IRRIGATION MANAGEMENT

SERIES

Considerations for Nozzle Package Selection for Center Pivots

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Approximately 90 percent of the irrigated acreage in Kansas is watered by center pivot systems. Center pivot irrigation systems have been adopted because of their ruggedness and versatility. Center pivots reduce the amount of labor associated with irrigation as compared to surface irrigation systems and usually applies water to a crop more efficiently and uniformly. Different nozzle package options for center pivot systems have been developed that efficiently and uniformly distribute a limited water supply over a large area. This is in response to declining well capacities and the desire of producers to reduce pressure requirements in order to minimize irrigation pumping costs.

It is important, when designing a nozzle package for a new system or replacing a nozzle package on an older system, to keep in mind the general sprinkler performance requirements. If these general requirements are not followed closely, a reduction in the system efficiency could occur, the result of increased runoff and reduced yields from under-watering due to poor uniformity. This bulletin covers general nozzle performance requirements. To provide a better understanding of conditions which reduce efficiency, the bulletin will discuss the different types of water losses associated with various nozzle types and configurations. Finally, a broad discussion of nozzle package options and the effects they have on system performance will be presented.

Sprinkler Nozzle Characteristics and Design Criteria

The water emitting devices that allow the distribution of water to a field from the center pivot system are often called the sprinkler package. However, the sprinkler package or nozzle package can be composed of a range of devices including impact sprinklers, fixed plate spray nozzles and moving plate spray nozzles. There has been some use of a fourth type of application device that utilizes drag hoses equipped with low flow emitters used in micro-irrigation tubes.

Impact sprinklers were used extensively on early water-driven center pivot systems. However, modern designs now utilize lower pressures and lower angles of water stream trajectories. Impacts can have single or double nozzle configurations. When properly overlapped, they can provide very uniform application patterns at relatively low water application rates. The low water application rate may be important for tight soils or fields with large slopes to prevent irrigation water runoff.

Fixed plate sprinklers or nozzles spread the water stream emitted from the nozzle orifices by directing the flow against stationary splash pads. The splash pads deflect the stream of water into the characteristic flow pattern that look like wagon wheel spokes. The splash pads can be flat, convex or concave and grooved or non-grooved. Grooved plates can have course to fine grooves. These configurations affect the stream pattern and droplet size.

Moving plate sprinklers or nozzles spread the water stream emitted from the nozzle orifices by directing the flow against splash pads that move in some fashion. Some rotate slowly; others spin rapidly; others wobble. Depending on the speed of the movement, some water patterns develop that look like slowly rotating spokes of water, while others breakup the water streaming into a blur of water droplets. In addition to the speed of rotation, these devices can also have various grooves and slot configurations to produce various droplet sizes.

The performance of each type of sprinkler nozzle is predictable as flow through the discharge opening or orifice is based on the opening size and the operating pressure. For a round orifice, the nozzle discharge can be calculated by

$$q = C_d\,(29.83) d^2 p^{0.5}$$

Where:

q = nozzle discharge in gpm

C_d = discharge coefficient
(often between 0.95 and 1.00)
d = nozzle diameter in inches
p = pressure in psi

Since flow varies by the square of diameter, doubling the diameter quadruples the flow where as doubling pressure would increase flow by about 40 percent as the flow changes by the square root of the pressure. However, pressure is an important operation factor once the nozzle orifice diameter is fixed for use in a specific sprinkler package as pressure has an effect on droplet size distribution and wetted diameter.

All nozzles should be operated within the manufacturer's recommended pressure range. Excessive pressure will result in a increase of small droplet sizes that are susceptible to wind drift and evaporation losses while under-pressuring will increase the drop size. Larger droplet sizes may have adverse affects on the soil surface due to higher impact energy or may affect coverage if the sprinkler package is used for chemigation. Operation outside the recommended pressure range, either high or low, usually decreases the effective wetted diameter. The wetted diameter of a nozzle refers to area of coverage of the nozzle.

