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In-field solar drying of ventilated large hay packages

Kenneth L. Pierce

To the Graduate Council:

I am submitting herewith a thesis written by Kenneth L. Pierce entitled "In-field solar drying of ventilated large hay packages." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

B.L. Bledsoe, Major Professor

We have read this thesis and recommend its acceptance:

L.R. Wilhelm, J.H. Reynolds

Accepted for the Council:
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(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Kenneth L. Pierce Jr. entitled "In-Field Solar Drying of Ventilated Large Hay Packages." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Mechanization.

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We have read this thesis
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John H Reynolds

Accepted for the Council:

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X

IN-FIELD SOLAR DRYING OF VENTILATED LARGE HAY PACKAGES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Kenneth L. Pierce, Jr.

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ABSTRACT

The purpose of this study was to test and develop a machine which would form, "from the tractor seat," a ventilation tunnel in a high-density round bale having a moisture content above 35%. The ventilation tunnel would vent the interior of the bale and allow drying of the hay by natural air flow.

High-moisture bales were pierced with either one tunnel or three tunnels. Bale dimensions were taken before and after piercing. The result of these measurements showed less than 5 cm (2 inch) change in any bale dimension as a result of the piercing operation. Hydraulic gauge pressure was recorded during the piercing operation to determine the force required to produce a tunnel. The mean force developed by a 20.3 cm (8 inch) cone in producing a center tunnel was 11528.94 Newtons (2591.81 pounds).

The drying experiments consisted of comparing the effects of black plastic, chimneys and the number of tunnels on the drying rate of the high-moisture bales. An analysis of variance of the amount of moisture loss indicated no significant difference in any of the various treatments at the 90% confidence level.

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CHAPTER I

INTRODUCTION

I. NEED

"While the process of drying certain agricultural products is not at all new, it was not until comparatively recent years that experimental dryers were built in this country, the scope of the field enlarged, the need of fundamental investigations realized, and the manufacture of commercial units begun. The artificial drying or dehydration of agricultural products is essentially an economic measure, and if sufficiently low cost methods of drying can be developed, it would seem that they may have a profound influence on the agriculture of this country" (Anonymous, 1933). This statement is perhaps more applicable today than when it was written in 1933. With increased energy and labor costs has come a desire to complete farm operations as quickly as possible and with less energy expended than in past years. Achievement of such a goal in forage harvesting has required several stages of mechanization and control of the associated plant losses in the harvesting process.

The losses involved in harvesting and drying forages represent a large portion of the crop value, even when dried under the most favorable conditions. Annual hay losses in America due to weather damage and machine manipulation amounted to 650 million dollars in the fifties (U.S.D.A., 1954). Equivalent tonnage losses would be even more valuable today, thus providing the economical demand for improvement of methods which is often required to obtain results.

A number of uncontrollable variables produce losses in forage harvesting. The major problem is the weather and the uncertainty of it. According to Pedersen & Buchele (1960), rain reduces the quality of hay by bleaching, leaching of the nutrients, and requirement of an increased mechanical treatments. If the time for swath drying can be reduced by any means, the effect of weather uncertainty can be greatly reduced. Decreased time requirement would also enable farmers to harvest more hay in a given time period and thus improve the efficiency of their operations.

Even without rain on the hay a large amount of loss occurs through leaf shatter. Shatter losses are caused by uneven drying of the hay plant. As hay cures the leaves dry faster than the stems, and with subsequent mechanical treatment of the low moisture hay, the leaves shatter and are lost. The leaves are a valuable part of the hay. Pedersen and Buchele (1960) reported that the leaves contained 70% of the total protein, and 90% of the carotene content of the plant. They estimated that at least 20% of the leaves were lost under good drying conditions.

II. HISTORICAL APPROACHES

The importance of preventing losses in forage harvesting operations has long been known. An article in Agricultural Engineering (Anonymous,

1933) gave a brief description of a new portable dryer in which new-mown loose alfalfa hay was chopped and conveyed through a dryer consisting of three concentric drums. The heat was furnished by an oil burning furnace.

Problems with the drying chamber included lack of capacity and sizable labor requirements to handle the loose hay. The logical step, therefore, was to move to the use of packaged hay. An example of large package hay drying was reported by Eller (1977) at The University of Tennessee. As with most drying operations, the large package hay drying required energy to force air through the package. To avoid this energy requirement a drying system using natural convection air flow might be appropriate.

Such natural convection drying might be done in the field, thus reducing the added expense of handling. Kohlhepp (1978) reported the unconfirmed success of an attachment on the plunger head of a conventional baler which produced a breather hole during baling to aid in mold elimination and reduced field curing requirements. Investigation of the feasibility of such an approach to hay drying was the topic of this thesis, which involved the construction and evaluation of a machine to pierce ventilation holes in high-density round bales to allow natural convection drying of the bales.

CHAPTER II

OBJECTIVES

The purpose of this study was to evaluate a machine designed to pierce a ventilation passage in a high-density large round bale of hay and to determine the effect of ventilation passages on bale drying rate. The specific objectives were:

1. To test and evaluate the concept and operation requirements of a piercing machine for producing ventilation passages in large round bales of hay.
2. To evaluate the effect of package ventilation passages on accelerated drying of high-density large round bales of grass hay packaged at 35% or greater moisture content.

Response variables for preliminary performance test were:

1. Force required to pierce the bale.
2. Diameter of tunnel remaining in hay after withdrawal of piercing cone.
3. Deformation of hay package.

Evaluation tests of the package ventilation effect on drying rate included the following response variables:

1. Moisture content change with time.
2. Package internal temperature change with time.

CHAPTER III

REVIEW OF LITERATURE

I. WEATHER EFFECT ON HAY HARVEST

Harvesting hay has always presented the farmer with a number of challenges, the major one being that of harvesting high quality hay in a short time period. The ideal harvesting method would produce dried hay with the same level of nutritional components as contained in the grass plant before it was mown. To retain a high level of nutrients the crop should be taken from the field at a higher moisture content than that acceptable for storage. By harvesting at a high moisture content, the farmer would lessen or eliminate entirely such things as rain damage during a prolonged field curing period and shatter losses from over dried leaves.

Beginning about 1930, several research studies have centered on reducing losses during forage harvesting. Zink (1935) reported that low humidities tended to produce "case hardening" and that it could relate to stem pliability and brittleness of hay along with leaf shatter caused by the brittleness. All of these characteristics were factors of market hay grading.

Concerning hay conditioning methods, Boyd (1959) reported the effect of hay conditioning machines on accelerated in-field drying rate for hay swaths. He determined that conditioning hay could reduce the drying time about 30%. By shortening the time requirement for in-field drying, the chances for putting up hay without damage from weather were greatly improved. Boyd also reported that conditioning conserved hay color and feed value because of shorter exposure to weather elements and less shattering. Other researchers reporting similar results were Bruhn (1955) who used alfalfa, Jones (1948) who crushed large stemmed plants such as sudan grass, and Zachariah (1958) who used red clover and soybeans as his hay crops.

Studies performed in Eastern Kansas by Fairbanks (1966) showed that the use of hay conditioning machines allowed alfalfa hay to be baled the same day it was cut. He also concluded that crushing the alfalfa plant stem probably increased the rate of carotene loss during field curing; however, due to the increased rate of drying and reduced drying time, the crushed hay carotene content would be equal to or higher at the time of storage than hay subjected to other conditioning treatments. Similar results were achieved by Hellwig (1976). He reported that a day could be saved by conditioning coastal bermudagrass. His study centered around a Tandem Roll Mower-Crusher which provided encouraging results; however, he thought that increased hay losses resulting from the two-pass treatments were too high for the machine to be feasible.

Paiepke (1970), from experiments which altered physical characteristics of alfalfa plants to increase the drying rate, concluded that with more surface area, water had less distance to travel in diffusing out of the alfalfa plant. The drying rate could also be increased by decreasing the resistance of the exposed surface of stems to water movement. Paiepke accomplished this with the use of a solvent which affected primarily the cutin on the stem surface.

II. MOISTURE EFFECT ON HAY PACKAGE

To bale hay at high moisture contents, a number of problems must be solved. Miller et al. (1967) reported that a cause and effect relationship exists between the moisture content of the hay at the time of baling and the temperature rise in the bale following baling. The heat rise was diagnosed as resulting from the oxidation of readily fermentable carbohydrates. This was a confirmation of work conducted by H. Miller (1947) at his dehydration operation in Nebraska. During the trip from the field, considerable heat developed in the hay, indicating microbiological oxidation and the consequent destruction of dry matter. Studies by Shepperson (1971) added further evidence that heating occured in bales of high moisture content. He reported temperatures up to nearly 150°F, and even more important, temperatures of over 100°F for several days. These temperatures resulted in a high degree of molding in the bale. Miller (1947) theorized that a transformation from grass protein to bacteria protein occurred in the bale. Protein content might not be greatly affected analytically, but the nutritional value might decrease slightly.

III. PACKAGE DENSITY AND THE RATE OF DRYING

Hay baled at high moisture content must be dried to an acceptable level for storage. Wood (1971) concluded that the rate of respiration in baled hay is a linear function of moisture content. He stated that for natural drying to take place, the respiration heat energy must be used both to increase the temperature of the drying air and to evaporate moisture. The problem is the lack of free air movement in a bale.

Mears (1970) concluded that to increase the drying rate it is necessary to increase the vapor pressure gradient or decrease the resistance to vapor movement in the material to be dried. Barre (1938) stated that moisture will move as a vapor from regions of higher partial vapor pressure to regions of lower partial vapor pressure. The rate of this movement is proportional to the vapor pressure gradient and inversely proportional to the resistance to vapor movement, thus the process can be considered one of diffusion. To decrease the moisture content of a bale, the moisture must diffuse through the bale to free air. VanDuyne (1964) concluded that moisture content was not a factor in the resistance of alfalfa hay to air flow within the range of 11 to 60% moisture content. The moisture content, however, tended to be a factor in the resistance to air flow of clover hay which was above 45% moisture content. The principal factors that affected the air flow resistance of baled alfalfa and clover hay were forage type, velocity of air, density of material (dry matter basis), length of compressed sample, and bale slice orientation.

If more free air space could be provided in the inner portion of the bale leading to the outside, the heat produced in the bale could be transported to the outside by convective air flow. The air movement from the inner portion of the bale would carry heat and moisture out of the bale.

CHAPTER IV

PRELIMINARY ANALYSIS OF PIERCER CONCEPT

The initial analysis of the piercer concept was done by the Agricultural Engineering 4640 design class at The University of Tennessee, Knoxville (Sanders, 1975). The objective was to design a mechanism, mountable on a category II three point hitch, capable of piercing ventilation passages in large round bales or stacks of hay having densities up to 240.3 kg/m^3 (15 lb/ft^3). The device was also to be marketable to the small farmer with a cost goal set at $1,500 for a completed piercer.

A review of literature by the design class revealed a lack of data on the force requirements for piercing fibrous materials. The initial step therefore was to measure the force requirement to penetrate a high density round bale.

I. INITIAL EXPERIMENTS

The laboratory experiment consisted of sawing a high density round bale in half. The bale halves were then positioned next to a hydraulic press which was used to force piercer cones into the bale. An experimental piercer cone of 7.6 cm (3 inch) base diameter was forced into each bale half at the same time. This test determined that force of 3469.6 N (780 pounds) was required to penetrate the bale with a 7.6 cm (3 inch) piercer cone having a 60^0 point.

These tests also showed that a larger cone must be used to form permanent tunnels in the hay bale. Upon removal of the 7.6 cm (3 inch) cone, the tunnel in the bale collapsed. For air to move through the bale, the tunnel must remain partially open, and to achieve this result the piercer cone must be larger than 7.6 cm (3 inch). The design classes suggested that the cone be 20.3 cm (8 inch) in diameter. Using a linear relationship, a 20.3 cm (8 inch) cone would require 9252.3 N (2,080 pounds) of force to pierce the bale.

II. MACHINE CONFIGURATION

The initial piercing machine design consisted of a tractor-mounted (three-point hitch) rigid frame to support the hydraulic cylinders powering the piercer cones. The two piercer cylinders were 147.3 cm (58 inch) stroke double-acting cylinders mounted on hinged arms that could swung back along the support frame for transport. The arms swing out perpendicular to the frame for the piercing operation.

III. PROBLEMS

Analysis of the initial design revealed a number of problems which required redesign of the machine. One requirement was a simplified hydraulic circuit. The initial control circuit was too complicated and expensive for the intended use of the machine. Strengthening of the main frame in the hitch area was required along with a more rigid support system for the cylinders. A reduction in mass of the hydraulic cylinders was also called for. The final redesign requirement was that of making the main-frame arms collapsible for added compactness during transport of the machine.

CHAPTER V

MACHINE DESCRIPTION

The piercer was designed for use on large round bales from 1.22 m to 1.83 m (4 ft. to 6 ft.) in length with the capability of forming a tunnel at any point on the bale cross-section. Positioning of the piercer cones relative to the bale cross-section was accomplished through the tractor three-point lift mechanism which attached to the piercer main frame. Varying the distance between the opposed piercer cones to accommodate bales of different length required a "span-adjust" mechanism incorporated into the piercer cone support arms.

Since the purpose of the piercer was to produce tunnels in high density round bales, the heart of the machine was the piercing cones and components to drive the cones into the bale. The other parts of the piercer were simply supportive components that provided positioning and transport of the piercing cones.

The initial cone design consisted of 11 gauge sheet metal welded about a 20.32 cm (8 inch) disc. The hub for the cone was a 7.62 cm (3 inch) steel rod machined to slide over the rod end of the telescoping cylinder which powered it. The back plate of the cone was 12.86 cm x 0.64 cm (5.062 inch x 0.25 inch) steel plate. The tip of the cone was also 7.62 cm (3 inch) steel rod which was machined to form the 60^0 included angle cone tip. The welded cone assembly was machined to a smooth surface and then painted with enamel with hardener added. The cones were attached to the piercing cylinders by means of a 3.18 cm (1.25 inch) diameter pin (Figure 1).

