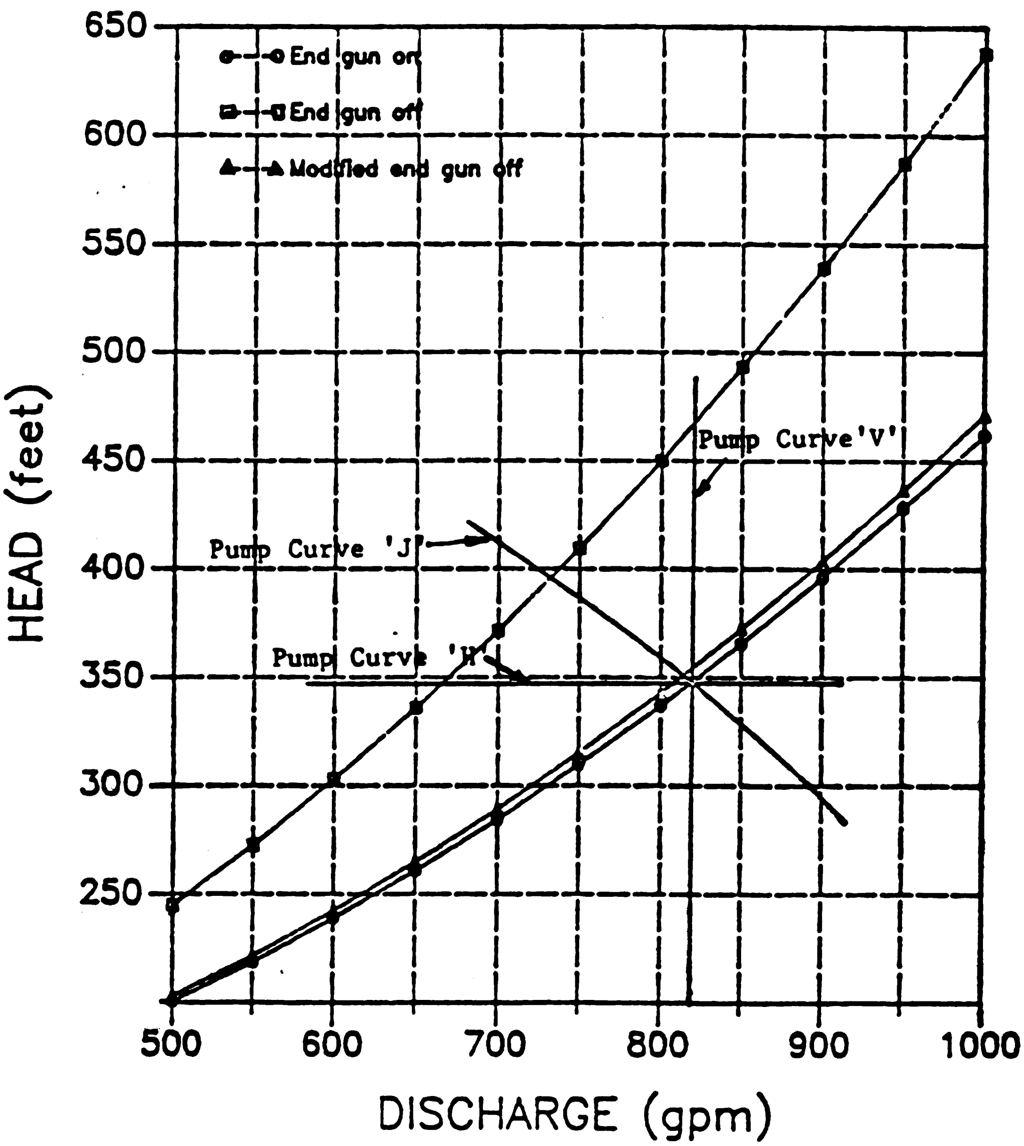


Figure 38. System curves and pump curves for different operating conditions and pumps.

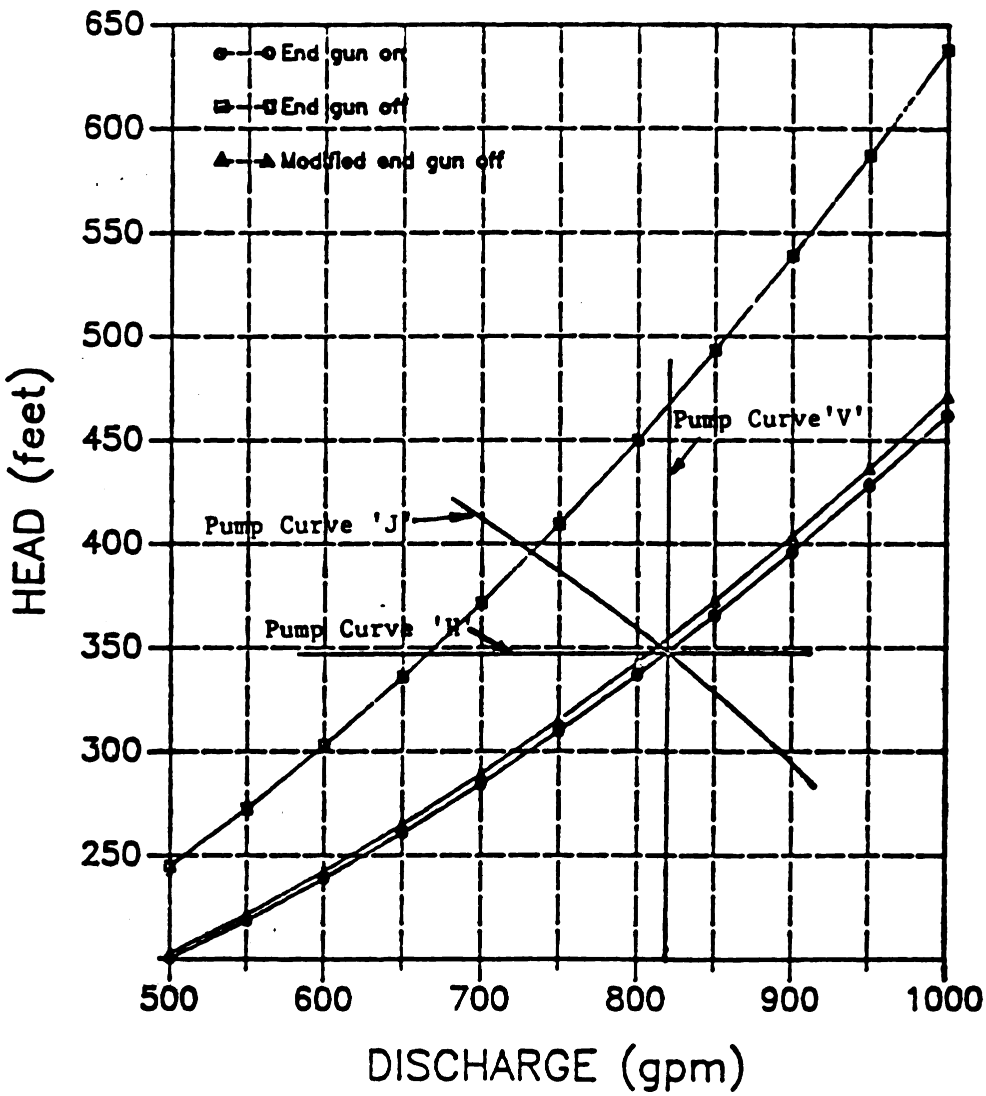


Figure 38. System curves and pump curves for different operating conditions and pumps.

Case No	Description
1	End gun on.
2	End gun off. Pump J
3	End gun off. Pump V
4	End gun off. Pump H
5	End gun off. Modified design

Figures 39 thru 43 are the results from NETWORK program using the finite element analysis method for case 1, case 2, case 3, case 4, and case 5 respectively. The detail simulation output of NETWORK is given in appendix B.

1. Field Performance Evaluation Simulation Model

Program "FIELD" (Appendix E) determines the depth of application of irrigation water 25 feet apart in the field. The speed of the last tower is 922.05 ft/hr at 100% timer setting (field data). The depth of application at spacings of 25 feet starting from the pivot point was obtained for all five cases for timer settings of 100%, 75%, 60%, 50%, 42%, 34%, 29%, 24%, 21%, 18%, 16%, 14%, 11%, and 9%. The application depth for the above timer settings for the five cases is given in Appendix F. The average application depth was obtained by taking the mean of the simulated application depth along the lateral line of the system (e.g. for 50% timer setting; Figure 45). Figure 44 is a plot showing the average application depth of water for different timer settings for the five different cases. The rate of change of in the average application depth of water with respect to the percentage timer setting is given by the slope of the graph. It is seen that the rate of

END GUN ON:

PRESSURE AT THE PIVOT = 88 PSI (203.4 FT)
TOTAL DISCHARGE = 825.2 GPM
PRESSURE DROP IN THE LATERAL LINE = 11.59 PSI (26.79 FT)
NO OF SPRINKLERS = 28

SP NO	SPACING (FT)	PRES PSI	HEAD FT	DRIS GPM	RADCOV FT
1	28.0	87.43	202.09	3.011	32.672
2	28.5	86.85	200.75	3.718	33.763
3	28.5	86.28	199.43	4.525	86.534
4	28.5	85.72	198.13	7.038	90.431
5	32.5	85.08	196.66	8.731	97.452
6	28.5	84.54	195.41	9.737	101.534
7	28.5	84.01	194.18	11.677	118.064
8	28.5	83.49	192.98	13.503	102.468
9	28.5	82.99	191.83	15.124	104.040
10	28.5	82.51	190.72	17.999	134.000
11	32.5	81.99	189.51	21.169	138.000
12	28.5	81.55	188.50	22.397	130.000
13	28.5	81.14	187.56	22.341	133.000
14	28.5	80.76	186.67	22.490	76.000
15	28.5	80.40	185.84	27.067	79.000
16	32.5	80.02	184.97	29.509	80.000
17	28.5	79.72	184.27	29.453	79.950
18	28.5	79.45	183.64	29.402	79.897
19	28.5	79.20	183.07	31.543	81.764
20	28.5	78.98	182.56	33.819	82.617
21	32.5	78.76	182.05	38.701	84.761
22	28.5	78.60	181.68	33.202	84.000
23	28.5	78.46	181.36	38.627	84.702
24	28.5	78.33	181.09	38.599	84.679
25	28.5	78.26	180.88	42.370	88.525
26	28.5	78.19	180.72	42.332	88.502
27	26.8	76.56	176.97	41.957	91.752
28	3.7	76.41	176.62	185.102	310.102

Figure 39. Field performance evaluation data obtained from the simulation model 'NETWORK' for the end gun on condition.

ENDGUN OFF:

PRESSURE AT THE PIVOT = 110 PSI (254.24 FT)
TOTAL DISCHARGE = 730.6 GPM
PRESSURE DROP IN THE LATERAL LINE = 7.01 PSI (16.2 FT)
NO OF SPRINKLERS WITH DISCHARGE = 27

NO	SPACING (FT)	PRES PSI	HEAD FT	GRIS GPM	RADCOV FT
1	28.0	109.55	253.21	3.370	53.814
2	28.5	109.09	252.15	4.167	53.000
3	28.5	108.64	251.10	5.077	89.405
4	28.5	108.19	250.07	7.907	95.349
5	32.5	107.69	248.91	9.845	102.799
6	28.5	107.26	247.93	10.991	107.937
7	28.5	106.85	246.97	13.169	124.847
8	28.5	106.45	246.05	15.247	113.851
9	28.5	106.07	245.17	17.098	117.322
10	28.5	105.71	244.33	20.374	134.000
11	32.5	105.32	243.43	23.925	138.000
12	28.5	105.00	242.69	23.422	138.000
13	28.5	104.70	242.01	25.387	133.000
14	28.5	104.44	241.39	25.502	76.000
15	28.5	104.19	240.82	30.553	79.000
16	32.5	103.94	240.24	33.664	80.000
17	28.5	103.75	239.80	33.633	80.000
18	28.5	103.58	239.41	33.606	80.000
19	28.5	103.44	239.08	33.946	82.000
20	28.5	103.32	238.80	38.588	83.000
21	32.5	103.20	238.53	44.295	85.000
22	28.5	103.13	238.38	38.226	84.000
23	28.5	103.08	238.25	44.267	85.000
24	28.5	103.04	238.16	44.259	85.000
25	28.5	103.01	238.11	48.574	97.000
26	28.5	103.00	238.08	48.571	97.000
27	26.8	102.91	237.86	48.733	100.000

Figure 40. Field performance evaluation data obtained from the simulation model 'NETWORK' for the end gun off with pump 'J' condition.

END GUN OFF:

PRESSURE AT THE PIVOT = 140.07 PSI (323.76 FT)
TOTAL DISCHARGE = 923.2 GPM
PRESSURE DROP IN THE LATERAL LINE = 8.85 PSI (20.5 FT)
NO OF SPRINKLERS WITH DISCHARGE = 27

NO	SPACING (FT)	PRES PSI	HEAD FT	QRIS GPM	RADCOV FT
1	28.0	139.50	322.45	3.803	34.000
2	28.5	138.93	321.13	4.702	73.000
3	28.5	138.37	319.83	5.730	92.227
4	28.5	137.81	318.54	8.924	99.546
5	32.5	137.19	317.10	11.112	108.039
6	28.5	136.66	315.87	12.405	115.622
7	28.5	136.14	314.68	14.865	120.000
8	28.5	135.64	313.53	17.211	125.535
9	28.5	135.17	312.43	19.362	128.255
10	28.5	134.72	311.38	23.002	134.000
11	32.5	134.23	310.26	26.936	138.000
12	28.5	133.83	309.34	28.712	138.000
13	28.5	133.47	308.50	28.672	138.000
14	28.5	133.13	307.72	28.890	76.000
15	28.5	132.83	307.01	34.226	79.000
16	32.5	132.51	306.29	38.047	80.000
17	28.5	132.27	305.74	38.012	80.000
18	28.5	132.06	305.25	37.982	90.000
19	28.5	131.89	304.84	40.485	82.000
20	28.5	131.74	304.50	43.481	83.000
21	32.5	131.60	304.18	50.013	93.000
22	28.5	131.51	303.97	43.362	84.000
23	28.5	131.44	303.81	49.982	85.000
24	28.5	131.39	303.70	49.973	85.000
25	28.5	131.36	303.63	54.813	97.000
26	28.5	131.33	303.60	54.810	97.000
27	26.8	131.22	303.31	55.118	100.000

Figure 41. Field performance evaluation data obtained from the simulation model 'NETWORK' for the end gun off with pump 'V' condition.

END GUN OFF:

PRESSURE AT THE PIVOT = 140.07 PSI (323.76 FT)
TOTAL DISCHARGE = 923.2 GPM
PRESSURE DROP IN THE LATERAL LINE = 8.85 PSI (20.5 FT)
NO OF SPRINKLERS WITH DISCHARGE = 27

NO	SPACING (FT)	PRES PSI	HEAD FT	DIS GPM	RADCOV FT
1	28.0	139.50	322.45	3.803	34.000
2	28.5	138.93	321.13	4.702	85.000
3	28.5	138.37	319.83	5.730	92.227
4	28.5	137.81	318.54	8.924	99.546
5	32.5	137.19	317.10	11.112	108.039
6	28.5	136.66	315.87	12.405	115.622
7	28.5	136.14	314.68	14.865	120.000
8	28.5	135.64	313.53	17.211	123.333
9	29.5	135.17	312.43	19.362	128.233
10	28.5	134.72	311.38	23.002	134.000
11	32.5	134.23	310.26	26.936	138.000
12	29.5	133.83	309.34	28.712	138.000
13	28.5	133.47	308.50	28.672	138.000
14	28.5	133.13	307.72	28.890	76.000
15	28.5	132.83	307.01	34.226	79.000
16	32.5	132.51	306.29	38.047	80.000
17	28.5	132.27	305.74	38.012	80.000
18	29.5	132.06	305.25	37.982	90.000
19	28.5	131.89	304.84	40.485	82.000
20	28.5	131.74	304.50	43.481	83.000
21	32.5	131.60	304.18	50.013	93.000
22	28.5	131.51	303.97	43.362	84.000
23	28.5	131.44	303.81	49.982	85.000
24	28.5	131.39	303.70	49.973	85.000
25	29.5	131.36	303.63	54.813	97.000
26	29.5	131.35	303.60	54.810	97.000
27	26.8	131.22	303.31	55.118	100.000

Figure 41. Field performance evaluation data obtained from the simulation model 'NETWORK' for the end gun off with pump 'V' condition.

END GUN OFF:

PRESSURE AT THE PIVOT = 92.84 PSI (214.59 FT)
TOTAL DISCHARGE = 670.8 GPM
PRESSURE DROP IN THE LATERAL LINE = 6.19 PSI (14.31 FT)
NUMBER OF SPRINKLERS WITH DISCHARGE= 27

NO	SPACING (FT)	PRES PSI	HEAD FT	DRIS GPM	RADCOV FT
1	28.0	92.44	213.67	3.096	33.000
2	28.5	92.04	212.75	3.827	24.000
3	28.5	91.65	211.83	4.663	87.579
4	28.5	91.25	210.92	7.262	92.452
5	32.5	90.82	209.91	9.041	99.313
6	28.5	90.44	209.05	10.092	102.974
7	28.5	90.08	208.21	12.092	120.368
8	28.5	89.73	207.41	13.998	106.229
9	28.5	89.40	206.63	15.697	107.981
10	28.5	89.08	205.90	18.702	134.000
11	32.5	88.74	205.11	22.004	138.000
12	28.5	88.46	204.47	23.329	138.000
13	28.5	88.20	203.87	23.295	138.000
14	28.5	87.97	203.33	23.474	76.000
15	28.5	87.75	202.83	28.197	79.000
16	32.5	87.53	202.32	30.873	80.000
17	28.5	87.36	201.93	30.843	80.000
18	28.5	87.22	201.60	30.817	80.000
19	28.5	87.09	201.31	33.044	82.000
20	28.5	86.99	201.06	35.461	83.000
21	32.5	86.89	200.84	40.647	85.000
22	28.5	86.83	200.69	34.962	84.000
23	28.5	86.78	200.58	40.621	85.000
24	28.5	86.75	200.51	40.613	85.000
25	28.5	86.73	200.46	44.591	91.756
26	28.5	86.72	200.44	44.589	91.752
27	26.8	86.65	200.27	44.669	95.157

Figure 42. Field performance evaluation data obtained from the simulation model 'NETWORK' for the end gun off with pump 'H' condition.

END GUN OFF (MODIFIED SYSTEM)

PRESSURE AT THE PIVOT = 90.78 PSI (209.83 FT)
TOTAL DISCHARGE = 824.9 GPM
PRESSURE DROP IN THE LATERAL LINE = 9.08 PSI (21.21 FT)
NO OF SPRINKLERS WITH DISCHARGE = 36

SP NO	SPACING (FT)	PRES PSI	HEAD FT	QRIS GPM	RADCOV (FT)
1	28.0	90.16	208.40	3.058	32.932
2	28.5	89.56	207.02	3.776	34.000
3	28.5	88.97	205.65	4.596	87.078
4	28.5	88.35	204.22	7.148	91.850
5	32.5	87.67	202.64	8.888	98.482
6	9.5	87.50	202.25	8.132	109.683
7	19.0	87.10	201.32	9.911	102.371
8	28.5	86.52	199.98	11.863	119.178
9	19.0	86.26	199.39	8.074	108.905
10	9.5	85.96	198.68	13.541	102.759
11	28.5	85.41	197.41	15.482	106.502
12	28.5	84.84	196.10	18.293	138.489
13	13.5	84.82	196.05	12.442	121.636
14	19.0	84.21	194.65	21.512	140.829
15	28.5	83.75	193.59	22.775	141.576
16	19.0	83.81	193.73	14.226	124.861
17	9.5	83.38	192.72	22.724	141.258
18	28.5	83.03	191.91	22.883	77.639
19	28.5	82.49	190.67	27.562	80.644
20	9.5	82.79	191.37	18.351	103.987
21	23.0	82.04	189.63	30.050	81.491
22	28.5	81.80	189.07	30.005	81.369
23	19.0	82.03	189.61	21.986	105.857
24	9.5	81.59	188.58	29.966	81.263
25	28.5	81.29	187.89	32.145	83.151
26	28.5	81.00	187.23	34.482	83.930
27	9.5	81.40	188.16	26.105	139.631
28	23.0	80.56	186.20	39.495	86.079
29	28.5	80.81	186.78	33.927	86.622
30	19.0	81.07	187.38	28.248	141.744
31	9.5	80.40	185.84	39.457	85.996
32	28.5	80.36	185.74	39.446	85.973
33	28.5	80.08	185.09	43.314	89.790
34	9.5	80.63	186.38	34.405	83.743
35	19.0	80.06	185.06	43.311	89.786
36	26.8	81.58	188.57	43.370	93.657

Figure 43. Field performance evaluation data obtained from the simulation model 'NETWORK' for the modified end gun off condition.

change of application depth is high at lower timer settings as compared at upper timer settings. The average application depth for a particular timer setting is lowest when the end gun is on. It is highest with pump 'V' when the end gun is off. After the modification of the design, it can be seen that the application depth increases for pumps H and J when the end gun is off. The depth is very close to the that given by the pump V. This implies that there is definitely some time savings to apply the same depth of water with the modification of the design when pumps H or J are used. It also shows that for a given % timer setting, say 30%, the application rate is significantly reduced when the end gun is on (i.e. 1.0 inch down to 0.8 inch or 20% drop; Figure 46). This causes the distribution efficiency to be low. The curve also shows that to compensate with the modified center pivot system, the percentage timer setting must be increased by approximately 4% with the end gun off to get a constant application depth thoughout the revolution of the lateral line. This implies that the distribution efficiency can be increased and less time will be required for irrigation by increasing the speed of the lateral line movement with the end gun off.

The model 'Field' was run to simulate the performance of the system with the end gun covering 33%, 50%, and 66% of the circular movement of the lateral line pipe (Figure 47). The effect of the change in the end gun on coverage on the application uniformity, time saving, and energy savings was studied by varying the end gun coverage.

Figures 48, 49, and 50 show the total time required to apply certain depth of water without modification in the system using pumps V, J, and H respectively. Figure 51 shows the total time required to apply

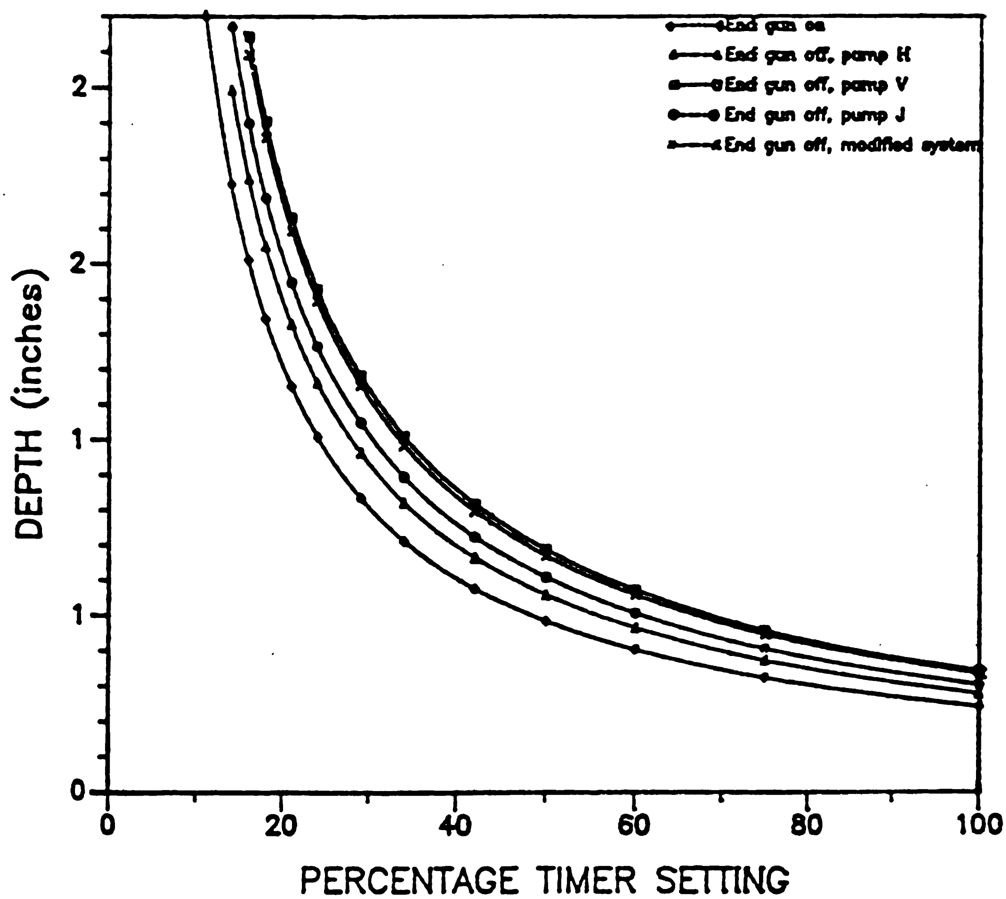


Figure 44. Graph showing the application depth of water for different timer settings.

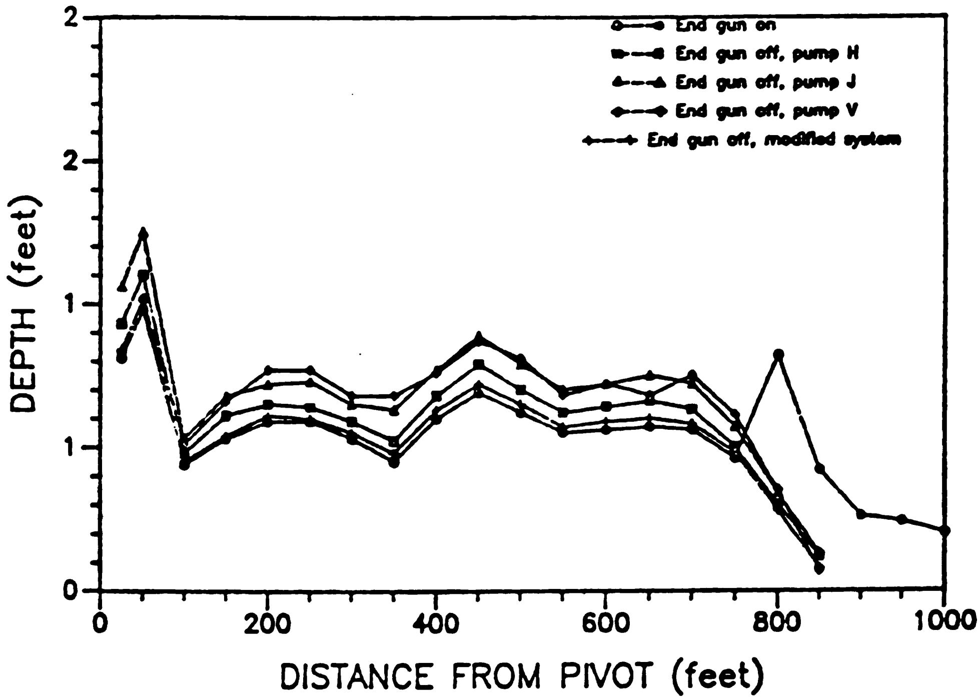


Figure 45. Graph showing the application depth along the lateral line in the field for 50% timer setting.

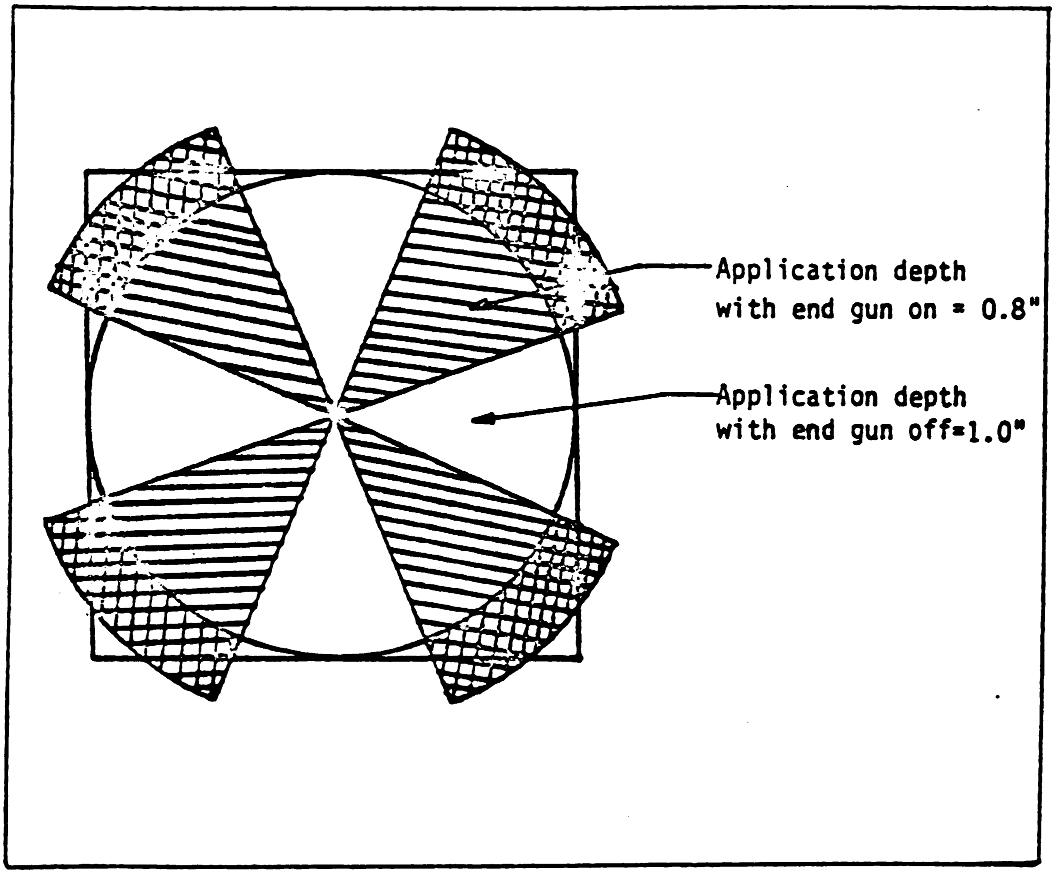


Figure 46. Example of the variation in the application depth for the end gun on and end gun off conditions for the same timer setting.

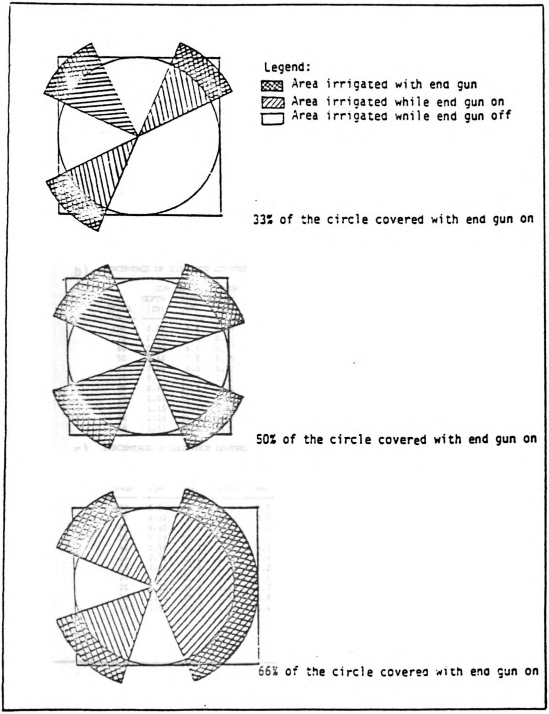


Figure 47. Example showing 33%, 50%, and 66% of the circle irrigated with the end gun on.