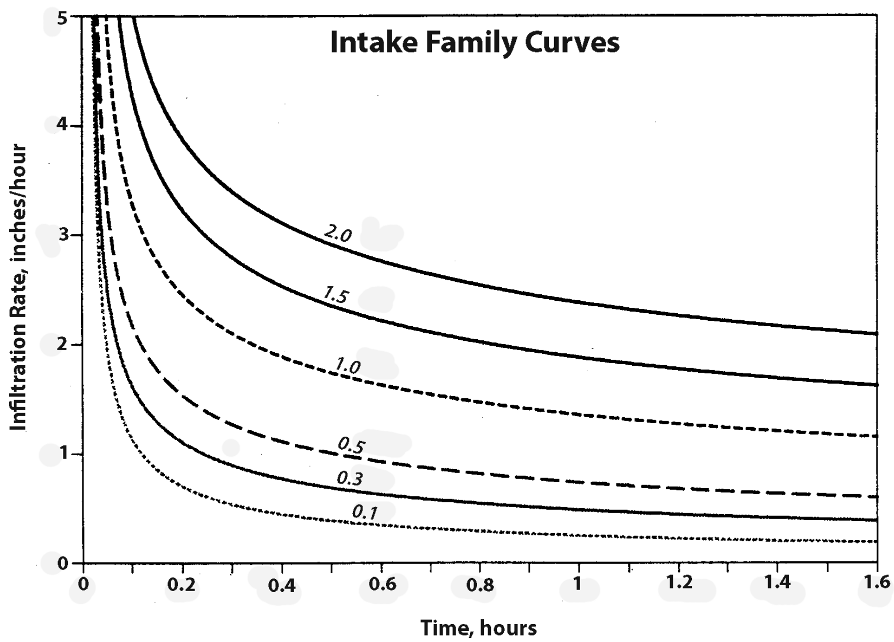
There are many sprinkler (nozzle) system design considerations, but the following are essential in determining adequate system performance: (1) application rate, (2) depth of application, (3) system irrigation capacity, and (4) uniformity of application.

Application Rate. Ideally, the application rate would be matched to the steady state soil intake rate. However, this design criterion was developed when the sprinkler packages were primarily high pressure, large wetted diameter impact sprinklers. The term application rate can also refer to several different measurements. The instantaneous application rate refers to the rate of water application at any given time. This value will very from zero to the peak instantaneous application rate as the nozzle package crosses a given point. The peak application rate generally refers to the maximum application rate for a system. The average application rate refers to how fast the water is applied by a device on the average over the wetted diameter of the device. The average system application rate refers to how fast the water is applied during the time it takes the system to irrigate a portion of a field.

The application rate for various nozzles along a center pivot increases with distance from the pivot point as more area is covered by the nozzle with distance, meaning more water must be applied in a given time to maintain a constant application depth along the lateral. This is why run off problems are generally associated with the outer edges of a center pivot unless soil or slope conditions are more limiting in an inner portion of the center pivot.

With the introduction of fixed plate and moving plate sprinkler nozzle options with smaller wetted diameters and the move towards lower positioning of nozzles (which also decreases wetter diameter), the system nozzle package design should also consider the amount of soil surface water storage that occurs during the irrigation event. However, the base soil infiltration rate is an important consideration.

Figure 1. Infiltration rate curves for major Natural Resources Conservation Service intake families. (Kranz, W., Central Plains Proceedings, 1994)



The NRCS Conservation Service (NRCS) has determined infiltration rates for most soils in the country. Soils with like infiltration rates were grouped into Intake Families. Each of these soil Intake Families has a specific soil intake curve as shown in Figure 1. The soil type(s) for any field of interest can be determined by referring to soil maps which are available at county extension or NRCS offices. Soil intake curves are a good place to start when determining the maximum application rate. Average application rates produced by different sprinkler packages, shown in Figure 2, illustrate that sprinkler packages with smaller wetted diameters have higher average application rates and vice versa. When trying to match the application rate of a system to the intake rate of the soil, it is helpful to put the intake rate curve and the application rate curve on the same figure.

This is shown in Figure 3 with the intake rate curve for the 0.5 NRCS Soil Intake Family and application rate curves for three different wetted radii (nozzle packages). The areas in Figure 3 where the application rate curves extend above the intake rate curve represent water that must be stored on the surface until infiltrated. Until it is infiltrated, it has a potential to run off. If this stored surface water does run off, it results in a reduction in system efficiency. Sprinkler packages with a greater wetted radius have a lower application rate, resulting in less water stored on the soil surface and therefore have less likelihood to produce runoff. Application rate is important when trying to eliminate runoff, and thus improve system efficiency.

Depth of Application. The amount of water applied during an irrigation event should not exceed the volume of water that the root zone can hold. If excess water is applied, water will be lost to deep percolation, thus reducing the overall irrigation efficiency.

Different types of soils have different soil water holding capacities. For optimal crop growth results, it is best to keep the soil water level between field capacity and about 50 percent of the available water in the crop root zone for the type of soil being irrigated. These levels are based on the tension required to extract water from the soil.

Field capacity is defined as the level of water remaining in a soil after gravitational water has been removed. The permanent wilting point is defined as that level of water at which the forces holding the water in the soil are equal to or greater than the maximum force that a plant can exert to extract this water. At this level, water is unavailable to the plant and the plant can no longer survive.

The soil water between field capacity and the permanent wilting point is the amount of water that is available for plant use. Application of water above field capacity results in soil that becomes saturated. This water will be more likely to be lost to runoff or deep percolation. Applying too little water will result in plant stress.