The piercing cylinders were two stage, telescoping, double acting hydraulic cylinders with each stage having a travel of 45.72 cm (18 inch). The first stage had a bore of 10.16 cm (4 inch) and the second stage had a 7.62 cm (3 inch) bore. Each cylinder was attached to a 15.24 cm x 15.24 cm x 0.64 cm (6 inch x 6 inch x 0.25 inch) support angle by two cylinder support brackets. These brackets were welded to the support angle, and the cylinder was bolted into the center of the brackets. The support angles were welded to support arms which were constructed of 10.16 cm x 15.24 cm x 0.96 cm (4 inch x 6 inch x 0.38 inch) steel tubing with the 15.24 cm (6 inch) face parallel to the ground (Figure 2). A gusset was added between the support angle and arm for added rigidity and strength during piercing.

The support arms were 133.35 cm (52.5 inch) long and had two 11.43 cm (4.5 inch) holes bored through the 15.24 cm (6 inch) face of the arm. The first hole was 10.16 cm (4 inch) from the end of the arm, and the second hole was 34.92 cm (13.75 inch) from the first on the center line of the arm. Sleeves were welded into the 11.43 cm (4.5 inch) holes. These sleeves were line bored to a diameter of 10.16 cm $\pm$ 0.00254 cm (4.009 inch $\pm$ 0.0001 inch). Each support arm was one bar of a four-bar parallel linkage; therefore the two support arms always remained parallel to one another (Figure 3).

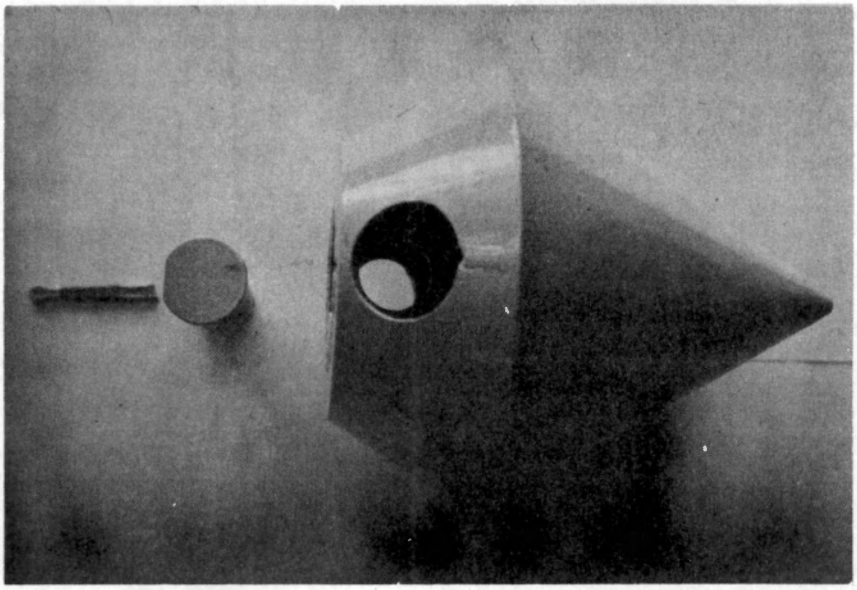


Figure 1. Piercing Cone with 60-Degree Included Angle Showing 3.18 cm (1.25 Inch) Diameter Connecting Pin.

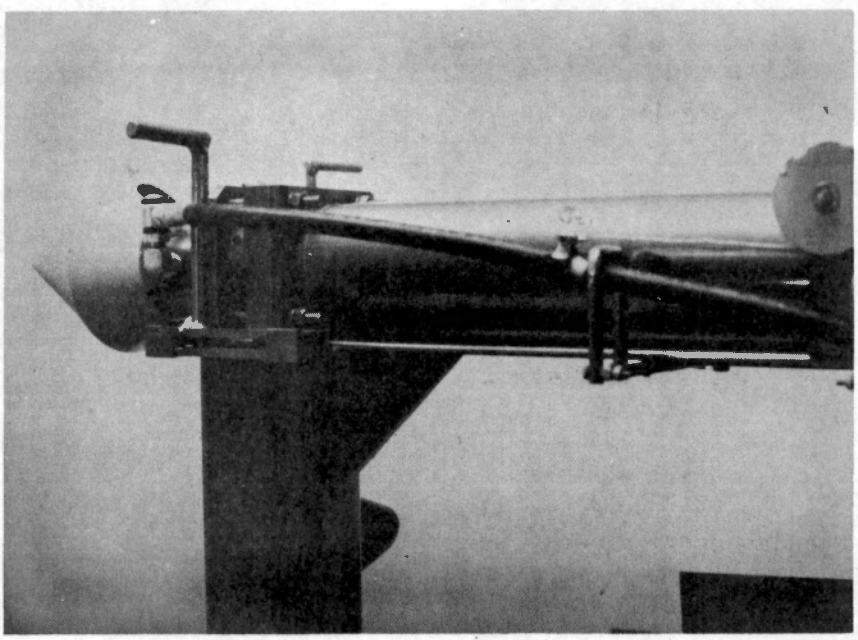


Figure 2. Overall View of Support Arm and Angle Configuration.

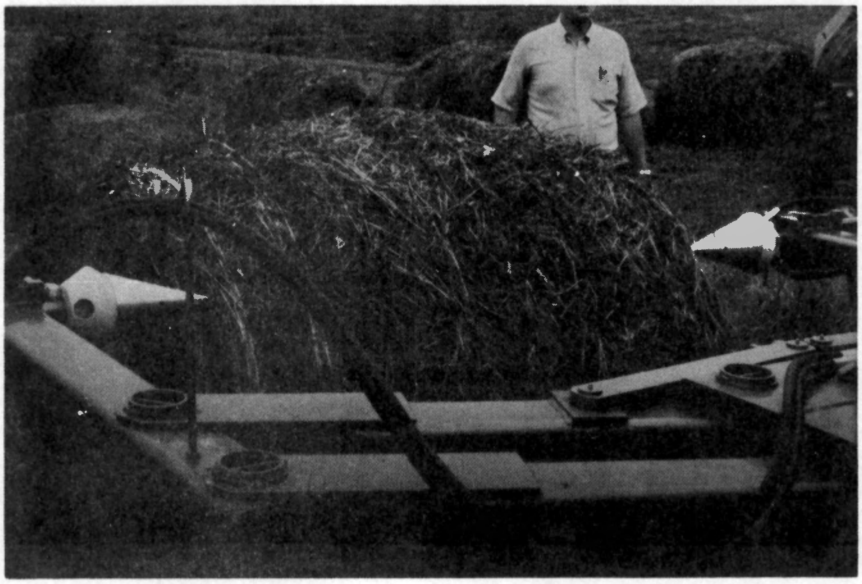


Figure 3. Front View of Four-Bar Parallel Linkage Connecting Support Arm to Main Frame.

Two linking beams connected each support arm to the main frame. These beams were 10.16 cm x 15.24 cm x 0.95 cm (4 inch x 6 inch x 0.38 inch) steel tubes with one end of both links having the same kind of sleeve as the support arm. On the opposite end were two 50.8 cm x 15.24 cm x 1.27 cm (20 inch x 6 inch x 0.5 inch) plates welded to the tube with a 10.1829 cm $\pm$ 0.0025 cm (4.009 inch $\pm$ 0.001 inch) hole bored through them. The 10.16 cm (4 inch) holes in these tubes were 107.95 cm (42.5 inch) apart on center. The rear link had two additional 10.16 cm x 15.24 cm x 1.27 cm (4 inch x 6 inch x 0.5 inch) steel plates welded on the 15.24 cm (6 inch) face of the beam. These were positioned such that a 3.8277 cm $\pm$ 0.0025 cm (1.507 inch $\pm$ 0.001 inch) hole could be bored 30.48 cm (12 inch) on center from the 11.43 cm (4.5 inch) diameter hole with the welded-in sleeve.

The links were secured to the support arms by means of pivot pins. These pins were constructed of 10.16 cm O.D. x 0.64 cm (4 inch O.D. x 0.25 inch) wall, drawn over mandrel steel tubing. Four support arm-to-link pivot pins were required for the complete machine. They were 16.66 cm (6.56 inch) long and had two 0.6747 cm (0.2656 inch) diameter holes drilled through both walls 0.9525 cm (0.375 inch) from each end of the tube. In the center of the pin a lubrication groove was cut and a hole tapped for a 1/4 - 28 UNF grease fitting. The pins were case hardened 0.0508 cm to 0.0762 cm (0.02 inch to 0.03 inch) deep to Rockwell C - 58 - 62 hardness.

The front and rear links were attached to the main frame which served as the fixed link of the four bar linkage. The main frame was a welded assembly made up of 5.08 cm x 25.4 cm x 0.635 cm (2 inch x 10 inch x 0.25 inch) steel tubing. The top portion consisted of two pieces of 5.08 cm x 25.4 cm (2 inch x 10 inch) steel tubing 95.25 cm (37.5 inch) long welded together. The bottom also consisted of two 5.08 cm x 25.4 cm (2 inch x 10 inch) steel tubing pieces welded together, but these pieces were 100.33 cm (39.5 inch) long. The top and bottom assemblies were spaced apart by two 10.16 cm x 15.24 cm x 0.96 cm (4 inch x 6 inch x 0.38 inch) steel tubes. These spacer tubes were positioned such that another 10.16 cm x 15.24 cm x 0.96 cm (4 inch x 6 inch x 0.38 inch) tube could be placed between them. With this configuration, the spacers for the main frame also served as guides for a span adjust slide (Figure 4).

Four bored and sleeved holes were required in the main frame identical to the two holes in each support arm. The spacing of the holes was 34.92 cm (13.75 inch) on center along the length of the frame and 74.93 cm (29.5 inch) on center across the frame. The sleeved holes were line bored to assure the holes being parallel. The pins used to attach the links to the frame were the same as those used to attach the links to the support arm except that the link-to-frame pivot pins were 24.28 cm (9.56 inch) long and had three lubrication grooves.

Standard Category II three-point hitch componets were included in the main frame to attach the machine to a tractor. A pedestal on the main frame provided the upper link attaching hole, and lower link pins were included on the bottom portion of the main frame. A hydraulic

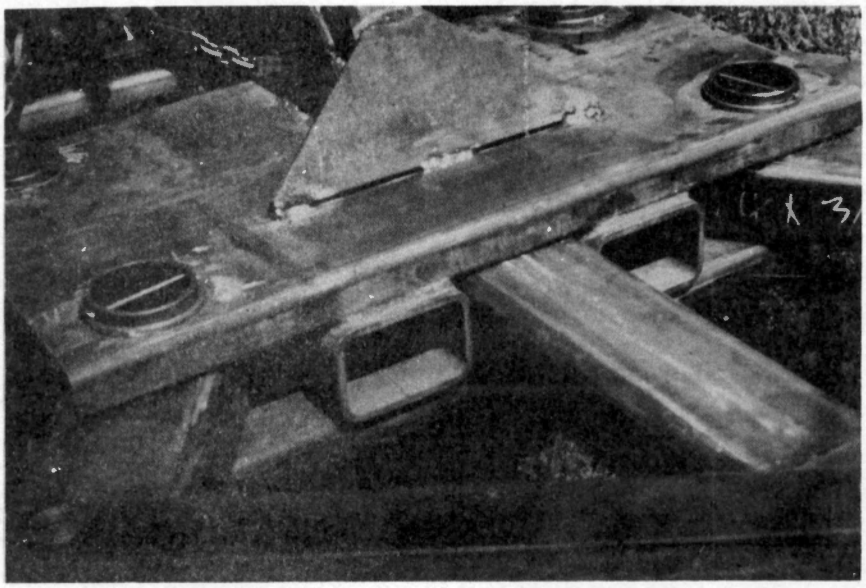


Figure 4. Rear View of Main Frame in Construction Stage Showing Rectangular Tubular Spacers which Serve also as Guides for the Span Adjust Slide.

cylinder operated the span adjustment of the machine (distance apart of initial position of piercing cone points). The base end mounting bracket for the cylinder attached to the two spacer tubes of the main frame. The main frame also had two supporting feet. These feet positioned the main frame above the ground when it was not connected to a tractor.

The span adjust slide was constructed of 10.16 cm x 15.24 cm x 0.96 cm (4 inch x 6 inch x 0.38 inch) tubing 125.42 cm (49.38 inch) long. On one end of the tube two 1.27 cm x 15.25 cm x 13.66 cm (0.3 inch x 6 inch x 5.28 inch) steel plates were welded to serve as a bearing surface for the span adjust link pivot pins. Two 4.44 cm (1.75 inch) diameter holes were bored through the plates for the case hardened pins which were 4.44 cm (1.75 inch) diameter x 18.88 cm (7.4 inch) in length. The plates comprising the span adjust cylinder base attaching bracket were of 2.22 cm x 7.62 cm x 26.36 cm (0.875 inch x 3 inch x 10.38 inch) size with a 3.22 cm (1.266 inch) diameter hole drilled for the cylinder attaching pin. The span adjust slide was attached to the parallel linkage rear links by means of auxiliary links. These links were constructed of 7.62 cm x 12.7 cm x 0.64 cm (3 inch x 5 inch x 0.25 inch) steel tubing 43.18 cm (17 inch) long. Steel plates 2.22 cm x 7.62 cm (0.875 inch x 3 inch) and 93.66 cm (36.875 inch) long, were welded to the 7.62 cm (3 inch) face of the tubes. Holes 3.8275 cm $\pm$ 0.0025 cm (1.507 inch $\pm$ 0.001 inch) were bored through both ends of the 2.22 cm x 7.62 cm

(0.875 inch x 3 inch) plate and were spaced 61.91 cm (24.375 inch) apart on center (Figure 5).

