HIGH TEMPERATURE CONTINUOUS FLOW GRAIN DRYING WITH CONCURRENT DRYING AND COUNTER-CURRENT COOLING

PART I: DESIGN AND TESTING

Thesis for the Degree of M. S.

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JAMES ALFRED CARRANO

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ABSTRACT

HIGH TEMPERATURE CONTINUOUS FLOW GRAIN DRYING
WITH CONCURRENT DRYING AND COUNTER-CURRENT COOLING

PART I: DESIGN AND TESTING

By

James Alfred Carrano

A working model of a high temperature continuous flow grain dryer using concurrent flow heating and counter-current flow cooling was designed, constructed and tested. The dryer's performance was affected by the hot air inlet design, grain spreading at the inlet, and unloader design and position. Problems in these areas were resolved and satisfactory performance was achieved. Grain dryers of the type used in these tests will be capable of maximized output when temperature-time relationships for grain quality have been established.

Approved William G. Bickert
Major Professor

Approved B A Stout
Department Chairman

HIGH TEMPERATURE CONTINUOUS FLOW GRAIN DRYING WITH CONCURRENT DRYING AND COUNTER-CURRENT COOLING

PART I*: DESIGN AND TESTING

by

James Alfred Carrano

A THESIS

Submitted to
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*PART II: SIMULATION AND OPTIMIZATION
by
Daniel G. Elzinga

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It was also a pleasure to work with Daniel Elzinga and I wish to thank him for the help he supplied on the portions of this project which were done jointly.

To the memory of my deceased father, Alfred, who would have greatly appreciated it, I dedicate this work.

James A. Carrano

Also To:

Mrs. A. Carrano
Mrs. Minnie Wilson
Mr. And Mrs. H. J. Thomas

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LIST OF SYMBOLS

d.a.	Abbreviation for dry air (no water vapor present).
G_{ad}	Rate of dry air movement, pounds of dry air per hour.
G_{aw}	Rate of wet air movement, pounds of moist air per hour.
G_p	Rate of grain movement, pounds per hour.
H	Specific humidity of air, pounds of water vapor per pound of dry air.
MC_{in}	Moisture content, initial, % dry basis.
MC_{out}	Moisture content, outlet, % dry basis.
RH	Relative humidity, percent.
T	Temperature, degrees Fahrenheit.
T_o	Initial temperature, degrees Fahrenheit.
w.a.	Abbreviation for wet or moist air.

LIST OF TERMS

Concurrent flow	Condition when the air and grain have flow velocities in the same direction.
Cooling air	Air from the air conditioning unit when used to cool the grain.
Counter-current flow	Condition when the air and grain have flow velocities in opposite directions.
Cross flow	Condition when the air and grain have flow velocities in perpendicular directions.
Heating air	Air when used to heat the grain in the drying section.
Hot air	Air which has passed through the burner or heater.

I. INTRODUCTION

Each year, a part of some farmers' time and money is spent on drying grain. The most popular method for this has been the deep bed dryer using heated air. With farmer work loads increasing and yields per acre climbing, more and more time will be spent drying grain in larger dryers. Shortening of drying and handling time would enable a farmer to spend more time on other farm management functions. To shorten drying time, continuous flow dryers which operate with higher air temperatures have come into use. But, the practice of using hotter air for drying has an upper limit and exceeding it can cause losses in grain quality; although the damage may not occur due to temperature alone but to the length of time at that temperature. This principle can be demonstrated dramatically by merely passing one's hand through a flame, first very quickly and again more slowly. Thus, it seems feasible that if grain were in contact with higher temperature air for a short time, no damage would result. The answer is in how high a temperature and how long?

1.1 Background on Continuous Flow Dryers

Much research has been done in the field of layer and batch drying but very little has been done in continuous flow drying. Continuous flow drying can be done with a number of different methods including cross flow, concurrent flow and counter-current flow.