Figure 2. Water application patterns for different sprinkler types for a 1.1-inch application amount. (Kranz, W., Central Plains Proceedings, 1994)

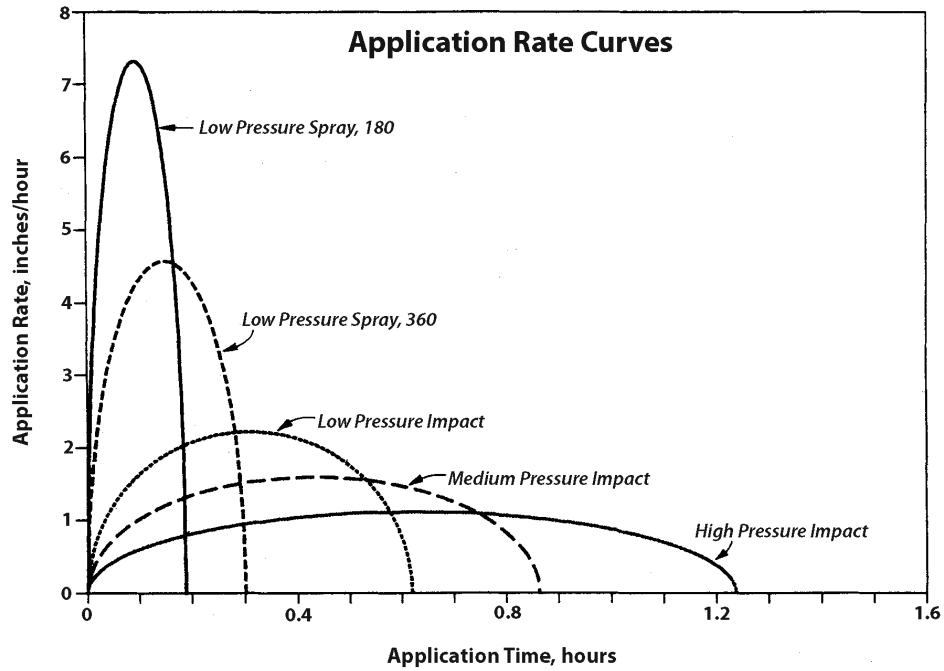
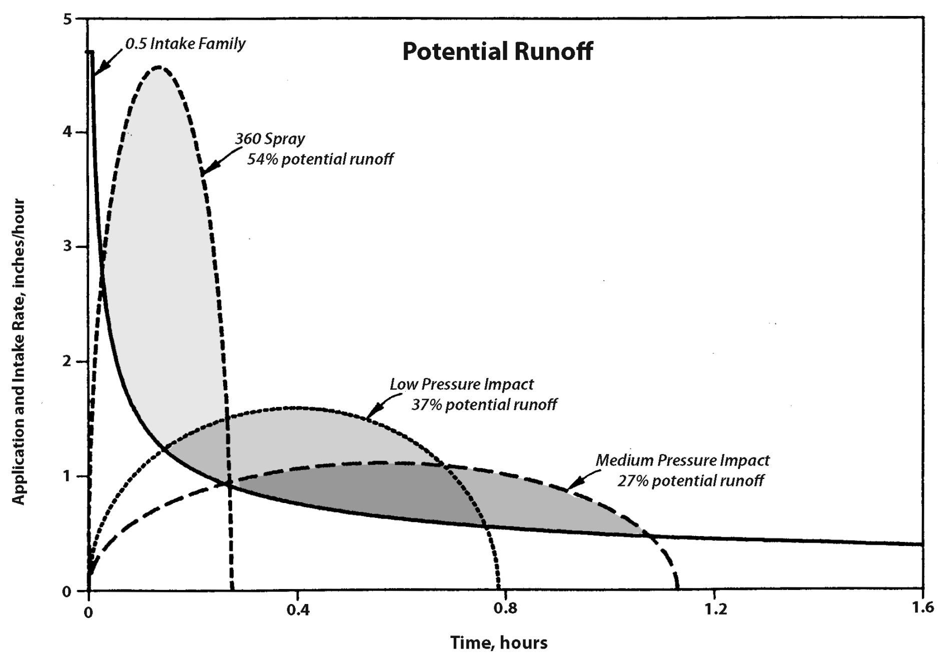


Figure 3. Potential runoff for a silt loam soil receiving a 1.1-inch water application without surface storage. (Kranz, W., Central Plains Proceedings, 1994).



Irrigation scheduling management procedures can be used to track soil water levels. Table 1 gives typical soil water levels for three soil textures. The root zone of the crop to be irrigated, along with the available water holding capacity for the soil being irrigated, determines the maximum application amount.

Table 2 summarizes crop water use characteristics for many irrigated crops and includes the root zone for several crops common to the central plains region. Multiplication of the root zone depth of the crop by the available water-holding capacity of the soil determines the total available water-holding capacity in the root zone. This is the most water that can be stored without water loss to deep percolation. The maximum amount that can be applied is less than this since the general irrigation management guideline is to prevent more than 50 percent soil water depletion.