The cylinder to move and hold the span adjust slide was a 10.16 cm (4 inch) diameter, double acting, extra heavy duty cylinder. The hydraulic fluid for the span adjust cylinder was supplied directly from the remote couplings of the tractor using the tractor direction control valve to operate the cylinder circuit. The span adjust cylinder had a retracted length of 73.66 cm (29 inch) and a stroke of 50.8 cm (20 inch). This travel varied the center line distances apart of the support arms from 149.86 cm (59 inch)-closed position-to 273.68 cm (107.75 inch)-completely open position (Figure 6 and Figure 7).

The piercer was designed to allow operation of both piercing cylinders simultaneously or either piercing cylinder individually. The hydraulic control circuit consisted of two 2-position, 6-way valves mounted on a telescoping control pedestal which in turn fastened to the main frame pedestal. The inlet and outlet pressure from the tractor remote hydraulic connection was monitored by two 20684.66 kPa (3000 psi) maximum pressure gauges positioned at the valve inlet ports. The schematic design of the piercing control circuit is shown in Figure 8. The telescoping cylinders had the inlet and outlet ports on the moving end of the cylinder. This configuration required that the hydraulic lines follow the piercing points into the bale, and the size and configuration of the swivel fittings required to allow this motion limited the size of the piercing point base to no less than 20.32 cm (8 inch).

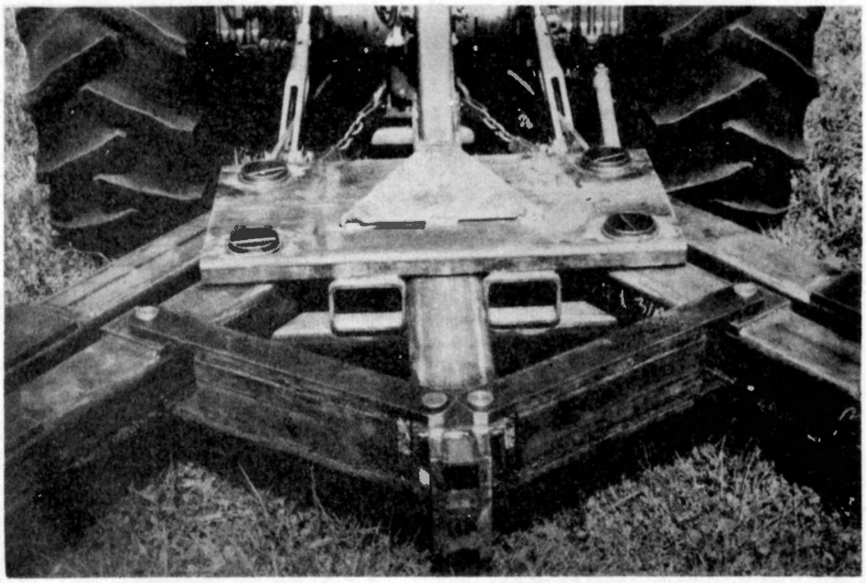


Figure 5. Rear View During Construction Stage of Auxiliary Links Connecting Span Adjust Slide to Rear Links of Parallel Linkage.

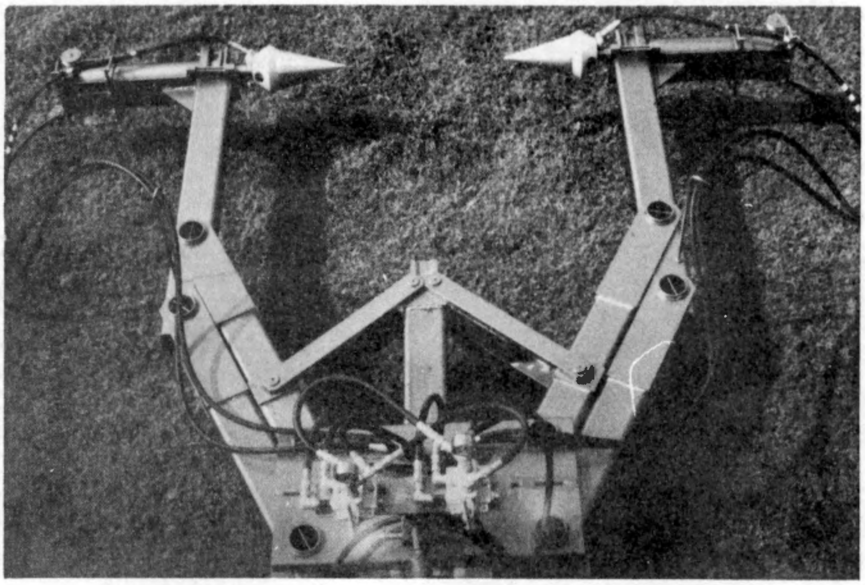


Figure 6. Overall View of Piercing Machine with Support Arms in Closed (Transport) Position.

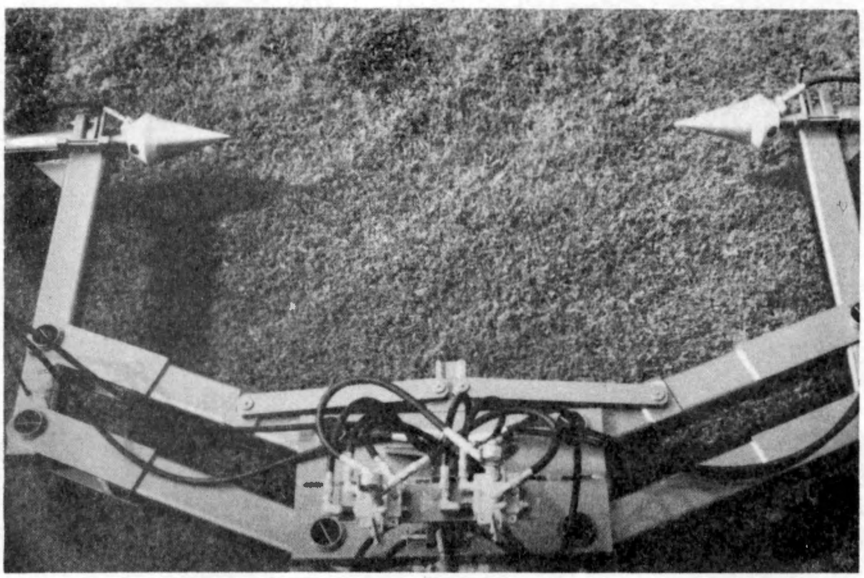
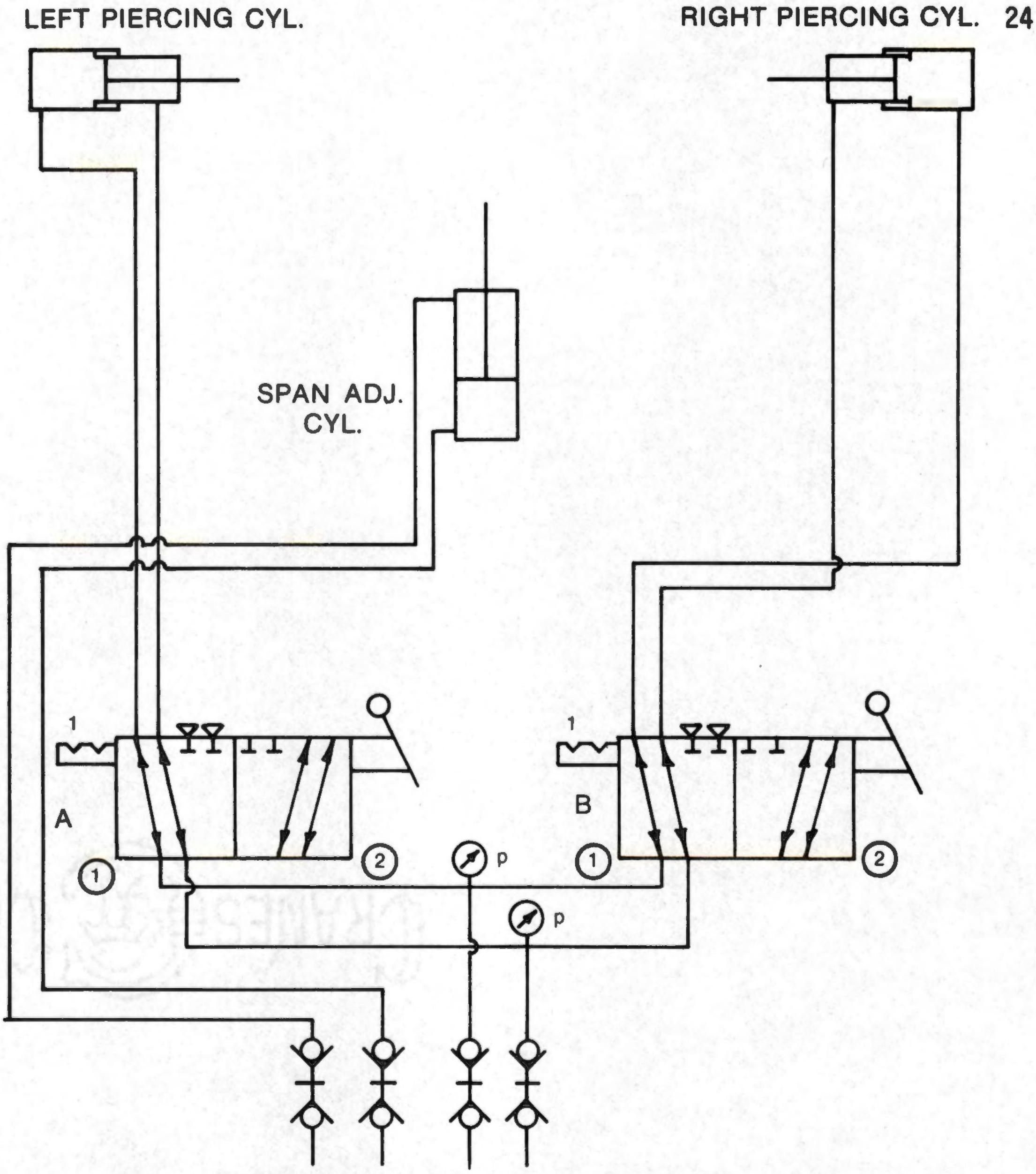


Figure 7. Overall View of Piercing Machine with Support Arms in Completely-Open Position.



FUNCTION	VALVE A		VALVE B	
	POS 1	POS 2	POS 1	POS 2
BOTH PIERCING CYLS.	X		X	
L. PIERCING CYL.	X			X
R. PIERCING CYL.		X	X	

Figure 8. Schematic Diagram of Piercing Control Circuit.

The difficulty involved in the operation was that of keeping the hoses from catching on frame parts as the cones were being retracted from the hay. The hoses were restrained parallel to the cylinder to avoid retraction problems. A set of inner and outer guides restrained the hoses in the desired travel path. The outer guides were constructed of 1.27 cm (0.5 inch) rod bent in a "U" shape 7.94 cm (3.12 inch) deep. The inner guide, spaced 20.32 cm (8 inch) from the outer guide, was also a "U" shaped rod but was 9.842 cm (3.875 inch) deep. A constant tension retraction reel pulled each hose out of the bale as the cylinders were retracted. A set of upper and lower horizontal guides was added to deflect the hose away from the cylinder at the end of the stroke. A 7.62 cm (3 inch) vertical guide was added to prevent the cone from rotating more than 25 degrees off center during retraction. Figures 9 and 10 show the hose retraction parts in the cylinder "extended" and "retracted" positions, respectively.

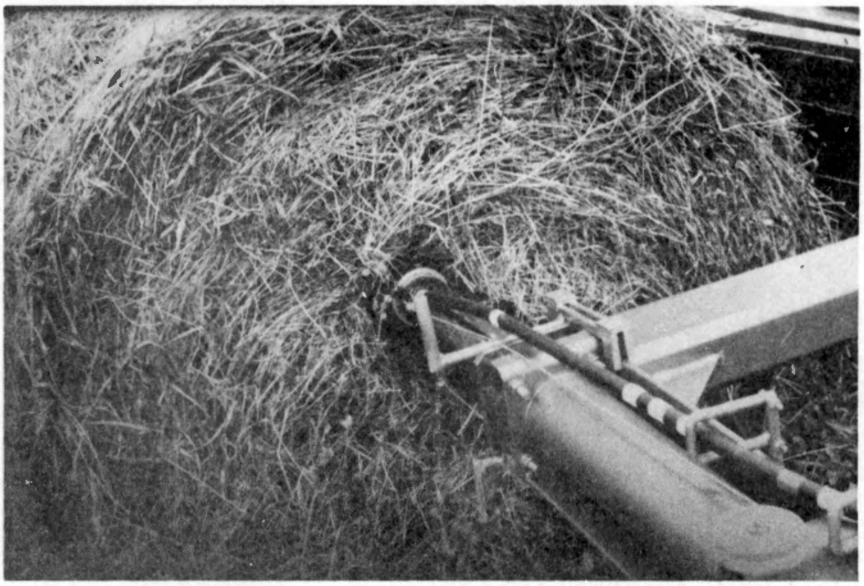


Figure 9. Overall View of Hose Guides and Retraction Parts with Cylinder in Extended Position.