UNMODIFIED SYSTEM WITH CONSTANT TIMER
APPLICATION UNIFORMITY (END GUN ON) =81.3
APPLICATION UNIFORMITY (END GUN OFF)=74.4

a) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 33

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	2.6	0.34	5.2	0.31	7.8	68.793
75	0.32	3.4	0.46	7.0	0.41	10.4	68.793
60	0.40	4.3	0.57	8.7	0.52	13.0	68.793
50	0.48	5.2	0.69	10.5	0.62	15.6	68.793
42	0.58	6.1	0.82	12.5	0.74	18.6	68.793
34	0.71	7.6	1.01	15.4	0.91	23.0	68.793
29	0.83	8.9	1.18	18.1	1.07	27.0	68.793
24	1.01	10.8	1.43	21.8	1.29	32.6	68.793
21	1.15	12.3	1.63	24.9	1.47	37.2	68.793
18	1.34	14.3	1.91	29.1	1.72	43.4	68.793
16	1.51	16.1	2.14	32.7	1.94	48.9	68.793

b) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 50

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	3.9	0.34	3.9	0.29	7.8	65.890
75	0.32	5.2	0.46	5.2	0.39	10.4	65.890
60	0.40	6.5	0.57	6.5	0.49	13.0	65.890
50	0.48	7.8	0.69	7.8	0.58	15.6	65.890
42	0.58	9.3	0.82	9.3	0.70	18.6	65.890
34	0.71	11.5	1.01	11.5	0.86	23.0	65.890
29	0.83	13.5	1.18	13.5	1.01	27.0	65.890
24	1.01	16.3	1.43	16.3	1.22	32.6	65.890
21	1.15	18.6	1.63	18.6	1.39	37.2	65.890
18	1.34	21.7	1.91	21.7	1.62	43.4	65.890
16	1.51	24.4	2.14	24.4	1.83	48.9	65.890

c) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 66

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	5.2	0.34	2.7	0.28	7.8	63.158
75	0.32	6.9	0.46	3.5	0.37	10.4	63.158
60	0.40	8.6	0.57	4.4	0.46	13.0	63.158
50	0.48	10.3	0.69	5.3	0.55	15.6	63.158
42	0.58	12.3	0.82	6.3	0.66	18.6	63.158
34	0.71	15.2	1.01	7.8	0.81	23.0	63.158
29	0.83	17.8	1.18	9.2	0.95	27.0	63.158
24	1.01	21.5	1.43	11.1	1.15	32.6	63.158
21	1.15	24.6	1.63	12.7	1.32	37.2	63.158
18	1.34	28.7	1.91	14.8	1.53	43.4	63.158
16	1.51	32.3	2.14	16.6	1.73	48.9	63.158

Figure 48. Application uniformity and time required to irrigate the field using pump V without the modification in the design of the system.

UNMODIFIED SYSTEM WITH CONSTANT TIMER
APPLICATION UNIFORMITY (END GUN ON) =81.3
APPLICATION UNIFORMITY (END GUN OFF)=74.2

a) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 33

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	2.6	0.30	5.2	0.28	7.8	71.071
75	0.32	3.4	0.41	7.0	0.38	10.4	71.071
60	0.40	4.3	0.51	8.7	0.47	13.0	71.071
50	0.48	5.2	0.61	10.5	0.57	15.6	71.071
42	0.58	6.1	0.72	12.5	0.67	18.6	71.071
34	0.71	7.6	0.89	15.4	0.83	23.0	71.071
29	0.83	8.9	1.05	18.1	0.98	27.0	71.071
24	1.01	10.8	1.27	21.8	1.18	32.6	71.071
21	1.15	12.3	1.45	24.9	1.35	37.2	71.071
18	1.34	14.3	1.69	29.1	1.57	43.4	71.071
16	1.51	16.1	1.90	32.7	1.77	48.9	71.071
14	1.73	18.4	2.17	37.4	2.02	55.9	71.071

b) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 50

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	3.9	0.30	3.9	0.27	7.8	69.465
75	0.32	5.2	0.41	5.2	0.36	10.4	69.465
60	0.40	6.5	0.51	6.5	0.45	13.0	69.465
50	0.48	7.8	0.61	7.8	0.55	15.6	69.465
42	0.58	9.3	0.72	9.3	0.65	18.6	69.465
34	0.71	11.5	0.89	11.5	0.80	23.0	69.465
29	0.83	13.5	1.05	13.5	0.94	27.0	69.465
24	1.01	16.3	1.27	16.3	1.14	32.6	69.465
21	1.15	18.6	1.45	18.6	1.30	37.2	69.465
18	1.34	21.7	1.69	21.7	1.52	43.4	69.465
16	1.51	24.4	1.90	24.4	1.71	48.9	69.465
14	1.73	27.9	2.17	27.9	1.95	55.9	69.465

c) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 66

%	GUN ON		GUN OFF		AVERAGE		UNIFORMITY
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	%
100	0.24	5.2	0.30	2.7	0.26	7.8	67.953
75	0.32	6.9	0.41	3.5	0.35	10.4	67.953
60	0.40	8.6	0.51	4.4	0.44	13.0	67.953
50	0.48	10.3	0.61	5.3	0.53	15.6	67.953
42	0.58	12.3	0.72	6.3	0.63	18.6	67.953
34	0.71	15.2	0.89	7.8	0.77	23.0	67.953
29	0.83	17.8	1.05	9.2	0.91	27.0	67.953
24	1.01	21.5	1.27	11.1	1.10	32.6	67.953
21	1.15	24.6	1.45	12.7	1.25	37.2	67.953
18	1.34	28.7	1.69	14.8	1.46	43.4	67.953
16	1.51	32.3	1.90	16.6	1.64	48.9	67.953
14	1.73	36.9	2.17	19.0	1.88	55.9	67.953

Figure 49. Application uniformity and time required to irrigate the field using pump J without the modification in the design of the system.

UNMODIFIED SYSTEM WITH CONSTANT TIMER SETTING
APPLICATION UNIFORMITY (END GUN ON) =81.3
APPLICATION UNIFORMITY (END GUN OFF)=74.1

a) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 33

%	GUN ON		GUN OFF		AVERAGE		
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	UNIFORMITY %
100	0.24	2.6	0.28	5.2	0.27	7.8	72.889
75	0.32	3.4	0.37	7.0	0.36	10.4	72.889
60	0.40	4.3	0.46	8.7	0.44	13.0	72.889
50	0.48	5.2	0.56	10.5	0.53	15.6	72.889
42	0.58	6.1	0.66	12.5	0.64	18.6	72.889
34	0.71	7.6	0.82	15.4	0.78	23.0	72.889
29	0.83	8.9	0.96	18.1	0.92	27.0	72.889
24	1.01	10.8	1.16	21.8	1.11	32.6	72.889
21	1.15	12.3	1.33	24.9	1.27	37.2	72.889
18	1.34	14.3	1.55	29.1	1.48	43.4	72.889
16	1.51	16.1	1.74	32.7	1.67	48.9	72.889
14	1.73	18.4	1.99	37.4	1.91	55.9	72.889
11	2.20	23.5	2.54	47.6	2.43	71.1	72.889

b) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 50

%	GUN ON		GUN OFF		AVERAGE		
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	UNIFORMITY %
100	0.24	3.9	0.28	3.9	0.26	7.8	72.282
75	0.32	5.2	0.37	5.2	0.35	10.4	72.282
60	0.40	6.5	0.46	6.5	0.43	13.0	72.282
50	0.48	7.8	0.56	7.8	0.52	15.6	72.282
42	0.58	9.3	0.66	9.3	0.62	18.6	72.282
34	0.71	11.5	0.82	11.5	0.77	23.0	72.282
29	0.83	13.5	0.96	13.5	0.90	27.0	72.282
24	1.01	16.3	1.16	16.3	1.09	32.6	72.282
21	1.15	18.6	1.33	18.6	1.24	37.2	72.282
18	1.34	21.7	1.55	21.7	1.45	43.4	72.282
16	1.51	24.4	1.74	24.4	1.63	48.9	72.282
14	1.73	27.9	1.99	27.9	1.86	55.9	72.282
11	2.20	35.5	2.54	35.5	2.37	71.1	72.282

c) PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = 66

%	GUN ON		GUN OFF		AVERAGE		
TIMER	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	DEPTH (IN)	TIME (HR)	UNIFORMITY %
100	0.24	5.2	0.28	2.7	0.25	7.8	71.711
75	0.32	6.9	0.37	3.5	0.34	10.4	71.711
60	0.40	8.6	0.46	4.4	0.42	13.0	71.711
50	0.48	10.3	0.56	5.3	0.51	15.6	71.711
42	0.58	12.3	0.66	6.3	0.61	18.6	71.711
34	0.71	15.2	0.82	7.8	0.75	23.0	71.711
29	0.83	17.8	0.96	9.2	0.88	27.0	71.711
24	1.01	21.5	1.16	11.1	1.06	32.6	71.711
21	1.15	24.6	1.33	12.7	1.21	37.2	71.711
18	1.34	28.7	1.55	14.8	1.41	43.4	71.711
16	1.51	32.3	1.74	16.6	1.59	48.9	71.711
14	1.73	36.9	1.99	19.0	1.82	55.9	71.711
11	2.20	46.9	2.54	24.2	2.31	71.1	71.711

Figure 50. Application uniformity and time required to irrigate the field using pump H without the modification in the design of the system.

NO OF SPRINKLERS INCLUDING END GUN= 36
SPEED OF THE LAST TOWER [illegible] MOVEMENT (FT/HR)= 614.70
DISTANCE FROM PIVOT TO LAST TOWER (FT) =[illegible]
APPLICATION UNIFORMITY (END GUN ON) =[illegible]
APPLICATION UNIFORMITY (END GUN OFF)=76.4

a) PERCENTAGE OF DISTANCE COVERED WITH GUN ON = 33 %

DEPTH IN INCH	END GUN ON TIMER %	END GUN ON TIME HR	END GUN OFF TIMER %	END GUN OFF TIME HR	UNIFORMITY %	TOTAL TIME HR
0.33	72.74	3.55	100.00	5.24	76.40	8.79
0.40	60.59	4.26	85.37	6.14	76.40	10.40
0.50	48.60	5.31	67.70	7.73	76.40	13.04
0.60	40.50	6.36	56.22	9.32	76.40	15.68
0.70	34.60	7.44	48.08	13.90	76.40	18.34
0.80	30.39	8.49	41.07	12.51	76.40	21.60
0.90	27.11	9.52	37.60	13.93	76.40	23.45
1.00	24.23	10.65	33.54	15.62	76.40	26.27
1.10	22.08	11.69	30.59	17.12	76.40	28.81
1.20	20.25	12.74	28.06	18.68	76.40	31.42
1.30	18.69	13.81	25.97	20.19	76.40	33.98
1.40	17.33	14.89	23.92	21.90	76.40	36.79
1.50	16.14	15.99	22.41	23.30	76.40	39.36
1.60	15.10	16.99	20.93	25.03	76.40	42.02
1.70	14.26	18.10	19.80	26.46	76.40	44.56
1.80	13.54	19.06	18.67	28.06	76.40	47.12
1.90	12.90	20.00	17.65	29.60	76.40	49.60
2.00	12.27	21.03	16.79	31.20	76.40	52.24

b) PERCENTAGE OF DISTANCE COVERED WITH GUN ON = 50 %

DEPTH IN INCH	END GUN ON TIMER %	END GUN ON TIME HR	END GUN OFF TIMER %	END GUN OFF TIME HR	UNIFORMITY %	TOTAL TIME HR
0.33	72.74	5.37	100.00	3.81	77.64	9.20
0.40	60.59	6.45	85.37	4.58	77.64	11.03
0.50	48.60	8.05	67.70	5.77	77.64	13.81
0.60	40.50	9.63	56.22	6.85	77.64	16.50
0.70	34.60	11.27	48.08	8.13	77.64	19.41
0.80	30.39	12.86	41.07	9.34	77.64	22.20
0.90	27.11	14.42	37.60	10.40	77.64	24.82
1.00	24.23	16.14	33.54	11.66	77.64	27.79
1.10	22.08	17.71	30.59	12.70	77.64	30.40
1.20	20.25	19.31	28.06	13.96	77.64	33.28
1.30	18.69	20.92	25.97	15.06	77.64	35.98
1.40	17.33	22.56	23.92	16.35	77.64	38.90
1.50	16.14	24.22	22.41	17.44	77.64	41.67
1.60	15.10	25.75	20.93	18.60	77.64	44.43
1.70	14.26	27.42	19.80	19.75	77.64	47.17
1.80	13.54	28.87	18.67	20.94	77.64	49.81
1.90	12.90	30.30	17.65	22.15	77.64	52.45
2.00	12.27	31.87	16.79	23.29	77.64	55.15

c) PERCENTAGE OF DISTANCE COVERED WITH GUN ON = 66 %

DEPTH IN INCH	END GUN ON TIMER %	END GUN ON TIME HR	END GUN OFF TIMER %	END GUN OFF TIME HR	UNIFORMITY %	TOTAL TIME HR
0.33	72.74	7.09	100.00	2.66	78.82	9.75
0.40	60.59	8.52	85.37	3.11	78.82	11.63
0.50	48.60	10.62	67.70	3.82	78.82	14.64
0.60	40.50	12.72	56.22	4.73	78.82	17.45
0.70	34.60	14.00	48.08	5.61	78.82	20.61
0.80	30.39	16.08	41.07	6.35	78.82	23.33
0.90	27.11	19.04	37.60	7.07	78.82	26.11
1.00	24.23	21.30	33.54	7.93	78.82	29.23
1.10	22.08	23.37	30.59	8.69	78.82	32.06
1.20	20.25	25.49	28.05	9.48	78.82	34.97
1.30	18.69	27.62	25.97	10.26	78.82	37.86
1.40	17.33	29.70	23.92	11.12	78.82	40.89
1.50	16.14	31.97	22.41	11.86	78.82	43.83
1.60	15.10	33.99	20.93	12.78	78.82	46.80
1.70	14.26	36.19	19.80	13.43	78.82	49.62
1.80	13.54	38.11	18.67	14.24	78.82	52.35
1.90	12.90	39.99	17.65	15.06	78.82	55.05
2.00	12.27	42.07	16.79	15.83	78.82	57.90

Figure 51. Application uniformity and time required to irrigate the field with the modification in the design of the system.

certain depth after the modification of the system. These figures also give the distribution efficiency for the end gun on and end gun off conditions.

The uniformity of application for the end gun on and end gun off conditions are about 81% and 74% respectively. This is based on the theoretical assumption that all sprinklers apply water in the field in an elliptical pattern.

The overall distribution efficiency depends upon the percentage of circle covered with the end gun on, and application uniformities and average application depths for the end gun on and end gun off conditions. The overall distribution efficiency for different cases are shown in Figures 48, 49, 50, and 51. The value of the overall distribution efficiency decreases as compared to the end gun on and end gun off system distribution efficiencies. This can also be understood by looking at the example given in Figure 46. The application depth for the given timer setting reduces from 1 inch to 0.8 inch when the end gun is turned on. This 20% change in the application depth reduces the overall distribution efficiency. Considering the application uniformity for the system with pump J, the uniformity for the end gun on and end gun off conditions are 81.3% and 74.2% respectively. But the overall uniformity reduced to 71% for the 33% end gun on coverage condition as a result of the reduction in the application depth from 1.05' to 0.83" for 29% timer setting (Figure 49).

The modification in the design of the center pivot system is such that the system operates with dual timer settings for the end gun on and end gun off conditions (Figure 51). Though the application uniformity using pump J is 74% for the end gun off conditions, the overall application uniformity is more than 76%. The timer setting is changed from 24% to 33.5% to apply an inch of water with the end gun off. Comparing the results of the unmodified system with the modified system, it is seen that the application uniformity increases from 71% to 76%, 69% to 78%, and 67% to 79% for the end gun covering 33%, 50%, and 66% of the circle respectively. This is an increase of 7 to 17% in the distribution efficiency of the system.

Wallace (1987) showed that for 50% soil water depletion schedule with rainfall,

$$\Delta Y = 1.08\Delta X \qquad [75]$$

where ΔY = change in the coefficient of variation of yield, and
ΔX = change in the coefficient of variation of irrigation.

Similarly for 50% soil water depletion schedule without rainfall, the relationship of the variation in the yield with the variation in the uniformity was given by

$$\Delta Y = 0.42\Delta X \qquad [76]$$

where ΔY and ΔX are as defined earlier.

These equations for corn show that the yield can be increased by improving the distribution efficiency of the irrigation system. Table 5 gives the overall view on the possible increase in the yield of corn with the modification in the design of the center pivot system using [75] and [76].

Table 5. Change in the yield of corn with the improvement in the irrigation application uniformity after the modification of the design of the center pivot system.

System with pump	% distance with end gun on	% change in distribution efficiency	% change in the yield of corn without rainfall	with rainfall
V	33	7.61	8.22	3.20
	50	11.75	12.69	4.94
	66	15.66	16.91	6.58
J	33	5.33	5.76	2.24
	50	8.17	8.82	3.43
	66	10.87	11.74	4.57
H	33	3.51	3.79	1.47
	50	5.36	5.79	2.25
	66	7.11	7.68	2.99

Table 5 shows that with an improvement in the distribution efficiency by 10% by using pump J, the yield can be increased by upto 11%. The maximum improvement in the distribution efficiency with the modification in the design of the center pivot design is for the system with steep pump curve.

As discussed above, it is clear that the yield of corn would be increased by upto 8.8% with a 8.17% increase in the application uniformity for the system with pump J. Assuming a yield of 140 bushels per acre, the 8.8% increase means an increase of 12.3 bushels per acre. The area of irrigation has been assumed to be 55 acres. Therefore the total increase in yield as a result of an increase in application uniformity would result be 676 bushels. This translates to $ 1691 at $2.50 per bushels.

C. Energy and Time Savings

The summary of the power required by the pumps for the conditions when the end gun is on, end gun is off, and the end gun is off with modifications is given in table 5. The efficiency of pump J with the end gun on is 82%. Since the pumps H and V are hypothetical, their efficiency are not known. Therefore their efficiencies at the operating points was assumed to be the same as that for pump J. The electrical power efficiency is assumed to be 70% for all the pumps. The total electrical power required is obtained by dividing the brake power by the electrical efficiency.

Pump V requires the most power when the end gun is off. This is also understood from Figure 30. With the end gun is off, the modification of the design of the system reduced the power requirement of pumps V and J by 30 hp and 1 hp respectively. The power requirement for pump H increased by 18 hp. But the power required after this increase is only 3 hp more than the end gun on condition. It is possible to replace pump V by a pump of 30 hp less capacity after the modification of the system.

Table 7 shows the energy required for the pumps to operate with the end gun on, end gun off, and end gun off with modifications in the design. Table 8 gives the total energy required for the pumps to operate for the modified system. Table 9 compares the total time and energy required to apply 0.5", 1.0", 1.5", and 2.0" of water between the modified and unmodified system. The values of energy and time given in Table 9 was obtained from Tables 7 and 8.

Table 6. Electrical power required to operate example pumps for the end gun on, end gun off, and modified end gun off conditions.

PUMP TYPE	OPERATING CONDITIONS	Q (gpm)	H (ft)	WATER POWER(hp)	EFF %	BRAKE POWER(hp)	ELECTRICAL POWER (hp)	ELECTRICAL POWER (hp)
H	END GUN ON	825.0	349	72.71	82	88.67	126.67	94.50
	END GUN OFF	670.5	349	59.09	81.5	72.51	103.58	77.27
	END GUN OFF (modified)	819.5	350	72.43	82	88.33	126.18	94.13
J	END GUN ON	825.0	349	72.71	82	88.67	126.67	94.50
	END GUN OFF	730.5	395	72.87	81.5	89.41	127.72	95.28
	END GUN OFF (modified)	819.5	352	72.86	82	88.86	126.93	94.69
V	END GUN ON	825.0	349	72.71	82	88.67	126.67	94.50
	END GUN OFF	825.0	470	97.92	81.5	120.14	171.63	128.04
	END GUN OFF (modified)	825.0	354	73.77	82	89.96	128.51	95.87

Table 7. Energy and time required for irrigation using different pumps without the modification in the design.

WATER DEPTH (IN) (CUTOFF)	PUMP TYPE USED	% CIRCLE END GUN ON	APPLICATION UNIFORMITY %	GUN ON			GUN OFF			TOTAL	
				POWER KW	TIME HR	ENERGY KW-HR	POWER KW	TIME HR	ENERGY KW-HR	ENERGY KW-HR	TIME HR
0.5	M	33	72.9	94.5	5.31	501.80	77.27	10.90	842.24	1344.04	16.14
		50	72.3	94.5	8.07	762.61	77.27	8.07	623.57	1386.18	16.14
		66	71.7	94.5	10.62	1003.59	77.27	5.30	409.53	1413.12	15.93
	V	33	68.8	94.5	5.31	501.80	128.04	10.90	1375.64	1877.44	16.18
		50	65.9	94.5	8.07	762.61	128.04	8.07	1033.23	1795.89	16.14
		66	63.2	94.5	10.62	1003.59	128.04	5.30	678.61	1682.22	15.93
	J	33	71.1	94.5	5.31	501.80	95.28	10.90	1038.55	1530.35	16.14
		50	69.5	94.5	8.07	762.61	95.28	8.07	768.91	1531.52	16.14
		66	68.0	94.5	10.62	1003.59	95.28	5.30	504.98	1508.57	15.93
1.0	M	33	72.9	94.5	10.65	1006.43	77.27	21.59	1668.26	2674.69	32.24
		50	72.3	94.5	16.14	1525.23	77.27	16.14	1247.14	2772.37	32.28
		66	71.7	94.5	21.30	2012.85	77.27	10.99	849.20	2862.05	32.29
	V	33	68.8	94.5	10.65	1006.43	128.04	21.59	2764.38	3770.81	32.24
		50	65.9	94.5	16.14	1525.23	128.04	16.14	2066.56	3571.79	32.28
		66	63.2	94.5	21.30	2012.85	128.04	10.99	1407.16	3420.01	32.29
	J	33	71.1	94.5	10.65	1006.43	95.28	21.59	2057.09	3063.52	32.24
		50	69.5	94.5	16.14	1525.23	95.28	16.14	1537.82	3063.05	32.28
		66	68.0	94.5	21.30	2012.85	95.28	10.99	1047.13	3059.98	32.29
1.5	M	33	72.9	94.5	15.99	1511.06	77.27	32.49	2510.50	4021.56	48.48
		50	72.3	94.5	24.22	2288.79	77.27	24.24	1873.02	4161.81	48.46
		66	71.7	94.5	31.97	3021.17	77.27	16.49	1274.18	4295.35	48.46
	V	33	68.8	94.5	15.99	1511.06	128.04	32.49	4160.02	5671.08	48.48
		50	65.9	94.5	24.22	2288.79	128.04	24.24	3099.86	5388.65	48.46
		66	63.2	94.5	31.97	3021.17	128.04	16.49	2111.38	5132.55	48.46
	J	33	71.1	94.5	15.99	1511.06	95.28	32.49	3095.65	4606.71	48.48
		50	69.5	94.5	24.22	2288.79	95.28	24.24	2309.59	4598.38	48.46
		66	68.0	94.5	31.97	3021.17	95.28	16.49	1571.17	4592.34	48.46
2.0	M	33	72.9	94.5	21.03	1987.33	77.27	43.26	3342.70	5330.03	64.19
		50	72.3	94.5	31.87	3011.72	77.27	32.17	2485.78	5497.50	64.04
		66	71.7	94.5	42.07	3975.62	77.27	21.99	1699.17	5674.79	64.04
	V	33	68.8	94.5	21.03	1987.33	128.04	43.26	5539.01	7526.34	64.19
		50	65.9	94.5	31.87	3011.72	128.04	32.17	4119.05	7130.77	64.04
		66	63.2	94.5	42.07	3975.62	128.04	21.99	2815.60	6791.22	64.04
	J	33	71.1	94.5	21.03	1987.33	95.28	43.26	4121.81	6109.14	64.19
		50	69.5	94.5	31.87	3011.72	95.28	32.17	3065.16	6076.88	64.04
		66	68.0	94.5	42.07	3975.62	95.28	21.99	2095.21	6070.83	64.04

Table 8. Energy and time required for irrigation using different pumps with the modification in the design.

WATER DEPTH (IN) (RUNOFF)	PUMP TYPE USED	% CIRCLE END GUN ON	APPLICATION UNIFORMITY %	GUN ON POWER KW	GUN ON TIME HR	GUN ON ENERGY KW-HR	GUN OFF POWER KW	GUN OFF TIME HR	GUN OFF ENERGY KW-HR	TOTAL ENERGY KW-HR	TOTAL TIME HR
0.5	H	33	76.4	94.5	5.31	501.80	94.1	7.73	727.39	1229.19	13.04
		50	77.6	94.5	8.05	760.73	94.1	5.77	542.96	1305.57	13.81
		66	78.8	94.5	10.62	1003.59	94.1	3.92	368.87	1372.46	14.54
	V	33	76.4	94.5	5.31	501.80	94.7	7.73	732.03	1233.83	13.04
		50	77.6	94.5	8.05	760.73	94.7	5.77	546.42	1309.03	13.81
		66	78.8	94.5	10.62	1003.59	94.7	3.92	371.22	1374.81	14.54
	J	33	76.4	94.5	5.31	501.80	95.9	7.73	741.31	1242.80	13.04
		50	77.6	94.5	8.05	760.73	95.9	5.77	553.34	1315.95	13.81
		66	78.8	94.5	10.62	1003.59	95.9	3.92	375.93	1379.52	14.54
1.0	H	33	76.4	94.5	10.65	1006.43	94.1	15.62	1469.84	2476.27	26.27
		50	77.6	94.5	16.14	1525.23	94.1	11.66	1097.21	2622.44	27.79
		66	78.8	94.5	21.30	2012.85	94.1	7.93	746.21	2759.06	29.23
	V	33	76.4	94.5	10.65	1006.43	94.7	15.62	1479.20	2485.63	26.27
		50	77.6	94.5	16.14	1525.23	94.7	11.66	1104.20	2629.43	27.79
		66	78.8	94.5	21.30	2012.85	94.7	7.93	750.97	2763.82	29.23
	J	33	76.4	94.5	10.65	1006.43	95.9	15.62	1497.95	2504.38	26.27
		50	77.6	94.5	16.14	1525.23	95.9	11.66	1118.19	2643.42	27.79
		66	78.8	94.5	21.30	2012.85	95.9	7.93	760.49	2773.34	29.23
1.5	H	33	76.4	94.5	15.99	1511.06	94.1	23.38	2200.06	3711.06	39.36
		50	77.6	94.5	24.22	2288.79	94.1	17.44	1641.10	3929.89	41.67
		66	78.8	94.5	31.97	3021.17	94.1	11.86	1116.03	4137.20	43.83
	V	33	76.4	94.5	15.99	1511.06	94.7	23.38	2214.09	3725.15	39.36
		50	77.6	94.5	24.22	2288.79	94.7	17.44	1651.57	3940.36	41.67
		66	78.8	94.5	31.97	3021.17	94.7	11.86	1123.14	4144.31	43.83
	J	33	76.4	94.5	15.99	1511.06	95.9	23.38	2242.14	3753.20	39.36
		50	77.6	94.5	24.22	2288.79	95.9	17.44	1672.50	3960.93	41.67
		66	78.8	94.5	31.97	3021.17	95.9	11.86	1137.37	4158.54	43.83
2.0	H	33	76.4	94.5	21.03	1987.34	94.1	37.59	2935.92	4923.25	52.24
		50	77.6	94.5	31.87	3011.72	94.1	28.04	2191.59	5203.25	55.15
		66	78.8	94.5	42.07	3975.62	94.1	19.09	1489.60	5465.22	57.90
	V	33	76.4	94.5	21.03	1987.34	94.7	30.51	2954.64	4941.97	52.24
		50	77.6	94.5	31.87	3011.72	94.7	22.73	2205.56	5217.28	55.15
		66	78.8	94.5	42.07	3975.62	94.7	15.56	1499.10	5474.72	57.90
	J	33	76.4	94.5	21.03	1987.34	95.9	34.44	2992.08	4979.41	52.24
		50	77.6	94.5	31.87	3011.72	95.9	25.69	2233.51	5245.41	55.15
		66	78.8	94.5	42.07	3975.62	95.9	17.49	1518.10	5493.72	57.90

Table 9. Energy and time savings with the modification of the center pivot system.

WATER DEPTH (M)	PUMP TYPE USED	SLOWER WITH CIRCLE (%)	TOTAL NOT MODIFIED: ENERGY KW-HR	TOTAL NOT MODIFIED: TIME HR	TOTAL MODIFIED: ENERGY KW-HR	TOTAL MODIFIED: TIME HR	CHANGE AFTER MODIFICATION OF THE SYSTEM: ENERGY KW-HR	ENERGY %	TIME HR	TIME %
0.5	H	33	1348.00	16.10	1229.10	13.00	-118.90	-8.95	-3.10	-19.21
		50	1386.18	16.10	1305.57	13.81	-80.61	-5.82	-2.33	-14.44
		66	1413.12	15.93	1372.46	14.54	-40.66	-2.88	-1.39	-8.73
	V	33	1877.44	16.10	1233.83	13.00	-643.61	-34.28	-3.10	-19.21
		50	1795.89	16.10	1309.03	13.81	-486.86	-27.11	-2.33	-14.44
		66	1682.22	15.93	1374.81	14.54	-307.41	-18.27	-1.39	-8.73
	J	33	1530.35	16.10	1294.65	13.00	-235.70	-15.40	-3.10	-19.21
		50	1531.52	16.14	1315.95	13.81	-215.57	-14.08	-2.33	-14.44
		66	1508.57	15.93	1379.52	14.54	-129.05	-8.55	-1.39	-8.73
1.0	H	33	2678.64	32.20	2476.27	26.27	-198.82	-7.42	-5.97	-18.52
		50	2772.37	32.28	2622.44	27.79	-149.93	-5.41	-4.49	-13.91
		66	2862.05	32.29	2759.06	29.23	-102.99	-3.60	-3.06	-9.48
	V	33	3770.81	32.20	2485.63	26.27	-1285.18	-34.08	-5.97	-18.52
		50	3571.79	32.28	2629.43	27.79	-942.36	-26.38	-4.49	-13.91
		66	3420.01	32.29	2763.82	29.23	-656.19	-19.19	-3.06	-9.48
	J	33	3060.52	32.20	2501.38	26.27	-559.14	-18.25	-5.97	-18.52
		50	3063.05	32.28	2643.42	27.79	-419.63	-13.70	-4.49	-13.91
		66	3059.98	32.29	2773.34	29.23	-286.64	-9.37	-3.06	-9.48
1.5	H	33	4021.96	48.48	3711.06	39.36	-310.90	-7.72	-9.12	-18.81
		50	4161.81	48.46	3929.89	41.67	-231.92	-5.57	-6.79	-14.01
		66	4295.35	48.46	4137.20	43.83	-158.15	-3.68	-4.63	-9.55
	V	33	5671.08	48.48	3725.15	39.36	-1945.93	-34.31	-9.12	-18.81
		50	5368.65	48.46	3940.38	41.67	-1428.28	-26.60	-6.79	-14.01
		66	5132.95	48.46	4144.31	43.83	-988.64	-19.25	-4.63	-9.55
	J	33	4606.71	48.48	3753.20	39.36	-853.51	-18.53	-9.12	-18.81
		50	4598.38	48.46	3960.93	41.67	-637.45	-13.86	-6.79	-14.01
		66	4592.34	48.46	4158.54	43.83	-433.80	-9.45	-4.63	-9.55
2.0	H	33	5330.03	64.19	4923.25	52.24	-406.78	-7.63	-11.95	-18.62
		50	5497.50	64.04	5203.31	55.15	-294.19	-5.35	-8.89	-13.88
		66	5674.79	64.04	5465.22	57.90	-209.57	-3.69	-6.14	-9.59
	V	33	7526.34	64.19	4941.97	52.24	-2584.37	-34.34	-11.95	-18.62
		50	7130.77	64.04	5217.28	55.15	-1913.49	-26.83	-8.89	-13.88
		66	6791.22	64.04	5414.72	57.90	-1376.50	-20.27	-6.14	-9.59
	J	33	6109.14	64.19	4979.41	52.24	-1129.73	-18.49	-11.95	-18.62
		50	6076.88	64.04	5245.23	55.15	-831.65	-13.69	-8.89	-13.88
		66	6070.83	64.04	5493.70	57.90	-577.13	-9.51	-6.14	-9.59

Table 10 summarizes the energy and time savings for different conditions. It is seen that the percentage of energy and time savings is independent of the depth of application of water per irrigation. The saving of time is the same for all the pumps because the timer setting of the unmodified system was fixed on the basis of application depth when the end gun is on. The timer setting in this case is not changed when the end gun is swithched off.