System Irrigation Capacity. System irrigation capacity is the average depth of water applied to the entire field if it were watered in one day. For example, a center pivot may be set to apply a one-inch application as it rotates around a field. However, it may require four days to complete an irrigation cycle. The system irrigation capacity is then 1 inch per four days or 0.25 inches/day.

The system capacity can be calculated using the following equation:

$$\text{System Irrigation Capacity} = \frac{\text{GPM (Hrs of operation/day)}}{450\ \text{(Acres)}}$$

where:

450 is a conversion factor; 450 gpm = 1 ac-in/hr

GPM = flow rate to irrigation system in gallons per minute

Acres = irrigated area, acres

HRS = Hours of operation per day; usually 24 hours/day

For example, a system irrigating 128 acres with 650 gpm and running continuously will have a system irrigation capacity of 0.27 in/day.

Notice that in this example, the irrigation time is for continuous operation of the system. Other factors to take into account when calculating the system capacity are possible hours lost to electrical load control or downtime needed for system maintenance or repair. For the percent of time that the system must be shut down, the capacity will have to be increased to compensate for the lost irrigation time. Figure 4 shows the relationship between system capacity and system length for three different peak water use rates.

The crop water use rate is variable from day to day and from season to season, depending on factors such as the type of crop, the stage of growth of the crop, and weather conditions. Daily peak water use values are shown in Table 2; however, soil water storage provides a buffer so system irrigation capacity is generally less than peak daily use rate. Deep rooted crops and high water-holding capacity soils will need less capacity for reliable crop production than shallow rooted crops and sandy soils. Many irrigation systems

Table 1. Water Holding Capacities of Soils.

Soil texture	Water per foot-depth of soil		Water available for plant use
	Field capacity (inches per foot)	Wilting point (inches per foot)	(inches per foot)
Sandy	0.75	0.25	0.50
Sandy Loam	1.30	0.30	1.00
Silt Loam	2.00	0.50	1.50
Clay Loam	3.00	1.00	2.00

Table 2. Seasonal Crop Water Use (ET), Typical Irrigation Capacity Requirement, Daily Peak Water Use, Critical Growth Stage, Typical Root Depth, and Typical Manage Depth for Various Crops Common to the Central Plains Region. (Shawcroft, R.W., Central Plains Proceedings, 1989)

Crop	Seasonal crop water use (ET)	Typical irrigation capacity required	Daily peak usage	Critical growth stages	Typical root depth	Typical managed depth
	(inches)	------- (inches per day) ------			------------ (feet) ------------	
Alfalfa	32-48*	0.40	0.55	after harvest	6-10	3-4
Corn	34-30	0.35	0.50	tasseling, silking	4-6	3
Dry beans	16-24	0.30	0.40	early bloom	3-4	2-3
Wheat	16-22	0.29	0.40	boot-heading	4-6	3
Sorghum	16-22	0.31	0.40	boot-heading	4-6	3
Sunflowers	16-20	0.26	0.30	flowering, maturity	4-6	3-4
Soybeans	18-24	0.31	0.40	germination, bloom-podding	4-6	3
Vegetable crops	16-20	0.29	0.30	reproductive stages	1-3	1

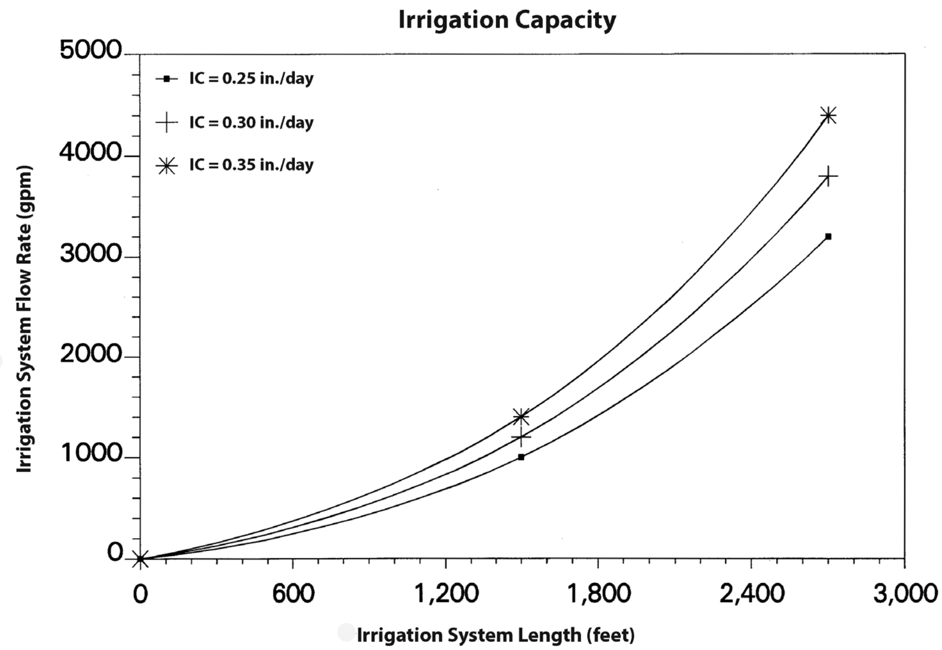
** Forage crops generally respond directly to the amount of water available. Alfalfa can use large amounts of water when growing seasons are long.*