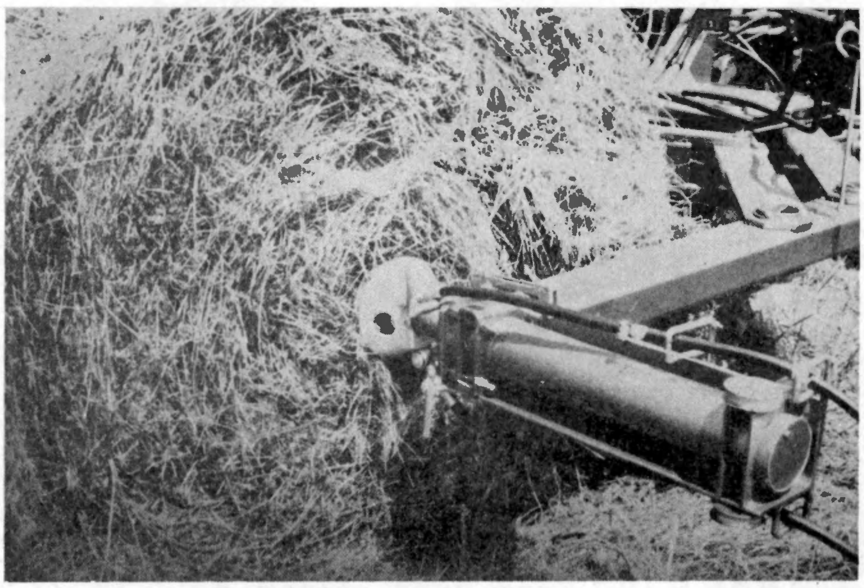


Figure 10. Overall View of Hose Guides and Retraction Parts with Cylinder in Retracted Position.

CHAPTER VI

PRELIMINARY EVALUATION EXPERIMENTS

I. RATIONALE

Preliminary testing of the piercer was planned to determine information on three aspects of the piercing operation:

1. Resulting ventilation tunnel size and location effect on size of tunnel;
2. Force requirements during the piercing operation; and
3. Package deformation due to piercing.

Conventionally cured, high-density round bales were selected for these tests.

II. EXPERIMENTAL PLAN

The initial evaluation plan called for six treatments with two replications of each. The treatments were as follows, with one bale used for each treatment:

1. A single 15.2 cm (6 inch) tunnel at the center of the bale.
2. A single 20.3 cm (8 inch) tunnel at the center of the bale.
3. Three 15.2 cm (6 inch) tunnels located at half the bale radius from the center and spaced 120 degrees apart.
4. Three 20.3 cm (8 inch) tunnels located a half the bale radius from the center and spaced 120 degrees apart.

5. A single 15.2 cm (6 inch) tunnel at the center with three 15.2 cm (6 inch) tunnels located half the bale radius from the center and spaced 120 degrees apart.
6. A single 20.3 cm (8 inch) tunnel at the center with three 20.3 cm (8 inch) tunnels located at half the bale radius from the center and spaced 120 degrees apart.

To produce the tunnel, the plan was to bring the two piercing cones to within 2.5 cm (1 inch) of each other inside the bale. At this point one of the cones would be retracted, the other cone would then complete the tunnel opening through the center of the bale. The cones were double faced with both front and rear cones having included angles of 60^{o} (Figure 11).

III. PROBLEMS

Some problems developed during the preliminary evaluation tests. The most prominent problem resulted from the 60^{o} cone being too blunt to correctly penetrate the hay. Thus a plug of hay formed in front of the cone and did not slide off the sides of the cone as desired. To solve this problem a second cone tip was machined with an included angle of 33^{o} and a large end diameter of 15.2 cm (6 inch). This new cone tip was designed to screw onto the old cone leaving only a 5.1 cm (2 inch) wide area with a 60^{o} face (Figure 12).

The original experimental plan called for two piercing cones, one a 15.2 cm (6 inch) diameter cone and one a 20.3 cm (8 inch) diameter

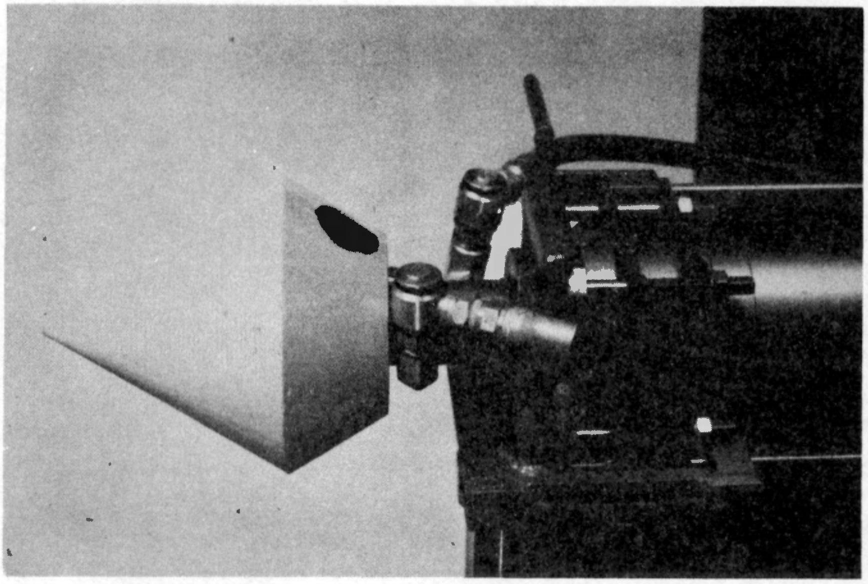


Figure 11. Double Faced 60-Degree Cone Attached to Piercing Cylinder.

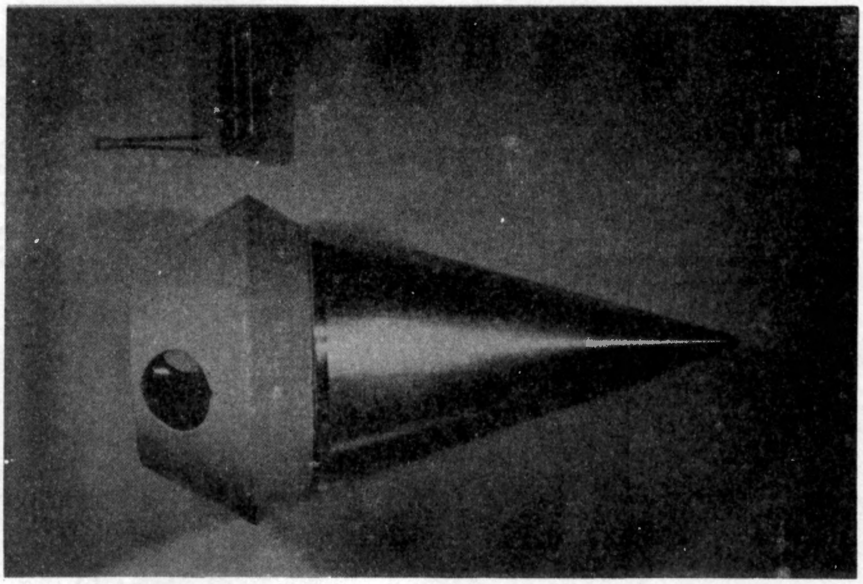


Figure 12. New 33-Degree Cone Screwed onto the Old 60-Degree Cone, Shown with Cylinder Connecting Pin.

cone. Because a minimum cone base of 20.3 cm (8 inch) was required for clearance of hydraulic connections, plans to include the 15.2 cm (6 inch) cone was discarded. With the telescoping cylinders having their inlet and outlet ports on the telescoping end, the connectors required more tunnel area than the 15.2 cm (6 inch) diameter cone could produce.

Another problem discovered during the initial operational test was that of knowing how far the cylinders had penetrated into the bale. This was very important in that the operator needed to bring the tips within 2.5 cm (1 inch) of each other without allowing the cones to touch or pass each other. If the cones were to touch, damage could occur to both the cones and the cylinders. The solution consisted of painting different colored bands on the span adjust slide and matching bands on the hydraulic hose at points where the cylinders would be within 2.5 cm (1 inch) of each other (Figures 13 and 14). The operator, by matching colors, could bring the tips within 2.5 cm (1 inch) of each other with total confidence regardless of the length of bale being pierced.

IV. RESULTS

Tunnel Size and Location

Even with the 33^{o} cones the operator could not produce a tunnel completely through the bale from the tractor seat. However, hay clogging in front of these cones was not as severe as it had been with the 60^{o}

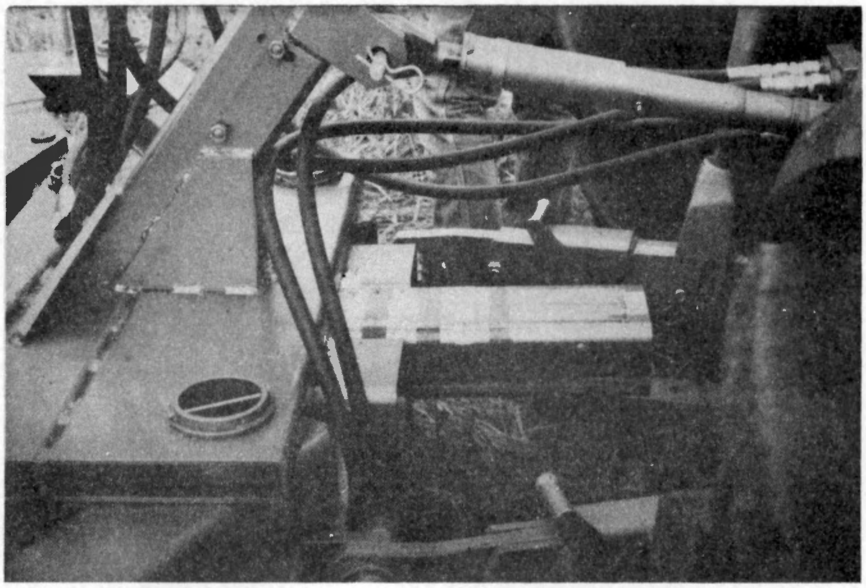


Figure 13. Colored Bands on Span Adjust Slide to Indicate Initial Distance Apart of Piercing Cone Tips.

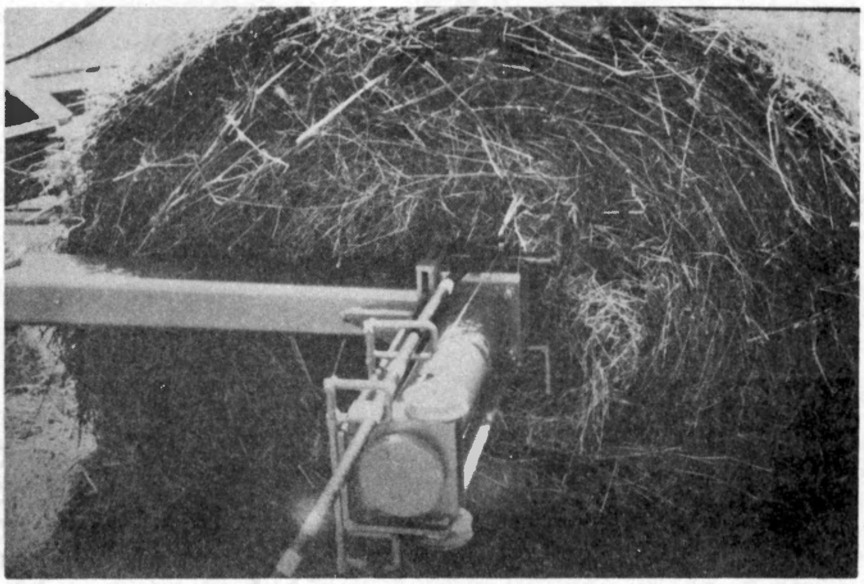


Figure 14. Colored Bands on Piercing Cylinder Hydraulic Hose to Gauge Extent of Piercing Cone Penetration into Bale.

cones. A reaction plate (Figure 15) was constructed and placed over the tip of the cone which had been retracted in an attempt to keep the reaction force in line with the piercing force of the opposing cone. This approach was not effective, however, in that the bale had a tendency to rotate and deform out of shape, and the plate was forced into the bale.

Hay at the center of the bale packed between the cone tips was the only obstruction to producing a tunnel completely through a bale. One solution for this problem was to open the remainder of the tunnel by hand. In doing so a 2.5 cm (1 inch), tapered rod was driven through the compacted area (Figure 16). A 7.6 cm (3 inch) pipe with a 60^{o} cone welded to the end was then driven through the opening left by the tapered rod (Figure 17). A tunnel believed to be of sufficient size was left in the bale after passing the pipe through the center.

Since plans to use the 15.2 cm (6 inch) cones were discarded the number of treatments consisted to only half the number originally planned. During the piercing of the first two bales, it was noted that the number of tunnels in a bale had little effect on the size of the tunnels in the bale. It was therefore decided that treatment six would serve for treatment four as well.

The results of the preliminary tests for tunnel size and shape are shown in Tables 1 and 2. Tunnel measurements were taken as shown in Figure 18. Typical shape of the center tunnels produced is shown in Figure 19. At a depth of 15.2 cm (6 inch) the vertical diameter was 18.5 cm (7.3 inch) and the horizontal diameter was 20.8 cm (8.2 inch).