Cross flow continuous dryers and deep bed dryers produce an overdried condition in the grain passing or positioned near the air inlet and an underdried condition in the grain near the exit. More uniform drying results when either concurrent or counter-current air flows are used. There are a few patents on drying methods using both concurrent and counter-current flows. On July 19, 1966, Heinrich Tillmanns received United States Patent Number 3,261,109 entitled, "Apparatus for Drying and Cooling Particulated Material". This patent describes an apparatus substantially vertical using an upper drying zone and a lower cooling zone. The material to be dried is fed in at the top and is discharged at the bottom. The cooling air is entered at the lower end and is partially exhausted in the center. The remainder of the air is heated in the central portion and is exhausted at the top. This system is a counter-current flow dryer for both heating and cooling. On February 7, 1967, Douglas L. Graham was granted United States Patent Number 3,302,299 entitled, "Drying Apparatus and Method". This system also uses an upper drying section and a lower cooling section but the drying section uses concurrent flow and the cooling section counter-current flow. Air, both cooling and heating, is exhausted in the central portion. The Anderson's in Maumee, Ohio, have a large dryer which uses this same principle. The M & W Perfect Kern'l dryer is commercially available and is modeled after Graham's apparatus.

1.2 Principles of Air and Grain Movement

Grain which is dried for wet milling is generally limited to 140° F kernel temperatures. Graham (1967) states, ".... high moisture corn can stand high drying rates without drying damage; while at lower moistures the grain can be damaged by high drying rates." Since concurrent flow drying is characterized by a continuously decreasing drying rate as drying occurs, it is ideal for higher temperature drying. Since initially the grain is cool and moist and the drying air very hot, evaporation of moisture from the grain is at a high rate. This high evaporation rate keeps the grain temperature below the air temperature and also drastically decreases the air temperature at the same time. As moisture is removed from the grain, the air and the grain theoretically approach the same temperature and the drying rate decreases. Thus, at the end of the drying section, the grain and air are ideally in equilibrium and moisture has transferred to the air.

Cracking occurs when warm grain is cooled rapidly. It is therefore necessary to cool the grain with air that becomes increasingly cooler as the grain temperature decreases. Counter-current cooling provides the proper cooling action for accomplishing this. If a vertical dryer is used, grain movement will be downward. By providing a cool air inlet at the lower end of the dryer, the grain temperature will decrease as the grain approaches the air inlet, optimally reaching the same temperature as the incoming cooling air at this point. It is necessary to have the cooling air move vertically upward through the downcoming grain. This is accomplished easily by providing an exhaust section immediately above the cooling section. An exhaust fan at this point would enable the heating air to move downward and the cooling air to move upward. The dryer constructed for this research uses the above principles and these are outlined in Figure 1.1A.

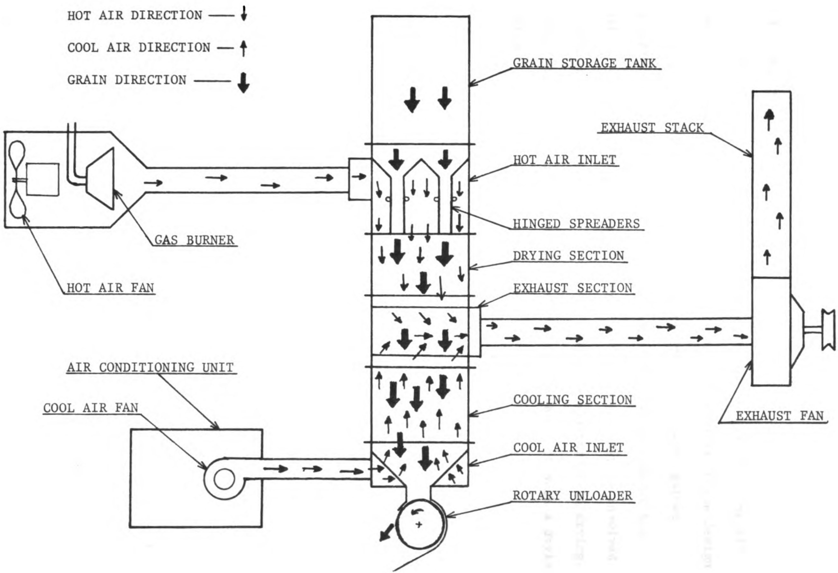


FIGURE 1.1A DRYER COMPONENTS SHOWING AIR AND GRAIN MOVEMENT

1.3 OBJECTIVES

The objectives of this sutdy were to gain an understanding of the principles of grain drying and apply these principles to the design of concurrent - counter-current flow grain dryers. Having gained an appreciation of the above, the next objective was to develop and build a working dryer capable of demonstrating the principles involved in concurrent flow heating - counter-current flow cooling grain drying. This dryer would be used to obtain representative data for such a drying system.