have a capacity at much less than the peak use rate. Systems in Kansas with capacity above 0.25 inches per day are generally low-risk when operated on high water holding capacity soils. On low water-holding capacity soils, such as sands, the water reserves are much less and system irrigation capacities of 0.3 in/days or greater are needed to prevent yield limiting water stress.

Uniformity of Application. When designing sprinkler irrigation systems, it is important to provide as uniform application as possible. A non-uniform application will result in areas of under-watering as well as areas of over-watering. This will result in reduced yields as well as decreased system efficiency. The uniformity of the sprinkler nozzle package design is determined by package design. It is affected by the operating conditions, and environmental factors, especially wind. Figure 5 shows the results of a center pivot uniformity test. Section A of the pivot illustrates a portion of the sprinkler package that was performing well. This area of the pivot has a coefficient of uniformity of almost 90 percent. In section B, a leaky boot connection between two spans was caught in one container. Section C represents the area covered by the outer two spans of the system that shows an area of over watering and under watering. This is better illustrated in Figure 6, which shows the test results of this area without the end gun. The difference in depth was the result of the nozzles for the two spans being switched at installation. Section D of Figure 5 demonstrates the effect of an improperly operating end gun. In this case, the end gun operation angle was improperly set and it was over spraying the nozzles of about one third of the last span and overhang of the center pivot. In this example, all of the causes of the poor uniformity were easily and inexpensively correctable.

Uniformity is decreased if system pressure is not kept at the design pressure. Wear of nozzles and incrustation build up can also affect the pattern.

Figure 4. Impact of potential ET estimate on system flow rate for different irrigation system lengths. (Kranz, W., Central Plains Proceedings, 1994.)



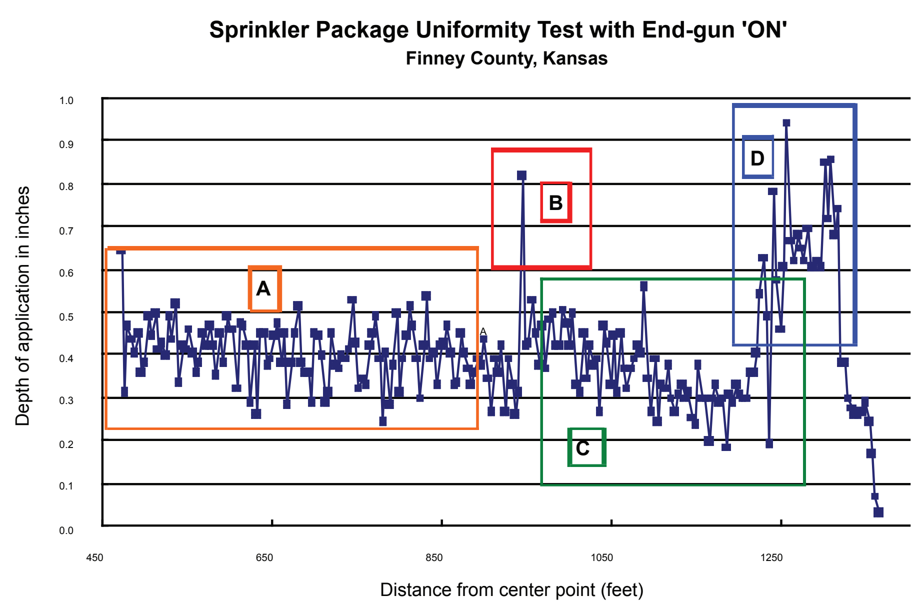
Canopy interference also effects distribution uniformity.

TYPES OF WATER LOSSES

From a practical standpoint, water that does not reach or remain in the root zone of the crop is not available to the plant and is therefore considered lost. The reduction in water made available to the plant reduces the water application efficiency of the entire system. Water losses occur in three areas: (1) air loss, (2) foliage loss, and (3) ground loss and are illustrated in Figure 7.

Air Loss. The two types of air water loss are drift and droplet evaporation. Drift involves wind blowing the water droplets off of a field or on to a non-targeted area of the field. This causes non-uniformity in the water application, and crops located in areas not receiving the proper amount of water may become stressed. Droplet

Figure 5. Mobile Irrigation Lab uniformity analysis of a center pivot sprinkler package.