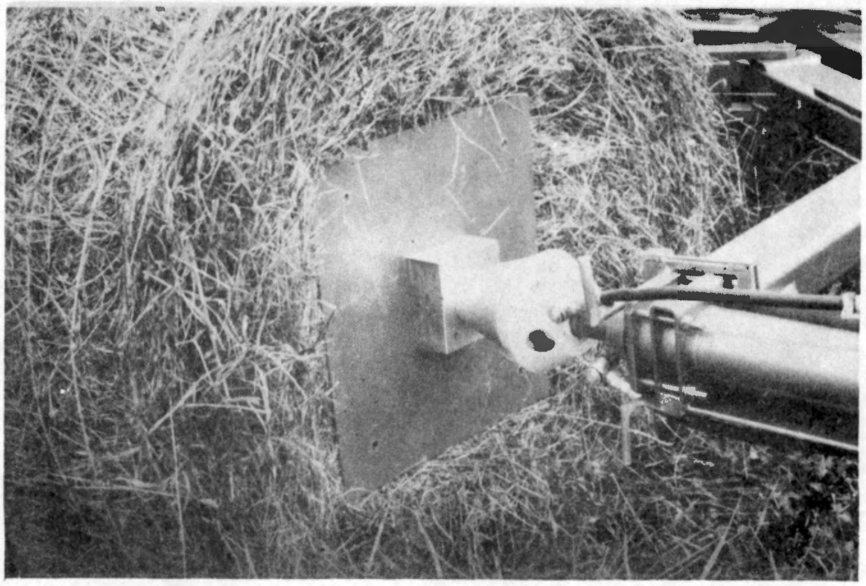


Figure 15. Reaction Plate to Keep Reaction Forces in Line with Piercing Force of the Opposing Cone.

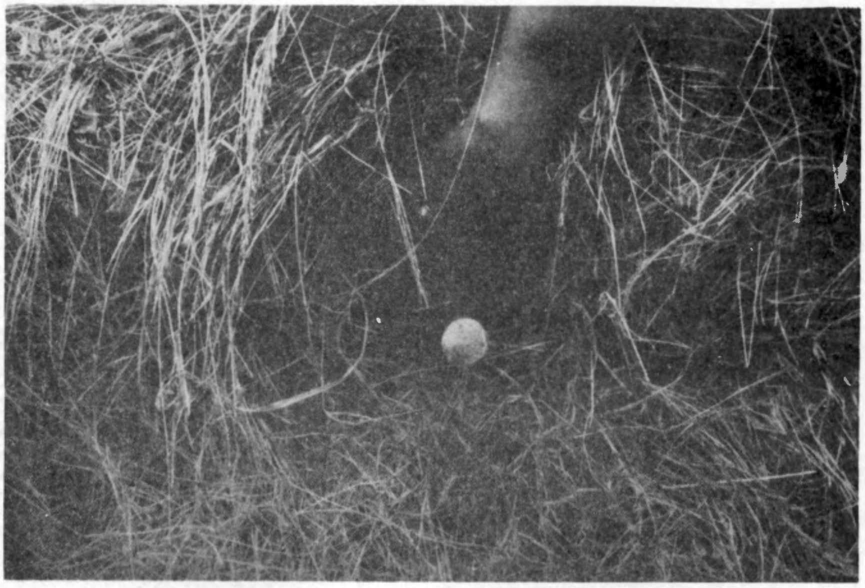


Figure 16. The 2.54 cm (1 Inch) Rod Used to Initially Open the Tunnel Center Portion After Piercing.

Figure 17. The 7.62 cm (3 Inch) Cone and Pipe Used to Completely Open Plug in Pierced Tunnels and to Maintain Tunnel Opening.

TABLE 1

CENTER TUNNEL DIMENSIONS BY SECTION FOR BALES PIERCED DURING PRELIMINARY TESTS
(AVERAGE FOR FOUR TUNNELS)

		At Piercing								2 Weeks After Piercing								Change	
		Vertical				Horizontal				Vertical				Horizontal				Mean	
Section		Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Vertical	Horizontal
1	0 cm (0 in.)	21.59 (8.50)	17.8 (7.0)	25.4 (10.0)	3.28 (1.29)	24.43 (9.62)	17.8 (7.0)	33.0 (13.0)	7.85 (3.09)	20.96 (8.25)	17.8 (7.0)	26.7 (10.5)	3.94 (1.55)	29.51 (11.62)	21.6 (8.5)	38.1 (15.0)	6.83 (2.69)	-0.64 (-0.25)	+5.05 (+1.99)
2	15.2 cm (6 in.)	20.96 (8.25)	16.5 (6.5)	24.1 (9.5)	3.35 (1.32)	23.01 (9.06)	15.2 (6.0)	33.0 (13.0)	8.86 (3.49)	23.98 (9.44)	14.0 (5.5)	21.6 (8.5)	7.85 (3.09)	24.43 (9.62)	15.2 (6.0)	36.8 (14.5)	10.39 (4.09)	+3.02 (+1.19)	+1.42 (+0.56)
3	30.5 cm (12 in.)	16.20 (6.38)	12.7 (5.0)	17.8 (7.0)	2.41 (0.95)	20.32 (8.00)	12.7 (5.0)	30.5 (12.0)	8.03 (3.16)	15.88 (6.25)	11.4 (4.5)	17.8 (7.0)	3.02 (1.19)	22.22 (8.75)	16.5 (6.5)	31.8 (12.5)	7.29 (2.87)	-0.33 (-0.13)	+1.91 (+0.75)
4	45.7 cm (18 in.)	12.22 (4.81)	10.2 (4.0)	14.0 (5.5)	1.57 (0.62)	13.18 (5.19)	10.2 (4.0)	20.3 (8.0)	4.85 (1.91)	8.58 (3.38)	7.6 (3.0)	15.2 (6.0)	6.32 (2.49)	13.00 (5.12)	8.9 (3.5)	22.9 (9.0)	6.58 (2.59)	-3.63 (-1.43)	-0.18 (-0.07)
5	61.0 cm (24 in.)	9.52 (3.75)	6.4 (2.5)	12.7 (5.0)	2.64 (1.04)	10.16 (4.00)	7.6 (3.0)	12.7 (5.0)	2.08 (0.82)	6.35 (2.50)	3.8 (1.5)	8.9 (3.5)	2.08 (0.82)	7.62 (3.00)	3.8 (1.5)	10.2 (4.0)	2.74 (1.08)	-3.18 (-1.25)	-2.54 (-1.00)
6	76.2 cm (30 in.)	5.08 (2.00)	2.5 (1.0)	7.6 (3.0)	2.08 (0.82)	5.72 (2.25)	2.5 (1.0)	7.6 (3.0)	2.44 (0.96)	1.27 (0.50)	0 (0)	5.1 (2.0)	2.54 (1.00)	1.27 (0.50)	0 (0)	5.1 (2.0)	2.54 (1.00)	-3.81 (-1.50)	-4.45 (-1.75)
7	91.4 cm (36 in.)	3.81 (1.50)	0 (0)	6.4 (2.5)	2.74 (1.08)	4.11 (1.62)	0 (0)	7.6 (3.0)	3.18 (1.25)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-3.81 (-1.50)	-4.11 (-1.62)
8	106.7 cm (42 in.)	6.98 (2.75)	2.5 (1.0)	10.2 (4.0)	3.35 (1.32)	6.98 (2.75)	2.5 (1.0)	10.2 (4.0)	3.35 (1.32)	3.18 (1.25)	0 (0)	8.9 (3.5)	4.22 (1.66)	4.11 (1.62)	0 (0)	8.9 (3.5)	4.80 (1.89)	-3.81 (-1.50)	-2.87 (-1.13)
9	121.9 cm (48 in.)	9.19 (3.62)	6.4 (2.5)	10.2 (4.0)	2.16 (0.85)	10.16 (4.00)	7.6 (3.0)	12.7 (5.0)	23.11 (0.91)	8.58 (3.38)	2.5 (1.0)	15.2 (6.0)	5.44 (2.14)	9.52 (3.75)	7.6 (3.0)	12.7 (5.0)	2.21 (0.87)	-0.61 (-0.24)	-0.64 (-0.25)
10	137.2 cm (54 in.)	12.06 (4.75)	12.7 (4.0)	14.0 (5.5)	1.62 (0.64)	15.24 (6.00)	11.4 (4.5)	17.8 (7.0)	3.10 (1.22)	13.97 (5.50)	7.6 (3.0)	21.6 (8.5)	5.76 (2.27)	13.66 (5.38)	12.7 (5.0)	14.0 (5.5)	0.64 (0.25)	+1.91 (+0.75)	-1.57 (-0.62)
11	152.4 cm (60 in.)	16.03 (6.31)	10.2 (5.0)	17.8 (7.0)	2.29 (0.90)	18.57 (7.31)	14.0 (5.5)	25.4 (10.0)	4.85 (1.91)	16.51 (6.50)	11.4 (4.5)	22.9 (9.0)	5.38 (2.12)	20.96 (8.25)	17.8 (7.0)	25.4 (10.0)	3.81 (1.50)	+0.48 (+0.19)	+2.39 (+0.94)
12	167.6 cm (66 in.)	20.96 (8.25)	20.3 (8.0)	22.9 (9.0)	1.27 (0.50)	22.86 (9.00)	17.8 (7.0)	30.5 (12.0)	5.49 (2.16)	21.89 (8.62)	12.7 (5.0)	30.5 (12.0)	8.64 (3.40)	24.13 (9.50)	21.6 (8.5)	26.7 (10.5)	2.31 (0.91)	+0.94 (+0.37)	+1.27 (+0.50)

TABLE 2

RADIALLY LOCATED TUNNEL DIMENSIONS BY SECTION FOR BALES PIERCED DURING PRELIMINARY TESTS
(AVERAGE FOR SIX TUNNELS)

Section		At Piercing								2 Weeks After Piercing								Change	
		Vertical				Horizontal				Vertical				Horizontal				Mean	
		Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Mean	Minimum	Maximum	Std. Dev.	Vertical	Horizontal
1	0 cm (0 in.)	20.32 (8.00)	15.2 (6.0)	25.4 (10.0)	4.47 (1.76)	25.20 (9.92)	22.9 (9.0)	27.9 (11.0)	2.34 (0.92)	23.70 (9.33)	12.7 (5.0)	33.0 (13.0)	7.70 (3.03)	29.01 (11.42)	17.8 (7.0)	47.0 (18.5)	10.08 (3.97)	+2.54 (+1.00)	+3.81 (+1.50)
2	15.2 cm (6 in.)	16.31 (6.42)	10.2 (4.0)	20.3 (8.0)	3.63 (1.43)	22.02 (8.67)	17.8 (7.0)	25.4 (10.0)	2.62 (1.03)	16.94 (6.67)	8.9 (3.5)	30.5 (12.0)	7.59 (2.99)	21.39 (8.42)	15.2 (6.0)	45.7 (18.0)	3.81 (1.50	+0.64 (+0.25)	-0.64 (-0.25)
3	30.5 cm (12 in.)	13.54 (5.33)	7.6 (3.0)	20.3 (8.0)	4.72 (1.86)	18.85 (7.42)	17.8 (7.0)	20.3 (8.0)	1.24 (0.49)	15.04 (5.92)	3.8 (1.5)	25.4 (10.0)	7.92 (3.12)	19.89 (7.83)	16.5 (6.5)	33.0 (13.0)	6.50 (2.56)	+1.50 (+0.59)	+1.04 (+0.41)
4	45.7 cm (18 in.)	11.63 (4.58)	0 (0)	17.8 (7.0)	6.55 (2.58)	12.70 (5.00)	0 (0)	17.8 (7.0)	6.38 (2.51)	11.0 (4.33)	0 (0)	20.3 (8.0)	7.59 (2.99)	12.90 (5.08)	0 (0)	17.8 (7.0)	6.73 (2.65)	-0.64 (-0.25)	+0.20 (+0.08)
5	61.0 cm (24 in.)	5.08 (2.00)	0 (0)	10.2 (4.0)	4.32 (1.70)	6.35 (2.50)	0 (0)	12.7 (5.0)	5.26 (2.07)	4.65 (1.83)	0 (0)	7.6 (3.0)	2.97 (1.17)	5.08 (2.00)	0 (0)	7.6 (3.0)	3.20 (1.26)	-0.43 (-0.17)	-1.27 (-0.50)
6	76.2 cm (30 in.)	0.43 (0.17)	0 (0)	2.5 (1.0)	1.04 (0.41)	0.43 (0.17)	0 (0)	2.5 (1.0)	1.04 (0.41)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-0.43 (-0.17)	-0.43 (-0.17)
7	91.4 cm (36 in.)	1.27 (0.50)	0 (0)	5.1 (2.0)	2.13 (0.84)	1.27 (0.50)	0 (0)	5.1 (2.0)	2.13 (0.84)	0.84 (0.33)	0 (0)	2.5 (1.0)	1.32 (0.52)	0.84 (0.33)	0 (0)	2.5 (1.0)	1.32 (0.52)	-0.43 (-0.17)	-0.43 (-0.17)
8	106.7 cm (42 in.)	6.88 (2.71)	2.5 (1.0)	15.2 (6.0)	5.05 (1.99)	7.32 (2.88)	3.8 (1.5)	12.7 (5.0)	3.45 (1.36)	3.38 (1.33)	0 (0)	12.7 (5.0)	5.49 (2.16)	3.38 (1.33)	0 (0)	12.7 (5.0)	5.49 (2.16)	-3.51 (-1.38)	-3.94 (-1.55)
9	121.9 cm (48 in.)	11.63 (4.58)	7.6 (3.0)	20.3 (8.0)	7.59 (2.29)	13.54 (5.33)	7.6 (3.0)	27.9 (11.0)	7.92 (3.12)	9.32 (3.67)	3.8 (1.5)	20.3 (8.0)	5.82 (2.29)	12.90 (5.08)	7.6 (3.0)	22.9 (9.0)	5.46 (2.15)	-2.31 (-0.91)	-0.64 (-0.25)
10	137 cm (54 in.)	14.40 (5.67)	8.9 (3.5)	30.5 (12.0)	8.18 (3.22)	16.94 (6.67)	8.9 (3.5)	31.8 (12.5)	8.97 (3.53)	15.24 (6.00)	8.9 (3.5)	30.5 (12.0)	8.03 (3.16)	17.35 (6.83)	11.4 (4.5)	25.4 (10.0)	4.72 (1.86)	+0.84 (+0.33)	+0.41 (+0.16)
11	152.4 cm (60 in)	16.08 (6.33)	10.2 (4.0)	30.5 (12.0)	7.59 (2.99)	18.85 (7.42)	14.0 (5.5)	30.5 (12.0)	6.55 (2.58)	16.94 (6.67)	11.4 (4.5)	26.7 (10.5)	5.44 (2.14)	21.16 (8.33)	19.0 (7.5)	22.9 (9.0)	1.73 (0.68)	+0.86 (+0.34)	+2.31 (+0.91)
12	167.6 cm (66 in.)	19.25 (7.58)	12.7 (5.0)	30.5 (12.0)	6.65 (2.62)	22.86 (9.00)	17.8 (7.0)	30.5 (12.0)	4.55 (1.79)	20.12 (7.92)	12.7 (5.0)	30.5 (12.0)	6.20 (2.44)	24.33 (9.58)	19.0 (7.5)	27.9 (11.0)	3.45 (1.36)	+0.86 (+0.34)	+1.47 (+0.58)