There is time and energy savings using the modified design for all pumps. Time savings vary from a low of 9% to a high of 19%. There are less savings in time and energy with the increase in the end gun on percentage coverage.

Conservation of energy increases with the increase in the pump curve steepness. There is savings of upto 34% in the energy cost for the system using pump V. The energy savings for the flat pump curve (pump H) is about 8% with the end gun covering 33% of the circle. Considering pump J, the energy and time savings for the end gun covering 33% of the circle are about 18% and 19% respectively.

This simulation model shows that any center pivot irrigation system can be modified to save time and/or energy. The capital cost in the installation of the pump can also be reduced when the pump has a very steep pump curve (e.g. reduction in pump capacity for the steep pump curve, pump V, by 30 hp with the modification in the design).

The changes in total energy and time for the season with the modification of the design of the center pivot system to irrigate corn, soybean, and potatoes are shown in Table 11. The unit cost of electrical

Table 10. Change in the energy and time requirements with the modification of the design of the center pivot system for different pumps.

PUMP TYPE	APPLICATION DEPTH	END GUN ON 33% CIRCLE				END GUN ON 50% CIRCLE				END GUN ON 66% CIRCLE			
		ENERGY VALUE	%	TIME VALUE	%	ENERGY VALUE	%	TIME VALUE	%	ENERGY VALUE	%	TIME VALUE	%
H	0.5	-114.9	-9	-3.1	-19	-80.6	-6	-2.3	-14	-40.7	-3	-1.4	-9
	1.0	-198.4	-7	-6.0	-19	-149.9	-5	-4.5	-14	-103.0	-4	-3.1	-9
	1.5	-310.5	-8	-9.1	-19	-231.9	-6	-6.8	-14	-158.1	-4	-4.6	-10
	1.9	-406.8	-8	-12.0	-19	-294.2	-5	-8.9	-14	-209.6	-4	-6.1	-10
V	0.5	-643.6	-34	-3.1	-19	-486.9	-27	-2.3	-14	-307.4	-18	-1.4	-9
	1.0	-1285.2	-34	-6.0	-19	-942.4	-26	-4.5	-14	-656.2	-19	-3.1	-9
	1.5	-1945.9	-34	-9.1	-19	-1448.3	-27	-6.8	-14	-988.2	-19	-4.6	-10
	1.9	-2584.7	-34	-12.0	-19	-1913.5	-27	-8.9	-14	-1376.5	-20	-6.1	-10
J	0.5	-287.6	-19	-3.1	-19	-215.6	-14	-2.3	-14	-129.0	-9	-1.4	-9
	1.0	-559.1	-18	-6.0	-19	-419.6	-14	-4.5	-14	-286.6	-9	-3.1	-9
	1.5	-853.5	-19	-9.1	-19	-637.4	-14	-6.8	-14	-433.8	-9	-4.6	-10
	2.0	-1129.7	-18	-12.0	-19	-831.6	-14	-8.9	-14	-577.1	-10	-6.1	-10

Table 11. The total energy and time changes to irrigate three crops for the whole season after the modification of the design of the center pivot system.

CROP NAME	TOTAL WATER (IN)	PUMP TYPE USED	%CIRCLE WITH END GUN ON	APPLICATION DEPTH PER IRRIGATION 0.5 inches			1.0 inches			1.5 inches			2.0 inches		
				TIME	KW-H	$	TIME	KW-H	$	TIME	KW-H	$	TIME	KW-H	$
CORN	20	N	33	-120	-4598	-460	-119	-3968	-397	-122	-4180	-418	-126	-4282	-428
			50	-93	-3220	-322	-90	-2999	-300	-91	-3092	-309	-94	-3097	-310
			66	-56	-1626	-163	-61	-2060	-206	-62	-2109	-211	-65	-2206	-221
		V	33	-120	-25784	-2578	-119	-25704	-2570	-122	-25946	-2595	-126	-27204	-2720
			50	-93	-19470	-1947	-90	-18847	-1885	-91	-19311	-1931	-94	-20182	-2018
			66	-56	-12296	-1230	-61	-13124	-1312	-62	-13177	-1318	-65	-14489	-1449
		J	33	-120	-11504	-1150	-119	-11183	-1118	-122	-11380	-1138	-126	-11892	-1189
			50	-93	-8623	-862	-90	-8393	-839	-91	-8499	-850	-94	-8754	-875
			66	-56	-5162	-516	-61	-5733	-573	-62	-5784	-578	-65	-6075	-608
POTATOES	15	N	33	-93	-3448	-345	-90	-2976	-298	-91	-3105	-311	-98	-3211	-321
			50	-70	-2418	-242	-67	-2249	-225	-68	-2319	-232	-70	-2323	-232
			66	-42	-1220	-122	-46	-1545	-155	-46	-1581	-158	-48	-1654	-165
		V	33	-93	-19308	-1931	-90	-19278	-1928	-91	-19459	-1946	-94	-20403	-2040
			50	-70	-18606	-1861	-67	-18135	-1814	-68	-14483	-1448	-70	-15107	-1511
			66	-42	-9222	-922	-46	-9843	-984	-46	-9882	-988	-48	-10867	-1087
		J	33	-93	-8628	-863	-90	-8387	-839	-91	-8535	-854	-94	-8919	-892
			50	-70	-6467	-647	-67	-6294	-629	-68	-6374	-637	-70	-6566	-657
			66	-42	-3571	-357	-46	-4299	-430	-46	-4338	-434	-48	-4556	-456
SOYBEANS	25	N	33	-155	-5747	-575	-149	-4960	-496	-152	-5175	-518	-157	-5352	-535
			50	-116	-4031	-403	-112	-3748	-375	-113	-3865	-387	-117	-3871	-387
			66	-70	-2033	-203	-77	-2575	-258	-77	-2636	-264	-81	-2757	-276
		V	33	-155	-32181	-3218	-149	-32130	-3213	-152	-32432	-3243	-157	-34005	-3400
			50	-116	-24343	-2434	-112	-23559	-2356	-113	-24138	-2414	-117	-25178	-2518
			66	-70	-15370	-1537	-77	-16405	-1640	-77	-16471	-1647	-81	-18112	-1811
		J	33	-155	-14380	-1438	-149	-13979	-1398	-152	-14225	-1423	-157	-14865	-1486
			50	-116	-10779	-1078	-112	-10491	-1049	-113	-10624	-1062	-117	-10983	-1098
			66	-70	-6452	-645	-77	-7166	-717	-77	-7230	-723	-81	-7594	-759

power is taken as 10 cents/Kw-hr. The dollar value is only for the energy and not time. Consideration the irrigation of corn, Table 11 shows that it is possible to save upto $ 2700.00 per season with the modification in the design of the center pivot system using pump V. The maximum time saving is about 124 hours. For the system used in Mr. Bement's farm (pump J), the possible saving in energy cost is in the range of $1100.00. The maximum possible time saving is about 124 hours. Considering a capital investment of $2000 to modify the existing system, the pay back period for the 50% circle-with-end gun-on system is about two years. Besides this, there is a saving in time (90 hours) per irrigation season which would increase the life of the pump and irrigation system as a whole . As discussed earlier, the other important and major improvement will be the increase in the application uniformity and potential yield. When the potential yield increase is combined to the annual possible savings of energy, the possible savings increases to more than $2500.00 and the payback period for the modification is less than one season.

D. Summary

The result and discussion section have demonstrated the possibility of energy and time conservation with the modification in the design of the center pivot irrigation system using auxiliary sprinklers which operate when the end gun is switched off. The range of energy savings depended on the type of pump used in the system. The time savings was independent of the type of pump used. Energy and time savings were independent of the irrigation interval. Besides time and energy, the capital investment could be significantly reduced with steep pump

curves. There could be a significant improvement in the application uniformity with the modification in the design, especially for steep pump curves, as a result of which the yield would also increase.

V. CONCLUSION AND RECOMMENDATIONS

The objectives of the proposed research have been addressed in full. Four computer programs were developed for the hydraulic and field performance analysis of the center pivot irrigation system. The possibility of energy and time savings with the modification in the design of the center pivot system were determined using these computer models.

The specific conclusion of the research are:

1. There will be energy savings when the center pivot irrigation system is modified to include auxiliary sprinklers.

a. The range of possible energy savings with the end gun covering 33% of the circle is between 8% and 34% depending upon the steepness of the pump curve. Energy savings increase with the steepness of the pump curve.

b. The required pump capacity can be significantly reduced for pumps with very steep pump curves.

2. The application uniformity will improve significantly with the modification in the design of the center pivot irrigation system. The

application uniformity increases upto 11% depending upon the steepness of the pump curve. This will increase the potential yield of crop upto 12%.

3. The irrigation time saving with the modification in the design of the system ranges between 9% to 19% depending upon the percentage of circle covered with the end gun on. The savings in time is not dependent on the type of the pump used.

The overall conclusion of the research is:

The modification in the design of the center pivot irrigation system will save time and energy and will increase application uniformity and yield, with the possible return in investment in the first season itself.

Recommendation for further research include:

1. Determine the energy and time savings that is possible by varying the timer setting between the end gun on and end gun off conditions without introducing the auxiliary sprinklers.

2. Study the contribution of the change in the pump curve efficiency and dual timer setting independent of each other.

APPENDIX A

SOURCE CODE OF THE HYDRAULIC NETWORK ANALYSIS MODEL "NETWORK"

```
REM ************************************************************************
REM *                          PROGRAM NETWORK                              *
REM *                                                                       *
REM *THIS PROGRAM ANALYSES THE CENTER PIVOT SYSTEM NETWORK STARTING FROM*
REM *   THE PIVOT POINT TO THE END SPRINKLER. THE INPUT IS THE PIVOT        *
REM *  PRESSURE, LENGTH OF THE SYSTEM, DIAMETER OF THE PIPE, AND THE        *
REM *                    SPRINKLERS CONFIGURATION                           *
REM *                                                                       *
REM *                     WRITTEN IN TURBO-BASIC                            *
REM ************************************************************************
REM INPUT FILE : GENDATA.DAT
REM OUTPUT FILE :FIELD.DAT                 ---- CAN BE SUPRESSED
                 DETAIL.DAT                ---- CAN BE SUPRESSED
                 MODEL.DAT
   MV%=80
   NV%=20
   DIM PRES(MV%),SPACING(MV%),PLAT(MV%,NV%),RADCOV(MV%,NV%)
   DIM QSPR(MV%,NV%),SIZE(MV%),LATEND(20),LATSUM(MV%),QLAT(MV%),H(MV%)
   DIM Z(MV%),P(MV%),R(MV%),CP(MV%),SAMEDIA(20),LATDIA(MV%),AREALAT(MV%)
   DIM VELLAT(MV%),REMO(MV%),FRICT(MV%),CONSTR(MV%),ELEV(MV%),KC(MV%)
   DIM CSP(MV%),KMAIN(MV%),KBRANCH(MV%),CPC(MV%),AREARIS(MV%)
   DIM DIARISER(MV%),ESP(MV%),RC(MV%,MV%+1),QRIS(MV%),G(MV%),
   DIM FRICTION(MV%),IFLG(MV%),OLDRC(MV%,MV+1),EXPO(26),LIMIT(26),KCC(26)
   DIM EXPON(MV%),FRSTRC(MV%,MV%+1),EBYD(MV%),Q(MV%)

   COMP=2
   WHILE COMP=2
   CLS:INPUT"DO YOU WANT TO SUPRESS THE OUTPUT FILE ? (Y/N) ",COMPR$(1)
   IF COMPR$(1)="Y" OR COMPR$(1)="y" THEN COMP = 0
   IF COMPR$(1)="N" OR COMPR$(1)="n" THEN COMP = 1
   WEND

   FIRST=2
   WHILE FIRST=2
   INPUT"DO YOU WANT PRESSURE AT ALL THE SPRINKLER NODES? Y/N ",FRST$(1)
   IF FRST$(1)="Y" OR FRST$(1)="y" THEN FIRST = 0
   IF FRST$(1)="N" OR FRST$(1)="n" THEN FIRST = 1
   WEND

   CHANGE=4
   WHILE CHANGE=4
   INPUT"RUN BOTH THE END GUN ON AND END GUN OFF CONDITION :(Y/N)",CH$(1)
   IF CH$(1)="Y" OR CH$(1)="y" THEN CHANGE = 0
   IF CH$(1)="N" OR CH$(1)="n" THEN
      CHANGE = 3
      WHILE CHANGE=3
      INPUT"RUN END GUN ON CONDITION :(Y/N)",CHH$(1)
      IF CHH$(1)="Y" OR CHH$(1)="y" THEN CHANGE = 2
      IF CHH$(1)="N" OR CHH$(1)="n" THEN CHANGE = 1
      WEND
```

```
    END IF
    WEND

    INPUT"ALLOWABLE ERROR IN SIMULATE PRESSURE HEAD IN FEET (DEFAULT IS 1)"_
         ,ALLERR
    IF ALLERR=0 THEN ALLERR=1
    NORUN = 1
    CHEKSPAC = 0
    ITER=0
    OFFGUN = 0

    INPUT"NUMBERS OF RUN TO BE MADE = ",RUNN
    OPEN "I",#9,"GENDAT.DAT"
    OPEN "O",#10,"FIELD.DAT"
    OPEN "O",#12,"DETAIL.DAT"
    OPEN "O",#14,"MODEL.DAT"

REM ************************************************************************
REM INPUT PIVOT PSI, TOTAL LENGTH (FT), DISTANCE TO LAST TOWER (FT)
REM       NUMBER OF SPRINKLERS, AND ESTIMATED END SPRINKLER PSI
REM ************************************************************************
    INPUT #9,PSUM,LATLEN,S,SPRINKLE,OPPRES
    IF RUNN=1 THEN INPUT"PRESSURE AT THE PIVOT=",PSUM:OPPRES=PSUM-10
    PE=PSUM:OP=OPPRES
    PRINT#14, CHR$(18);:PRINT#14, CHR$(27) "E";:PRINT#14, CHR$(27) "G";
    PRINT#12, CHR$(18);:PRINT#12, CHR$(27) "E";:PRINT#12, CHR$(27) "G";
    PRINT#14,TAB(25)"DATA AND RESULTS":PRINT#14,:PRINT#14,:PRINT#14,
    PRINT#14,TAB(12)"No of sprinklers in the system= ";sprinkle
    PRINT#14,TAB(12)"Total length of lateral= ";latlen;" ft"
    PRINT#14,TAB(12)"Distance to last tower= ";s;" ft"
    PRINT#14,TAB(12)"Maximum Allowable error in calculating pressure";_
           Allerr;" ft
    PRINT#14,:PRINT#14,

    ELEMENT = SPRINKLE*2
    NNODE = ELEMENT+1
    HSUM = 2.3114*PSUM
    H(1)=HSUM:P(1)=PSUM:OPHEAD=OPPRES*2.3114

   CALL DIFFSPRINKLER(PLAT(),RADCOV(),QSPR(),SPACING(),CHEKSPAC,ELEMENT,IFLG())
    IF CHEKSPAC <> LATLEN THEN
10     CALL CHECKLENGTH(CHEKSPAC,LATLEN)
    END IF

    IF CHANGE = 1 THEN
       ELEMENT = ELEMENT-2
       NNODE = NNODE-2
       SFLG=1
    END IF
   CALL SPRINKLERCOEFF(PLAT(),QSPR(),SPACING(),ELEMENT,IFLG(),KC(),EXPON(),1)
```

```
REM***************************************************************************
REM**************INPUT THE DIAMETER OF THE LATERAL LINE*******************
REM***************************************************************************
20 CLS:INPUT"Is the diameter of the lateral line constant throuout? (Y/N)",
           DiaCon$
   GOTO 40
30  INPUT DIACON$
40  IF DIACON$ = "Y" OR DIACON$ = "y" then
       INPUT"Diameter of the lateral line pipe in inches = ",SIZE
     ELSEIF DIACON$ = "N"  or DIACON$ = "n" then
       CALL PipeDiameter(size(),samedia())
     ELSE
       PRINT"The only possible choice is (Y)es or (N)o"
       GOTO 30
   END IF

   SUMSPACE=0
   J=1
   PRINT#14,:PRINT#14,:
   PRINT#14,TAB(12) "DIAMETER        DISTANCE FROM PIVOT(ft)"
   PRINT#14,TAB(12) "(inches)            FROM         TO"
   PRINT#14,TAB(12) "--------         ---------   --------"
   IF DIACON$ = "Y" or DIACON$ = "y" THEN
     FOR I =  1 TO ELEMENT STEP 2
        LATDIA(1) = SIZE/12
    NEXT I
     PRINT#14,TAB(12) USING"  ##.##                    0        ####.#";_
                             SIZE,LATLEN
    ELSE
     FOR I = 1 TO ELEMENT
        IF I/2<>INT(I/2) THEN
           SUMSPACE = SPACING(I) + SUMSPACE
           LATSUM(1) = SUMSPACE
           IF SUMSPACE > SAMEDIA(j) THEN
              J = J + 1
              IF J > 1 THEN
                 PRINT#14,TAB(12) USING_
                          "  ##.##                ####.#     ####.#";_
                             SIZE(J),SAMEDIA(J-1),SAMEDIA(J)
              END IF
           END IF
           LATDIA(1) = SIZE(j)/12
           IF I = 1 THEN
              PRINT#14,TAB(12) USING"  ##.##                    0 ";_
                          SIZE(J),SAMEDIA(1)
              GOTO 45
           END IF
        END IF
45     NEXT
  END IF
```

```
REM*****************************************************************************
REM************Relative Roughness of all the elements******************
REM*****************************************************************************
    INPUT"Roughness of the pipe in inches (default is 0.0006) = ",E
    IF E = 0 THEN E = 0.0006
    PRINT#14,:PRINT#14,TAB(12) USING"PIPE ROUGHNESS=#.######inches";E
    FOR I = 1 TO ELEMENT
         IF I/2 <> INT(I/2) THEN
            EBYD(I) = E / (LATDIA(I)*12)
         END IF
    NEXT

REM*****************************************************************************
REM********INCLUDE THE ELEVATION AT DIFFERENT POINTS IN THE FIELD*******
REM*****************************************************************************
50 INPUT"Is the field assumed to be plain, i.e. negligible slope? Y/N ",Z$
    GOTO 70
60  LOCATE 16,25:INPUT"Please press 'Y' or 'N' ", Z$
70  IF Z$ = "Y" OR  Z$ = "y" THEN
       PRINT#14,TAB(12)"SLOPE OF THE FIELD IS NEGLIGIBLE"
       FOR I = 1 TO NNODE
           Z(I) = 0
       NEXT I
      ELSEIF Z$ = "N" OR  Z$ = "n" THEN
       CALL ELEVATION(NNODE,SPACING(),Z())
     ELSE
       GOTO 60
    END IF

REM*****************************************************************************
REM***************DIAMETER AND AREA OF THE  RISER ********************
REM*****************************************************************************
    INPUT"Diameter of the risers (excluding end sprinkler) in inches: ",_
          DIARISER
    FOR I = 1 TO ELEMENT
         IF I/2 = INT(I/2)THEN
            AREARIS(I) = (3.14/4)*((DIARISER/12)^2)
            DIARISER(I)=DIARISER/12
         END IF
    NEXT I
    PRINT#14,TAB(12) USING"RISER DIAMETER = ##.####  inches";DIARISER
    INPUT"Diameter of the end sprinkler riser: ",DIARISE:CLS



    PRINT#14,TAB(12) USING_
                    "END GUN RISER DIAMETER = ##.####  inches";DIARISE
    AREARIS(ELEMENT)= (3.14/4)*((DIARISE/12)^2)
    DIARISER(ELEMENT) = DIARISE/12
```

```
REM****************************************************************************
REM**************** INITIALIZE THE PRESSURE AT THE NODES *****************
REM*****************AND DISCHARGE FROM THE SPRINKLERS******************
REM****************************************************************************
80  HEADLOSS= PSUM-OPPRES:sumlen=0

    FOR I = 1 TO ELEMENT
        IF I/2 = INT(I/2)THEN
           SUMLEN = SPACING(I-1) +SUMLEN
           X=SUMLEN/LATLEN

REM****DISTFACT IS CALCULATED USING THE BETA DISTRIBUTION FUNCTION****

           DISTFACT = 1 - (15/8)*(X- (2*(X^3)/3) + ((X^5)/5))
           P(I) = HEADLOSS*DISTFACT + OPPRES
           IF P(I-2)-P(I)=0 THEN P(I) = P(I-2) - 0.0001
           H(I)= P(I)*2.3114
           P(I+1) = P(I)-0.5 : H(I+1)=P(I+1)*2.3114
           QRIS(I) = KC(I)*H(I+1)^EXPON(I)
        END IF
    NEXT I

REM****************************************************************************
REM***CALCULATE THE FLOW IN THE LATERAL LINE TO CALCULATE FRICTION LOSS**
REM****************************************************************************
    QLAT(ELEMENT) = 0
    FOR J =1 TO ELEMENT
        IF I/2 <>INT(I/2) THEN
           IF I=1 THEN
              QLAT(ELEMENT-J)=QRIS(ELEMENT)
            ELSE
              QLAT(ELEMENT-J)=QRIS(ELEMENT-J+1) + QLAT(ELEMENT-J+2)
           END IF
        END IF
    NEXT J

    IF COMP = 1 THEN
       IF ITER=0 THEN
          PRINT#12,"           INITIALISED DISCHARGE"
          PRINT#12,"           ELEMENT       DISCHARGE"
          PRINT#12,"           -------       ---------"
          FOR I=1 TO ELEMENT
              IF I/2<>INT(I/2) THEN
                 PRINT#12,USING"        ###          ###.##";I,QLAT(I)
               ELSE
                 PRINT#12,USING"        ###          ###.##";I,QRIS(I)
              END IF
          NEXT
       END IF
    END IF
```

```
REM***********************************************************************
REM*********VELOCITY,REYNOLD NO,FRICTION LOSS IN THE LATERAL LINE**********
REM***********************************************************************
REM KINEMATIC VISCOSITY = 0.00001059 CU FT / SEC AT 68DEG FAR (20 DEG C)
    TOTFRIC = 0
90  FOR I = 1 TO element
        IF I/2<>INT(I/2)THEN
           AREALAT(I) = (3.14/4)*(LATDIA(I)^2)
           VELLAT(I)=QLAT(I)/(448.8*AREALAT(I))
           RENO(I) = (VELLAT(I)*LATDIA(I))/(0.00001059)
           FRICT(I) =1.325 * (LOG(0.27*EBYD(I) + _
                                        5.72*((1/RENO(I))^0.9))^(-2))
           R(I) = 8*FRICT(I)*SPACING(I) / _
                               32.2*(448.8^2)*(3.14159^2)*((LATDIA(I))^5))
           FRICTION(I)=R(I)*((QLAT(I))^2)
        END IF
        TOTFRIC=FRICTION(I)+TOTFRIC

    NEXT I

REM**********************************************************************
REM******DETERMINE COEFFICIENT TO BUILD THE GLOBAL STIFFNESS MATRIX*****
REM**********************************************************************
REM VALUE OF m FOR THE DARCY'S METHOD = 2
    M = 2 .

REM*********************DETERMINE PIPE COEFFICIENT**********************
110 FOR I = 1 TO ELEMENT
        IF I/2<>INT(I/2) THEN
           CP(I) = 0
           IF I = 1 THEN
              NUMER = (Z(1)+H(1) - Z(2)-H(2))^((1-M)/M)
              GOTO 120
           END IF
           DELTAh=Z(I-1)+H(I-1)-Z(I+1)-H(I+1)




           IF DELTAh =0  THEN DELTAh = 0.0000001
           NUMER = DELTAh^((1-M)/M)
120        CONST = (R(I))^(1/M)
           CP(I) = NUMER/CONST
        END IF
    NEXT I

REM*****************DETERMINRE SPRINKLER COEFFICIENT********************
    FOR I =1 TO ELEMENT
        IF I/2 = INT(I/2) THEN
           CSP(I) = (Kc(I)) /((H(I+1))^(1-EXPON(I)))
```

```
        END IF
    NEXT I

REM**********CALCULATE THE TEE AND ELBOW LOSS COEFFICIENT KPC**********
    KCP = 1
    IF FLAGG=0 THEN
       PRINT#14,TAB(12) USING"K FOR TEE AND ELBOW COMPONENTS = ##.##";KCP
       FLAGG=1
    END IF
    FOR I = 1 TO ELEMENT




        IF I/2=INT(I/2) THEN
           KSP(I)=(8*KCP)/(32.2*(3.1412^2)*(DIARISER(I)^4)*(448.8^2))
           CPC(I)=((H(I)-H(I+1))^-0.5)/(KSP(I)^0.5)
        END IF
    NEXT I

REM*************************************************************************
REM****************DEVELOP GLOBAL STIFFNESS MATRIX**************************
REM*************************************************************************
    ROW=NNODE
    COL=NNODE+1

    LOCATE 6,23:PRINT"Building global stiffness matrix"
    LOCATE 7,30:PRINT"***Please Wait***"
    FOR R = 1 TO ROW
        G(R) = 0
        RC(R,COL)=G(R)
        OLDRC(R,COL)=H(R)
        IF ITER=0 THEN FRSTRC(R,COL)=H(R)
        FOR C = 1 TO col
            RC(R,C) = 0
            RC(C,R) = 0
        NEXT C
    NEXT R

    FOR I=1 TO ELEMENT
        IF I/2 <> INT(I/2) THEN
           IF I=1 THEN
              RC(1,1) = CP(1)
              RC(1,2) = -CP(1)
              RC(2,1) = -CP(1)
              RC(2,2) = CP(1)
              G(1)=CP(1)*(Z(2)-Z(1)) + G(I)
              G(2)=-CP(1)*(Z(2)-Z(1)) + G(I)
             ELSE
```

```
            RC(I-1,I-1)= CP(I) + CPC(I) + RC(I-1,I-1)
            RC(I-1,I+1)=-CP(I) - CPC(I) + RC(I-1,I+1)
            RC(I+1,I-1)=-CP(I) - CPC(I) + RC(I+1,I-1)
            RC(I+1,I+1)= CP(I) + CPC(I) + RC(I+1,I+1)
            G(I-1) = CP(I)*(Z(I+1)-Z(I-1)) + G(I-1)
            G(I+1) =-CP(I)*(Z(I+1)-Z(I-1)) + G(I+1)
         END IF
       ELSE
         RC(I,I)     = CPC(I) + RC(I,I)
         RC(I,I+1)   =-CPC(I) + RC(I,I+1)
         RC(I+1,I)   =-CPC(I) + RC(I+1,I)
         RC(I+1,I+1)= CPC(I) + CSP(I) +RC(I+1,I+1)
      END IF
   NEXT I
   LOCATE 6,23:PRINT"                                  "
   LOCATE 7,30:PRINT"                    "


REM************INCLUDE THE BOUNDARY CONDITION IN THE NETWORK************
RC(1,1)=1
RC(1,COL)=HSUM
FOR I = 2 TO ROW
   RC(1,I) = 0
NEXT I

REM*********************************************************************
REM**********GAUSSIAN ELIMINATION METHOD TO SOLVE FOR HEAD**************
REM*********************************************************************
   IF ITER = 0 THEN
      FOR I=0 TO ITR
          LOCATE 13+I,31:PRINT"                    "
      NEXT I
   END IF
  LOCATE 11,11:PRINT"NO OF EQUATIONS ";ROW
  LOCATE 11,47:PRINT"SOLVING EQUATION "
  LOCATE 13+ITER,31:print"ITERATION NO ";iter
  LOCATE 10,30:PRINT"***Please Wait***"

  IF ITER = 0 THEN
     IF CHANGE = 1 THEN
        LOCATE 13,68:PRINT"END GUN OFF"
        LOCATE 14,68:PRINT"RUN NO  ";NORUN
        IF  CHANGE=1 AND  SFLG<>1 THEN LOCATE 15,1:PRINT"RUN COMPLETE"
       ELSE
        LOCATE 13,1:PRINT"END GUN ON"
        LOCATE 14,1:PRINT"RUN NO ";NORUN
    END IF
 END IF
```

```
   FOR L = 1 TO ROW
       LOCATE 11,64:PRINT L
       PP=RC(L,L)
       FOR J = 1 TO COL
           RC(L,J)=RC(L,J)/PP
       NEXT J
       FOR K = 1 TO ROW
           PP=RC(K,L)
           IF L-K=0 OR PP=0 THEN GOTO 130
           FOR J=1 TO COL
               RC(K,J) = RC(K,J) - PP*RC(L,J)
           NEXT J
130    NEXT K
    NEXT L
    ITR = ITER

REM************************************************************************
REM*********ITERATION NO AND IF CONDITION FOR MORE ITERATIONS*************
REM************************************************************************
    ITERFLAG = 1
    FOR I = 1 TO ROW
        IF ABS(RC(I,COL)-OLDRC(I,COL))>ALLERR THEN
           ITERFLAG = 0
        END IF
    NEXT
    FOR I = 1 TO ROW
        IF ITERFLAG = 0 THEN
           OLDRC(I,col) = RC(I,col)
        END IF
    NEXT I

REM************************************************************************
REM**********CALCULATION OF DISCHARGE FROM THE SPRINKLERS*****************
REM************************************************************************
    FOR I=1 TO ROW
        H(I)=RC(I,COL)
        P(I)=H(I)/2.3114
        IF I/2=INT(I/2)THEN
           QRIS(I)=KC(I)*(H(I)^EXPON(I))
        END IF
    NEXT I

REM*********CALCULATION OF DISCHARGE IN THE LATERAL ELEMENT*************
    QLAT(ROW)=0
    FOR I=1 TO ELEMENT
        K = ELEMENT-I+1
        IF K/2 <> INT(K/2) THEN
           QLAT(K) = QRIS(K+1)+QLAT(K+2)
        END IF
    NEXT I
```

```
    ITER=ITER+1
    IF ITERFLAG = 0 THEN GOTO 90
    FOR I = 1 TO ROW
        IF I/2=INT(I/2) THEN
           Q(I)=QRIS(I)
          ELSE
           Q(I)=QLAT(I)
        END IF
    NEXT I

REM*****************************************************************
REM***PRINT PRESSURE AT THE NODES AND DISCHARGE FROM THE SPRINKLERS*****
REM*****************************************************************
    IF FIRST = 0 THEN
       PRINT#12,"TOTAL ITERATION = ";ITER:print#12,
       PRINT#12, chr$(15);
       PRINT#12,"                            HEAD(FT)
       PRINT#12,"NODE        INITIAL                  FINAL        DIFFERNECE
       PRINT#12," NO    (ft)    (psi)        (ft)    (psi)   (ft)      %
       PRINT#12,"----  ---------------      --------------   ----------
       FOR I= 1 TO ROW
           DIFF=100*((FRSTRC(I,COL)-H(I))/FRSTRC(I,COL))
           PRINT#12,USING _
           "###   ###.##  ###.###     ###.###  ###.## ##.##  ##.#
           I,FRSTRC(I,COL),frstrc(i,col)/2.3114,H(I),h(I)/2.3114,DIFF,_
           (diff*100)/(frstrc(i,col)),I,Q(I)
       NEXT I

REM*******************************************************************
REM******WRITE RESULTS IN THE DATA FILE TO BE USED FOR IRRIGATION*********
REM*********************PERFORMANCE EVALUATION**************************
       FOR I=1 TO ELEMENT
           PRINT#10,USING"##,###.###,####.###";I,P(I);H(I)
           IF I/2=INT(I/2)THEN
              IFLG=IFLG(I):Q=QRIS(I)
              CALL INTERPOLATION(QSPR( ),RADCOV( ),I,IFLG,Q,SOLU)
              PRINT#10,USING"###.###,###.###";QRIS(I),SOLU
             ELSE
              PRINT#10,USING"####.###,###.##";QLAT(I),SPACING(I)
           END IF
       NEXT
    END IF
REM****************** THE SUMMARY OF THE RESULTS**********************
 IF COMP = 1 THEN
PRINT#12,_
"EL LATDIA  AREA    QLAT   VELOCITY REYNOLD FRIC(f)    R     H LOSS TLOSS"
PRINT#12,_                                                                "
"-- ------ ------ -------- -------- ------- ------  -------- ------ ------"
FOR I=1 TO ELEMENT
    PRINT#12, USING_
```

```
"## ##.## ###.## ####.# ##.## ######## #.#### ##.# ##.##### ##.## ##";-
 I,LATDIA(I),AREALAT(I),QLAT(I),VELLAT(I),RENO(I),FRICT(I),R(I),FRICTI(I),-
 TOTFRIC
NEXT
PRINT#12,:PRINT#12,:PRINT#12,
PRINT#12," NODE    HEAD(ft)  HEAD(PSI)    ELEV     R(I)     LATDIA""
PRINT#12," ----    --------  ---------    -----  -------    ------ "
      FOR I =1 TO NNODE
          PRINT#12, USING_
      " ###       ###.#####    ###.#####    ##.##   ##.#######   ##.##";_
        I,H(I),H(I)/2.3114,Z(I),R(I),LATDIA(I)
      NEXT I
PRINT#12,:PRINT#12,:PRINT#12,
PRINT#12,"ELEM NODE    DISC    FRIC       CSP        CPC        CP     "
PRINT#12,"---- ----    ----    ----       ---        ---        ----   "
      FOR I= 1 TO NNODE
          IF I=1 THEN PRINT#10,USING_
 " ##  ## ##   ###.#   ##.##             ####.###   ####.###   ###.# ###";-
  1,1,2,QLAT(1),FRICTION(1),CPC(1),CP(1),H(1),H(2)
          IF I>1 THEN
             IF I/2=INT(I/2) THEN
                PRINT#12,USING_
 " ##  ## ##   ###.#         ####.###   ####.###               ###.# ###";-
               I,I,I+1,QRIS(I),CSP(I),CPC(I),H(I),H(I+1)
               ELSE
               PRINT#12,USING_
 " ##  ## ##   ###.#   ##.##             ####.###   ####.###   ###.# ###";-
               I,I-1,I+1,QLAT(I),FRICTION(I),CPC(I),CP(I),H(I-1),H(I+2)
             END IF
          END IF
      NEXT I
   END IF

   IF RUNN=1 THEN GOTO 140
   IF OFFGUN=0 THEN ENDFLO=QRIS(ELEMENT)
   IF CHANGE=1 THEN ENDFLO=0
   ITERR(NORUN)=ITER : PSUMR(2,NORUN)=PSUM : HSUMR(2,NORUN)=PSUM*2.3114
   PENDR(NORUN)=P(ELEMENT) : QENDR(NORUN)=ENDFLO :
   HENDR(NORUN)=PENDR(NORUN)*2.3114 : QSUMR(2,NORUN)=QLAT(1) :
   PDROPR(NORUN)=PSUM-P(ELEMENT) : HDROPR(NORUN)=PDROPR(NORUN)*2.3114
   QEBYQP(NORUN)=100*(QENDR(NORUN)/QSUMR(2,NORUN))


REM*********************************************************************
REM***********DIFFERENT CONDITION OF PRESSURE AND FLOW*******************
REM********************** FOR NEXT RUN***********************************
140  INK$(1)="Y"
     IF NORUN=RUNN AND (CHANGE=1 OR CHANGE=2) THEN INK$(1)="N"
     IF INK$(1)="Y" then
        ENDS$(1)="Y"
```

```
        IF (NORUN=RUNN AND CHANGE=0) OR CHANGE=1 THEN ENDS$(1)="N"
        IF CHANGE = 2 THEN ENDS$(1)="Y"
        IF CHANGE = 0 AND ENDS$(1)="N" THEN GOTO 160
150     NORUN = NORUN + 1
        ITER=0
        PSUM1=PSUM+5
        OPPRES=4+P(ELEMENT)
        OPHEAD=OPPRES*2.3114:P(NNODE)=OPPRES:H(ELEMENT)=OPHEAD
        PSUM = PSUM1 :HSUM= PSUM*2.3114 :P(1)=PSUM:H(1)=HSUM
        IF CHANGE=1 OR OFFGUN = 1 THEN
           NNODE= NNODE+2
           ELEMENT = ELEMENT+2
           LATLEN = LATLEN + SPACING(ELEMENT-1)
        END IF
        IF ENDS$(1)="Y" THEN GOTO 80
        LATLEN = LATLEN - SPACING(ELEMENT-1)
        IF OFFGUN=0 THEN
           NORUN=1
           PSUM = PE :HSUM= PSUM*2.3114 :P(1)=PSUM:H(1)=HSUM
           OPPRES=OP:OPHEAD=OPPRES*2.3114:H(ELEMENT)=OPHEAD
           P(ELEMENT)=OPPRES
        END IF
        ELEMENT = ELEMENT - 2
        NNODE = NNODE - 2
        CHANGE = 1
        OFFGUN = 1
        GOTO 80
     ELSE
REM*********************************************************************
        IF RUNN=1 THEN GOTO 170
160     IFLGG(2)=NORUN:DUMMY(2)=0:KCCC(2)=0:EXPP(2)=0

        CALL SPRINKLERCOEFF_
              (PSUMR(),QSUMR(),DUMMY(),2,IFLGG(),KCCC(),EXPP( ),2)
        KCCC=KCCC(2) :EXPP=EXPP(2)
        PRINT#14,:PRINT#14,:PRINT#14,

        IF CHANGE = 0 OR CHANGE=2 THEN PRINT#14,_
                         "                          END GUN ON"
        IF CHANGE = 1 THEN PRINT#14,_
                         "                          END GUN OFF"
        PRINT#14,
        PRINT#14,TAB(12)_
"RUN   Ppivot Hpivot   Pend   Hend    Pdrop  Hdrop   Qpivot  Qend ";_
PRINT#14,TAB(12)_
"NO    (PSI)  (FT)     (PSI)  (FT)    (PSI)  (FT)     (GPM)  (GPM)";_
 PRINT#14,TAB(12)_
"---   ------ ------   ----   -----   -----  -----   ------  -----";_
FOR I = 1 TO NORUN
    PRINT#14,TAB(12)USING_
"###   ###.## ###.##   ##.#   ###.#   ##.##  ##.##   ####.#  ###.#";_
```

```
 I,PSUMR(2,I),HSUMR(2,I),PENDR(I),HENDR(I),PDROPR(I),HDROPR(I),QSUMR(2,I),_
     QENDR(I),QEBYQP(NORUN),ITERR(I)
        NEXT I
        PRINT#14,PRINT#14,TAB(12)_
                           "THE Q VS H RELATIONSHIP AT THE PIVOT IS GIVEN BY"
        PRINT#14,TAB(25) USING_
                           " Q=###.###(H^^#.######)";KCCC,EXPP
170     IF CHANGE=0 OR CHANGE=2 THEN LOCATE 15,1:PRINT"RUN COMPLETE"
        IF CHANGE=1THEN LOCATE 15,68:PRINT"RUN COMPLETE"
        IF INK$(1) ="y" or INK$(1)="Y" then GOTO 150
        STOP:END
    END IF

SUB DIFFSPRINKLER_
         (PLAT(2),RADCOV(2),QSPR(2),SPACING(1),CHEKSPAC,ELEMENT,IFLG(1))
REM*********************************************************************
REM************   SUB DIFFSPRINKLER(NNODE)    *************************
REM*********************************************************************
    DIM FLAG(30)
    COLUM=1:FLAG=2

REM*********************************************************************
REM      INPUT PSI, GPM, AND RADIUS OF COVERAGE  FROM THE FILE
REM*********************************************************************
    FOR K=1 TO ELEMENT
        IF K/2 = INT(K/2) THEN
           POSN=FLAG
           SELECT CASE COLUM
             CASE 1
                  POSI=2:COLUM=2
             CASE 2
                  POSI=28:COLUM=3
             CASE 3
                  POSI=56:COLUM=1
           END SELECT
           LOCATE POSN,POSI:LPRINT
           LOCATE POSN+1,POSI:LPRINT
           LOCATE POSN+2,POSI:LPRINT,"SPRINKLER NO ";K/2
           LOCATE POSN+3,POSI:LPRINT,"P(psi)  R(ft)   Q(gpm)"
180        FOR I=1 TO 100
               INPUT #9,PLAT(K,I)
               IF PLAT(K,I)=999 THEN IFLG(K)=I-1:I=100:GOTO 190
               INPUT #9,RADCOV(K,I),QSPR(K,I)
               LOCATE POSN+1,POSI:
               PRINT#14,USING_
               "###    ###.#    ###";PLAT(K,I),RADCOV(K,I),QSPR(K,I)
               PRINT USING_
               "###    ###.##    ###";PLAT(K,I),QSPR(K,I),RADCOV(K,I)
               POSN=POSN+1
190        NEXT I
```

```
        END IF
        IF COLUM=1 THEN FLAG=POSN+2
    NEXT K
    FOR I=1 TO ELEMENT
        IF I/2 <>INT(I/2)THEN
           INPUT #9,SPACING(I)
        END IF
    NEXT I
    INPUT #9,CHEKSPAC
END SUB


SUB CHECKLENGTH(CHEKspac,LATLEN)
REM**********************************************************************
REM*********CHECK IF THE TOTAL LENGTH IS EQUAL TO SUM OF ELEMENT LENGTH**
REM**********************************************************************
 PRINT"The total length of the lateral does not match with the summation"
 PRINT"of the distances given above. Input the spacing of the sprinklers"
 PRINT"Calculated length of the lateral line = ";latlen
 PRINT"user input summation of the lateral elements = ";chekspac
 PRINT"PROGRAM TERMINATED":STOP:END
END SUB

SUB INTERPOLATION(PLAT(2),VARI(2),I,IFLG,H,SOLU)
REM**********************************************************************
REM**********INTERPOLATION OF Q,H,AND RADIUS OF CURVATURE****************
REM**********************************************************************

   EXACT = 0:LFLG=0:HFLG=0
   FOR J = 1 TO IFLG
       IF PLAT(I,J)<H THEN
          LFLG =J
        ELSEIF PLAT(I,J)>H THEN
          HFLG =J: J=IFLG
        ELSE
          EXACT = J
      END IF
   NEXT J

   IF EXACT<>0 then
       SOLU = VARI(I,EXACT)
     ELSE
       SOLU =(((VARI(I,hflg)-VARI(I,lflg))*(H-plat(I,lflg)))/_
                           (plat(I,hflg)-plat(I,lflg))) + VARI(I,lflg)
   END IF
END SUB
```

```
SUB SPRINKLERCOEFF(P(2),Q(2),SPACING(1),ELEMENT,IFLG(1),KC(1),EXPON(1),FLA)
REM**************************************************************************
REM*********DEFINING OR CALCULATING SPRINKLER COEFFICIENT*****************
REM**************************************************************************
    DIM X(60,13),Y(60,13)
    IF FLAG = 1 THEN
PRINT#14,TAB(12)"SPR  SPACING  DISTANCE FROM      CALCULATED          REG"
PRINT#14,TAB(12)"NO    (ft)    PIVOT (ft)      KC          a          EQ"
PRINT#14,TAB(12)"---  -------- ------------   -------   --------     ---"
    END IF

REM*****************PROGRAM LINEAR REGRESSION**************************
    POSN=3:LATLEN=0
    FOR I=1 TO ELEMENT
        SUMX=0 :SUMY=0
        SUMX2=0:SUMY2=0:SUMXY=0
        IF I/2=INT(I/2)THEN
            FOR J=1 TO IFLG(I)
                X(I,J)=LOG(P(I,J)*2.3114)
                Y(I,J)=LOG(Q(I,J))
                SUMX=X(I,J)+SUMX
                SUMY=Y(I,J)+SUMY
                SUMX2=X(I,J)^2 + SUMX2
                SUMY2=Y(I,J)^2 + SUMY2
                SUMXY=X(I,J)*Y(I,J)+SUMXY
            NEXT J
            N=IFLG(I)
            MEANX=SUMX/N
            MEANY=SUMY/N
            CBASEX=(SUMX^2)/N
            SUMX2BAR=SUMX2-CBASEX
            CBASEY=(SUMY^2)/N
            SUMY2BAR=SUMY2-CBASEY
            CBASEXY=(SUMX*SUMY)/N
            SUMXYBAR=SUMXY-CBASEXY

            SLOPE=SUMXYBAR/SUMX2BAR
            INTERCPT=MEANY-SLOPE*MEANX
            KC(I)=EXP(INTERCPT)
            EXPON(I)=SLOPE
            POSN=POSN+1
            LATLEN=SPACING(I-1)+LATLEN
            IF FLAG = 1 THEN
               PRINT#14,TAB(12) USING_
 "###     ##.#        ###.#      ###.####  ###.####   Q=###.##(H^#.##)";_
               I/2,SPACING(I-1),LATLEN,KC(I),EXPON(I),KC(I),EXPON(I)
            END IF
        END IF
    NEXT I
```

```
REM THE FIRST NINE SPRINKLERS IN THE SYSTEM CONSIDERED HAVE PRESSURE
REM REGULATING VALVES THAT HAVE THE CHANGE THE COEFFICIENTS TO
REM THE FOLLOWING :
    IF FLAG = 1 THEN
       KC(2 ) = .2118
       KC(4 ) = .2624
       KC(6 ) = .3204
       KC(8 ) = .5
       KC(10 ) = .624
       KC(12 ) = .698
       KC(14 ) = .838
       KC(16 ) = .972
       KC(18 ) = 1.092
       FOR I = 2 TO 18
           IF I/2=INT(I/2)THEN
              EXPON(I)=0.5
           END IF
       NEXT
   END IF
END SUB

SUB ELEVATION(NNODE,SPACING(1),ELEV(1))
REM****************************************************************
REM*******DEFINE FIELD SLOPE AT THE SPRINKLER POINT******************
REM****************************************************************
   CLS:PRINT_
  "FIELD SLOPE AT VARYING DISTANCE FROM THE PIVOT (DOWNHILL IS NEGATIVE)"
   PRINT:PRINT"Distance from pivot        Elevation"
   PRINT"     (feet)                 (feet)"
   PRINT"-------------------         ---------"
   PRINT"  At the pivot                 0
   POSN = 7
   ELEV(1)=0: IF FLAG<>1 THEN LATSUM=0
   FOR I = 1 TO ELEMENT
       IF I/2<>INT(i/2)THEN
          IF FLAG = 1 THEN
             CLS:PRINT"Distance from pivot       Elevation"
             PRINT"     (feet)               (feet)"
             PRINT"-------------------       ---------"
             FLAG = 0 :POSN = 4
            ELSE
             LATSUM = SPACING(1)
          END IF
          LOCATE POSN,6:PRINT LATSUM:LOCATE POSN,30:INPUT,elev(I)
          POSN = POSN+1 : LATSUM=LATSUM+SPACING(I)
          ELEV(I+1)=ELEV(I)
          IF POSN = 25 OR POSN =50 THEN FLAG=1:GOTO 200
       END IF
200    NEXT I
END SUB
```

```
SUB PipeDiameter(size(1),samedia(1))
REM*************************************************************************
REM*****************INPUT THE DIAMETER OF THE PIPE***************************
REM*************************************************************************
    CLS
    INPUT"How many sizes of pipe are there in the lateral line? ",sizeNo
    POSI = 6
    Print"Pipe No.    Size in inches     Distance from Pivot in feet "
    PRINT"--------    -------------         START              END"
    PRINT"                                  ---------------------------"
    PRINT:FOR I = 1 TO SIZEno
        LOCATE POSI,4:PRINT POSI-5
        LOCATE POSI,17:INPUT,SIZE(I)
        IF I=1 THEN
             LOCATE POSI,36:PRINT 0:LOCATE POSI,52:INPUT,SAMEDIA(I)
          ELSEIF I>1 THEN
             LOCATE POSI,36:PRINT SAMEDIA(I-1):LOCATE POSI,52
               INPUT,SAMEDIA(I)
       END IF
        POSI = POSI + 1
    NEXT I
    SIZENO=2
    SIZE(1)=5.79:SAMEDIA(1)=765
    SIZE(2)=2.78:SAMEDIA(2)=787
END SUB
```