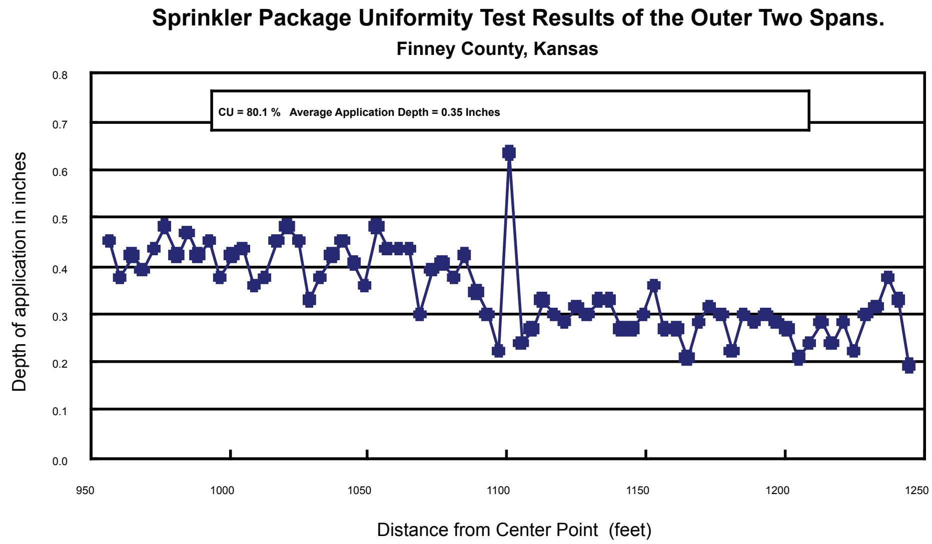
evaporation is the case where water from droplets actually evaporates before it reaches the crop canopy or the soil while in flight. These types of losses can be reduced by selecting nozzles that produce large droplets and move the discharge point closer to the ground.

Foliage Loss. Upon entering the canopy of the crop, water can be lost to plant interception or to evaporation. Interception is water that is "caught" and held on the plant material surfaces, and is usually quickly evaporated back to the atmosphere. Foliage evaporation losses refer to water evaporating from the foliage surface during the time that location is being wetted. To reduce water losses in the canopy, discharge points have been moved closer to the ground to limit the surface wetting of crop canopy and reduce the time irrigation wetting occurs at a location.

Ground Loss. Once the water reaches the ground, it can be lost in several ways. If water application rates are higher than the soil intake rates, water can either be held in surface storage or runoff. Runoff water can either leave the field or just move to a different location within the field. Water movement within the field causes non-uniformity in the application and reduces the efficiency of the application. If the soil receiving the runoff as infiltration is over-watered, then the excess water is lost to deep percolation. The portion of the field losing water will have less water available to meet crop needs.

Water being held in surface storage will either infiltrate or evaporate. The stored water lost to evaporation reduces the application amount and thus the application efficiency. If the depth of application exceeds the soil water storage capacity within the root zone, water will be lost to deep percolation. This is when water infiltrates below the crop root zone. Ground level losses of water can be reduced by using different tillage techniques and reducing the application depth of each irrigation event. However decreasing the application depth per irrigation event increases the number of events needed to apply the seasonal water needs and subjecting the water application to additional foliage water loss.

Figure 6. Depth of application catch for two spans of a center pivot with a span reversal of the nozzles.



NOZZLE PACKAGE OPTIONS

There are many different types of nozzle available for selection, each of which can be operated at various pressures, mounted at various heights, equipped with different orifice sizes and spaced at various widths from other nozzles, making hundreds of possible choices among nozzle packages. Nozzles are designed to provide a specific water release pattern when provided with a specified pressure. If the nozzles are not used within the given specifications, they will not perform as designed and may reduce application efficiencies significantly. Table 3 shows the relationships between the nozzle types and their design pressure range. As might be expected, different nozzles provide different output and application characteristics. Table 4 gives the rating of output characteristics for Sprinklers 2 through 7 from Table 3. These characteristics determine the types of water losses to which each nozzle is susceptible.

Average Application Rate. The average application rate is calculated by dividing the application amount by the time of application. Nozzles operating at different pressures provide a different wetted radius. It has already been noted that smaller wetted radii (lower operating pressures) provide a higher average application rate. Table 4 shows that Nozzle 2, with the lowest operating pressure, has the highest average application rate. If the average application rate for a nozzle of interest is significantly higher than the intake rate of the soil to be irrigated, the potential for runoff is high.