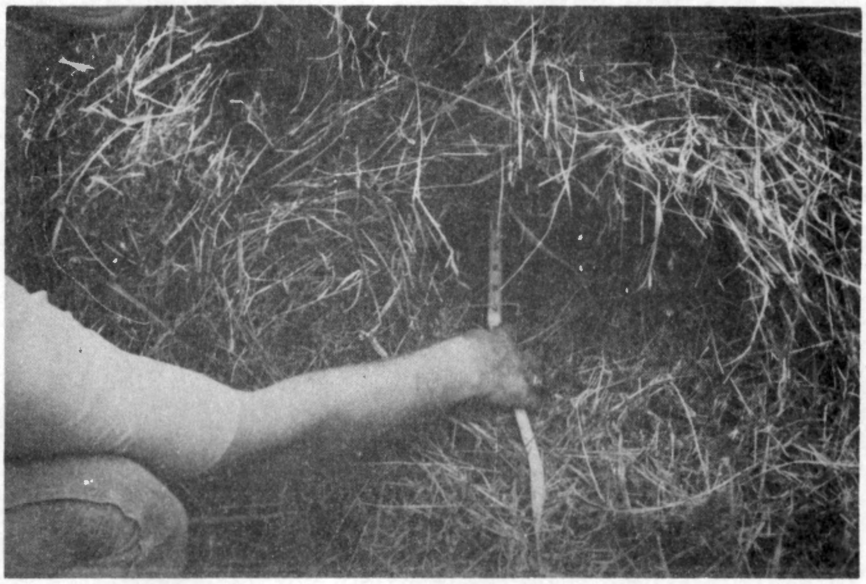


Figure 18. Method Used to Measure Tunnel Diameter.

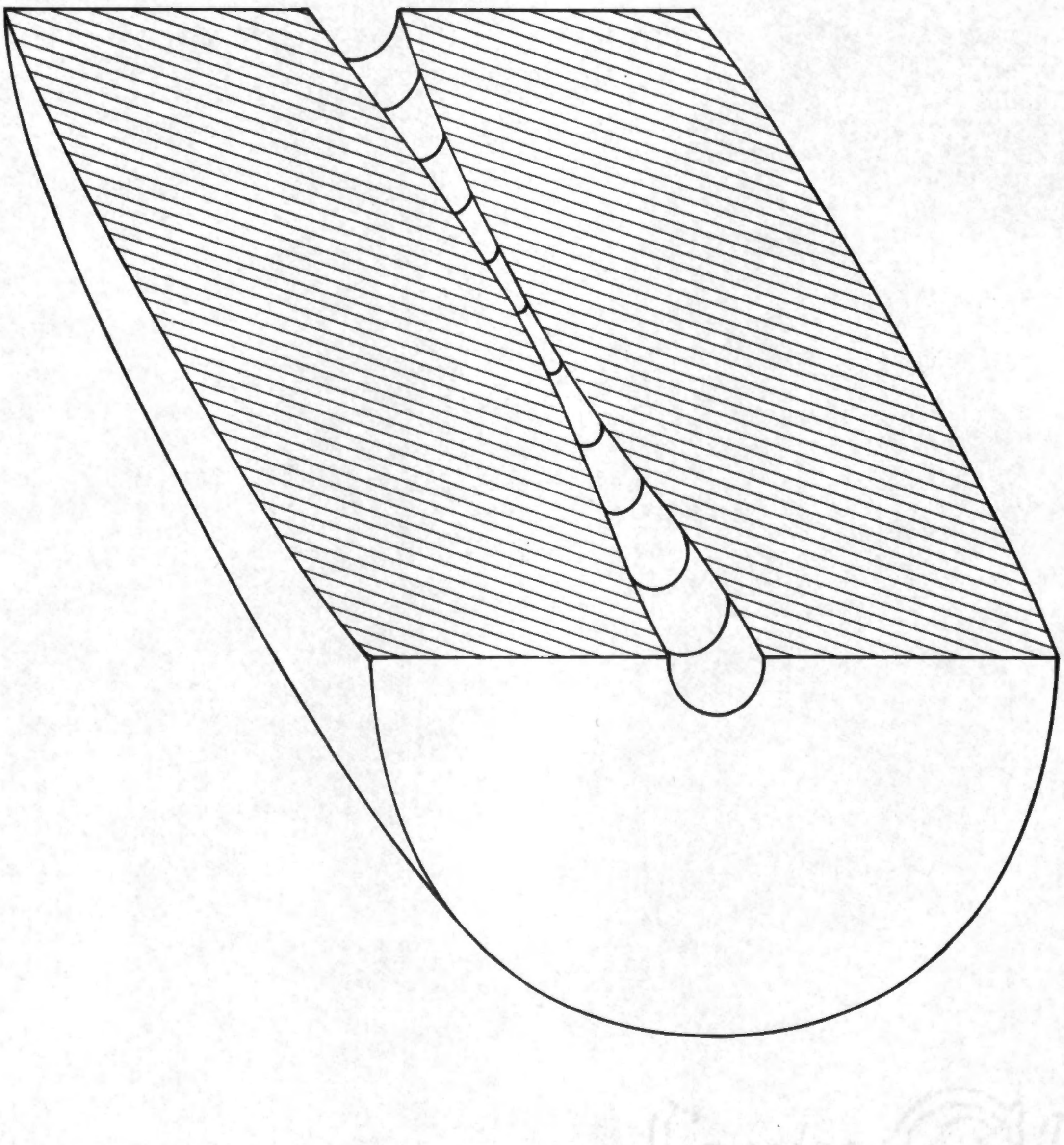


Figure 19. Pictorial Schematic of Overall Shape of Pierced Tunnels.

After forcing the tunnel completely through the center of the bale, the mean diameters of the tunnel at 76.2 cm (30 inch) depth into the bale was 4.4 cm (1.8 inch) vertical diameter and 4.95 cm (2.0 inch) horizontal diameter. At the completion of the preliminary tests the mean diameters at 15.24 cm (6 inch) depth had increased to 20.2 cm (8.0 inch) vertical and 22.7 cm (8.9 inch) horizontal. This increase was attributed to manipulation of the opening in taking the depth measurements. At the 76.2 cm (30 inch) depth, the mean measurements were 0.64 cm (0.25 inch) vertical diameter and 0.64 cm (0.25 inch) horizontal diameter.

Even though the central tunnel opening had a mean diameter of only 0.64 cm (0.25 inch), the 7.6 cm (3 inch) pipe could be easily forced through the bale at the end of the preliminary testing period. Thus it was decided that the tunnel would serve as an effective air passage for in-field drying.

Force Requirements

Prior to these tests little was known about the force required to penetrate a high density round bale. Since the piercing rams were hydraulically driven, force was determined by means of pressure gauges. The piercing cylinders were telescopic, double acting cylinders with a 45.7 cm (18 inch) stroke per stage. The first 45.7 cm (18 inch) stroke was made by the piston of the 10.2 cm (4 inch) bore cylinder, the second stage stroke was made by the piston of the 7.6 cm (3 inch) bore cylinder. Knowing the bore and the depth to which the cylinder was extended, the hydraulic pressure could be readily converted to force of penetration. The pressure applied to the cylinders was gauged immediately after the fluid left the tractor remote couplings and just before the fluid was divided to the two telescoping cylinders (Figure 20).

Results of the force measurements for the initial tests are shown in Table 3 and 4. The mean force requirement for the center tunnel at the 83.8 cm (33 inch) depth was 9083.4 N (2042 lbs.); the maximum force required was 11179.6 N (2513 lbs.). For the tunnels at half the radius from the bale center the mean force was 4424.9 N (995 lbs.), and the maximum force was 8385 N (1885). The piercer was designed to produce over 26689 N (6000 lbs.) of force; therefore, the preliminary tests showed piercing force requirements well within the capabilities of the machine.

Package Deformation

The consequence of the piercing operation on the bale shape and dimensions was important. If one tunnel could be pierced in the bale, how many more tunnels could be pierced in the same bale without destroying it? The answer to this question was surprising in that little change occurred in bale mean dimensions with an increase in the number of tunnels pierced in the bale. Measurement of bale end and center section diameter and bale length at three locations, top and left and right sides, provided data for the comparison. The measurements were made before and after each piercing operation.

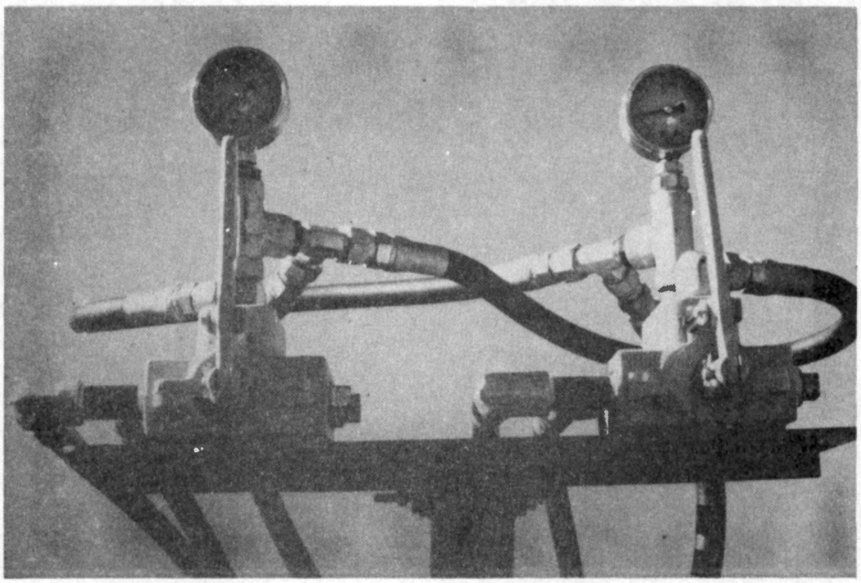


Figure 20. Gauges Used to Measure Hydraulic Pressure During Piercing.

TABLE 3

GAUGE PRESSURE AND FORCE TO PIERCE CENTER TUNNEL DURING PRELIMINARY TESTS
(AVERAGE FOR FOUR TUNNELS)

	Depth of Piercing							
	43.2 to 53.3 cm (17 to 21 inch)		53.3 to 63.5 cm 21 to 25 inch)		63.5 to 73.7 cm (25 to 29 inch)		73.7 to 83.8 cm (29 to 33 inch)	
Mean								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	517.13	(75.00)	1120.44	(162.50)
Force N (lbs.)	0	(0)	0	(0)	4192.31	(942.47)	9083.44	(2042.04)
Minimum								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	0	(0)	861.9	(125.0)
Force N (lbs.)	0	(0)	0	(0)	0	(0)	6987.3	(1570.8)
Maximum								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	861.9	(125)	1379	(200)
Force N (lbs.)	0	(0)	0	(0)	6987.3	(1570.8)	11179.6	(2513.3)
Standard Deviation								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	372.33	(54.00)	222.50	(32.27)
Force N (lbs.)	0	(0)	0	(0)	3018.47	(678.58)	1803.84	(405.52)

TABLE 4

GAUGE PRESSURE AND FORCE TO PIERCE RADIALLY LOCATED TUNNELS DURING PRELIMINARY TESTS
(AVERAGE FOR SIX TUNNELS)

	Depth of Piercing							
	43.2 to 53.3 cm (17 to 21 inch)		53.3 to 63.5 cm (21 to 25 inch)		63.5 to 73.7 cm (25 to 29 inch)		73.7 to 83.8 cm (29 to 33 inch)	
Mean								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	287.31	(41.67)	545.81	(79.16)
Force N (lbs.)	0	(0)	0	(0)	2329.27	(523.64)	4424.87	(994.75)
Minimum								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	0	(0)	0	(0)
Force N (lbs.)	0	(0)	0	(0)	0	(0)	0	(0)
Maximum								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	1034.2	(150)	1034.2	(150)
Force N (lbs.)	0	(0)	0	(0)	8384.7	(1885)	8384.7	(1885)
Standard Deviation								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	458.17	(66.45)	441.69	(64.06)
Force N (lbs.)	0	(0)	0	(0)	3714.40	(835.03)	3580.82	(805.00)

Piercing the center tunnel increased the bale mean width dimension by less than 1.3 cm (0.5 inch) and decreased the bale mean length dimension by less than 1.3 cm (0.5 inch). The bales pierced with four tunnels showed similar results. The mean width dimension increased by less than 3.8 cm (1.5 inch) and the mean length dimension decreased by less than 1.3 cm (0.5 inch).

These measurements showed that the hay was compacted only about the tunnel walls and not throughout the bale. The fact that forming four 20.3 cm (8 inch) tunnels in a bale did not increase the bale width by more than 3.8 cm (1.5 inch) was the most encouraging finding of the preliminary tests.