APPENDIX B

OUTPUT RESULTS FROM THE SIMULATION MODEL "NETWORK"

Case 1 : end gun on

TOTAL ITERATION = 6
ALLOWABLE ERROR = .5 FT

NODE NO	HEAD (FT) INITIALIZED (ft)	(psi)	FINAL (ft)	(psi)	DIFFERENCE (ft)	%	DISCHARGE ELEMENT NO	FLOW (gpm)
1	203.40	88.000	203.403	88.00	0.00	0.0	1	825.2
2	201.62	87.230	202.086	87.43	-0.23	-0.1	2	3.0
3	200.47	86.730	202.061	87.42	-0.79	-0.4	3	822.2
4	199.82	86.451	200.755	86.85	-0.47	-0.2	4	3.7
5	198.67	85.951	200.717	86.84	-1.03	-0.5	5	818.5
6	198.04	85.679	199.453	86.23	-0.70	-0.4	6	4.5
7	196.89	85.179	199.379	86.26	-1.27	-0.6	7	814.0
8	196.28	84.920	198.128	85.72	-0.94	-0.5	8	7.0
9	195.13	84.420	197.996	85.66	-1.47	-0.8	9	806.9
10	194.53	84.074	196.664	85.00	-1.20	-0.6	10	8.8
11	193.17	83.574	196.460	85.00	-1.70	-0.9	11	798.2
12	192.66	83.355	195.406	84.84	-1.42	-0.7	12	9.8
13	191.51	82.855	195.153	84.43	-1.90	-1.0	13	788.4
14	191.03	82.657	194.177	84.01	-1.64	-0.9	14	11.7
15	189.90	82.157	193.817	83.85	-2.06	-1.1	15	776.7
16	189.31	81.983	192.982	83.49	-1.83	-1.0	16	13.5
17	188.35	81.483	192.554	83.33	-2.21	-1.2	17	763.2
18	188.03	81.349	191.027	82.99	-2.02	-1.1	18	15.1
19	186.87	80.849	191.250	82.73	-2.33	-1.2	19	748.1
20	186.63	80.744	190.716	82.51	-2.19	-1.2	20	18.0
21	185.48	80.244	189.875	82.15	-2.37	-1.3	21	730.1
22	185.14	80.098	189.503	81.99	-2.36	-1.3	22	21.2
23	183.98	79.598	188.350	81.49	-2.37	-1.3	23	708.9
24	183.92	79.572	188.232	81.53	-2.49	-1.4	24	22.4
25	182.77	79.072	187.212	81.00	-2.43	-1.3	25	686.5
26	182.80	79.057	187.557	81.14	-2.60	-1.4	26	22.3
27	181.65	78.557	186.274	80.59	-2.55	-1.4	27	664.2
28	181.70	78.644	186.670	80.76	-2.69	-1.5	28	22.5
29	180.62	78.144	185.370	80.20	-2.63	-1.5	29	641.7
30	180.63	78.244	185.840	80.40	-2.76	-1.5	30	27.1
31	179.70	77.744	183.972	79.59	-2.38	-1.3	31	614.6
32	179.92	77.842	184.967	80.02	-2.80	-1.6	32	29.5
33	178.77	77.342	182.759	79.07	-2.23	-1.2	33	585.1
34	179.21	77.555	184.270	79.72	-2.82	-1.6	34	29.5
35	178.06	77.055	182.071	78.77	-2.23	-1.3	35	555.7
36	178.60	77.271	183.658	79.45	-2.82	-1.6	36	29.4
37	177.45	76.771	181.444	78.50	-2.23	-1.3	37	526.3
38	178.09	77.050	183.068	79.20	-2.79	-1.6	38	31.5
39	176.94	76.550	180.554	78.11	-2.04	-1.2	39	494.7
40	177.67	76.869	182.561	78.98	-2.73	-1.5	40	33.8
41	176.52	76.369	179.683	77.74	-1.79	-1.0	41	460.9
42	177.30	76.708	182.055	78.76	-2.68	-1.5	42	38.7
43	176.15	76.208	178.321	77.15	-1.23	-0.7	43	422.2
44	177.06	76.605	181.679	78.60	-2.61	-1.5	44	33.2
45	175.91	76.105	178.904	77.40	-1.70	-1.0	45	389.0
46	176.90	76.555	181.357	78.46	-2.52	-1.4	46	38.6
47	175.74	76.055	177.637	76.85	-1.08	-0.6	47	350.4
48	176.79	76.406	181.093	78.33	-2.43	-1.4	48	38.6
49	175.64	75.906	177.778	76.74	-0.99	-0.5	49	311.8
50	176.73	76.461	180.881	78.26	-2.35	-1.3	50	42.4
52	176.71	76.452	180.721	78.19	-2.27	-1.3	52	42.4
53	175.55	75.952	176.281	76.27	-0.41	-0.2	53	227.1
54	176.71	76.450	176.970	76.56	-0.15	-0.1	54	42.0
55	175.55	75.950	172.614	74.68	1.67	1.0	55	185.1
56	176.71	76.450	176.620	76.41	0.05	0.0	56	185.1
57	175.55	75.950	171.364	74.14	2.38	1.4		

Case i : end gun on

EL	LATDIA (FT)	AREA (SQ FT)	QLAT (GPM)	VELOCITY (FT/SEC)	REYNOLD NO	FRICTION FACTOR(F)	*	H LOSS (FT)	TOT H LOSS (FT)
1	0.40	0.10	823.20	10.06	490440	0.014643	0.0000020	1.33	1.33
3	0.40	0.10	822.19	10.03	434707	0.014649	0.0000020	1.35	2.68
5	0.40	0.10	818.40	9.98	434722	0.014657	0.0000020	1.34	4.02
7	0.40	0.10	813.93	9.93	452209	0.014667	0.0000020	1.32	5.33
9	0.40	0.10	806.91	9.84	446399	0.014682	0.0000023	1.49	6.83
11	0.40	0.10	798.16	9.73	443439	0.014701	0.0000020	1.28	8.11
13	0.40	0.10	788.60	9.61	435019	0.014722	0.0000020	1.23	9.35
15	0.40	0.10	776.73	9.47	[illegible]	0.014749	0.0000020	1.21	10.57
17	0.40	0.10	763.22	9.31	424034	0.014780	[illegible]	1.17	11.74
19	0.40	0.10	748.10	9.12	[illegible]	0.014816	[illegible]	1.13	12.87
21	0.40	0.10	730.10	8.90	[illegible]	[illegible]	0.0000023	1.23	14.10
23	0.40	0.10	708.93	8.64	393379	0.014915	0.0000020	1.02	15.12
25	0.40	0.10	686.83	8.37	381440	0.014973	0.0000020	0.96	16.08
27	0.40	0.10	664.19	8.10	369032	0.015033	0.0000020	0.90	16.99
29	0.40	0.10	641.70	7.83	[illegible]	0.015103	0.0000021	0.83	17.83
31	0.40	0.10	614.66	7.50	[illegible]	0.015190	[illegible]	0.89	18.73
33	0.40	0.10	583.13	7.14	323120	[illegible]	[illegible]	0.71	19.44
35	0.40	0.10	553.67	6.78	[illegible]	[illegible]	[illegible]	0.65	20.09
37	0.40	0.10	526.27	6.42	[illegible]	[illegible]	[illegible]	0.59	20.67
39	0.40	0.10	494.73	6.03	274916	[illegible]	[illegible]	0.52	21.19
41	0.40	0.10	460.91	5.62	254134	[illegible]	[illegible]	0.52	21.72
43	0.40	0.10	422.21	5.15	234640	[illegible]	[illegible]	0.39	22.10
44	0.40	0.10	389.01	4.75	[illegible]	[illegible]	[illegible]	0.33	22.44
45	0.40	0.10	353.38	4.27	194769	[illegible]	[illegible]	0.28	22.71
47	0.40	0.10	311.78	3.80	173310	0.016779	[illegible]	0.22	22.94
51	0.40	0.10	269.41	3.29	149778	0.017127	[illegible]	0.17	23.11
53	0.23	0.04	227.04	12.82	262937	0.016643	[illegible]	4.32	27.43
55	0.23	0.04	183.10	9.80	214370	0.017074	0.0000118	0.41	27.83

ELEM NO	NODES I	J	DISC GPM	FRIC LOSS	CSP	CPC	CP	HEAD(FT) UP	DN
1	1	2	823.2	1.33			630.800	202.4	202.1
2	2	3	3.0		0.018	130.680		202.1	202.1
3	3	4	822.2	1.35			611.887	202.1	200.8
4	4	5	3.7		0.019	98.271		200.8	200.7
5	4	6	818.3	1.34			614.346	200.8	199.4
6	6	7	4.8		0.023	81.226		199.4	199.4
7	6	8	814.0	1.32			617.433	199.4	198.1
8	8	9	7.0		0.036	52.969		198.1	198.0
9	8	10	806.9	1.40			343.689	198.1	196.7
10	10	11	8.8		0.048	42.988		196.7	196.5
11	10	12	798.2	1.28			[illegible]	196.7	195.4
12	12	13	9.8		[illegible]	38.616		195.4	195.3
13	12	14	788.4	1.23			[illegible]	195.4	194.2
14	14	15	11.7		0.060	32.480		194.2	193.8
15	14	16	776.7	1.21			644.048	194.2	193.0
16	16	17	13.8		0.070	28.200		193.0	192.8
17	16	18	763.2	1.17			684.267	193.0	191.8
18	18	19	15.1		0.079	25.276		191.8	191.2
19	18	20	748.1	1.13			[illegible]	191.8	190.7
20	20	21	18.0		[illegible]	21.349		190.7	189.9
21	20	22	730.1	1.23			597.063	190.7	189.5
22	22	23	21.2		0.112	18.374		189.5	188.3
23	22	24	708.9	1.02			698.904	189.5	188.5
24	24	25	22.6		0.119	17.311		188.5	187.2
25	24	26	686.3	0.96			719.283	188.5	187.6
26	26	27	22.3		0.120	17.333		187.6	186.3
27	26	28	664.2	0.90			740.846	187.6	186.7
28	28	29	22.8		0.121	17.242		186.7	185.4
29	28	30	641.7	0.83			764.063	186.7	185.8
30	30	31	27.1		0.146	14.428		185.8	184.0
31	30	32	614.6	0.89			[illegible]	185.8	185.0
32	32	33	29.8		0.161	13.286		185.0	182.0
33	32	34	585.1	0.71			829.430	185.0	184.3
34	34	35	29.5		0.161	13.311		184.3	182.1
35	34	36	553.7	0.65			[illegible]	184.3	183.6
36	36	37	29.6		0.161	13.333		183.6	181.4
37	36	38	526.3	0.59			911.376	183.6	183.1
38	38	39	31.5		0.170	12.464		183.1	180.6
39	38	40	494.7	0.52			962.686	183.1	182.6
40	40	41	33.8		0.187	11.662		182.6	179.[illegible]
41	40	42	460.9	0.52			[illegible]	182.6	182.1
42	42	43	38.7		0.218	10.239		182.1	178.3
43	42	44	422.2	0.39			1107.553	182.1	181.7
44	44	45	33.2		0.184	11.873		181.7	178.9
45	44	46	389.0	0.33			1191.633	181.7	181.4
46	46	47	38.6		0.218	10.279		181.4	177.6
47	46	48	[illegible]	0.28			1307.677	181.4	181.1
48	48	49	38.6		0.218	10.286		181.1	177.6
49	49	50	311.8	0.22			1452.103	181.1	180.9
50	50	51	42.4		0.237	9.416		180.9	176.4
51	50	52	269.4	0.17			[illegible]	180.9	180.7
52	52	53	42.4		0.237	9.420		180.7	176.3
53	52	54	227.1	4.32			[illegible]	180.7	177.0
54	54	55	[illegible]		0.240	[illegible]		[illegible]	173.6
55	54	56	183.1	0.41			[illegible]	[illegible]	176.0
56	56	57	183.1		[illegible]	34.643		176.6	171.6
57	56	58	0.0	0.00			[illegible]	176.6	176.6

Case 2: end gun off, pump 'J'