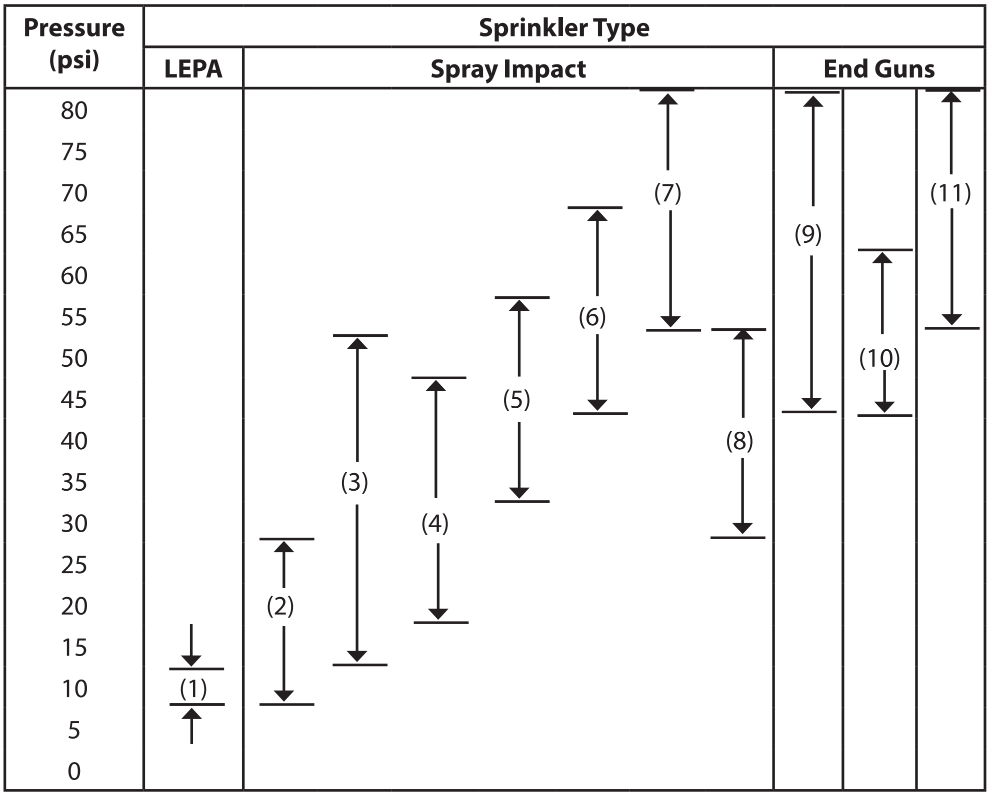
Peak Application Rate. The peak application rate is the rate at which water is supplied to the soil at a given point in time and at a specified location. Selecting a sprinkler package with a peak application rate that is too great could cause runoff to develop.

The key is to match the peak application rate to the soil infiltration rate and soil surface water storage capacity. Three factors that affect the peak application rate are (1) system length, (2) system capacity, and (3) nozzle wetted radius. The following equation can be used to calculate the peak application rate:

where:

$$I_p = \frac{(K \times Q_p)}{(R_s \times R_p)}$$

Table 3. Minimum end pressures on center pivots and linear move systems for various sprinkler devices. (Kranz, W., et. Al., Central Plains Proceedings, 1990)



(1) LEPA
(2) Spray Nozzles
(3) Rotators
(4) Small Impacts – Modified Nozzles
(5) Small Impacts – Round Hole Nozzles
(6) Large Impacts – Round Hole Nozzles
(7) Larger Impacts – (1¼”) Round Nozzles
(8) Impact End Gun – Modified Nozzle
(9) Impact End Gun – Round Hole Nozzle
(10) Gun Type End Gun – Modified Nozzle
(11) Gun Type End Gun – Round Hole Nozzle

K = constant, 122.5

Q_p = irrigation system capacity, gpm

R_s = system length, ft.

R_{sp} = wetted radius of nozzle, ft.

I_p = peak water application rate, in/hr

This equation indicates that as the system length increases (along with the needed increase in system capacity to meet the peak water use rate), the peak application rate increases. Figure 8 provides a visual representation of how wetted radius impacts the peak application rate as system length increases.

Wetted Radius. The wetted radius of a sprinkler is the distance water will travel from the nozzle before striking the ground. Nozzles that have a large wetted radius also tend to have a large droplet size and operate at higher pressures as indicated in Table 4. Wetted radius is also an indication of the average application rate. A larger wetted radius will have a lower average application rate and thus the potential for runoff will be lower.

Table 4. Rating of output characteristics of sprinklers 2 through 7 from Table 3. (Kranz, W., et. al., Central Plains Proceedings, 1990)

Characteristic	Sprinkler with the Highest	Sprinkler with the Lowest
Average application	(2)	(7)
Instantaneous application rate	(7)	(2)
Wetted radius	(7)	(2)
Water droplet size	(7)	(2)

Water Droplet Size. The water droplet size is determined by such things as operating pressure, size and shape of the opening on the nozzle, and what type of pad or arm the nozzle is equipped with. The important properties of water droplet size to remember are: (1) large droplets have a high instantaneous application rate that can cause crusting on unprotected soil, which can increase the potential for runoff; and (2) small droplets are more susceptible to drift and evaporation losses. Table 4 gives water droplet size comparisons.