CHAPTER VII

THE EFFECT OF PIERCED TUNNELS ON PACKAGE IN-FIELD DRYING RATES

I. EXPERIMENTAL PLAN

The drying experiments were conducted in a completely randomized design. The experiment included six treatments and one control with two replications of each evaluated simultaneously. The treatments were as follows:

1. One tunnel placed at the center of the bale;
2. One tunnel placed at the center of the bale with the bale wrapped in black plastic;
3. One tunnel placed at the center of the bale with a chimney in one end of the tunnel;
4. One tunnel placed at the center of the bale with the bale wrapped in black plastic and a chimney placed in one end of the tunnel;
5. Three tunnels spaced 120^{o} apart at half the radius from the bale center;
6. Three tunnels spaced 120^{o} apart at half the radius from the bale center with the bale wrapped in black plastic; and
7. Control bale (no treatment).

The response variables measured were:

1. Moisture content change with time (from core samples taken every other day); and

2. Package internal temperature recorded every thirty minutes during the drying period.
3. Piercing force.

Other independent variables monitored were:

1. Ambient air dry-bulb temperature;
2. Incoming total solar radiation on roof-type collector inclined 16^{o} to the horizontal;
3. Wind speed and direction; and
4. Air flow through pierced tunnel.

After a bale was pierced, it was transported to the area at which the bales were to be located during the test. There the bale axis was placed on a North-South line and designated bales were wrapped in black plastic (Figure 21). The chimneys were also inserted at this time (Figure 22). The bales with a single tunnel were instrumented with two thermocouples, one above and one below the tunnel at one half the bale radius. The bales with three tunnels were instrumented with a single thermocouple placed at the center of the bale.

Measurements of air flow through the tunnel was done by using a hot wire anemometer inserted into a 15.2 cm (6 inch) pipe. The anemometer was positioned as suggested by Dwyer Instruments (1963) to obtain a velocity profile. The depth of penetration of the hot wire anemometer was such that readings were taken at the centers of equal concentric areas, the mean air flow then being the average of the measurements taken.

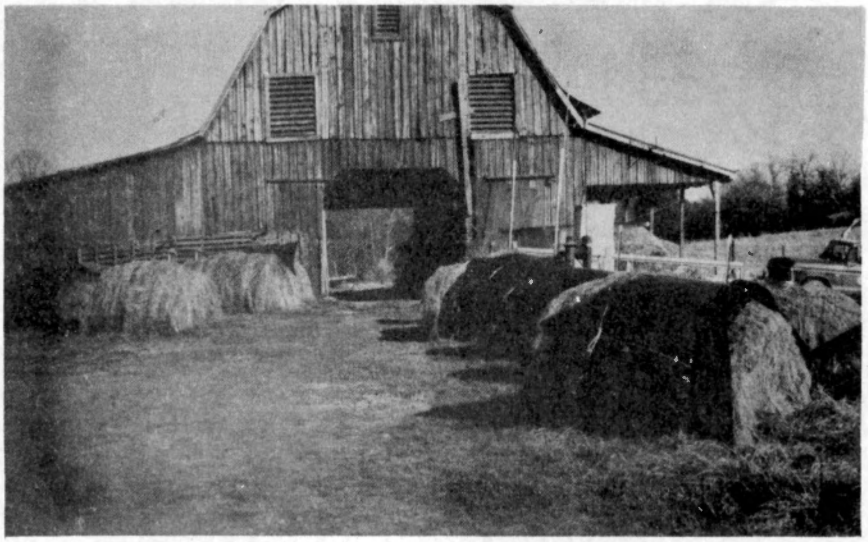


Figure 21. Overall View of Bales Positioned on North-South Line Showing the Various Bale Treatments.

Figure 22. Typical Chimney Placement During Drying Test.

II. RESULTS

A maximum force of 27949 Newtons (6283 lbs.) was required to produce a 20.3 cm (8 inch) tunnel in a high density, high moisture hay bale. This force occurred during the last 10.2 cm (4 inch) of piercing a center tunnel. The mean force for producing a center tunnel was 17992 Newtons (4045 lbs.), which is well within the working limits of the piercing machine. The piercing pressures and forces for both the center tunnels and the radially located tunnels are shown in Tables 5 and 6. Mean force to pierce a radially located tunnel was approximately 40% less than the force required for the center tunnels.

As in the preliminary tests, the piercer was unable to produce a tunnel completely through the bale. The same procedure used in the preliminary tests to open the tunnel was used on the high moisture bales, but the plug in the center of the tunnel proved to be too resilient to allow driving the 7.6 cm (3 inch) cone through the plug. A 7.6 cm (3 inch) coring tool (Figure 23) was constructed to bore through the plug. By utilizing two boring passes from each end of the bale the tunnel was opened sufficiently to allow passing a 7.6 cm (3 inch) pipe through the tunnel with ease. The amount of total package deformation due to the piercing and coring operations was approximately the same as was reported in the preliminary tests.

The in-field drying tests extended over an eight week period from September 14, 1979 to November 6, 1979. A number of environmental changes

TABLE 5

GAUGE PRESSURE AND FORCE TO PIERCE CENTER TUNNELS IN HIGH MOISTURE[1] HAY

	Depth of Piercing			
	43.2 to 53.3 cm (17 to 21 inch)	53.3 to 63.5 cm (21 to 25 inch)	63.5 to 73.7 cm (25 to 29 inch)	73.7 to 83.8 cm (29 to 33 inch)
Mean				
Gauge Pressure				
kPa (psi)	560.22 (81.25)	1142.02 (165.63)	1745.33 (253.13)	2219.36 (321.88)
Force N (lbs.)	4541.72 (1021.02)	9258.39 (2081.37)	14149.48 (3180.93)	17992.43 (4044.86)
Minimum				
Gauge Pressure				
kPa (psi)	0 (0)	689.5 (100)	1379 (200)	1379 (200)
Force N (lbs.)	0 (0)	5589.8 (1256.6)	11179.6 (2513)	11179.6 (2513.3)
Maximum				
Gauge Pressure				
kPa (psi)	1034.3 (150)	1379 (200)	2068.5 (300)	3447.5 (500)
Force N (lbs.)	8384.7 (1885)	11179.6 (2513.3)	16769.4 (3769.9)	27949 (6283.2)
Standard Deviation				
Gauge Pressure				
kPa (psi)	398.94 (57.86)	290.45 (42.125)	297.66 (43.17)	660.82 (95.84)
Force N (lbs.)	3234.26 (727.09)	2354.71 (529.36)	2413.11 (542.49)	5357.26 (1204.36)

[1] Mean moisture content was 46% wet basis.

TABLE 6

GAUGE PRESSURE AND FORCE TO PIERCE RADIALLY LOCATED TUNNELS IN HIGH MOISTURE[1] HAY

	Depth of Piercing							
	43.2 to 53.3 cm (17 to 21 inch)		53.3 to 63.5 cm (21 to 25 inch)		63.5 to 73.7 cm (25 to 29 inch)		73.7 to 83.8 cm (29 to 33 inch)	
Mean								
Gauge Pressure								
kPa (psi)	387.84	(56.25)	790.03	(114.58)	1134.78	(164.58)	9805.34	(206.25)
Force N (lbs.)	3144.27	(706.86)	6404.77	(1439.85)	9199.68	(2068.17)	11528.94	(2591.81)
Minimum								
Gauge Pressure								
kPa (psi)	0	(0)	0	(0)	0	(0)	172.4	(25)
Force N (lbs.)	0	(0)	0	(0)	0	(0)	1397.4	(314.2)
Maximum								
Gauge Pressure								
kPa (psi)	1034.2	(150)	1379	(200)	2068	(300)	2068.5	(300)
Force N (lbs.)	8384.7	(1885)	11179.6	(2513.3)	16769.4	(3769.9)	16769.4	(3769.9)
Standard Deviation								
Gauge Pressure								
kPa (psi)	389.77	(56.53)	576.22	(83.57)	740.32	(107.37)	682.12	(98.93)
Force N (lbs.)	3159.93	(710.38)	4671.39	(1050.17)	6001.76	(1349.25)	5529.98	(1243.19)

[1] Mean moisture content was 46% wet basis.

Figure 23. Coring Tool Used to Bore Through Plug in High-Moisture Bales.

occurred during the period. A typical solar insolation record made during the experiment is shown in Figure 24. The wind speed and direction during the typical good drying day was from the west at 3.2 km/h (2 mile/hour). The mean ambient air dry bulb temperature (average of 48 observations taken at 30 minute intervals over a 24 hour period) for a typical good drying day was 11.57^{o}C (52.83^{o}F). Plots of the average daily temperature for the bales and for ambient air are shown in Figures 25 and 26. The bale temperature was used as an indicator of the progress of the drying in that as the bale temperature approached ambient air temperature, drying was completed.

Approximately three weeks after piercing, the tunnels had almost closed. Each day the 7.6 cm (3 inch) pipe was passed through the tunnel to reopen the passage. The tendency of the bales to close and the hot wire anemometer sensitivity to any air movement made collecting the tunnel air flow data difficult and questionable. Comparison of the mean air flow of the tunnels among treatments indicated that bales wrapped in black plastic without a chimney had the highest mean air flow (Table 7). However this variation in air flow could be due to the tunnel size and amount of collapsing of the tunnel.

An analysis of variance of the change in moisture content of the hay over the drying period indicated that there was not a significant difference in drying rates among the various treatments. Contrasts included in the analysis (Table 8) support this conclusion in every case except the contrast of one tunnel versus three tunnels. This contrast

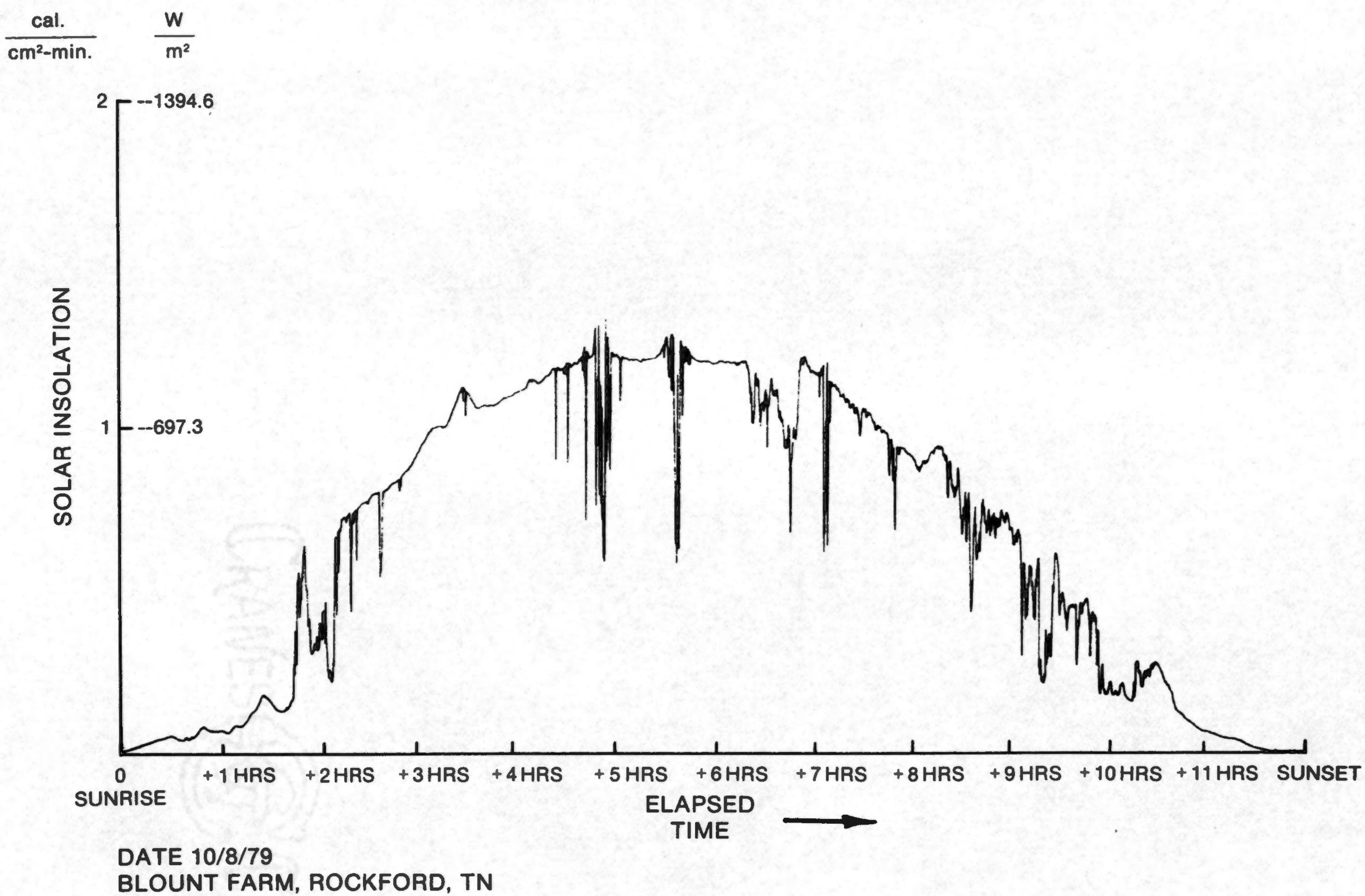


Figure 24. Graph of Typical Insolation during the Drying Experiment.