TOTAL ITERATION = 5
ALLOWABLE ERROR = .5 FT

NODE NO	HEAD INITIAL (ft)	(psi)	HEAD FINAL (ft)	(psi)	DIFFERENCE (ft)	%	DISCHARGE ELEMENT NO	FLOW (gpm)
1	234.25	110.000	234.234	110.00	0.00	0.0	1	730.8
2	233.18	109.533	233.205	109.55	-0.01	-0.0	2	3.4
3	232.02	109.033	233.172	109.53	-0.46	-0.2	3	727.1
4	232.08	109.061	232.147	109.09	-0.03	-0.0	4	4.2
5	230.93	108.561	232.097	109.07	-0.47	-0.2	5	722.9
6	231.00	108.593	231.100	108.64	-0.04	-0.0	6	5.1
7	249.85	108.093	231.027	108.60	-0.47	-0.2	7	717.9
8	249.94	108.153	230.067	108.19	-0.08	-0.0	8	7.9
9	248.78	107.653	249.895	108.11	-0.45	-0.2	9	710.0
10	248.75	107.620	248.913	107.69	-0.06	-0.0	10	9.8
11	247.60	107.120	248.650	107.53	-0.42	-0.2	11	700.1
12	247.74	107.184	247.928	107.26	-0.07	-0.0	12	11.0
13	246.59	106.684	247.602	107.12	-0.41	-0.2	13	689.1
14	246.77	106.762	246.972	106.85	-0.08	-0.0	14	13.2
15	245.61	106.262	246.510	106.65	-0.37	-0.1	15	676.0
16	245.83	106.356	246.050	106.45	-0.09	-0.0	16	15.2
17	244.68	105.856	245.457	106.19	-0.31	-0.1	17	660.7
18	244.94	105.969	245.168	106.07	-0.09	-0.0	18	17.1
19	243.78	105.469	244.402	105.74	-0.25	-0.1	19	643.6
20	244.09	105.602	244.327	105.71	-0.10	-0.0	20	20.4
21	242.93	105.102	243.234	105.24	-0.13	-0.1	21	623.2
22	243.18	105.211	243.426	105.32	-0.10	-0.0	22	23.9
23	242.03	104.711	241.962	104.68	0.03	0.0	23	599.3
24	242.45	104.892	242.691	105.00	-0.10	-0.0	24	23.4
25	241.29	104.392	241.046	104.29	0.10	0.0	25	573.9
26	241.77	104.598	242.013	104.70	-0.10	-0.0	26	25.4
27	240.61	104.098	240.373	103.99	0.10	0.0	27	548.5
28	241.15	104.330	241.391	104.44	-0.10	-0.0	28	25.6
29	239.99	103.830	239.726	103.71	0.11	0.0	29	522.9
30	240.89	104.088	240.822	104.19	-0.10	-0.0	30	30.6
31	239.43	103.588	238.479	103.18	0.40	0.2	31	492.4
32	240.02	103.843	240.243	103.94	-0.09	-0.0	32	33.7
33	238.87	103.343	237.425	102.72	0.60	0.3	33	458.7
34	239.59	103.657	239.798	103.75	-0.08	-0.0	34	35.6
35	238.44	103.157	236.983	102.53	0.61	0.3	35	425.1
36	239.22	103.498	239.411	103.58	-0.08	-0.0	36	35.6
37	238.07	102.998	236.601	102.36	0.62	0.3	37	391.5
38	238.91	103.364	239.080	103.44	-0.07	-0.0	38	35.9
39	237.76	102.864	235.882	102.05	0.79	0.3	39	355.8
40	238.66	103.254	238.803	103.32	-0.06	-0.0	40	38.6
41	237.50	102.754	235.141	101.73	1.00	0.4	41	316.9
42	238.44	103.157	238.547	103.20	-0.05	-0.0	42	44.3
43	237.28	102.657	233.787	101.15	1.47	0.6	43	272.6
44	238.29	103.094	238.377	103.13	-0.04	-0.0	44	38.2
45	237.14	102.594	234.784	101.58	0.99	0.4	45	234.4
46	238.19	103.050	238.249	103.08	-0.02	-0.0	46	44.3
47	237.03	102.550	233.495	101.02	1.49	0.6	47	190.1
48	238.13	103.022	238.161	103.04	-0.02	-0.0	48	44.3
49	236.97	102.522	233.409	100.98	1.50	0.6	49	145.9
50	238.09	103.007	238.107	103.01	-0.01	-0.0	50	48.6
51	236.93	102.507	232.438	100.56	1.90	0.8	51	97.3
52	238.08	103.001	238.091	103.00	-0.00	0.0	52	48.8
53	236.92	102.501	232.413	100.55	1.90	0.8	53	48.7
55	236.92	102.500	237.467	102.74	-0.23	-0.1		

Case 2: end gun off, pump 'J'

EL NO	LATRIA (FT)	AREA (SQ FT)	QLAT (GPM)	VELOCITY (FT/SEC)	REYNOLD NO	FRICTION FACTOR (F)	e	H LOSS (FT)	TOT H (FT)
1	0.40	0.18	730.40	8.91	405779	0.014860	0.0000020	1.06	1.06
3	0.40	0.18	727.11	8.87	403907	0.014868	0.0000020	1.07	2.13
5	0.40	0.18	722.96	8.81	401592	0.014879	0.0000020	1.06	3.19
7	0.40	0.18	717.86	8.75	398772	0.014892	0.0000020	1.05	4.24
9	0.40	0.18	709.96	8.66	394380	0.014912	0.0000023	1.17	5.40
11	0.40	0.18	700.11	8.54	388911	0.014938	0.0000020	1.00	6.40
13	0.40	0.18	689.12	8.40	382806	0.014968	0.0000020	0.97	7.37
15	0.40	0.18	673.95	8.24	373490	0.015003	0.0000020	0.93	8.30
17	0.40	0.18	660.70	8.06	367021	0.015048	0.0000020	0.89	9.20
19	0.40	0.18	643.61	7.85	357524	0.015099	0.0000021	0.88	10.08
21	0.40	0.18	623.23	7.60	346208	0.015163	0.0000024	0.91	10.96
23	0.40	0.18	599.31	7.31	332916	0.015241	0.0000021	0.75	11.71
25	0.40	0.18	573.89	7.00	316794	0.015329	0.0000021	0.69	12.40
27	0.40	0.18	548.30	6.69	304491	0.015424	0.0000021	0.63	13.03
29	0.40	0.18	522.92	6.38	290481	0.015[illegible]	0.0000021	0.58	13.61
31	0.40	0.18	492.36	6.00	273509	0.015[illegible]57	0.0000024	0.59	14.20
33	0.40	0.18	453.70	5.59	254[illegible]09	0.015717	0.0000022	0.43	14.63
35	0.40	0.18	423.07	5.18	236175	0.015996	0.0000022	0.39	15.04
37	0.40	0.18	391.46	4.77	217418	0.016193	0.0000022	0.34	15.38
39	0.40	0.18	355.52	4.33	197490	0.016434	0.0000022	0.28	15.66
41	0.40	0.18	316.93	3.86	176023	0.016736	0.0000026	0.26	15.93
43	0.40	0.18	272.63	3.32	151449	0.017123	0.0000023	0.17	16.10
45	0.40	0.18	234.41	2.86	130215	0.017602	0.0000024	0.13	16.23
47	0.40	0.18	190.14	2.32	105626	0.018259	0.0000025	0.09	16.32
49	0.40	0.18	145.88	1.78	81038	0.019197	0.0000026	0.06	16.38
51	0.40	0.18	97.31	1.19	54056	0.020813	0.0000028	0.03	16.40
—	0.23	0.04	48.74	2.38	54380	0.021091	0.0001089	0.28	16.66

ELEM NO	NODES U	NODES D	DISC GPM	FRIC f	CSP	CPC	CP	HEAD (FT) UP	HEAD (FT) DN
1	1	2	730.5	1.06			692.123	234.3	233.2
2	2	3	3.4		0.013	101.920		233.2	233.2
3	2	4	727.1	1.07			682.699	233.2	232.1
4	4	5	4.2		0.017	83.640		232.1	232.1
5	4	6	722.9	1.06			686.217	232.1	231.1
6	6	7	5.1		0.020	69.801		231.1	231.0
7	6	8	717.9	1.05			690.888	231.1	230.1
8	8	9	7.9		0.032	45.887		230.1	229.9
9	8	10	710.0	1.17			611.316	230.1	228.9
10	10	11	9.8		0.040	37.377		228.9	228.7
11	10	12	700.1	1.00			700.082	228.9	227.9
12	12	13	11.0		0.044	33.713		227.9	227.6
13	12	14	689.1	0.97			716.064	227.9	227.0
14	14	15	13.2		0.053	28.445		227.0	226.5
15	14	16	676.0	0.93			728.400	227.0	226.1
16	16	17	15.2		0.062	24.821		226.1	225.6
17	16	18	660.7	0.89			743.231	226.1	225.2
18	18	19	17.1		0.070	22.299		225.2	224.6
19	18	20	643.6	0.88			760.632	225.2	224.3
20	20	21	20.4		0.084	18.922		224.3	223.5
21	20	22	623.2	0.91			686.164	224.3	223.4
22	22	23	23.9		0.099	16.296		223.4	223.0
23	22	24	599.3	0.75			809.717	223.4	222.7
24	24	25	25.4		0.108	15.401		222.7	221.0
25	24	26	573.9	0.69			840.886	222.7	222.0
26	26	27	25.4		0.108	15.422		222.0	220.6
27	26	28	548.3	0.63			874.689	222.0	221.4
28	28	29	25.6		0.106	15.313		221.4	219.7
29	28	30	522.9	0.58			912.664	221.4	220.8
30	30	31	30.6		0.128	12.978		220.8	218.8
31	30	32	492.6	0.59			842.753	220.8	220.2
32	32	33	33.7		0.141	11.863		220.2	217.4
33	32	34	458.7	0.43			1021.667	220.2	219.8
34	34	35	33.6		0.141	11.875		219.8	217.0
35	34	36	423.1	0.39			1090.760	219.8	219.4
36	36	37	33.6		0.141	11.884		219.4	216.6
37	36	38	391.5	0.34			1170.814	219.4	219.1
38	38	39	35.9		0.151	11.165		219.1	215.9
39	38	40	355.5	0.28			1271.440	219.1	218.8
40	40	41	38.6		0.163	10.436		218.8	215.1
41	40	42	316.9	0.26			1229.730	218.8	218.5
42	42	43	44.3		0.187	9.209		218.5	213.8
43	42	44	272.6	0.17			1591.983	218.5	218.4
44	44	45	38.2		0.161	10.551		218.4	214.8
45	44	46	234.4	0.13			1809.023	218.4	218.2
46	46	47	44.3		0.188	9.216		218.2	213.3
47	46	48	190.1	0.09			2152.176	218.2	218.2
48	48	49	44.3		0.188	9.216		218.2	213.6
49	48	50	145.9	0.06			2681.482	218.2	218.1
50	50	51	48.6		0.206	8.401		218.1	212.6
51	50	52	97.3	0.03			3726.002	218.1	218.1
52	52	53	48.6		0.206	8.402		218.1	212.6
53	52	54	48.7	0.23			224.628	218.1	217.9
54	54	55	48.7		0.303	112.428		217.9	217.3
55	54	56	0.0	0.00			0.000	217.9	217.9

Case 3: end gun off, pump 'V'

TOTAL ITERATION = 6
ALLOWABLE ERROR = .5 FT

NODE NO	HEAD(FT) INITIAL (ft)	(psi)	FINAL (ft)	(psi)	DIFFERNECE (ft)	%	DISCHARGE ELEMENT NO	FLOW (gpm)
1	323.76	140.070	323.738	140.07	0.00	0.0	1	824.6
2	322.82	139.665	322.450	139.50	0.12	0.0	2	3.8
3	321.67	139.165	322.410	139.49	-0.23	-0.1	3	820.8
4	321.88	139.256	321.130	138.93	0.23	0.1	4	4.7
5	320.72	138.756	321.070	138.91	-0.11	-0.0	5	816.1
6	320.94	138.850	319.825	138.37	0.33	0.1	6	5.7
7	319.78	138.350	319.736	138.33	0.01	0.0	7	810.3
8	320.02	138.451	318.557	137.81	0.46	0.1	8	8.9
9	318.86	137.951	318.323	137.72	0.17	0.1	9	801.4
10	318.99	138.007	317.099	137.19	0.59	0.2	10	11.1
11	317.83	137.507	316.773	137.05	0.33	0.1	11	790.3
12	318.11	137.628	315.870	136.66	0.71	0.2	12	12.4
13	316.96	137.128	315.465	136.48	0.47	0.1	13	777.9
14	317.27	137.262	314.678	136.14	0.82	0.3	14	14.9
15	316.11	136.762	314.100	135.89	0.64	0.2	15	763.0
16	316.45	136.910	313.529	135.64	0.92	0.3	16	17.2
17	315.30	136.410	312.759	135.31	0.81	0.3	17	745.8
18	315.68	136.575	312.429	135.17	1.03	0.3	18	19.3
19	314.52	136.075	311.463	134.75	0.97	0.3	19	726.5
20	314.94	136.257	311.391	134.72	1.13	0.4	20	23.0
21	313.79	135.757	310.020	134.13	1.20	0.4	21	703.5
22	314.16	135.917	310.257	134.23	1.24	0.4	22	26.9
23	313.00	135.417	308.462	133.45	1.47	0.5	23	676.6
24	313.52	135.641	309.341	133.83	1.33	0.4	24	28.7
25	312.36	135.141	307.240	132.92	1.64	0.5	25	647.9
26	312.93	135.386	308.497	133.47	1.42	0.5	26	28.7
27	311.78	134.886	306.401	132.56	1.72	0.6	27	619.2
28	312.39	135.153	307.722	133.13	1.50	0.5	28	28.9
29	311.24	134.653	305.593	132.21	1.81	0.6	29	590.3
30	311.91	134.943	307.013	132.83	1.57	0.5	30	34.2
31	310.75	134.443	304.050	131.54	2.16	0.7	31	556.1
32	311.42	134.731	306.291	132.51	1.68	0.5	32	38.0
33	310.26	134.231	302.652	130.94	2.45	0.8	33	518.0
34	311.05	134.570	305.736	132.27	1.71	0.5	34	38.0
35	309.89	134.070	302.104	130.70	2.51	0.8	35	480.0
36	310.73	134.432	305.255	132.06	1.76	0.6	36	38.0
37	309.57	133.932	301.628	130.50	2.57	0.8	37	442.0
38	310.46	134.315	304.842	131.89	1.81	0.6	38	40.5
39	309.30	133.815	300.755	130.11	2.77	0.9	39	401.6
40	310.24	134.220	304.497	131.74	1.85	0.6	40	43.5
41	309.08	133.720	299.780	129.70	3.01	1.0	41	358.1
42	310.06	134.136	304.179	131.60	1.89	0.6	42	50.0
43	308.89	133.636	297.997	128.92	3.53	1.1	43	308.1
44	309.92	134.081	303.967	131.51	1.92	0.6	44	43.4
45	308.76	133.581	299.278	129.48	3.07	1.0	45	264.7
46	309.83	134.043	303.807	131.44	1.94	0.6	46	50.0
47	308.67	133.543	297.633	128.77	3.38	1.2	47	214.7
48	309.77	134.019	303.699	131.39	1.96	0.6	48	50.0
49	308.62	133.519	297.526	128.72	3.59	1.2	49	164.7
50	309.74	134.006	303.631	131.36	1.97	0.6	50	54.8
51	308.59	133.506	296.226	128.17	4.00	1.3	51	109.9
52	309.73	134.001	303.598	131.35	1.98	0.6	52	54.8
53	308.57	133.501	296.225	128.16	4.00	1.3	53	55.1
54	309.77	134.000	303.559	131.22	2.07	0.7	54	55.1

Case 3: end gun off, pump 'Y'

EL NO	LAT DIA (FT)	AREA (SQ FT)	FLAT (GPM)	VELOCITY (FT/SEC)	REYNOLDS NO	FRICTION FACTOR (F)	*	H LOSS (FT)	TOT H (FT)
1	0.48	0.18	834.57	10.03	490121	0.014644	0.0000070	1.35	1.35
3	0.48	0.18	830.77	10.01	456008	0.014652	0.0000070	1.34	2.68
5	0.48	0.18	816.07	9.95	[illegible]	0.014662	0.0000070	1.33	4.01
7	0.48	0.18	810.34	9.88	[illegible]	0.014674	0.0000070	1.31	5.32
9	0.48	0.18	801.41	9.77	[illegible]	0.014694	[illegible]	1.47	6.79
11	0.48	0.18	790.30	9.64	[illegible]	0.014718	[illegible]	1.25	8.04
13	0.48	0.18	777.89	9.49	432191	0.014746	[illegible]	1.22	9.26
15	0.48	0.18	763.03	9.30	[illegible]	0.014781	[illegible]	1.17	10.43
17	0.48	0.18	745.82	9.09	414371	[illegible]	[illegible]	1.12	11.55
19	0.48	0.18	726.32	8.86	[illegible]	0.014859	[illegible]	1.07	12.62
21	0.48	0.18	703.31	8.58	[illegible]	0.014929	[illegible]	1.15	13.77
23	0.48	0.18	676.28	8.25	[illegible]	0.015003	[illegible]	0.94	14.70
25	0.48	0.18	647.87	7.90	[illegible]	[illegible]	[illegible]	0.86	15.57
27	0.48	0.18	619.19	7.55	[illegible]	0.015173	[illegible]	0.79	16.36
29	0.48	0.18	590.31	7.20	[illegible]	[illegible]	[illegible]	0.73	17.08
31	0.48	0.18	556.08	6.78	[illegible]	[illegible]	[illegible]	0.74	17.82
33	0.48	0.18	518.63	6.32	[illegible]	[illegible]	[illegible]	0.57	18.39
35	0.48	0.18	480.02	5.85	[illegible]	0.015715	[illegible]	0.49	18.89
37	0.48	0.18	442.04	5.39	[illegible]	[illegible]	[illegible]	0.42	19.31
39	0.48	0.18	401.58	4.90	[illegible]	0.016133	[illegible]	0.35	19.66
41	0.48	0.18	358.07	4.37	[illegible]	0.016416	[illegible]	0.33	19.99
43	0.48	0.18	308.66	3.76	171139	0.016313	[illegible]	0.22	20.21
45	0.48	0.18	264.70	3.23	147087	0.017240	[illegible]	0.16	20.37
47	0.48	0.18	214.71	2.62	[illegible]	0.017874	[illegible]	0.11	20.49
49	0.48	0.18	164.74	2.01	91533	0.018758	[illegible]	0.07	20.55
51	0.48	0.18	109.93	1.34	61077	0.020290	[illegible]	0.03	20.59
53	0.33	0.34	55.13	1.92	63784	0.020689	0.0001034	0.31	20.90

ELEM NO	NODES U	D	DISC GPM	[illegible]	[illegible]	[illegible]	CP	HEAD(FT) UP	DN
1	1	2	834.6	1.35			636.3	323.8	322.4
2	2	3	2.8		0.012	93.900		322.4	322.4
3	2	4	820.8	1.34			617.782	322.4	321.1
4	4	5	4.7		0.018	78.260		321.1	321.1
5	4	6	810.1	1.33			630.981	321.1	319.8
6	6	7	5.7		0.018	64.687		319.8	319.7
7	6	8	810.3	1.31			634.877	319.8	318.5
8	8	9	8.9		[illegible]	48.101		318.5	318.5
9	8	10	801.4	1.47			[illegible]	318.5	317.1
10	10	11	11.1		[illegible]	34.041		317.1	316.8
11	10	12	790.3	1.25			[illegible]	317.1	315.9
12	12	13	12.6		[illegible]	30.668		315.9	315.8
13	12	14	777.9	1.22			648.016	315.9	314.7
14	14	15	14.9		0.047	25.694		314.7	314.1
15	14	16	763.0	1.17			659.266	314.7	313.5
16	16	17	17.2		[illegible]	22.299		313.5	312.0
17	16	18	745.8	1.12			672.678	313.5	312.4
18	18	19	19.3		0.063	19.962		312.4	311.5
19	18	20	726.3	1.07			680.407	312.4	311.4
20	20	21	23.0		0.074	16.804		311.4	310.0
21	20	22	703.3	1.15			631.130	311.4	310.3
22	22	23	26.9		0.087	14.474		310.3	308.6
23	22	24	676.6	0.94			733.873	310.3	309.3
24	24	25	28.7		0.093	13.612		309.3	307.2
25	24	26	647.9	0.86			761.427	309.3	308.5
26	26	27	28.7		0.093	[illegible]		308.5	306.4
27	26	28	619.2	0.79			[illegible]	308.5	307.7
28	28	29	28.9		0.094	[illegible]		307.7	306.6
29	28	30	590.3	0.73			[illegible]	307.7	307.0
30	30	31	34.2		0.112	11.096		307.0	304.1
31	30	32	556.1	0.74			763.181	307.0	306.3
32	32	33	38.0		0.123	10.289		306.3	302.7
33	32	34	518.0	0.57			[illegible]	306.3	305.7
34	34	35	38.0		0.123	10.399		305.7	302.1
35	34	36	480.0	0.49			980.348	305.7	305.3
36	36	37	38.0		0.123	10.407		305.3	301.6
37	36	38	442.0	0.42			1061.268	305.3	304.8
38	38	39	40.5		0.134	9.789		304.8	300.7
39	38	40	401.6	0.35			[illegible]	304.8	304.5
40	40	41	43.5		0.144	9.144		304.5	299.8
41	40	42	358.1	0.33			[illegible]	304.5	304.2
42	42	43	53.0		0.166	8.004		304.2	298.0
43	42	44	308.1	0.22			[illegible]	304.2	304.0
44	44	45	47.6		0.144	8.371		304.0	299.3
45	44	46	256.7	0.16			[illegible]	304.0	303.8
46	46	47	50.3		[illegible]	8.309		303.8	297.6
47	46	48	214.7	0.11			[illegible]	303.8	303.7
48	48	49	[illegible]		0.198	6.613		303.7	297.3
49	48	50	[illegible]	0.07			[illegible]	303.7	303.6
50	50	51	54.8		0.193	[illegible]		303.6	296.8
51	50	52	109.9	0.03			2764.528	303.6	303.6
52	52	53	[illegible]		0.181	7.759		303.6	296.2
53	52	54	[illegible]	0.31			[illegible]	303.6	303.3
54	54	55	[illegible]		0.182	10.399		303.3	302.8
55	54	56	0	0.40			[illegible]	303.3	302.8

Case 4: end gun off, pump'H'

TOTAL ITERATION = 6
ALLOWABLE ERROR = .5 FT

NODE NO	HEAD(FT) INITIAL (ft)	(psi)	FINAL (ft)	(psi)	DIFFERENCE (ft)	%	DISCHARGE ELEMENT NO	FLOW (gpm)
1	214.59	92.840	214.590	92.84	0.00	0.0	1	670.5
2	213.23	92.251	213.672	92.44	-0.21	-0.1	2	3.1
3	212.07	91.751	213.641	92.43	-0.74	-0.3	3	667.4
4	211.83	91.654	212.745	92.04	-0.42	-0.2	4	3.8
5	210.69	91.154	212.698	92.02	-0.93	-0.5	5	663.6
6	210.48	91.064	211.829	91.65	-0.64	-0.3	6	4.7
7	209.33	90.564	211.760	91.62	-1.16	-0.6	7	658.9
8	209.14	90.403	210.924	91.25	-0.85	-0.4	8	7.3
9	207.99	89.903	210.768	91.19	-1.34	-0.6	9	651.7
10	207.64	89.833	209.914	90.82	-1.09	-0.5	10	9.0
11	206.49	89.333	209.679	90.71	-1.54	-0.7	11	642.6
12	206.37	89.284	209.052	90.44	-1.30	-0.6	12	10.1
13	205.21	88.784	208.762	90.32	-1.73	-0.8	13	632.5
14	205.14	88.750	208.215	90.08	-1.50	-0.7	14	12.1
15	203.98	88.250	207.809	89.91	-1.88	-0.9	15	620.4
16	203.95	88.233	207.408	89.73	-1.69	-0.8	16	14.0
17	202.80	87.733	206.874	89.50	-2.01	-1.0	17	606.4
18	202.82	87.750	206.633	89.40	-1.83	-0.9	18	15.7
19	201.67	87.250	205.973	89.11	-2.13	-1.1	19	590.7
20	201.75	87.286	205.099	89.08	-2.05	-1.0	20	18.7
21	200.60	86.786	204.931	88.68	-2.19	-1.1	21	572.0
22	200.61	86.792	205.110	88.74	-2.24	-1.1	22	22.0
23	199.45	86.292	203.866	88.20	-2.21	-1.1	23	550.0
24	199.65	86.390	204.467	88.46	-2.40	-1.2	24	23.3
25	198.53	85.890	203.050	87.86	-2.29	-1.2	25	526.7
26	198.82	86.019	203.674	88.20	-2.54	-1.3	26	23.3
27	197.67	85.519	202.491	87.61	-2.44	-1.2	27	503.4
28	198.04	85.680	203.329	87.97	-2.67	-1.3	28	23.8
29	196.88	85.180	201.926	87.36	-2.56	-1.3	29	479.9
30	197.53	85.373	202.631	87.73	-2.79	-1.4	30	28.2
31	196.18	84.873	200.857	86.90	-2.39	-1.2	31	451.7
32	196.62	85.065	202.324	87.53	-2.90	-1.5	32	30.9
33	195.46	84.565	199.990	86.52	-2.32	-1.2	33	420.9
34	196.08	84.830	201.934	87.36	-2.99	-1.5	34	30.8
35	194.92	84.330	199.605	86.36	-2.40	-1.2	35	390.0
36	195.61	84.629	201.596	87.22	-3.06	-1.6	36	30.8
37	194.45	84.129	199.270	86.21	-2.48	-1.3	37	359.2
38	195.22	84.459	201.307	87.09	-3.12	-1.6	38	33.0
39	194.06	83.959	198.659	85.95	-2.37	-1.2	39	326.2
40	194.90	84.320	201.064	86.99	-3.16	-1.6	40	35.5
41	193.74	83.820	198.047	85.68	-2.22	-1.1	41	290.7
42	194.61	84.198	200.842	86.89	-3.20	-1.6	42	40.6
43	193.46	83.698	196.963	85.21	-1.81	-0.9	43	250.0
44	194.43	84.119	200.694	86.83	-3.22	-1.7	44	33.0
45	193.28	83.619	197.757	85.56	-2.32	-1.2	45	215.1
46	194.30	84.063	200.582	86.78	-3.23	-1.7	46	40.6
47	193.15	83.563	196.707	85.10	-1.84	-1.0	47	174.5
48	194.22	84.028	200.506	86.75	-3.24	-1.7	48	40.6
49	193.07	83.528	196.633	85.07	-1.85	-1.0	49	138.8
50	194.18	84.009	200.459	86.73	-3.23	-1.7	50	44.6
51	193.02	83.509	195.861	84.74	-1.47	-0.8	51	89.2
52	194.16	84.001	200.436	86.72	-3.23	-1.7	52	44.6
53	193.00	83.501	195.839	84.73	-1.47	-0.8	53	44.7
55	193.00	83.500	199.922	86.49	-3.39	-1.9		

Case 4: end gun off, pump 'H'

EL NO	LATDIA (FT)	AREA SQ FT	QLAT (GPM)	VELOCITY (FT/SEC)	REYNOLD NO	FRICTION FACTOR(F)	E	H LOSS (FT)	TOT H (FT)
1	0.48	0.18	670.20	8.17	372176	0.015022	0.0000020	0.90	0.90
3	0.48	0.18	667.40	8.12	370456	0.015031	0.0000020	0.91	1.81
5	0.48	0.18	663.58	8.08	368330	0.015042	0.0000020	0.90	2.71
7	0.48	0.18	658.91	8.02	365740	0.015055	0.0000021	0.89	3.60
9	0.48	0.18	651.65	7.94	361707	0.015077	0.0000023	0.99	4.60
11	0.48	0.18	642.61	7.83	356687	0.015104	0.0000021	0.84	5.44
13	0.48	0.18	632.52	7.71	351083	0.015133	0.0000021	0.82	6.27
15	0.48	0.18	620.43	7.56	344368	0.015172	0.0000021	0.79	7.06
17	0.48	0.18	606.43	7.39	336996	0.015219	0.0000021	0.76	7.82
19	0.48	0.18	590.73	7.20	327721	0.015272	0.0000021	0.72	8.55
21	0.48	0.18	572.03	6.97	317499	[illegible]	0.0000024	0.78	9.32
23	0.48	0.18	550.65	6.70	305777	0.015420	0.0000021	0.63	9.96
25	0.48	0.18	526.70	6.42	292331	0.015512	0.0000021	0.59	10.54
27	0.48	0.18	503.40	6.13	279400	0.015610	0.0000021	0.54	11.08
29	0.48	0.18	479.93	5.85	265370	0.015716	0.0000021	0.49	11.57
31	0.48	0.18	451.73	5.50	250717	[illegible]	[illegible]	0.50	12.08
33	0.48	0.18	430.86	5.13	239231	0.016020	[illegible]	0.39	12.46
35	0.48	0.18	390.01	4.75	216462	0.016234	[illegible]	0.34	12.80
37	0.48	0.18	357.20	4.35	[illegible]	0.016410	[illegible]	0.29	13.08
39	0.48	0.18	326.15	3.97	181010	0.016662	[illegible]	0.24	13.33
41	0.48	0.18	290.69	3.54	161334	0.016976	[illegible]	0.22	13.55
43	0.48	0.18	250.05	3.05	138777	0.017410	0.0000024	0.15	13.70
45	0.48	0.18	215.08	2.62	119374	0.017872	0.0000024	0.11	13.81
47	0.48	0.18	174.46	2.13	96879	[illegible]	[illegible]	0.08	13.89
49	0.48	0.18	133.80	1.63	74299	[illegible]	[illegible]	0.05	13.93
51	0.48	0.18	89.26	1.09	49540	0.021196	0.0000029	0.03	13.96
53	0.23	0.04	44.67	2.36	51639	0.021481	0.0001077	0.21	14.17

ELEM NO	NODES U	NODES D	DISC GPM	FRIC ft	CBP	CPC	CP	HEAD(FT) UP	HEAD(FT) DN
1	1	2	670.3	0.90			726.221	214.6	213.7
2	2	3	3.1		0.014	97.983		213.7	213.6
3	2	4	667.4	0.91			716.223	213.7	212.7
4	4	5	3.8		0.018	81.386		212.7	212.7
5	4	6	663.6	0.90			719.823	212.7	211.8
6	6	7	4.7		0.022	68.463		211.8	211.8
7	6	8	658.9	0.89			724.390	211.8	210.9
8	8	9	7.3		0.034	46.475		210.9	210.8
9	8	10	651.7	0.99			641.826	210.9	209.9
10	10	11	9.0		0.043	38.370		209.9	209.7
11	10	12	642.6	0.84			740.716	209.9	209.1
12	12	13	10.1		0.048	34.086		209.1	208.8
13	12	14	632.5	0.82			731.272	209.1	208.2
14	14	15	12.1		0.058	29.762		208.2	207.8
15	14	16	620.4	0.79			764.244	208.2	207.4
16	16	17	14.0		0.068	26.159		207.4	206.9
17	16	18	606.6	0.76			779.779	207.4	206.6
18	18	19	15.7		0.076	23.698		206.6	206.0
19	18	20	590.7	0.72			798.098	206.6	205.9
20	20	21	18.7		0.091	20.342		205.9	205.0
21	20	22	572.0	0.78			719.987	205.9	205.1
22	22	23	22.0		0.100	17.684		205.1	204.9
23	22	24	550.0	0.63			849.248	205.1	204.5
24	24	25	23.3		0.115	16.781		204.5	204.1
25	24	26	526.7	0.59			882.047	204.5	203.9
26	26	27	23.3		0.113	16.881		203.9	203.8
27	26	28	503.4	0.54			917.308	203.9	203.3
28	28	29	23.3		0.116	16.609		203.3	201.9
29	28	30	479.9	0.49			956.983	203.3	202.8
30	30	31	28.2		0.140	14.227		202.8	200.9
31	30	32	451.7	0.50			984.844	202.8	202.3
32	32	33	30.9		0.154	13.159		202.3	200.0
33	32	34	430.9	0.39			1072.260	202.3	201.9
34	34	35	30.8		0.154	13.170		201.9	199.6
35	34	36	390.0	0.34			1164.040	201.9	201.6
36	36	37	30.8		0.154	13.180		201.6	199.3
37	36	38	359.2	0.29			1229.446	201.6	201.3
38	38	39	33.0		0.165	12.405		201.3	198.7
39	38	40	326.2	0.24			1333.553	201.3	201.1
40	40	41	35.5		0.178	11.671		201.1	198.0
41	40	42	290.7	0.22			1393.483	201.1	200.8
42	42	43	40.6		0.204	10.379		200.8	197.0
43	42	44	250.0	0.15			1674.879	200.8	200.7
44	44	45	35.0		0.176	11.821		200.7	197.8
45	44	46	215.1	0.11			1906.801	200.7	200.6
46	46	47	40.6		0.205	10.385		200.6	196.7
47	46	48	174.5	0.08			2272.122	200.6	200.5
48	48	49	40.6		0.205	10.386		200.5	196.6
49	48	50	133.8	0.05			2838.943	200.5	200.5
50	50	51	44.6		0.225	9.383		200.5	195.9
51	50	52	89.3	0.03			2963.390	200.5	200.4
52	52	53	44.6		0.222	9.386		200.4	195.8
53	52	54	44.7	0.21			271.822	200.4	200.3
54	54	55	44.7		0.223	127.343		200.3	199.9
55	54	56	6.3	0.00			0.000	200.3	200.3