A trend in recent years has been to use lower pressure nozzles which reduces the overall pressure required for the system and lowers pumping costs. Since lower pressure nozzles have a smaller droplet size, they have been moved closer to the ground to reduce evaporation and drift losses. Lower pressure nozzles also increase the average application rate, requiring that special attention being given to reducing the potential for runoff.

LEPA Nozzles. The LEPA (Low Energy Precision Application) nozzle was not included in the above comparisons. The operating pressure and the position of the nozzle that is close to the ground means the wetted radius for LEPA nozzles are very small. This also means that the average application rate is very high. LEPA has been described by some as a traveling flood irrigation system, and because of its characteristics, must be used in conjunction with special practices. LEPA packages were developed to serve low irrigation capacity systems on level fields. LEPA nozzle spacing is usually twice the row spacing (5 ft. for 30-inch rows) and the rows must be planted in a circle. In addition, special tillage practices, such as dammer-diking or furrow-diking, must be used to control runoff.

Figure 7. Illustration of different types of water losses associated with sprinkler systems. (Schneider, A.D. and T.A. Howell, Central Plains Proceedings, 1993)

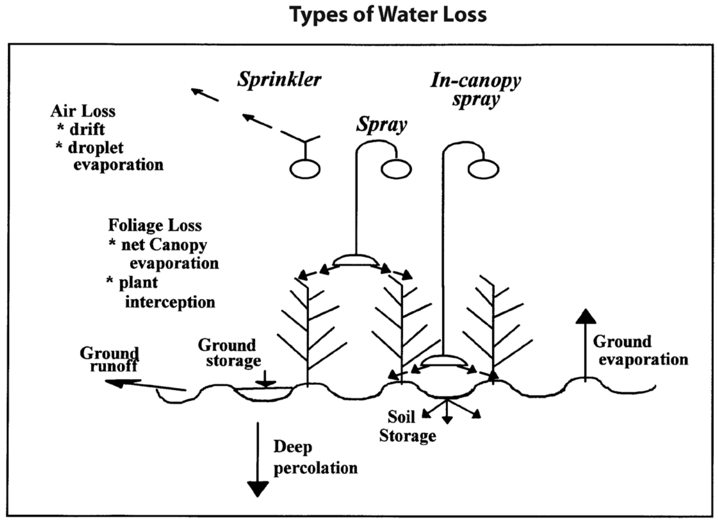
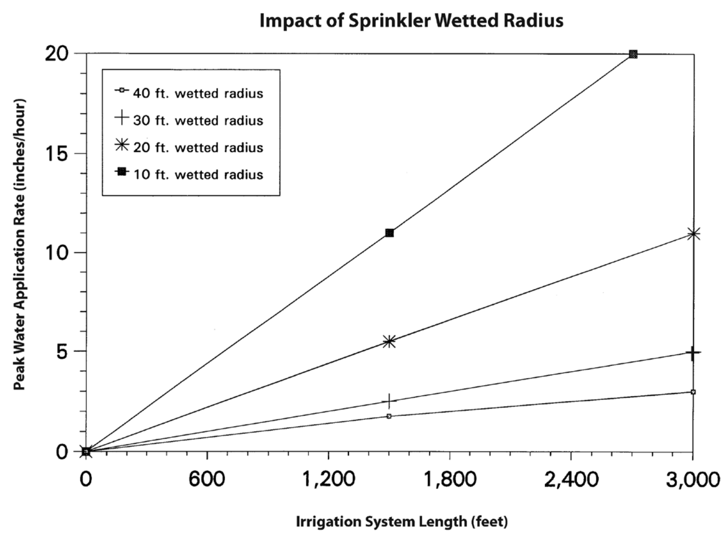


Figure 8. Impact of sprinkler wetted radius on peak water application rate when designed for 0.35″ day ETp. (Kranz, W., Central Plains Proceedings, 1994)



SUMMARY

Center pivot systems are popular because of the ability to provide efficient and uniform application of irrigation water for a wide variety of crops and field conditions when equipped with a properly designed and operated nozzle package. Center pivot labor requirements also tend to be low as compared to surface irrigation system requirements.

There are many different nozzle package options associated with center pivot systems. Consideration must be given to the overall system performance rather than to fixing one problem. A trend in recent years has been to use low-pressure nozzles. These reduce the overall pressure requirement of the system and help reduce operating costs. Since lower pressure nozzles have a smaller droplet size, they are more susceptible to drift and evaporation losses. Lower pressure nozzles also increase the average application rate, increasing the potential for runoff. The capacity needed to effectively water a given field may not be met by a system whose pressure has been reduced solely for the purpose of reducing pumping costs. This is a good example of how focusing on one aspect of the system can lead to other problems elsewhere on the system. When designing a new system or converting an older system, consideration should be given to the general nozzle performance requirements as well as to cost reduction and water loss reduction.

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