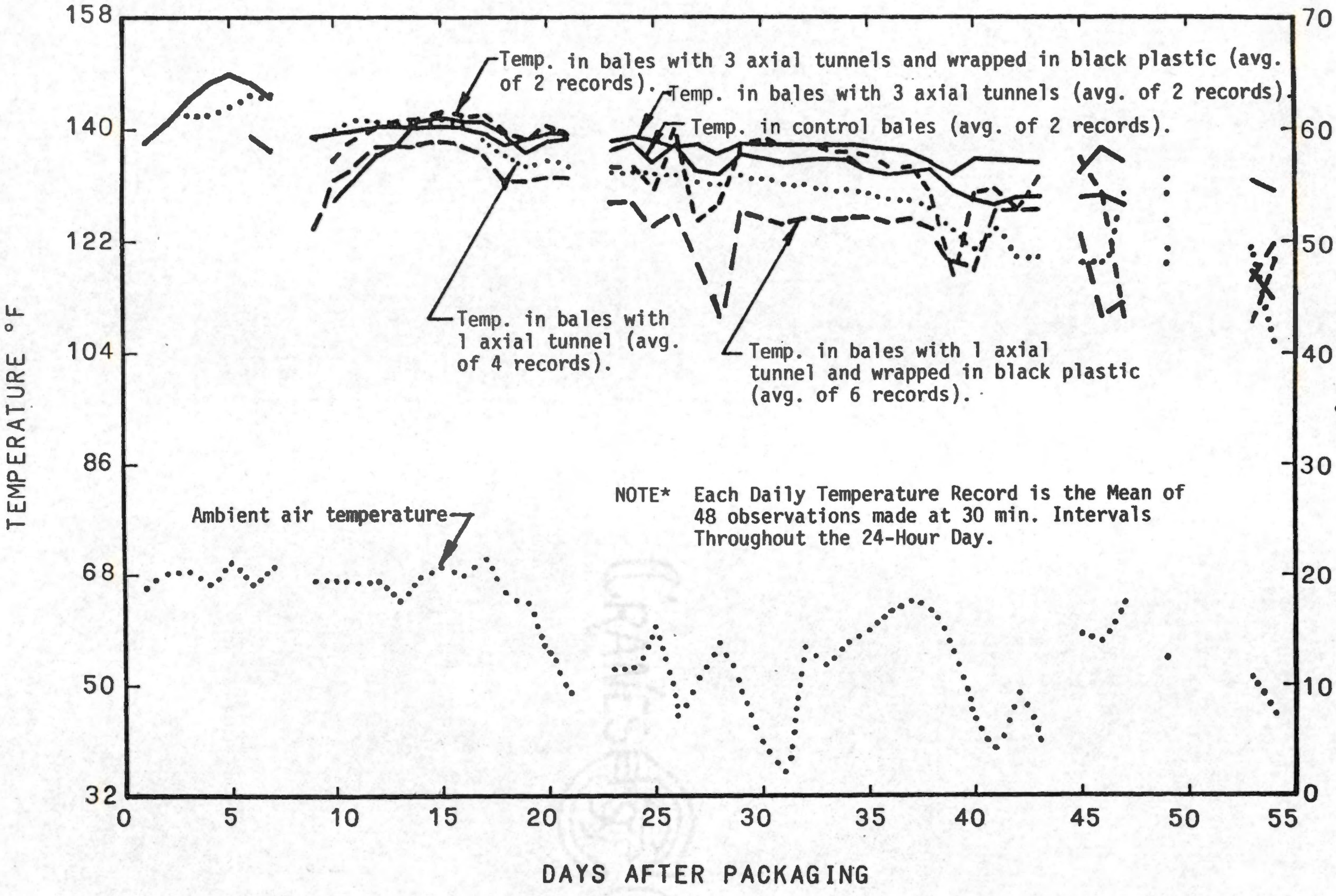


Figure 25. Average Daily Temperatures for Selected One-Tunnel and Three-Tunnel Bales and Ambient Air During Drying Period.

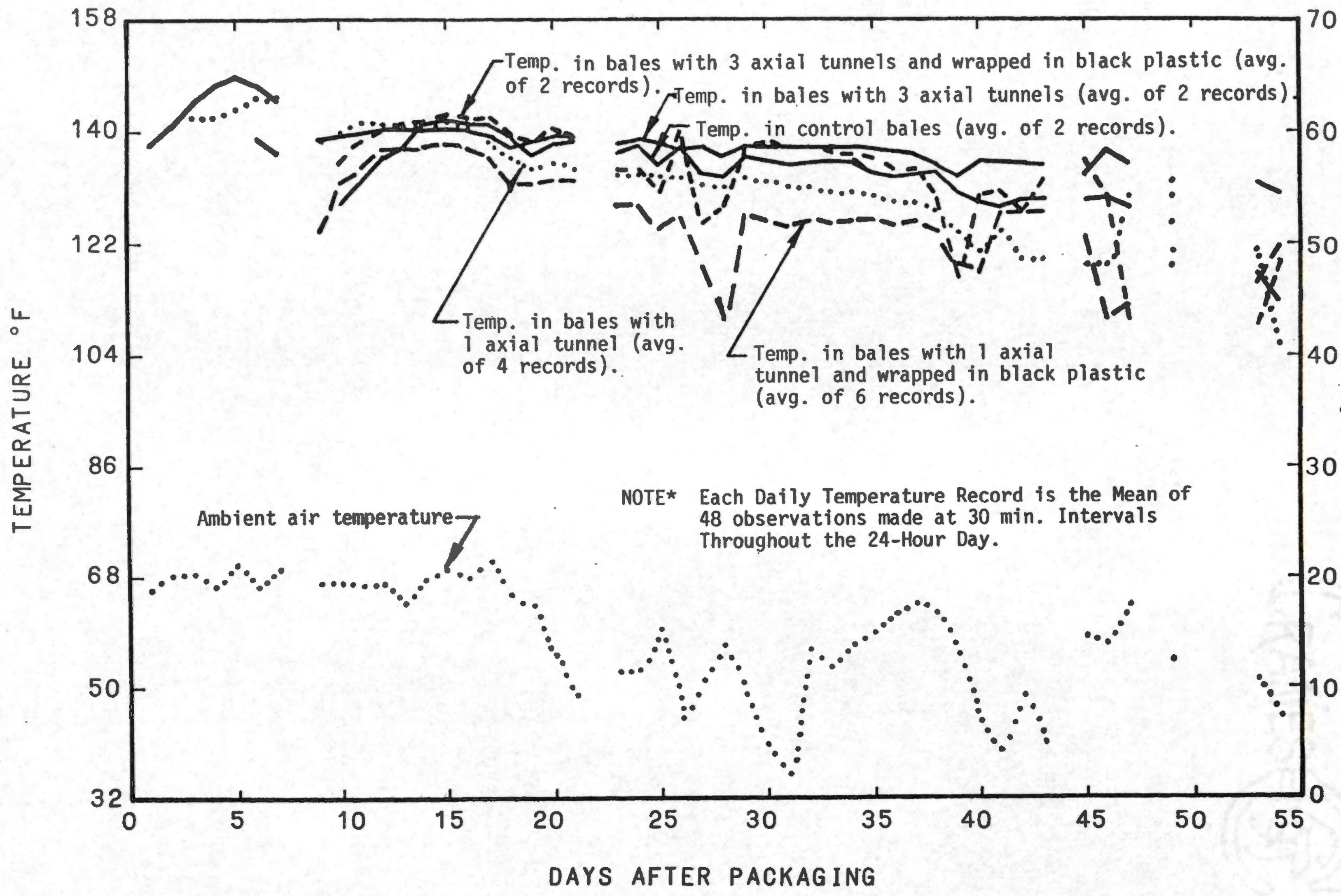


Figure 26. Average Daily Temperatures for One-Tunnel Bale Treatments and for Ambient Air During Drying Period.

TABLE 7

AIR FLOW THROUGH BALES, PIERCED WITH SINGLE TUNNEL

Treatment	Mean cm/Sec.	Mean (Ft/Sec)	Standard Deviation cm/Sec	Standard Deviation (Ft/Sec)
With Chimney				
Rep. 1	4.89	(0.16)	2.90	(0.10)
Rep. 2	7.75	(0.25)	7.03	(0.23)
Rep. 1 and Rep. 2	6.32	(0.21)	4.97	(0.16)
Without Chimney				
Rep. 1	11.85	(0.30)	12.76	(0.42)
Rep. 2	2.10	(0.07)	1.66	(0.05)
Rep. 1 and Rep. 2	7.00	(0.20)	7.21	(0.24)
Black Plastic and Chimney				
Rep. 1	5.55	(0.18)	5.39	(0.18)
Rep. 2	4.62	(0.15)	1.81	(0.06)
Rep. 1 and Rep. 2	5.09	(0.17)	3.60	(0.12)
Black Plastic Without Chimney				
Rep. 1	12.85	(0.42)	14.26	(0.47)
Rep. 2	12.13	(0.40)	7.71	(0.25)
Rep. 1 and Rep. 2	12.49	(0.41)	10.98	(0.36)

Mean Air Flow = 7.72 cm/Sec (0.25 Ft/Sec)

Standard Deviation = 4.07 cm/Sec (0.13 Ft/Sec)

Standard Error of Mean = 2.04 cm/Sec (0.07 Ft/Sec)

Coefficient of Variation = 52.77%

TABLE 8

ANALYSIS OF VARIANCE FOR MOISTURE LOSS DUE TO PIERCING

Source	Degrees of Freedom	Mean Square	F-Ratio	Prob F
Treatment	6	67.1978	2.51	0.0456
One Tunnel VS One Tunnel with Chimney	1	31.5256	0.58	0.4721
One Tunnel Black Plastic VS One Tunnel Black Plastic with Chimney	1	32.7936	0.60	0.4637
One Tunnel without Plastic VS One Tunnel with Plastic	1	88.5062	1.62	0.2436
Three Tunnels VS Three Tunnels with Black Plastic	1	1.8180	0.03	0.8604
One Tunnel VS Three Tunnels	1	145.0680	2.66	0.1471
All Treatments VS Control	1	103.4756	1.90	0.2110
Bales (Treatment)	7	54.5982	2.04	0.0856
Time	4	432.0017	16.11	0.0001
Time * Treatment	24	9.7017	0.36	0.9932
Error	28	26.8203		
Corrected Total	69	50.6839		

Mean Moisture Loss = 14.97 percentage points (wet basis)

Standard Deviation = 5.18 percentage points (wet basis)

Coefficient of Variation = 34.59%

Standard Error of Mean = 1.64

indicated no significant difference at the 90% level of probability but a significant difference at the 95% level. This uncertainty and the high coefficient of variation associated with treatments is an indication that more replications were needed in the experiment.

The mean moisture change for each treatment (Table 9) shows a high degree of variation between treatments. These mean values indicate that the treatment of three tunnels without black plastic lost the most moisture.

TABLE 9

MEAN MOISTURE LOSS IN PERCENTAGE POINTS BY TREATMENTS

Treatment	No. of Samples	Mean Loss Percentage points (wet basis)
5 3 tunnels without black plastic	10	17.97
6 3 tunnels with black plastic	10	17.36
2 1 tunnel without chimney with black plastic	10	17.14
4 1 tunnel with chimney with black plastic	10	14.57
1 1 tunnel without chimney without black plastic	10	14.14
7 control	10	11.99
3 1 tunnel with chimney without black plastic	10	11.62

Mean Moisture Loss = 14.97 percentage points (wet basis)

Standard Deviation = 5.18 percentage points (wet basis)

Coefficient of Variation = 34.59%

Standard Error of Mean = 1.64

CHAPTER VIII

SUMMARY AND CONCLUSION

Hay losses due to shatter and weather could be lessened by baling hay at high moisture contents (35 to 45% wet basis). Previous studies have shown that good quality hay can be produced from hay bales at 35% moisture, but this hay had to be dried by artificial means such as solar heated air forced through the bale.

With the machine developed in this study, large round bales (680 kg (1500 lb.)) of high moisture hay (45 to 48% moisture content) was pierced with 20.3 cm (8 inch) cones. The mean force required for producing the center tunnels with these cones was 11528.9 Newtons (2591.8 pounds). The piercing machine could not produce a tunnel completely through a bale, but with the use of a 7.6 cm (3 inch) coring tool the remainder of the tunnel could be opened with two boring passes from each end of the bale. The purpose of the tunnel was to provide more surface area for moisture and heat transfer from the bale to free air by natural convection.

Piercing of up to three tunnels did not change any bale dimension more than 5 cm (2 inch). The multiple tunnels in a bale had a tendency to collapse quicker than single tunnels. However, at the end of three weeks it was difficult to keep even the single tunnels open. At the end of the three week period, individual tunnels in the three tunnel bales could not be opened at all by the use of the 7.6 cm (3 inch) pipe.

A statistical analysis of bale drying rates indicated that at the 95% level of confidence no significant difference existed in the drying rates of the various treatments; however at the 85% level of confidence a significant difference existed between single tunnels and multiple tunnels. This difference in significance shows a need for additional replications to have a more sensitive test.

Good quality hay was not produced from hay baled at 46% moisture content in this experiment. The drying rates were too slow to prevent spoilage. The study did prove, however, that tunnels could be forced in high-density round bales, with the major portion of the tunnel being formed "from the tractor seat"; but during the coarse of drying the tunnels had to be reopened often.

I. RECOMMENDATION FOR FUTURE STUDY

A model study should be conducted to determine the optimum tunnel diameter, the optimum number of tunnels and best tunnel location for natural convection drying. If results of the theoretical study are promising, the possibility of a baler which forms a tunnel during baling should be given serious consideration.

A comparison of the drying rates of pierced bales versus unpierced bales in a forced air drying experiment should be made. The tunnel should be used as a plenum chamber within the bale with one end of the bale on the dryer manifold and the opposite end blocked with a plate.

The possibility of connecting two or more bale tunnels together in a series arrangement (with bales aligned end-to-end) for use with a forced air dryer should be examined thoroughly. Such an arrangement would eliminate the need for specialized handling equipment as is required with the present forced air dryer at the Knoxville experiment station.

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