Case 5: end gun off , design modified

TOTAL ITERATION = 3

NODE NO	HEAD(FT) INITIALIZED (ft)	(psi)	FINAL (ft)	(psi)	DIFFERENCE (ft)	%	DISCHARGE ELEMENT NO	FLOW (gpm)
1	209.78	90.760	209.783	90.76	0.00	0.0	1	824.9
2	208.21	90.093	208.436	90.18	-0.09	-0.0	2	3.1
3	207.09	89.593	208.397	90.16	-0.63	-0.3	3	821.9
4	206.68	89.419	207.075	89.59	-0.19	-0.1	4	3.3
5	205.53	88.919	207.018	89.56	-0.73	-0.4	5	818.1
6	205.14	88.751	205.726	89.01	-0.29	-0.1	6	4.6
7	203.98	88.251	205.646	88.97	-0.82	-0.4	7	813.5
8	203.62	88.093	204.392	88.43	-0.38	-0.2	8	7.1
9	202.46	87.593	204.219	88.35	-0.87	-0.4	9	806.4
10	201.93	87.361	202.898	87.78	-0.48	-0.2	10	3.9
11	200.77	86.861	202.644	87.67	-0.93	-0.5	11	797.5
12	201.44	87.151	202.470	87.60	-0.51	-0.3	12	3.1
13	200.28	86.651	202.252	87.50	-0.98	-0.5	13	789.3
14	200.48	86.737	201.630	87.23	-0.57	-0.3	14	9.9
15	199.33	86.237	201.322	87.10	-1.00	-0.5	15	779.4
16	199.09	86.134	200.401	86.70	-0.66	-0.3	16	11.9
17	197.93	85.634	199.980	86.52	-1.03	-0.5	17	767.6
18	198.19	85.745	199.605	86.36	-0.71	-0.4	18	8.1
19	197.03	85.245	199.390	86.26	-1.20	-0.6	19	759.5
20	197.75	85.554	199.215	86.19	-0.74	-0.4	20	13.5
21	196.59	85.054	198.684	85.96	-1.06	-0.5	21	746.0
22	196.47	85.002	198.084	85.70	-0.82	-0.4	22	15.5
23	195.32	84.502	197.414	85.41	-1.27	-0.5	23	730.5
24	195.26	84.478	196.999	85.23	-0.89	-0.5	24	13.3
25	194.11	83.978	196.102	84.84	-1.03	-0.5	25	712.2
26	194.71	84.240	196.509	85.02	-0.92	-0.5	26	12.4
27	193.56	83.740	196.051	84.82	-1.29	-0.7	27	699.7
28	193.97	83.918	195.842	84.73	-0.97	-0.5	28	21.5
29	192.81	83.418	194.652	84.21	-0.95	-0.5	29	678.2
30	192.92	83.463	194.898	84.32	-1.03	-0.5	30	22.8
31	191.76	82.963	193.585	83.75	-0.95	-0.5	31	655.5
32	192.26	83.179	194.308	84.07	-1.06	-0.6	32	14.2
33	191.11	82.679	193.730	83.81	-1.37	-0.7	33	641.2
34	191.95	83.043	194.026	83.94	-1.08	-0.6	34	22.7
35	190.79	82.543	192.718	83.38	-1.01	-0.5	35	618.5
36	191.06	82.660	193.232	83.60	-1.14	-0.6	36	22.9
37	189.90	82.160	191.908	83.03	-1.05	-0.6	37	595.6
38	190.26	82.314	192.495	83.28	-1.17	-0.6	38	27.6
39	189.10	81.814	190.666	82.49	-0.83	-0.4	39	568.1
40	190.01	82.207	192.270	83.18	-1.19	-0.6	40	18.4
41	188.86	81.707	191.368	82.79	-1.33	-0.7	41	549.7
42	189.45	81.965	191.758	82.96	-1.22	-0.6	42	30.0
43	188.30	81.465	189.634	82.04	-0.71	-0.4	43	519.7
44	188.04	81.699	191.108	82.72	-1.24	-0.7	44	30.0
45	187.68	81.199	189.069	81.80	-0.74	-0.4	45	489.7
46	188.48	81.543	190.848	82.57	-1.26	-0.7	46	22.0
47	187.32	81.043	189.613	82.03	-1.22	-0.7	47	467.7
48	188.31	81.471	190.692	82.50	-1.26	-0.7	48	30.0
49	187.15	80.971	188.573	81.59	-0.76	-0.4	49	437.7
50	187.87	81.279	190.278	82.32	-1.23	-0.7	50	32.1
51	186.71	80.779	187.891	81.29	-0.63	-0.3	51	405.6
52	187.51	81.122	189.922	82.17	-1.29	-0.7	52	34.5
53	186.35	80.622	187.227	81.00	-0.47	-0.3	53	371.1
54	187.40	81.078	189.821	82.12	-1.29	-0.7	54	36.1
55	186.25	80.578	188.156	81.40	-1.02	-0.6	55	335.0
56	187.19	80.384	189.607	82.03	-1.29	-0.7	56	39.5
57	186.03	80.484	186.224	80.56	-0.09	-0.1	57	305.5
58	186.98	80.894	189.337	81.94	-1.29	-0.7	58	33.9
59	185.82	80.394	186.779	80.81	-0.51	-0.3	59	271.6
60	186.88	80.850	189.205	81.89	-1.23	-0.7	60	28.2
61	185.72	80.350	187.377	81.07	-0.89	-0.5	61	243.3
62	185.83	80.831	189.239	81.87	-1.29	-0.7	62	39.5
63	185.68	80.331	185.841	80.40	-0.09	-0.0	63	203.8
64	186.74	80.792	189.140	81.83	-1.28	-0.7	64	39.4
65	185.59	80.292	185.744	80.36	-0.08	-0.0	65	164.4
66	186.69	80.770	189.074	81.63	-1.28	-0.7	66	43.3
67	185.54	80.270	185.087	80.08	0.24	0.1	67	121.1
68	185.68	80.756	189.052	81.80	-1.27	-0.7	68	34.4
69	185.58	80.265	186.377	80.63	-0.46	-0.2	69	98.7
70	186.67	80.761	189.248	81.79	-1.27	-0.7	70	43.3
71	185.52	80.261	185.061	80.06	0.25	0.1	71	43.6
72	186.47	[illegible]	188.926	81.74	-1.21	-0.6	72	43.4
73	185.51	[illegible]	188.566	81.58	-1.65	-0.9	73	0.0

APPENDIX C

SOURCE CODE OF THE SIMULATION MODEL "SYSTEM"

```
REM ***********************************************************************
REM *                         PROGRAM SYSTEM                              *
REM *                                                                     *
REM * THIS PROGRAM CALCULATES THE DISCHARGE-HEAD (Q-H) RELATIONSHIP AT    *
REM *      THE PUMP FOR THE CENTER PIVOT SYSTEM BASED ON THE KNOWN        *
REM *  RELATIONSHIP OF Q-H AT THE PIVOT POINT (CALCULATED BY PROGRAM      *
REM *      "NETWORK") ,SUCTION HEAD,DELIVERY HEAD, AND THE LENGTH         *
REM *                      OF THE MAIN PIPE LINE                          *
REM *THE Q-H RELATIONSHIP DATA OBTAINED FROM THIS PROGRAM IS USED TO      *
REM *         PLOT THE SYSTEM CURVE SO THAT THE OPERATING POINT OF        *
REM *                      THE PUMP CAN BE DETERMINED                     *
REM *                                                                     *
REM *                      WRITTEN IN TURBO-BASIC                         *
REM ***********************************************************************

CLS:INPUT"DELIVERY HEAD (FT)=",DH
INPUT"SUCTION HEAD (FT)=",SH
FIXED=SH+DH
INPUT"ROUGHNESS OF THE PIPE (INCHES)=",E
INPUT"DIAMETER OF THE PIPE (INCHES)=",D
INPUT"DIAMETER OF THE SUCTION PIPE (INCHES)=",DS

MAINDI=D/12:SUCTDI=DS/12
AREA = (3.14/4)*(MAINDI^2):AREAS=(3.14/4)*(SUCTDI^2)
EBYD=E/D:EBYSD=E/DS

INPUT"LENGTH OF THE DELIVERY PIPE (FEET)=",L
INPUT"COEFFICIENT OF THE SYSTEM AT THE PIVOT=",K
INPUT"EXPONENT OF THE SYSTEM AT THE PIVOT=",A

VHC=385.9*(D^4)
OPEN "O",#1,"SYSTEM.DAT"

INPUT"LOWER RANGE OF DISCHARGE IN GPM=",GPM1
INPUT"UPPER RANGE OF DISCHARGE IN GPM=",GPM2

QSUM=GPM1-((GPM2-GPM1)/10)

CLS
PRINT#1,CHR$(18);:PRINT#1, CHR$(27) "E";
PRINT#1, CHR$(27) "G":PRINT#1,
PRINT#1,TAB(12) USING"ELEVATION HEAD (FT)=###.#";DH
PRINT#1,TAB(12) USING"LIFT FROM WATER LEVEL TO GROUND LEVEL (FT)=###.#";SH
PRINT#1,TAB(12) USING"ROUGHNESS OF THE PIPE (INCHES)=#.######";E
PRINT#1,TAB(12) USING"DIAMETER OF THE PIPE (INCHES)=##.####";D
```

```
PRINT#1,TAB(12) USING"DIAMETER OF THE SUCTION PIPE=##.####";DS
PRINT#1,TAB(12) USING"LENGTH OF THE DELIVERY PIPE (FEET)=####.#";L
PRINT#1,TAB(12) USING"COEFFICIENT OF THE SYSTEM AT THE PIVOT=###.####";K
PRINT#1,TAB(12) USING"EXPONENT OF THE SYSTEM AT THE PIVOT=#.####";A
PRINT#1,:PRINT#1,
PRINT#1,TAB(12)_
"QSUM  FIXED H  FRIC HEAD  FRIC HEAD  VEL HEAD   OPR HEAD  TOTAL HEAD"
PRINT#1,TAB(12)_
"GPM     FT      DEL(FT)    SUCT(FT)      FT          FT          FT
PRINT#1,TAB(12)_
"----  -------  ---------  ---------  ---------  --------  ----------"

FOR I=1 TO 11
    QSUM=QSUM+((GPM2-GPM1)/10)
    VELO=QSUM/(448.8*AREA)
    VELOS=QSUM/(448.8*AREAS)
    RENO = (VELO*MAINDI)/(0.00001059)
    RENOS= (VELOS*SUCTDI)/(0.00001059)
    FRICT =1.325 * (LOG(0.27*EBYD + 5.72*((1/RENO)^0.9))^(-2))
    FRICTS=1.325 * (LOG(0.27*EBYDS+ 5.72*((1/RENOS)^0.9))^(-2))
    R=8*FRICT*L / (32.2*(448.8^2)*(3.14159^2)*(MAINDI^5))
    RS=8*FRICTS*SH / (32.2*(448.8^2)*(3.14159^2)*(SUCTDI^5))
    FHEAD=1.1*R*(QSUM^2)
    FHEADS=1.1*RS*(QSUM^2)
    VELHEAD=(QSUM^2)/VHC
    SPRHEAD=(QSUM/K)^(1/A)
    HEAD(I)=FIXED+VELHEAD+SPRHEAD+FHEAD+FHEAD2
    PRINT#1,TAB(12) USING_
  "####  ###.##  ####.####  ####.####   ###.####  ####.###  ####.####";_
   QSUM,FIXED,FHEAD,FHEADS,VELHEAD,SPRHEAD,HEAD(I)
NEXT
PRINT"RUN COMPLETE. OUTPUT FILE IS 'SYSTEM.DAT'"
STOP
END
```

APPENDIX D

SOURCE CODE OF THE AUXILLARY SPRINKLER SIMULATION MODEL "AUXISPR"

```
REM ****************************************************************************
REM *                          PROGRAM AUXISPR                                 *
REM *                                                                          *
REM *  THIS PROGRAM DETERMINES THE POSITION AND REQUIRED CAPACITY OF           *
REM *        THE AUXILLARY SPRINKLERS THAT ARE TO BE ADDED IN THE              *
REM *           CENTER PIVOT IRRIGATION SYSTEM FOR THE                         *
REM *               MODIFICATION OF THE DESIGN SO                              *
REM *      THAT THE PUMP ALWAYS OPERATES AT A FIXED OPERATING POINT            *
REM *                                                                          *
REM *                        WRITTEN IN TURBO-BASIC                            *
REM ****************************************************************************

REM STATEMENT 500 CONTAINS THE DISTANCE OF THE PLUGS FROM THE PIVOT POINT
REM IN THE SYSTEM

    DIM L(100),TOTL(100),QOUT(50),Q(100)

    OPEN "O",#1,"OUTLET.DAT"

    INPUT"END GUN DISCHARGE = ";QE
    INPUT"LENGTH OF THE LATERAL LINE = ";TL
    INPUT"MINIMUM DISCHARGE TO PASS THRU THE AUXILLARY SPRINKLERS = ";QMIN

REM INPUT THE POSITION OF THE PLUGS IN THE SYSEM AT DATA STATEMENT 500

    RESTORE 500
    TOTL(0)=0
    FOR I = 1 TO 100
        READ TOTL(I)
        IF TOTL(I) = 999 THEN OUTNO=I-1:I=100: GOTO 10
10  NEXT I

    FOR I = 1 TO OUTNO
        Q(I)=QE*(1-((TOTL(I)/TL)^2))
    NEXT I

    J=1:QUP=QE:FLAG=0
    PRINT#1,TAB(12)"DESIGN DATA :":PRINT#1,
    PRINT#1,TAB(12) USING"SYSTEM LENGTH = ###.# FT";TL
    PRINT#1,TAB(12) USING"DISCHARGE THRU THE END GUN = ###.# GPM";QE
    PRINT#1,TAB(12) USING_
                   "MINIMUM DISCHARGE THRU THE SPRINKLER =## GPM";QMIN
```

```
    PRINT#1,:PRINT#1,TAB(12)_
" NO   PLUG  DISTANCE FROM   DISCHARGE    SPRINKLER   NOZZLE   EXPECTED"
PRINT#1,TAB(12)_
"        NO    PIVOT (FT)      (GPM)        MODEL       SIZE    PRES(PSI)"

PRINT#1,TAB(12)_
"----  ----  -------------   ---------    ---------   ------   ---------"
    FOR I = 1 TO OUTNO-1
        Q=QUP-Q(I)
        IF Q<QMIN THEN GOTO 20
        IF QUP<>QE AND FLAG>I-NO THEN GOTO 20
        QUP=Q(I)
        QOUT(J)=Q
        L(J)=TOTL(I)
        IF J = 2 THEN FLAG=I-NO
        NO=I
        PRINT#1,
PRINT#1,TAB(12) USING" ##     ##        ###.#        ###.##;J,I,L(J),QOUT(J)
        J=J+1
20  NEXT I

    QTOTAL=0
    FOR I=1 TO J-1
        QTOTAL = QOUT(I) + QTOTAL
    NEXT I
    PRINT#1,:PRINT#1,TAB(12) USING_
    "DISCHARGE DISTRIBUTED ALONG THE LATERAL LINE = ###.# GPM";QTOTAL
    PRINT"OUTPUT IN FILE : OUTLAET.DAT"

500 DATA 9,18,37.5,47,66,75.5,94.5,104,123,132.5,155.5,165,184,193.5,212.5,
        222,241,250.5,269.5,279,302,311.5,330.5,340,359,368.5,387.5,397,
        416,425.5,444.5,458,477,486.5,505.5,515,534,543.5,562.5,572,591,
        600.5,623.5,633,652,661.5,680.5,690,709,718.15,737.5,747,769.3,
        776.3,999
```

APPENDIX E

SOURCE CODE OF THE FIELD PERFORMANCE EVALUATION SIMULATION MODEL "FIELD"

```
REM ***********************************************************************
REM *                         PROGRAM  FIELD                              *
REM *                                                                     *
REM *  THIS PROGRAM SIMULATES THE DEPTH OF APPLICATION OF WATER IN THE    *
REM *FIELD BASED ON THE GIVEN DISCHARGE AND RADIUS OF COVERAGE FROM THE*
REM * FROM INDIVIDUAL SPRINKLERS IN THE CENTER PIVOT IRRIGATION SYSTEM.*
REM * IT ALSO DETERMINES THE TOTAL TIME REQUIRED FOR ONE REVOLUTION OF *
REM * THE CENTER PIVOT IRRIGATION SYSTEM FOR DIFFERENT IRRIGATION DEPTH*
REM *                    AND % OF END GUN ON CONDITION                    *
REM *                                                                     *
REM *                       WRITTEN IN TURBO-BASIC                        *
REM ***********************************************************************

    MV%=40
    DIM SPAC(MV%,2),L(MV%,2),Q(MV%,2),R(MV%,2)
    DIM QMAX(MV%,2),P(50),mRATIO(MV%),nRATIO(MV%),DEPTH(50)
    DIM UNIF(2),DEPTHS(MV%,2),TIMES(15),TIMEX(MV%,2),DEPT(MV%)
    DIM VEL(MV%,2),TIMEEG(3,MV%,2),TIMETOT(MV%,3),EG(3),EGL(3),EOL(3)


    INPUT"NO OF SPRINKLERS = ",SPR
    INPUT"SPEED OF THE LAST TOWER AT 100% MOVEMENT (FT/HR) = ",U
    INPUT"DISTANCE FROM PIVOT TO LAST TOWER (FT) = ",TL
    U=922.05/1.5:TL=765
    TLEN=2*3.141592654*TL
    W1=U/TL : L(0,1)=0:L(0,2)=0

    OPEN "I",#1,"a:\FIELD.DAT\CEOFMOD.DAT"
    OPEN "O",#2,"D:\SRP2\TB\\DATA\FMODD.DAT"

    FOR J = 1 TO 2
        IF J=1 THEN SPR=36
        IF J=2 THEN SPR=28
        FOR I = 1 TO SPR
            INPUT #1,DUMMY,SPAC(I,J),DUM,DUMM,Q(I,J),R(I,J)
            L(I,J)=L(I-1,J)+SPAC(I,J)
        NEXT I
    NEXT J

    RESTORE 900
    FOR I=1 TO 15
        READ TIMES(I)
    NEXT I

    ALL=19:FLG1=0
```

```
FOR L = 1 TO 2
    IF L = 1 THEN PRINT#2,TAB(12)"END GUN OFF":SPR=36
    IF L = 2 THEN PRINT#2,:PRINT#2,TAB(12)"END GUN ON":SPR=28
    IF L=2 THEN QLAST=Q(SPR,L)
    CLS:LOCATE 12,28:PRINT"***PLEASE WAIT****
    LOCATE 14,29:PRINT"COMPUTING SET ";L
    COVER=L(SPR,L)+R(SPR,L)*0.75
    N=INT(COVER/25)
    IF N-(COVER/25)>0.5 THEN N=N-1
    DSUM=0
    FOR K=1 TO 15
        IF K=1 THEN:LOCATE 12,28:PRINT"***PLEASE WAIT****
        PRINT K
        SUMM=0:VAR=0:VAR1=0:VAR2=0:CONS=0:RESULT=0:DSUM=0
        W=W1*(0.01*TIMES(K))
        PRINT#2,
        PRINT#2,TAB(12) USING"TIMER SETTING =### %";W*100/W1
        PRINT#2,TAB(12)" S    DISTANCE     DEPTH"
        PRINT#2,TAB(12)" NO    (FT)       (INCH)
        PRINT#2,TAB(12)"---  --------    -------"
        FOR J= 1 TO N
            P(J)=J*25:SUMM=0:VAR=0:VAR1=0:VAR2=0:CONS=0:RESULT=0
            FOR I = 1 TO SPR
                IF L=2 AND P(J)<787 THEN
                   Q(SPR,2)=0
                  ELSEIF L=2 AND P(J)=>787 THEN
                   Q(SPR,2)=QLAST
                END IF
                mRATIO(I)=(P(J)-L(I,L))/R(I,L)
                IF mRATIO(I)=<-1 THEN GOTO 30
                IF mRATIO(I)=> 1 THEN GOTO 10
                COSN=(L(I,L)^2 + P(J)^2 - R(I,L)^2)/(2*L(I,L)*P(J))
                SINN=(1-(COSN^2))^0.5
                WT=ATN(SINN/COSN)
                QMAX(I,L) =(61.2789*Q(I,L)*.375)/(WT*R(I,L)*L(I,L))
                nRATIO(I) = L(I,L)/R(I,L)
                VAR =(4*(nRATIO(I)*(nRATIO(I)+mRATIO(I))))/(1-(mRATIO(I)^2)
                CALL INTEGRATION(WT,VAR,RESULT)
                SUMM = QMAX(I,L)*((1-mRATIO(I)^2)^0.5)*RESULT + SUMM
10          NEXT I
30          DEPTH(J) = (4/W)*SUMM
            PRINT#2,TAB(12) USING"###  ####.##   ###.###";J,J*25,DEPTH(J)
            DSUM = DSUM + DEPTH(J)
        NEXT J
        AVGD=DSUM/N
        DEPTHS(K,L)=AVGD
        IF AVGD>2 THEN K=15
  NEXT K
```

```
IF L=2 THEN
   VALU=SPR-1
  ELSE
   VALU=SPR
END IF

   COVER=L(VALU,L)+R(VALU,L)*0.75
   N=INT(COVER/25)
   IF N-(COVER/25)>0.5 THEN N=N-1

CALL APPuniformity(N,K,DEPTH(),P(),UNIFORM)
UNIF(L)=UNIFORM
PRINT#2, "% TIMER      AVERAGE"
PRINT#2,"SETTING     DEPTH(IN)"
PRINT#2,"-------     ---------"

FOR K = 1 TO 15
    PRINT#2, USING" ###        ##.###";TIMES(K),DEPTHS(K,L)
    IF DEPTHS(K,L)>2 THEN K=15
NEXT K

DEPT(0)=0.1
FOR I=1 TO 19
    DEPT(I)=DEPT(I-1)+0.1
NEXT I

ADDS=0:K=1
    FOR I=1 TO ALL+1
        IF FLG1=1 THEN
           ADDS=ADDS+0.10
           DEPT(I)=ADDS
        END IF
        IF FLG1=1 AND I=1 AND L=2 THEN
           DEPT(1)=DEPTHS(1,1)
           ADDS=0.1*INT(DEPT(1)*100/10)
        END IF
        IF I=1 AND L=1 AND DEPTHS(1,1)>DEPT(1) THEN
           DEPT(1)=DEPTHS(1,L)
           ADDS=0.1*INT(DEPT(1)*10)
           FLG=1:FLG1=1
           IF L=1 THEN ALL=ALL-((ADDS-0.2)*10)
        END IF
40      IF DEPTHS(K,L)<DEPT(I) THEN
           K=K+1
           IF DEPT(I)>2 THEN
              K=K-1
```

```
                GOTO 45
             END IF
             GOTO 40
          END IF
45 TIMEX(I.L)=TIMES(K-1)-((TIMES(K-1)-TIMES(K))/(DEPTHS(K,L)_
      -DEPTHS(K-1,L)))*(DEPT(I)-DEPTHS(K-1,L))
          IF FLG=1 THEN FLG=0
          VEL(I,L) = U*TIMEX(I,L)/100
       NEXT I
    NEXT L

    EG(1)=0.33 : EG(2)=0.50 : EG(3)=0.66
    PRINT#2,
PRINT#2,TAB(12) USING"APPLICATION UNIFORMITY (END GUN ON) =##.#";UNIF(2)
PRINT#2,TAB(12) USING"APPLICATION UNIFORMITY (END GUN OFF)=##.#";UNIF(1)
PRINT#2,:PRINT#2,TAB(12)"UNMODIFIED SYSTEM WITH CONSTANT TIMER"

    FOR P = 1 TO 3
        EGL(P)=TLEN*EG(P)
        EOL(P)=TLEN*(1-EG(P))
    PRINT#2,
 PRINT#2,TAB(12)_
"PERCENTAGE OF DISTANCE COVERED WITH END GUN ON = ";EG(P)*100
 PRINT#2,:PRINT#2,TAB(12)_
"             GUN ON          GUN OFF          AVERAGE"
PRINT#2,TAB(12)_
"   %     DEPTH   TIME  DEPTH    TIME    DEPTH    TIME  UNIFORMITY"
PRINT#2,TAB(12)_
" TIMER    (IN)   (HR)   (IN)    (HR)    (IN)     (HR)        %"
PRINT#2,TAB(12)_
"------- ------------ ------------ ------------ -----------
        FOR I=1 TO 15
            AVGAPP=EG(P)*DEPTHS(I,2)+(1-EG(P))*DEPTHS(I,1)
            TIME2=EGL(P)/(0.01*TIMES(I)*U)
            TIME1=EOL(P)/(0.01*TIMES(I)*U)
            AVGTIM=TIME1+TIME2
            AVGUNI=((DEPTHS(I,2)*EG(P)*UNIF(2) +_
                        DEPTHS(I,1)*(1-EG(P))*UNIF(1))/(DEPTHS(I,1)))
            PRINT#2,TAB(12) USING_
            " ###     #.##    ##.#    #.##    ##.#     #.##  ##.#  ##.###";_
            TIMES(I),DEPTHS(I,2),TIME2,DEPTHS(I,1),TIME1,AVGAPP,_
                                  AVGTIM,AVGUNI
            IF DEPTHS(I,1)>2 THEN I=15
        NEXT I

        FOR I=1 TO ALL
            TIMEEG(P,I,2)=EGL(P)/VEL(I,2)
```

```
        TIMEEG(P,I,1)=EOL(P)/VEL(I,1)
        TIMETOT(I,P)=TIMEEG(P,I,1)+TIMEEG(P,I,2)
    NEXT I
NEXT P
PRINT#2,:PRINT#2,
PRINT#2,TAB(12) USING" NO OF SPRKNKLERS INCLUDING END GUN= ##";SPR
PRINT#2,TAB(12) USING_
    " SPEED OF THE LAST TOWER AT 100% MOVEMENT (FT/HR)= ###.##";U
PRINT#2,TAB(12) USING_
    " DISTANCE FROM PIVOT TO LAST TOWER (FT) =###.# ";TL
PRINT#2,TAB(12) USING_
    " APPLICATION UNIFORMITY (END GUN ON) =##.#";UNIF(2)
PRINT#2,TAB(12) USING_
    " APPLICATION UNIFORMITY (END GUN OFF)=##.#";UNIF(1)
PRINT#2,:PRINT#2,
FOR P = 1 TO 3
    TOTUNIF = EG(P)*UNIF(2)+(1-EG(P))*UNIF(1)
    PRINT#2,
    PRINT#2,TAB(12) USING_
      " PERCENTAGE OF DISTANCE COVERED WITH GUN ON = ### %";EG(P)*100
    PRINT#2,TAB(12)_
      "DEPTH    END GUN ON    END GUN OFF
    PRINT#2,TAB(12)_
      " IN    TIMER   TIME   TIMER   TIME    UNIFORMITY TOTAL TIME"
    PRINT#2,TAB(12)_
      "INCH     %      HR      %      HR         %            HR"
    PRINT#2,TAB(12)_
      "-----  ------  ----  ------  ----  ----------- ----------"
    FOR I = 1 TO ALL
      PRINT#2,TAB(12) USING_
      "##.##   ###.##  ##.##  ###.##  ##.##     ##.##       ###.##";_
       DEPT(I),TIMEX(I,2),TIMEEG(P,I,2),TIMEX(I,1),TIMEEG(P,I,1),_
              TOTUNIF,TIMETOT(I,P)
    NEXT I
print#2,:print#2,
NEXT P
PRINT"DONE":STOP
END

SUB APPuniformity(N,K,D(2),P(1),UNIFORM)
SUM1=0 : SUM2 = 0 : SUM3 = 0
FOR J = 1 TO N
    SUM1 = P(J)*D(J,K) + SUM1
    SUM2 = P(J) + SUM2
NEXT J
CONS = SUM1/SUM2
FOR J = 1 TO N
    SUM3 = P(J)*(ABS(D(J,K)-CONS)) + SUM3
```

```
    NEXT J
    UNIFORM = 100*(1.0 - (SUM3/SUM1))
    END SUB

    SUB INTEGRATION(WT,VAR,RESULT)
    H = WT/50
    SUM=0
    SUM = (1-VAR*SIN(0)*SIN(0))^0.5
50  FOR I = 1 TO 50
        IF I = 50 THEN
            A=(1-VAR*SIN((I*H)/2)*SIN((I*H)/2))
            IF A<0.0 THEN A=0
            SUM = SUM + A^0.5
          ELSE
            A=(1-VAR*SIN((I*H)/2)*SIN((I*H)/2))
            IF A<0 THEN A=0
            SUM = SUM + 2*(A^0.5)
        END IF
    NEXT I
    RESULT = SUM*(H/2)
    END SUB


REM DATA OBTAINED FROM HEERMANN AND HEIN ASAE PAPER
500 DATA 40,50.3,2.5,40,83.4,2.8,40,115.4,3.0,44,
    DATA 147.4,4.8,44,179.4,4.7
    DATA 47,211.4,5.7,49,243.4,6.7,49,275.4,6.8,49,
    DATA 307.4,6.9,50,339.4,7.9
    DATA 52,371.4,9.3,51,403.4,9.1,51,435.4,9.1,53,
    DATA 467.4,11.6,53,499.4,11.4
    DATA 53,531.4,11.2,53,563.4,11.2,53,595.4,11.4,62,
    DATA 627.4,13.9,62,659.4,13.9
    DATA 61,691.4,13.5,61,723.4,13.5,61,755.4,13.5,58,
    DATA 787.4,14.1,58,819.4,15.1
    DATA 58,851.4,15.1,60,833.4,16.3,60,915.4,16.3,61,
    DATA 947.4,17.7,61,979.4,17.9
    DATA 61,1011.5,17.7,61,1044.6,17.9,61,
    DATA 1068.6,20.2,63,1092.6,20.8
    DATA 63,1125.7,20.8,63,1149.7,20.8,63,1173.6,23.1,63,
    DATA 1206.7,23.1,63,1230.7,14.3

    REM % OF TIME END GUN IS ON
900 DATA 100,75,60,50,42,34,29,24,21,18,16,14,11,9,7
```

APPENDIX F

OUTPUT FROM THE SIMULATION MODEL "FIELD"

END GUN ON

TIMER SETTING = 100 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.403
2	50.00	0.491
3	75.00	0.303
4	100.00	0.217
5	125.00	0.239
6	150.00	0.265
7	175.00	0.283
8	200.00	0.296
9	225.00	0.301
10	250.00	0.293
11	275.00	0.280
12	300.00	0.263
13	325.00	0.219
14	350.00	0.227
15	375.00	0.256
16	400.00	0.301
17	425.00	0.323
18	450.00	0.346
19	475.00	0.337
20	500.00	0.307
21	525.00	0.279
22	550.00	0.274
23	575.00	0.274
24	600.00	0.280
25	625.00	0.283
26	650.00	0.285
27	675.00	0.284
28	700.00	0.278
29	725.00	0.266
30	750.00	0.232
31	775.00	0.184
32	800.00	0.203
33	825.00	0.150
34	850.00	0.103
35	875.00	0.067
36	900.00	0.063
37	925.00	0.061
38	950.00	0.058
39	975.00	0.054
40	1000.00	0.049

TIMER SETTING = 60 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.671
2	50.00	0.818
3	75.00	0.505
4	100.00	0.362
5	125.00	0.398
6	150.00	0.442
7	175.00	0.471
8	200.00	0.494
9	225.00	0.502
10	250.00	0.488
11	275.00	0.466
12	300.00	0.439
13	325.00	0.366
14	350.00	0.378
15	375.00	0.427
16	400.00	0.502
17	425.00	0.539
18	450.00	0.576
19	475.00	0.561
20	500.00	0.512
21	525.00	0.465
22	550.00	0.456
23	575.00	0.457
24	600.00	0.467
25	625.00	0.471
26	650.00	0.475
27	675.00	0.473
28	700.00	0.463
29	725.00	0.443
30	750.00	0.386
31	775.00	0.307
32	800.00	0.339
33	825.00	0.250
34	850.00	0.171
35	875.00	0.112
36	900.00	0.106
37	925.00	0.101
38	950.00	0.096
39	975.00	0.090
40	1000.00	0.082

TIMER SETTING = 42 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.959
2	50.00	1.169
3	75.00	0.721
4	100.00	0.518
5	125.00	0.568
6	150.00	0.631
7	175.00	0.673
8	200.00	0.706
9	225.00	0.718
10	250.00	0.697
11	275.00	0.666
12	300.00	0.627
13	325.00	0.522
14	350.00	0.540
15	375.00	0.609
16	400.00	0.718
17	425.00	0.770
18	450.00	0.823
19	475.00	0.802
20	500.00	0.732
21	525.00	0.665
22	550.00	0.651
23	575.00	0.653
24	600.00	0.667
25	625.00	0.673
26	650.00	0.679
27	675.00	0.675
28	700.00	0.661
29	725.00	0.632
30	750.00	0.551
31	775.00	0.438
32	800.00	0.484
33	825.00	0.357
34	850.00	0.244
35	875.00	0.159
36	900.00	0.151
37	925.00	0.145
38	950.00	0.138
39	975.00	0.129
40	1000.00	0.118

TIMER SETTING = 75 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.537
2	50.00	0.654
3	75.00	0.404
4	100.00	0.290
5	125.00	0.318
6	150.00	0.353
7	175.00	0.377
8	200.00	0.395
9	225.00	0.402
10	250.00	0.391
11	275.00	0.373
12	300.00	0.351
13	325.00	0.292
14	350.00	0.303
15	375.00	0.341
16	400.00	0.402
17	425.00	0.431
18	450.00	0.461
19	475.00	0.449
20	500.00	0.410
21	525.00	0.372
22	550.00	0.365
23	575.00	0.366
24	600.00	0.373
25	625.00	0.377
26	650.00	0.380
27	675.00	0.378
28	700.00	0.370
29	725.00	0.354
30	750.00	0.309
31	775.00	0.246
32	800.00	0.271
33	825.00	0.200
34	850.00	0.137
35	875.00	0.089
36	900.00	0.084
37	925.00	0.081
38	950.00	0.077
39	975.00	0.072
40	1000.00	0.066

TIMER SETTING = 50 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.805
2	50.00	0.982
3	75.00	0.606
4	100.00	0.435
5	125.00	0.477
6	150.00	0.530
7	175.00	0.565
8	200.00	0.593
9	225.00	0.603
10	250.00	0.586
11	275.00	0.560
12	300.00	0.527
13	325.00	0.439
14	350.00	0.454
15	375.00	0.512
16	400.00	0.603
17	425.00	0.646
18	450.00	0.692
19	475.00	0.674
20	500.00	0.615
21	525,00	0.558
22	550.00	0.547
23	575.00	0.549
24	600.00	0.560
25	625.00	0.565
26	650.00	0.570
27	675.00	0.567
28	700.00	0.555
29	725.00	0.531
30	750.00	0.463
31	775.00	0.368
32	800.00	0.406
33	825.00	0.300
34	850.00	0.205
35	875.00	0.134
36	900.00	0.127
37	925.00	0.122
38	950.00	0.116
39	975.00	0.108
40	1000.00	0.099

TIMER SETTING = 34 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.184
2	50.00	1.443
3	75.00	0.891
4	100.00	0.639
5	125.00	0.702
6	150.00	0.779
7	175.00	0.831
8	200.00	0.872
9	225.00	0.886
10	250.00	0.861
11	275.00	0.823
12	300.00	0.775
13	325.00	0.645
14	350.00	0.668
15	375.00	0.753
16	400.00	0.886
17	425.00	0.951
18	450.00	1.017
19	475.00	0.991
20	500.00	0.904
21	525.00	0.821
22	550.00	0.804
23	575.00	0.807
24	600.00	0.824
25	625.00	0.831
26	650.00	0.839
27	675.00	0.834
28	700.00	0.817
29	725.00	0.781
30	750.00	0.681
31	775.00	0.542
32	800.00	0.598
33	825.00	0.441
34	850.00	0.302
35	875.00	0.197
36	900.00	0.186
37	925.00	0.179
38	950.00	0.170
39	975.00	0.159
40	1000.00	0.145

TIMER SETTING = 29 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.388
2	50.00	1.692
3	75.00	1.044
4	100.00	0.750
5	125.00	0.823
6	150.00	0.913
7	175.00	0.975
8	200.00	1.022
9	225.00	1.039
10	250.00	1.010
11	275.00	0.965
12	300.00	0.909
13	325.00	0.756
14	350.00	0.783
15	375.00	0.883
16	400.00	1.039
17	425.00	1.114
18	450.00	1.192
19	475.00	1.162
20	500.00	1.060
21	525.00	0.963
22	550.00	0.943
23	575.00	0.946
24	600.00	0.966
25	625.00	0.974
26	650.00	0.983
27	675.00	0.978
28	700.00	0.957
29	725.00	0.916
30	750.00	0.798
31	775.00	0.635
32	800.00	0.701
33	825.00	0.517
34	850.00	0.354
35	875.00	0.231
36	900.00	0.218
37	925.00	0.210
38	950.00	0.199
39	975.00	0.187
40	1000.00	0.170

TIMER SETTING = 21 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.917
2	50.00	2.337
3	75.00	1.442
4	100.00	1.035
5	125.00	1.136
6	150.00	1.261
7	175.00	1.346
8	200.00	1.411
9	225.00	1.435
10	250.00	1.395
11	275.00	1.333
12	300.00	1.255
13	325.00	1.045
14	350.00	1.081
15	375.00	1.219
16	400.00	1.435
17	425.00	1.539
18	450.00	1.647
19	475.00	1.604
20	500.00	1.463
21	525.00	1.329
22	550.00	1.302
23	575.00	1.307
24	600.00	1.334
25	625.00	1.345
26	650.00	1.358
27	675.00	1.350
28	700.00	1.322
29	725.00	1.265
30	750.00	1.102
31	775.00	0.877
32	800.00	0.968
33	825.00	0.715
34	850.00	0.488
35	875.00	0.319
36	900.00	0.301
37	925.00	0.290
38	950.00	0.275
39	975.00	0.258
40	1000.00	0.235

TIMER SETTING = 16 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.517
2	50.00	3.067
3	75.00	1.892
4	100.00	1.359
5	125.00	1.491
6	150.00	1.656
7	175.00	1.767
8	200.00	1.852
9	225.00	1.884
10	250.00	1.831
11	275.00	1.749
12	300.00	1.647
13	325.00	1.371
14	350.00	1.419
15	375.00	1.600
16	400.00	1.883
17	425.00	2.020
18	450.00	2.161
19	475.00	2.106
20	500.00	1.921
21	525.00	1.745
22	550.00	1.709
23	575.00	1.715
24	600.00	1.751
25	625.00	1.766
26	650.00	1.782
27	675.00	1.772
28	700.00	1.735
29	725.00	1.660
30	750.00	1.447
31	775.00	1.151
32	800.00	1.270
33	825.00	0.938
34	850.00	0.641
35	875.00	0.418
36	900.00	0.396
37	925.00	0.381
38	950.00	0.362
39	975.00	0.338
40	1000.00	0.309

TIMER SETTING = 24 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.678
2	50.00	2.045
3	75.00	1.262
4	100.00	0.906
5	125.00	0.994
6	150.00	1.104
7	175.00	1.178
8	200.00	1.235
9	225.00	1.256
10	250.00	1.220
11	275.00	1.166
12	300.00	1.098
13	325.00	0.914
14	350.00	0.946
15	375.00	1.067
16	400.00	1.256
17	425.00	1.347
18	450.00	1.441
19	475.00	1.404
20	500.00	1.281
21	525.00	1.163
22	550.00	1.140
23	575.00	1.143
24	600.00	1.167
25	625.00	1.177
26	650.00	1.188
27	675.00	1.181
28	700.00	1.157
29	725.00	1.107
30	750.00	0.965
31	775.00	0.767
32	800.00	0.847
33	825.00	0.625
34	850.00	0.427
35	875.00	0.279
36	900.00	0.264
37	925.00	0.254
38	950.00	0.241
39	975.00	0.225
40	1000.00	0.206

TIMER SETTING = 18 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.237
2	50.00	2.727
3	75.00	1.682
4	100.00	1.208
5	125.00	1.326
6	150.00	1.472
7	175.00	1.571
8	200.00	1.647
9	225.00	1.674
10	250.00	1.627
11	275.00	1.555
12	300.00	1.464
13	325.00	1.219
14	350.00	1.261
15	375.00	1.422
16	400.00	1.674
17	425.00	1.796
18	450.00	1.921
19	475.00	1.872
20	500.00	1.707
21	525.00	1.551
22	550.00	1.520
23	575.00	1.524
24	600.00	1.556
25	625.00	1.570
26	650.00	1.584
27	675.00	1.575
28	700.00	1.543
29	725.00	1.476
30	750.00	1.286
31	775.00	1.023
32	800.00	1.129
33	825.00	0.834
34	850.00	0.570
35	875.00	0.372
36	900.00	0.352
37	925.00	0.338
38	950.00	0.321
39	975.00	0.301
40	1000.00	0.275

TIMER SETTING = 14 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.876
2	50.00	3.506
3	75.00	2.163
4	100.00	1.553
5	125.00	1.704
6	150.00	1.892
7	175.00	2.019
8	200.00	2.117
9	225.00	2.153
10	250.00	2.092
11	275.00	1.999
12	300.00	1.882
13	325.00	1.567
14	350.00	1.621
15	375.00	1.828
16	400.00	2.153
17	425.00	2.309
18	450.00	2.470
19	475.00	2.406
20	500.00	2.195
21	525.00	1.994
22	550.00	1.954
23	575.00	1.960
24	600.00	2.001
25	625.00	2.018
26	650.00	2.037
27	675.00	2.025
28	700.00	1.983
29	725.00	1.897
30	750.00	1.654
31	775.00	1.315
32	800.00	1.451
33	825.00	1.072
34	850.00	0.732
35	875.00	0.478
36	900.00	0.452
37	925.00	0.435
38	950.00	0.413
39	975.00	0.386
40	1000.00	0.353

TIMER SETTING = 11 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	3.660
2	50.00	4.462
3	75.00	2.753
4	100.00	1.976
5	125.00	2.169
6	150.00	2.408
7	175.00	2.570
8	200.00	2.694
9	225.00	2.740
10	250.00	2.663
11	275.00	2.544
12	300.00	2.395
13	325.00	1.994
14	350.00	2.063
15	375.00	2.327
16	400.00	2.740
17	425.00	2.938
18	450.00	3.144
19	475.00	3.063
20	500.00	2.794
21	525.00	2.538
22	550.00	2.487
23	575.00	2.495
24	600.00	2.546
25	625.00	2.569
26	650.00	2.592
27	675.00	2.577
28	700.00	2.524
29	725.00	2.415
30	750.00	2.105
31	775.00	1.674
32	800.00	1.847
33	825.00	1.364
34	850.00	0.932
35	875.00	0.609
36	900.00	0.576
37	925.00	0.554
38	950.00	0.526
39	975.00	0.492
40	1000.00	0.449

% TIMER SETTING	AVERAGE DEPTH (IN)
100	0.242
75	0.323
60	0.403
50	0.484
42	0.576
34	0.712
29	0.834
24	1.008
21	1.152
18	1.344
16	1.512
14	1.728
11	2.199

END GUN OFF WITH PUMP #

TIMER SETTING = 100 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.418
2	50.00	0.507
3	75.00	0.313
4	100.00	0.223
5	125.00	0.243
6	150.00	0.271
7	175.00	0.290
8	200.00	0.306
9	225.00	0.308
10	250.00	0.300
11	275.00	0.291
12	300.00	0.272
13	325.00	0.230
14	350.00	0.238
15	375.00	0.267
16	400.00	0.314
17	425.00	0.337
18	450.00	0.361
19	475.00	0.353
20	500.00	0.323
21	525.00	0.292
22	550.00	0.286
23	575.00	0.288
24	600.00	0.294
25	625.00	0.297
26	650.00	0.302
27	675.00	0.300
28	700.00	0.292
29	725.00	0.275
30	750.00	0.239
31	775.00	0.190
32	800.00	0.141
33	825.00	0.087
34	850.00	0.038

TIMER SETTING = 60 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.697
2	50.00	0.846
3	75.00	0.521
4	100.00	0.371
5	125.00	0.405
6	150.00	0.452
7	175.00	0.483
8	200.00	0.510
9	225.00	0.514
10	250.00	0.500
11	275.00	0.485
12	300.00	0.454
13	325.00	0.383
14	350.00	0.396
15	375.00	0.444
16	400.00	0.524
17	425.00	0.562
18	450.00	0.602
19	475.00	0.588
20	500.00	0.538
21	525.00	0.487
22	550.00	0.477
23	575.00	0.479
24	600.00	0.490
25	625.00	0.495
26	650.00	0.503
27	675.00	0.500
28	700.00	0.487
29	725.00	0.459
30	750.00	0.398
31	775.00	0.316
32	800.00	0.235
33	825.00	0.144
34	850.00	0.064

TIMER SETTING = 42 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.996
2	50.00	1.208
3	75.00	0.744
4	100.00	0.530
5	125.00	0.57
6	150.00	0.646
7	175.00	0.690
8	200.00	0.728
9	225.00	0.734
10	250.00	0.714
11	275.00	0.692
12	300.00	0.649
13	325.00	0.548
14	350.00	0.566
15	375.00	0.635
16	400.00	0.748
17	425.00	0.803
18	450.00	0.860
19	475.00	0.839
20	500.00	0.769
21	525.00	0.696
22	550.00	0.682
23	575.00	0.685
24	600.00	0.700
25	625.00	0.707
26	650.00	0.718
27	675.00	0.715
28	700.00	0.696
29	725.00	0.655
30	750.00	0.569
31	775.00	0.452
32	800.00	0.335
33	825.00	0.206
34	850.00	0.091

TIMER SETTING = 75 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.558
2	50.00	0.677
3	75.00	0.417
4	100.00	0.297
5	125.00	0.324
6	150.00	0.362
7	175.00	0.387
8	200.00	0.408
9	225.00	0.411
10	250.00	0.400
11	275.00	0.388
12	300.00	0.363
13	325.00	0.307
14	350.00	0.317
15	375.00	0.356
16	400.00	0.419
17	425.00	0.450
18	450.00	0.482
19	475.00	0.470
20	500.00	0.431
21	525.00	0.390
22	550.00	0.382
23	575.00	0.383
24	600.00	0.392
25	625.00	0.396
26	650.00	0.402
27	675.00	0.400
28	700.00	0.390
29	725.00	0.367
30	750.00	0.319
31	775.00	0.253
32	800.00	0.188
33	825.00	0.116
34	850.00	0.051

TIMER SETTING = 50 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.837
2	50.00	1.015
3	75.00	0.625
4	100.00	0.445
5	125.00	0.486
6	150.00	0.542
7	175.00	0.580
8	200.00	0.612
9	225.00	0.617
10	250.00	0.600
11	275.00	0.582
12	300.00	0.545
13	325.00	0.460
14	350.00	0.476
15	375.00	0.533
16	400.00	0.628
17	425.00	0.675
18	450.00	0.723
19	475.00	0.705
20	500.00	0.646
21	525.00	0.584
22	550.00	0.573
23	575.00	0.575
24	600.00	0.588
25	625.00	0.594
26	650.00	0.604
27	675.00	0.600
28	700.00	0.584
29	725.00	0.551
30	750.00	0.478
31	775.00	0.379
32	800.00	0.282
33	825.00	0.173
34	850.00	0.077

TIMER SETTING = 34 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.231
2	50.00	1.492
3	75.00	0.919
4	100.00	0.655
5	125.00	0.715
6	150.00	0.798
7	175.00	0.853
8	200.00	0.900
9	225.00	0.907
10	250.00	0.882
11	275.00	0.855
12	300.00	0.801
13	325.00	0.677
14	350.00	0.700
15	375.00	0.784
16	400.00	0.924
17	425.00	0.992
18	450.00	1.063
19	475.00	1.037
20	500.00	0.950
21	525.00	0.859
22	550.00	0.842
23	575.00	0.846
24	600.00	0.864
25	625.00	0.873
26	650.00	0.888
27	675.00	0.883
28	700.00	0.859
29	725.00	0.810
30	750.00	0.703
31	775.00	0.558
32	800.00	0.414
33	825.00	0.255
34	850.00	0.113

TIMER SETTING = 29 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.443
2	50.00	1.750
3	75.00	1.078
4	100.00	0.768
5	125.00	0.838
6	150.00	0.935
7	175.00	1.000
8	200.00	1.055
9	225.00	1.063
10	250.00	1.034
11	275.00	1.003
12	300.00	0.939
13	325.00	0.793
14	350.00	0.820
15	375.00	0.919
16	400.00	1.083
17	425.00	1.163
18	450.00	1.246
19	475.00	1.216
20	500.00	1.114
21	525.00	1.007
22	550.00	0.987
23	575.00	0.991
24	600.00	1.013
25	625.00	1.024
26	650.00	1.041
27	675.00	1.035
28	700.00	1.008
29	725.00	0.949
30	750.00	0.824
31	775.00	0.654
32	800.00	0.486
33	825.00	0.299
34	850.00	0.132

TIMER SETTING = 21 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.992
2	50.00	2.416
3	75.00	1.488
4	100.00	1.060
5	125.00	1.157
6	150.00	1.291
7	175.00	1.381
8	200.00	1.457
9	225.00	1.468
10	250.00	1.427
11	275.00	1.385
12	300.00	1.297
13	325.00	1.095
14	350.00	1.133
15	375.00	1.270
16	400.00	1.496
17	425.00	1.606
18	450.00	1.720
19	475.00	1.679
20	500.00	1.538
21	525.00	1.391
22	550.00	1.363
23	575.00	1.369
24	600.00	1.399
25	625.00	1.414
26	650.00	1.437
27	675.00	1.430
28	700.00	1.392
29	725.00	1.311
30	750.00	1.138
31	775.00	0.903
32	800.00	0.671
33	825.00	0.413
34	850.00	0.183

TIMER SETTING = 16 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.615
2	50.00	3.171
3	75.00	1.954
4	100.00	1.392
5	125.00	1.519
6	150.00	1.695
7	175.00	1.812
8	200.00	1.912
9	225.00	1.927
10	250.00	1.873
11	275.00	1.818
12	300.00	1.703
13	325.00	1.438
14	350.00	1.487
15	375.00	1.667
16	400.00	1.963
17	425.00	2.108
18	450.00	2.258
19	475.00	2.203
20	500.00	2.019
21	525.00	1.826
22	550.00	1.789
23	575.00	1.797
24	600.00	1.837
25	625.00	1.855
26	650.00	1.886
27	675.00	1.876
28	700.00	1.826
29	725.00	1.721
30	750.00	1.493
31	775.00	1.185
32	800.00	0.880
33	825.00	0.542
34	850.00	0.240

TIMER SETTING = 24 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.743
2	50.00	2.114
3	75.00	1.302
4	100.00	0.928
5	125.00	1.013
6	150.00	1.130
7	175.00	1.208
8	200.00	1.275
9	225.00	1.285
10	250.00	1.249
11	275.00	1.212
12	300.00	1.135
13	325.00	0.959
14	350.00	0.991
15	375.00	1.111
16	400.00	1.309
17	425.00	1.405
18	450.00	1.505
19	475.00	1.469
20	500.00	1.346
21	525.00	1.217
22	550.00	1.193
23	575.00	1.198
24	600.00	1.224
25	625.00	1.237
26	650.00	1.257
27	675.00	1.251
28	700.00	1.218
29	725.00	1.147
30	750.00	0.996
31	775.00	0.790
32	800.00	0.587
33	825.00	0.361
34	850.00	0.160

TIMER SETTING = 18 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.324
2	50.00	2.819
3	75.00	1.737
4	100.00	1.237
5	125.00	1.350
6	150.00	1.507
7	175.00	1.611
8	200.00	1.700
9	225.00	1.713
10	250.00	1.665
11	275.00	1.616
12	300.00	1.514
13	325.00	1.278
14	350.00	1.322
15	375.00	1.481
16	400.00	1.745
17	425.00	1.874
18	450.00	2.007
19	475.00	1.959
20	500.00	1.795
21	525.00	1.623
22	550.00	1.590
23	575.00	1.597
24	600.00	1.633
25	625.00	1.649
26	650.00	1.676
27	675.00	1.668
28	700.00	1.623
29	725.00	1.529
30	750.00	1.327
31	775.00	1.054
32	800.00	0.782
33	825.00	0.482
34	850.00	0.213

TIMER SETTING = 14 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.988
2	50.00	3.624
3	75.00	2.233
4	100.00	1.591
5	125.00	1.736
6	150.00	1.937
7	175.00	2.071
8	200.00	2.185
9	225.00	2.202
10	250.00	2.141
11	275.00	2.077
12	300.00	1.946
13	325.00	1.643
14	350.00	1.699
15	375.00	1.905
16	400.00	2.244
17	425.00	2.409
18	450.00	2.580
19	475.00	2.518
20	500.00	2.307
21	525.00	2.087
22	550.00	2.045
23	575.00	2.054
24	600.00	2.099
25	625.00	2.120
26	650.00	2.155
27	675.00	2.144
28	700.00	2.087
29	725.00	1.966
30	750.00	1.707
31	775.00	1.355
32	800.00	1.006
33	825.00	0.619
34	850.00	0.274

TIMER SETTING = 11 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	3.803
2	50.00	4.613
3	75.00	2.842
4	100.00	2.024
5	125.00	2.209
6	150.00	2.465
7	175.00	2.636
8	200.00	2.781
9	225.00	2.803
10	250.00	2.725
11	275.00	2.644
12	300.00	2.477
13	325.00	2.091
14	350.00	2.162
15	375.00	2.424
16	400.00	2.856
17	425.00	3.066
18	450.00	3.284
19	475.00	3.205
20	500.00	2.937
21	525.00	2.656
22	550.00	2.602
23	575.00	2.614
24	600.00	2.672
25	625.00	2.699
26	650.00	2.743
27	675.00	2.729
28	700.00	2.657
29	725.00	2.503
30	750.00	2.172
31	775.00	1.724
32	800.00	1.280
33	825.00	0.788
34	850.00	0.349

% TIMER SETTING	AVERAGE DEPTH (IN)
100	0.279
75	0.372
60	0.465
50	0.558
42	0.664
34	0.821
29	0.962
24	1.162
21	1.329
18	1.550
16	1.744
14	1.993
11	2.536

END GUN OFF WITH PUMP V

TIMER SETTING = 100 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.528
2	50.00	0.623
3	75.00	0.385
4	100.00	0.263
5	125.00	0.308
6	150.00	0.342
7	175.00	0.350
8	200.00	0.358
9	225.00	0.355
10	250.00	0.364
11	275.00	0.353
12	300.00	0.325
13	325.00	0.299
14	350.00	0.313
15	375.00	0.350
16	400.00	0.385
17	425.00	0.414
18	450.00	0.444
19	475.00	0.433
20	500.00	0.397
21	525.00	0.359
22	550.00	0.352
23	575.00	0.354
24	600.00	0.362
25	625.00	0.365
26	650.00	0.374
27	675.00	0.372
28	700.00	0.358
29	725.00	0.331
30	750.00	0.284
31	775.00	0.224
32	800.00	0.169
33	825.00	0.105
34	850.00	0.065

TIMER SETTING = 60 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.880
2	50.00	1.038
3	75.00	0.641
4	100.00	0.438
5	125.00	0.514
6	150.00	0.570
7	175.00	0.583
8	200.00	0.596
9	225.00	0.591
10	250.00	0.606
11	275.00	0.588
12	300.00	0.541
13	325.00	0.499
14	350.00	0.521
15	375.00	0.583
16	400.00	0.642
17	425.00	0.690
18	450.00	0.739
19	475.00	0.722
20	500.00	0.661
21	525.00	0.599
22	550.00	0.586
23	575.00	0.589
24	600.00	0.603
25	625.00	0.609
26	650.00	0.624
27	675.00	0.620
28	700.00	0.597
29	725.00	0.551
30	750.00	0.473
31	775.00	0.374
32	800.00	0.281
33	825.00	0.175
34	850.00	0.108

TIMER SETTING = 42 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.258
2	50.00	1.483
3	75.00	0.916
4	100.00	0.625
5	125.00	0.734
6	150.00	0.814
7	175.00	0.833
8	200.00	0.852
9	225.00	0.845
10	250.00	0.866
11	275.00	0.840
12	300.00	0.773
13	325.00	0.713
14	350.00	0.745
15	375.00	0.833
16	400.00	0.917
17	425.00	0.985
18	450.00	1.056
19	475.00	1.031
20	500.00	0.945
21	525.00	0.856
22	550.00	0.838
23	575.00	0.842
24	600.00	0.861
25	625.00	0.870
26	650.00	0.891
27	675.00	0.885
28	700.00	0.852
29	725.00	0.787
30	750.00	0.676
31	775.00	0.534
32	800.00	0.402
33	825.00	0.250
34	850.00	0.155

TIMER SETTING = 75 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.704
2	50.00	0.830
3	75.00	0.513
4	100.00	0.350
5	125.00	0.411
6	150.00	0.456
7	175.00	0.466
8	200.00	0.477
9	225.00	0.473
10	250.00	0.485
11	275.00	0.471
12	300.00	0.433
13	325.00	0.399
14	350.00	0.417
15	375.00	0.467
16	400.00	0.514
17	425.00	0.552
18	450.00	0.591
19	475.00	0.577
20	500.00	0.529
21	525.00	0.479
22	550.00	0.469
23	575.00	0.472
24	600.00	0.482
25	625.00	0.487
26	650.00	0.499
27	675.00	0.496
28	700.00	0.477
29	725.00	0.441
30	750.00	0.379
31	775.00	0.299
32	800.00	0.225
33	825.00	0.140
34	850.00	0.087

TIMER SETTING = 50 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.056
2	50.00	1.245
3	75.00	0.770
4	100.00	0.525
5	125.00	0.617
6	150.00	0.684
7	175.00	0.699
8	200.00	0.715
9	225.00	0.710
10	250.00	0.727
11	275.00	0.706
12	300.00	0.649
13	325.00	0.599
14	350.00	0.626
15	375.00	0.700
16	400.00	0.771
17	425.00	0.828
18	450.00	0.887
19	475.00	0.866
20	500.00	0.794
21	525.00	0.719
22	550.00	0.704
23	575.00	0.707
24	600.00	0.723
25	625.00	0.731
26	650.00	0.749
27	675.00	0.744
28	700.00	0.716
29	725.00	0.661
30	750.00	0.568
31	775.00	0.449
32	800.00	0.338
33	825.00	0.210
34	850.00	0.130

TIMER SETTING = 34 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.553
2	50.00	1.832
3	75.00	1.132
4	100.00	0.773
5	125.00	0.907
6	150.00	1.006
7	175.00	1.029
8	200.00	1.052
9	225.00	1.043
10	250.00	1.070
11	275.00	1.038
12	300.00	0.955
13	325.00	0.881
14	350.00	0.920
15	375.00	1.030
16	400.00	1.133
17	425.00	1.217
18	450.00	1.305
19	475.00	1.274
20	500.00	1.167
21	525.00	1.057
22	550.00	1.035
23	575.00	1.040
24	600.00	1.063
25	625.00	1.075
26	650.00	1.101
27	675.00	1.094
28	700.00	1.053
29	725.00	0.972
30	750.00	0.835
31	775.00	0.660
32	800.00	0.497
33	825.00	0.308
34	850.00	0.191

TIMER SETTING = 29 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.821
2	50.00	2.147
3	75.00	1.327
4	100.00	0.906
5	125.00	1.063
6	150.00	1.179
7	175.00	1.206
8	200.00	1.233
9	225.00	1.223
10	250.00	1.254
11	275.00	1.217
12	300.00	1.119
13	325.00	1.032
14	350.00	1.079
15	375.00	1.207
16	400.00	1.329
17	425.00	1.427
18	450.00	1.529
19	475.00	1.493
20	500.00	1.368
21	525.00	1.239
22	550.00	1.213
23	575.00	1.219
24	600.00	1.247
25	625.00	1.260
26	650.00	1.291
27	675.00	1.282
28	700.00	1.235
29	725.00	1.140
30	750.00	0.979
31	775.00	0.773
32	800.00	0.582
33	825.00	0.362
34	850.00	0.224

TIMER SETTING = 21 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.515
2	50.00	2.965
3	75.00	1.833
4	100.00	1.251
5	125.00	1.468
6	150.00	1.628
7	175.00	1.665
8	200.00	1.703
9	225.00	1.689
10	250.00	1.732
11	275.00	1.680
12	300.00	1.545
13	325.00	1.426
14	350.00	1.490
15	375.00	1.667
16	400.00	1.835
17	425.00	1.971
18	450.00	2.112
19	475.00	2.062
20	500.00	1.890
21	525.00	1.711
22	550.00	1.676
23	575.00	1.684
24	600.00	1.722
25	625.00	1.740
26	650.00	1.782
27	675.00	1.771
28	700.00	1.705
29	725.00	1.574
30	750.00	1.352
31	775.00	1.068
32	800.00	0.804
33	825.00	0.499
34	850.00	0.309

TIMER SETTING = 16 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	3.301
2	50.00	3.892
3	75.00	2.405
4	100.00	1.642
5	125.00	1.927
6	150.00	2.137
7	175.00	2.186
8	200.00	2.235
9	225.00	2.217
10	250.00	2.273
11	275.00	2.206
12	300.00	2.028
13	325.00	1.871
14	350.00	1.955
15	375.00	2.188
16	400.00	2.408
17	425.00	2.586
18	450.00	2.772
19	475.00	2.707
20	500.00	2.480
21	525.00	2.246
22	550.00	2.199
23	575.00	2.210
24	600.00	2.260
25	625.00	2.284
26	650.00	2.339
27	675.00	2.324
28	700.00	2.238
29	725.00	2.066
30	750.00	1.775
31	775.00	1.402
32	800.00	1.055
33	825.00	0.655
34	850.00	0.406

TIMER SETTING = 24 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.201
2	50.00	2.595
3	75.00	1.603
4	100.00	1.094
5	125.00	1.285
6	150.00	1.425
7	175.00	1.457
8	200.00	1.490
9	225.00	1.478
10	250.00	1.515
11	275.00	1.470
12	300.00	1.352
13	325.00	1.247
14	350.00	1.304
15	375.00	1.459
16	400.00	1.605
17	425.00	1.724
18	450.00	1.848
19	475.00	1.804
20	500.00	1.654
21	525.00	1.497
22	550.00	1.466
23	575.00	1.474
24	600.00	1.507
25	625.00	1.523
26	650.00	1.560
27	675.00	1.549
28	700.00	1.492
29	725.00	1.377
30	750.00	1.183
31	775.00	0.935
32	800.00	0.704
33	825.00	0.437
34	850.00	0.270

TIMER SETTING = 18 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.934
2	50.00	3.460
3	75.00	2.138
4	100.00	1.459
5	125.00	1.713
6	150.00	1.899
7	175.00	1.943
8	200.00	1.987
9	225.00	1.971
10	250.00	2.020
11	275.00	1.960
12	300.00	1.803
13	325.00	1.663
14	350.00	1.738
15	375.00	1.945
16	400.00	2.141
17	425.00	2.299
18	450.00	2.464
19	475.00	2.406
20	500.00	2.205
21	525.00	1.996
22	550.00	1.955
23	575.00	1.965
24	600.00	2.009
25	625.00	2.030
26	650.00	2.079
27	675.00	2.066
28	700.00	1.989
29	725.00	1.836
30	750.00	1.577
31	775.00	1.246
32	800.00	0.938
33	825.00	0.583
34	850.00	0.361

% TIMER SETTING	AVERAGE DEPTH (IN)
100	0.343
75	0.457
60	0.572
50	0.686
42	0.817
34	1.009
29	1.183
24	1.429
21	1.633
18	1.905
16	2.143

DD GUN OFF WITH PUMP J

TIMER SETTING = 100 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.463
2	50.00	0.550
3	75.00	0.341
4	100.00	0.239
5	125.00	0.276
6	150.00	0.306
7	175.00	0.308
8	200.00	0.326
9	225.00	0.326
10	250.00	0.317
11	275.00	0.316
12	300.00	0.293
13	325.00	0.262
14	350.00	0.261
15	375.00	0.300
16	400.00	0.342
17	425.00	0.367
18	450.00	0.393
19	475.00	0.384
20	500.00	0.352
21	525.00	0.318
22	550.00	0.312
23	575.00	0.313
24	600.00	0.320
25	625.00	0.324
26	650.00	0.331
27	675.00	0.329
28	700.00	0.317
29	725.00	0.293
30	750.00	0.251
31	775.00	0.199
32	800.00	0.150
33	825.00	0.093
34	850.00	0.057

TIMER SETTING = 60 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.771
2	50.00	0.916
3	75.00	0.568
4	100.00	0.399
5	125.00	0.460
6	150.00	0.510
7	175.00	0.514
8	200.00	0.544
9	225.00	0.543
10	250.00	0.529
11	275.00	0.527
12	300.00	0.488
13	325.00	0.436
14	350.00	0.435
15	375.00	0.500
16	400.00	0.570
17	425.00	0.612
18	450.00	0.656
19	475.00	0.640
20	500.00	0.586
21	525.00	0.531
22	550.00	0.520
23	575.00	0.522
24	600.00	0.534
25	625.00	0.539
26	650.00	0.552
27	675.00	0.548
28	700.00	0.528
29	725.00	0.488
30	750.00	0.419
31	775.00	0.331
32	800.00	0.249
33	825.00	0.155
34	850.00	0.096

TIMER SETTING = 42 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.101
2	50.00	1.309
3	75.00	0.811
4	100.00	0.569
5	125.00	0.657
6	150.00	0.729
7	175.00	0.734
8	200.00	0.777
9	225.00	0.776
10	250.00	0.756
11	275.00	0.753
12	300.00	0.697
13	325.00	0.623
14	350.00	0.622
15	375.00	0.715
16	400.00	0.814
17	425.00	0.874
18	450.00	0.936
19	475.00	0.914
20	500.00	0.838
21	525.00	0.758
22	550.00	0.742
23	575.00	0.746
24	600.00	0.762
25	625.00	0.770
26	650.00	0.789
27	675.00	0.784
28	700.00	0.754
29	725.00	0.697
30	750.00	0.599
31	775.00	0.473
32	800.00	0.356
33	825.00	0.221
34	850.00	0.137

TIMER SETTING = 75 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.617
2	50.00	0.733
3	75.00	0.454
4	100.00	0.319
5	125.00	0.368
6	150.00	0.408
7	175.00	0.411
8	200.00	0.435
9	225.00	0.434
10	250.00	0.423
11	275.00	0.422
12	300.00	0.390
13	325.00	0.349
14	350.00	0.348
15	375.00	0.400
16	400.00	0.456
17	425.00	0.489
18	450.00	0.524
19	475.00	0.512
20	500.00	0.469
21	525.00	0.424
22	550.00	0.416
23	575.00	0.418
24	600.00	0.427
25	625.00	0.431
26	650.00	0.442
27	675.00	0.439
28	700.00	0.423
29	725.00	0.390
30	750.00	0.335
31	775.00	0.265
32	800.00	0.199
33	825.00	0.124
34	850.00	0.077

TIMER SETTING = 50 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.925
2	50.00	1.099
3	75.00	0.682
4	100.00	0.478
5	125.00	0.552
6	150.00	0.613
7	175.00	0.617
8	200.00	0.653
9	225.00	0.652
10	250.00	0.635
11	275.00	0.632
12	300.00	0.586
13	325.00	0.524
14	350.00	0.522
15	375.00	0.600
16	400.00	0.684
17	425.00	0.734
18	450.00	0.787
19	475.00	0.768
20	500.00	0.704
21	525.00	0.637
22	550.00	0.624
23	575.00	0.627
24	600.00	0.640
25	625.00	0.647
26	650.00	0.663
27	675.00	0.658
28	700.00	0.634
29	725.00	0.585
30	750.00	0.503
31	775.00	0.397
32	800.00	0.299
33	825.00	0.186
34	850.00	0.115

TIMER SETTING = 34 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.360
2	50.00	1.617
3	75.00	1.002
4	100.00	0.703
5	125.00	0.812
6	150.00	0.901
7	175.00	0.907
8	200.00	0.960
9	225.00	0.958
10	250.00	0.933
11	275.00	0.930
12	300.00	0.861
13	325.00	0.770
14	350.00	0.768
15	375.00	0.883
16	400.00	1.005
17	425.00	1.080
18	450.00	1.157
19	475.00	1.129
20	500.00	1.035
21	525.00	0.936
22	550.00	0.917
23	575.00	0.921
24	600.00	0.942
25	625.00	0.952
26	650.00	0.974
27	675.00	0.968
28	700.00	0.932
29	725.00	0.861
30	750.00	0.740
31	775.00	0.584
32	800.00	0.440
33	825.00	0.273
34	850.00	0.169

TIMER SETTING = [illegible] %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	[illegible]
2	50.00	[illegible]
3	75.00	[illegible]
4	100.00	[illegible]
5	125.00	[illegible]
6	150.00	[illegible]
7	175.00	[illegible]
8	200.00	[illegible]
9	225.00	1.124
10	250.00	1.094
11	275.00	1.090
12	300.00	1.010
13	325.00	0.903
14	350.00	0.901
15	375.00	1.035
16	400.00	1.179
17	425.00	1.266
18	450.00	1.356
19	475.00	1.324
20	500.00	1.213
21	525.00	1.090
22	550.00	1.075
23	575.00	1.000
24	600.00	1.104
25	625.00	1.116
26	650.00	1.142
27	675.00	1.135
28	700.00	1.093
29	725.00	1.009
30	750.00	0.867
31	775.00	0.685
32	800.00	0.516
33	825.00	0.320
34	850.00	0.190

TIMER SETTING = [illegible] %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	[illegible]
2	50.00	[illegible]
3	75.00	[illegible]
4	100.00	[illegible]
5	125.00	[illegible]
6	150.00	1.459
7	175.00	1.468
8	200.00	1.554
9	225.00	1.552
10	250.00	1.511
11	275.00	1.506
12	300.00	1.395
13	325.00	1.247
14	350.00	1.244
15	375.00	1.429
16	400.00	1.628
17	425.00	1.748
18	450.00	1.873
19	475.00	1.828
20	500.00	1.675
21	525.00	1.516
22	550.00	1.485
23	575.00	1.492
24	600.00	1.525
25	625.00	1.541
26	650.00	1.570
27	675.00	1.567
28	700.00	1.509
29	725.00	1.394
30	750.00	1.197
31	775.00	0.946
32	800.00	0.712
33	825.00	0.442
34	850.00	0.273

TIMER SETTING = 16 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.892
2	50.00	3.436
3	75.00	[illegible]
4	100.00	1.497
5	125.00	1.726
6	150.00	1.914
7	175.00	1.927
8	200.00	2.339
9	225.00	2.037
10	250.00	1.983
11	275.00	1.976
12	300.00	1.830
13	325.00	1.637
14	350.00	1.632
15	375.00	1.876
16	400.00	2.137
17	425.00	2.294
18	450.00	2.458
19	475.00	2.399
20	500.00	2.199
21	525.00	1.980
22	550.00	1.949
23	575.00	1.958
24	600.00	2.001
25	625.00	2.022
26	650.00	2.071
27	675.00	2.057
28	700.00	1.980
29	725.00	1.820
30	750.00	1.572
31	775.00	1.243
32	800.00	0.934
33	825.00	0.580
34	850.00	0.350

TIMER SETTING = 24 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.927
2	50.00	2.291
3	75.00	1.429
4	100.00	0.996
5	125.00	1.150
6	150.00	1.276
7	175.00	1.285
8	200.00	1.360
9	225.00	1.358
10	250.00	1.322
11	275.00	1.317
12	300.00	1.220
13	325.00	1.091
14	350.00	1.088
15	375.00	1.251
16	400.00	1.424
17	425.00	1.530
18	450.00	1.439
19	475.00	1.600
20	500.00	1.466
21	525.00	1.326
22	550.00	1.299
23	575.00	1.305
24	600.00	1.334
25	625.00	1.348
26	650.00	1.380
27	675.00	1.371
28	700.00	1.320
29	725.00	1.220
30	750.00	1.048
31	775.00	0.828
32	800.00	0.623
33	825.00	0.307
34	850.00	0.239

TIMER SETTING = 18 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.570
2	50.00	3.054
3	75.00	1.893
4	100.00	1.329
5	125.00	1.534
6	150.00	1.702
7	175.00	1.713
8	200.00	1.813
9	225.00	1.810
10	250.00	1.783
11	275.00	1.756
12	300.00	1.637
13	325.00	1.455
14	350.00	1.451
15	375.00	1.667
16	400.00	1.899
17	425.00	2.039
18	450.00	2.185
19	475.00	2.133
20	500.00	1.954
21	525.00	1.768
22	550.00	1.732
23	575.00	1.740
24	600.00	1.779
25	625.00	1.798
26	650.00	1.841
27	675.00	1.878
28	700.00	1.760
29	725.00	1.626
30	750.00	1.397
31	775.00	1.104
32	800.00	0.831
33	825.00	0.516
34	850.00	0.319

TIMER SETTING = 14 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	3.304
2	50.00	3.927
3	75.00	2.434
4	100.00	1.788
5	125.00	1.972
6	150.00	2.188
7	175.00	2.302
8	200.00	2.331
9	225.00	2.320
10	250.00	2.267
11	275.00	2.250
12	300.00	2.082
13	325.00	1.870
14	350.00	1.868
15	375.00	2.104
16	400.00	2.442
17	425.00	2.622
18	450.00	2.809
19	475.00	2.742
20	500.00	2.513
21	525.00	2.274
22	550.00	2.227
23	575.00	2.238
24	600.00	2.287
25	625.00	2.311
26	650.00	2.366
27	675.00	2.351
28	700.00	2.263
29	725.00	2.081
30	750.00	1.796
31	775.00	1.419
32	800.00	1.068
33	825.00	0.643
34	850.00	0.418

% TIMER SETTING	AVERAGE DEPTH (IN)
100	0.304
75	0.405
60	0.506
50	0.608
42	0.723
34	0.894
29	1.048
24	1.266
21	1.447
18	1.608
16	1.899
14	2.170

END GUN OFF WITH MODIFIED DESIGN

END GUN OFF

TIMER SETTING =100 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.413
2	50.00	0.511
3	75.00	0.336
4	100.00	0.256
5	125.00	0.295
6	150.00	0.332
7	175.00	0.356
8	200.00	0.387
9	225.00	0.391
10	250.00	0.382
11	275.00	0.357
12	300.00	0.338
13	325.00	0.285
14	350.00	0.284
15	375.00	0.335
16	400.00	0.381
17	425.00	0.411
18	450.00	0.437
19	475.00	0.427
20	500.00	0.404
21	525.00	0.365
22	550.00	0.337
23	575.00	0.363
24	600.00	0.360
25	625.00	0.341
26	650.00	0.342
27	675.00	0.371
28	700.00	0.376
29	725.00	0.357
30	750.00	0.307
31	775.00	0.269
32	800.00	0.177
33	825.00	0.084
34	850.00	0.037

TIMER SETTING = 60 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.688
2	50.00	0.852
3	75.00	0.561
4	100.00	0.427
5	125.00	0.491
6	150.00	0.553
7	175.00	0.593
8	200.00	0.645
9	226.00	0.652
10	250.00	0.637
11	275.00	0.596
12	300.00	0.563
13	325.00	0.474
14	350.00	0.473
15	375.00	0.559
16	400.00	0.635
17	425.00	0.686
18	450.00	0.728
19	475.00	0.712
20	500.00	0.673
21	525.00	0.608
22	550.00	0.562
23	575.00	0.604
24	600.00	0.599
25	625.00	0.568
26	650.00	0.570
27	675.00	0.618
28	700.00	0.623
29	725.00	0.595
30	750.00	0.511
31	775.00	0.414
32	800.00	0.295
33	825.00	0.141
34	850.00	0.062

TIMER SETTING = 42 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.982
2	50.00	1.217
3	75.00	0.801
4	100.00	0.610
5	125.00	0.702
6	150.00	0.790
7	175.00	0.847
8	200.00	0.921
9	225.00	0.932
10	250.00	0.911
11	275.00	0.849
12	300.00	0.804
13	325.00	0.677
14	350.00	0.676
15	375.00	0.798
16	400.00	0.907
17	425.00	0.980
18	450.00	1.040
19	475.00	1.010
20	500.00	0.961
21	525.00	0.869
22	550.00	0.803
23	575.00	0.863
24	600.00	0.856
25	625.00	0.811
26	650.00	0.814
27	675.00	0.882
28	700.00	0.891
29	725.00	0.849
30	750.00	0.730
31	775.00	0.592
32	800.00	0.421
33	825.00	0.201
34	850.00	0.089

TIMER SETTING = 75 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.550
2	50.00	0.681
3	75.00	0.449
4	100.00	0.342
5	125.00	0.393
6	150.00	0.442
7	175.00	0.474
8	200.00	0.516
9	225.00	0.522
10	250.00	0.510
11	275.00	0.476
12	300.00	0.451
13	325.00	0.379
14	350.00	0.378
15	375.00	0.447
16	400.00	0.508
17	425.00	0.549
18	450.00	0.582
19	475.00	0.570
20	500.00	0.538
21	525.00	0.487
22	550.00	0.450
23	575.00	0.483
24	600.00	0.479
25	625.00	0.456
26	650.00	0.466
27	675.00	0.494
28	700.00	0.499
29	725.00	0.476
30	750.00	0.409
31	775.00	0.331
32	800.00	0.236
33	825.00	0.133
34	850.00	0.050

TIMER SETTING = 50 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	0.825
2	50.00	1.022
3	75.00	0.673
4	100.00	0.513
5	125.00	0.590
6	150.00	0.664
7	175.00	0.712
8	200.00	0.774
9	225.00	0.783
10	250.00	0.765
11	275.00	0.713
12	300.00	0.676
13	325.00	0.569
14	350.00	0.568
15	375.00	0.670
16	400.00	0.762
17	425.00	0.823
18	450.00	0.873
19	475.00	0.855
20	500.00	0.807
21	525.00	0.730
22	550.00	0.675
23	575.00	0.725
24	600.00	0.719
25	625.00	0.681
26	650.00	0.684
27	675.00	0.741
28	700.00	0.748
29	725.00	0.714
30	750.00	0.613
31	775.00	0.497
32	800.00	0.354
33	825.00	0.169
34	850.00	0.074

TIMER SETTING = 34 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.213
2	50.00	1.503
3	75.00	0.990
4	100.00	0.754
5	125.00	0.867
6	150.00	0.976
7	175.00	1.046
8	200.00	1.138
9	225.00	1.151
10	250.00	1.125
11	275.00	1.049
12	300.00	0.994
13	325.00	0.837
14	350.00	0.835
15	375.00	0.986
16	400.00	1.120
17	425.00	1.210
18	450.00	1.284
19	475.00	1.257
20	500.00	1.187
21	525.00	1.074
22	550.00	0.992
23	575.00	1.066
24	600.00	1.058
25	625.00	1.002
26	650.00	1.005
27	675.00	1.090
28	700.00	1.100
29	725.00	1.049
30	750.00	0.902
31	775.00	0.731
32	800.00	0.520
33	825.00	0.249
34	850.00	0.110

TIMER SETTING = 29 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.422
2	50.00	1.762
3	75.00	1.160
4	100.00	0.864
5	125.00	1.016
6	150.00	1.144
7	175.00	1.227
8	200.00	1.334
9	225.00	1.349
10	250.00	1.319
11	275.00	1.230
12	300.00	1.165
13	325.00	0.981
14	350.00	0.979
15	375.00	1.156
16	400.00	1.313
17	425.00	1.419
18	450.00	1.506
19	475.00	1.474
20	500.00	1.392
21	525.00	1.259
22	550.00	1.163
23	575.00	1.250
24	600.00	1.240
25	625.00	1.174
26	650.00	1.179
27	675.00	1.278
28	700.00	1.290
29	725.00	1.230
30	750.00	1.058
31	775.00	0.857
32	800.00	0.610
33	825.00	0.291
34	850.00	0.128

TIMER SETTING = 21 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.964
2	50.00	2.433
3	75.00	1.602
4	100.00	1.220
5	125.00	1.404
6	150.00	1.500
7	175.00	1.694
8	200.00	1.843
9	225.00	1.863
10	250.00	1.821
11	275.00	1.698
12	300.00	1.609
13	325.00	1.355
14	350.00	1.352
15	375.00	1.586
16	400.00	1.814
17	425.00	1.959
18	450.00	2.079
19	475.00	2.035
20	500.00	1.922
21	525.00	1.739
22	550.00	1.607
23	575.00	1.727
24	600.00	1.712
25	625.00	1.622
26	650.00	1.628
27	675.00	1.765
28	700.00	1.781
29	725.00	1.699
30	750.00	1.461
31	775.00	1.184
32	800.00	0.842
33	825.00	0.402
34	850.00	0.177

TIMER SETTING = 16 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.578
2	50.00	3.194
3	75.00	2.103
4	100.00	1.602
5	125.00	1.842
6	150.00	2.074
7	175.00	2.224
8	200.00	2.418
9	225.00	2.446
10	250.00	2.390
11	275.00	2.229
12	300.00	2.112
13	325.00	1.778
14	350.00	1.774
15	375.00	2.095
16	400.00	2.381
17	425.00	2.572
18	450.00	2.729
19	475.00	2.671
20	500.00	2.523
21	525.00	2.282
22	550.00	2.109
23	575.00	2.266
24	600.00	2.248
25	625.00	2.128
26	650.00	2.136
27	675.00	2.316
28	700.00	2.338
29	725.00	2.230
30	750.00	1.917
31	775.00	1.553
32	800.00	1.105
33	825.00	0.528
34	850.00	0.233

TIMER SETTING = 24 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	1.719
2	50.00	2.129
3	75.00	1.402
4	100.00	1.068
5	125.00	1.228
6	150.00	1.382
7	175.00	1.483
8	200.00	1.612
9	225.00	1.630
10	250.00	1.593
11	275.00	1.486
12	300.00	1.408
13	325.00	1.186
14	350.00	1.183
15	375.00	1.397
16	400.00	1.587
17	425.00	1.714
18	450.00	1.819
19	475.00	1.781
20	500.00	1.682
21	525.00	1.521
22	550.00	1.406
23	575.00	1.511
24	600.00	1.498
25	625.00	1.419
26	650.00	1.424
27	675.00	1.544
28	700.00	1.559
29	725.00	1.486
30	750.00	1.278
31	775.00	1.036
32	800.00	0.737
33	825.00	0.352
34	850.00	0.155

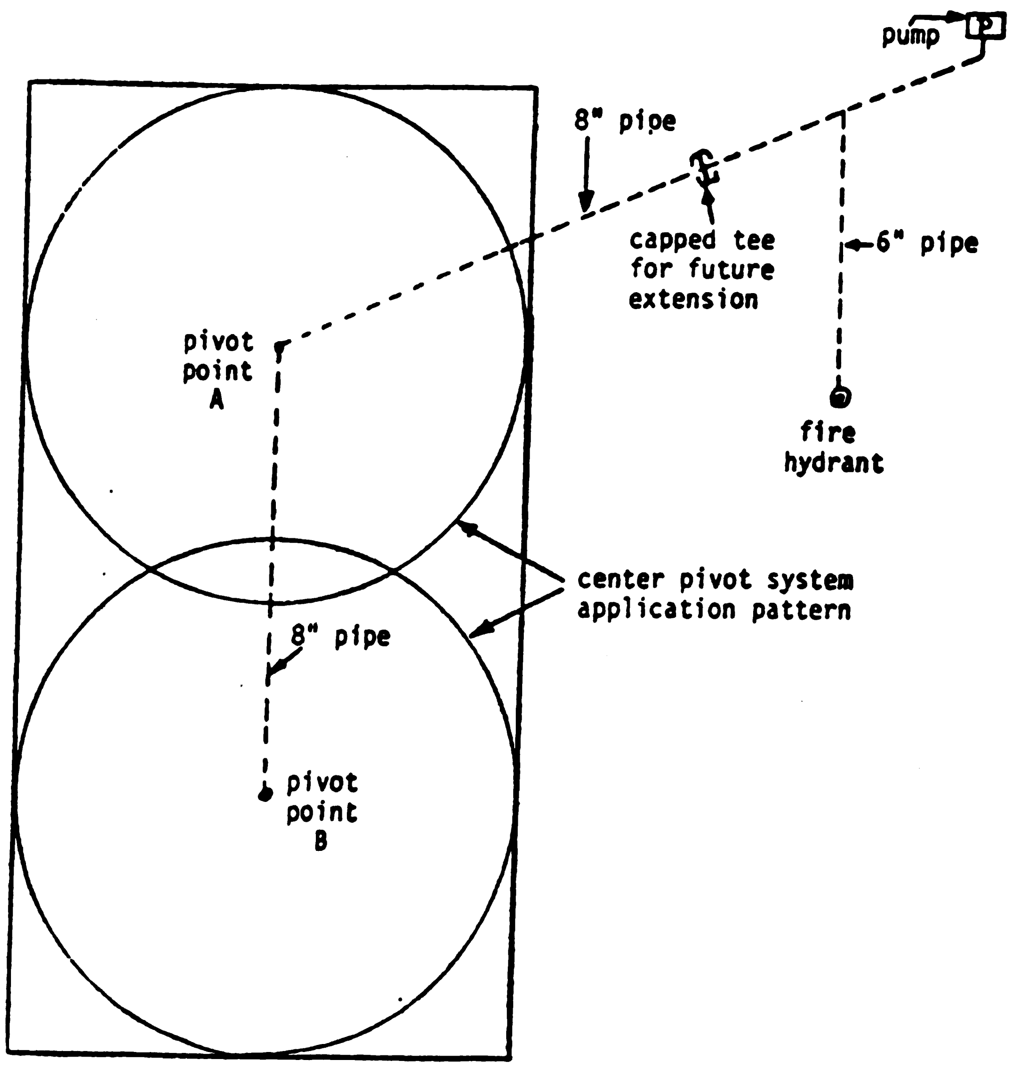
TIMER SETTING = 18 %

S NO	DISTANCE (FT)	DEPTH (INCH)
1	25.00	2.292
2	50.00	2.839
3	75.00	1.869
4	100.00	1.424
5	125.00	1.638
6	150.00	1.843
7	175.00	1.977
8	200.00	2.150
9	225.00	2.174
10	250.00	2.125
11	275.00	1.981
12	300.00	1.877
13	325.00	1.581
14	350.00	1.577
15	375.00	1.862
16	400.00	2.116
17	425.00	2.286
18	450.00	2.426
19	475.00	2.375
20	500.00	2.242
21	525.00	2.028
22	550.00	1.874
23	575.00	2.014
24	600.00	1.998
25	625.00	1.892
26	650.00	1.899
27	675.00	2.059
28	700.00	2.078
29	725.00	1.982
30	750.00	1.704
31	775.00	1.381
32	800.00	0.982
33	825.00	0.469
34	850.00	0.207

% TIMER SETTING	AVERAGE DEPTH(IN)
100	0.335
75	0.446
60	0.550
50	0.669
42	0.797
34	0.984
29	1.154
24	1.395
21	1.594
18	1.859
16	2.092

APPENDIX G

IRRIGATION SYSTEM PLAN LAYOUT OF MR. JERRY BEMEANT'S FARM


pump
8" pipe
capped tee
for future
extension
6" pipe
pivot
point
A
fire
hydrant
center pivot system
application pattern
8" pipe
pivot
point
B

LIST OF REFERENCES

Anon 1. 1986. Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot, Corner Pivot, and Moving Lateral Irrigation Machines Equipped with Spray or Sprinkler Nozzles. ASAE Standard: ASAE S436.

Anon 2. 1983. Sprinkler Irrigation. Sprinkler Irrigation Association, Silver Spring, Maryland.

Anon 3. 1983. Hydraulic Institute Standards. Hydraulic Institute, Cleveland, Ohio.

Anon 4. 1986. Nelson Agricultural Impact Sprinklers. Nelson Irrigation Corporation, Walla Walla, Washington.

Bernuth, R.D. von. 1982. Nozzling Considerations for Center Pivots with End Guns. Transactions of the ASAE 83:419-422.

Bittinger, M.W. and Longenbaugh, R.A. 1962. Theoritical Distribution of Water from a Moving Irrigation Sprinkler. Transactions of the ASAE 62:26-30.

Bralts, V.F. 1983. Hydraulic Design and Field Evaluation of Drip Irrigation Submain Units. Ph.D. thesis (Agricultural Engineering). Michigan State University, East Lansing.

Bralts, V.F. and Segerlind, L.J. 1985. Finite Element Analysis of Drip Irrigation Submain Units.Transactions of the ASAE 3:809-814

Chenoweth, H. and Crawford C. 1974. Pipe Network Analysis. Journal of the American Water Works Associations, Jan. 1974.

Chu, S.T. and Moe, D.L. 1972. Hydraulics of a Center Pivot System. Transaction of the ASAE 72:894-896.

Dillon,Jr, R.C., Hiler, E.A., and Vittetoe G. 1972. Center-Pivot Sprinkler Design Based on Intake Characteristics. Transactions of the ASAE 72:996-1001.

Garde, R.J. and Mirajgaoker, A.G. 1977. Engineering Fluid Mechanics. Nem Chand and Brothers, Roorkee, India.

Haghighi, K. and Bralts, V.F. 1987. Modelling and Formulation of Distribution Network Components: A Finite Element Approach. ASAE Winter Meeting 1987, Paper no. 87-2609.

Hart, Wm. E. and Reynold, Wm. N. 1965. Analytical Design of a Sprinkler Systems. Transactions of the ASAE 65:83-89.

Heermann, D.F. and Hein, P.R. 1968. Performance Characteristics of Self-Propelled Center-Pivot Irrigation System. Transactions of the ASAE 68:11-15.

James, L.G. 1988. Principles of Farm Irrigation System Design. John Wiley and Sons, New York.

Jensen, M.E. 1982. Water Resource Technology and Management. Proceeding of RCA symposium, Dec 5-9 1982. Washington, D.C.

Jeppson, R.W. 1982. Analysis of Flow in Pipe Networks. Ann Arbor Science Publishers, Ann Arbor, Michigan.

Karmeli, David. 1978. Estimating Sprinkler Distribution Patterns Using Linear Regression. Transactions of the ASAE 78:682-686.

Kincaid, D.C. and Heermann, D.F. 1970. Pressure Distribution on a Center-Pivot Sprinkler Irrigation System. Transactions of the ASAE 70:556-558.

Kincaid,D.C., Heermann,D.F., and Kruse,E.G. 1969. Application Rates and Runoff in Center-Pivot Sprinkler Irrigation. Transactions of the ASAE 69:790-797.

Massey, F.C., Skaggs, R.W., and Sneed, R.E. 1983. Energy and Water Requirements for Subirrigation vs. Sprinkler Irrigation. Transactions of the ASAE 83:126-133.

Pair, C.H. 1968. Water Distribution Under Sprinkler Irrigation. Transactions of the ASAE 68:648-651.

Perrold, R.P. 1977. Design of Irrigation Pipe Laterals with Multiple Outlets. Journal of Irrigation and Drainage Division, ASCE. IR2:179-195.

Postel, Sandra. 1985. Conserving Water: The Untapped Alternative. Worldwatch paper 67. Worldwatch Institute.

Saldivia,L.A., Bralts,V.F., and Segerlind,L.J.1987. Hydraulic Design of Sprinkler Irrigation System Components Using the Finite Element Method. ASAE Winter Meeting 1987, Paper no. 87-2795.

Segerlind, L.J. 1984. Applied Finite Element Analysis. John Wiley and Sons, New York.

Shamir, U. and Howard, C.D. 1968. Water Distribution Systems Analysis. Journal of the Hydraulics Division, ASCE HY1:219-234.

Solomon, K. and Kodoma, M. 1978. Center Pivot End Sprinkler Pattern Analysis and Selection. Transactions of the ASAE 78:706-712.

Swamee, P.K. and Jain, A.K. 1978. Explicit Equations for Pipe Flow Problems. Journal of the Hydraulic Division, ASCE .HY5:657-664.

Villemonte, J.R. 1977. Some Basic Concepts on Flow in Branching Conduits. Journal of the Hydraulic Division, ASCE HY7:685-697.

Wallace, S. 1987. An analysis of Irrigation Uniformity and Scheduling Effects on Simulated Maize Yield in Humid Regions. M.S. Thesis submitted to Michigan State UNiversity, EastLansing, Michigan.

Wiggert,D.C. and Potter,J . 1989 (Unpublished). Engineering Fluid Mechanics.

Wood D.J. and Charles C.O.A. 1972. Hydraulic Network Analysis Using Linear Theory. Journal of Hydraulic Division, HY7:1157-1170.

Wood, D.J. and Rayes, A.G. 1981. Reliability of Alogorithms for Pipe Network Analysis. Journal of Hydraulics Division, ASCE HY10:1145-1161.

MICHIGAN STATE UNIV. LIBRARIES
31293006895134