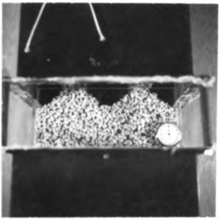
II. EXPERIMENTAL

2.1 DESIGN CRITERIA

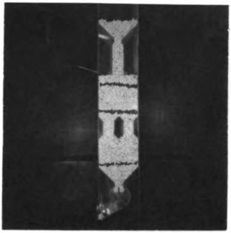
It was desired to build a dryer which permitted the entrance of both product and heated air at the top, exit of product and entrance of cooling air at the bottom, and exhausting of both heating and cooling air in the central portion. Such a dryer would have a drying zone in the upper portion and a cooling zone in the lower portion. It was also desirable to be able to vary the lengths of these sections with ease. A third design factor was ease of construction and variability of functions, i.e., the design must permit the dryer to be used either completely as a concurrent dryer or completely as a counter-current dryer. For these reasons, a square cross section,to give simplicity in symmetry, was decided upon. Thus, modular construction would allow interchangeability of both vertical position and face orientation.

The necessity of spreading the grain would have to be determined experimentally, since there are dryers both with and without spreaders in use. It was hoped, for simplicity, that the spreaderless type would be successful. With this in mind, it was decided to place chambers in the dryer which would split the grain flow into two flow streams, each of which would have an increased flow velocity due to the restriction in the cross sectional area. The angle of repose of the grain would cause it to form two ridges under the flow streams and troughs in the center and on both sides. (See Figure 2.1A). Similar chambers could be used to provide an exhaust section by merely making the chambers from perforated plates. A hopper bottom with perforated plates would provide an entrance for the cooling air. Airtight unloading could be accomplished by use of a rotary airlock feeder mechanism.

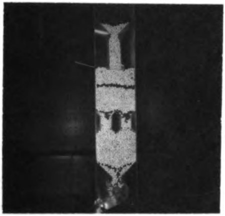
A half-scale clear plastic (Plexiglas) model was constructed to test the design before actual construction of the dryer. Critical design changes arose from the use of this model. Grain flow studies were carried out by filling the model dryer with beans. Some of the beans were painted and placed as layers in the model (See Figure 2.1B). While the model was unloading, pictures were taken at time intervals to give a record of the grain flow pattern. The grain flow through the restrictions was very satisfactory (See Figures 2.1C and 2.1D). However, the unloading was off-center and created a stall area on the front side (closest side when viewing the unloading grain) (See Figures 2.1E and 2.1F). This condition was corrected in the full scale dryer and a satisfactory unloading was achieved.



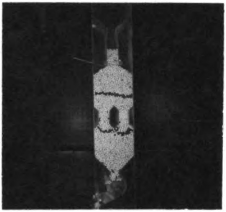
A. GRAVITY FORMED RIDGES AND TROUGHS



B. PLASTIC MODEL



C. LAYER OF GRAIN ENTERING CHAMBER



D. LAYER EXITING CHAMBER

E. OFF CENTER UNLOADING

F. STALL AREA ON LEFT

FIGURES 2.1A through 2.1F

2.2 Description of Apparatus

2.21 Dryer Construction

The dryer has six basic sections. These are, from top to bottom (See Figure 2.21A), the grain storage tank, the hot air inlet section, the drying section, the exhaust section, the cooling section, and the cool air inlet and unloader section. All sections were constructed from 14 gage steel plate bent and welded to form one foot by one foot inside dimension tubes of varying lengths depending upon the section requirements. A square ring made from one inch by one-eighth inch steel bar with 9/32 inch holes for 1/4 inch bolts was welded to each end of a section for fastening the sections together. The bolt hole spacing was symmetric so the sections could be assembled in any orientation. A section of such construction will hereafter be referred to as a basic section (See Figure 2.21B). All sections were painted with extreme high temperature paint and were assembled with two asbestos gaskets at each connection.

The grain storage tank was two feet square and three feet in length. A cover was made 26 1/8 inches by 26 1/8 inches to accomodate the outer edge of the topmost steel ring. A rubber gasket was glued to the cover to provide an airtight seal when the cover was fastened in place. An adapter was welded to the bottom of the storage tank to provide a smooth transition to the one foot square sections below (See Figure 2.21C).

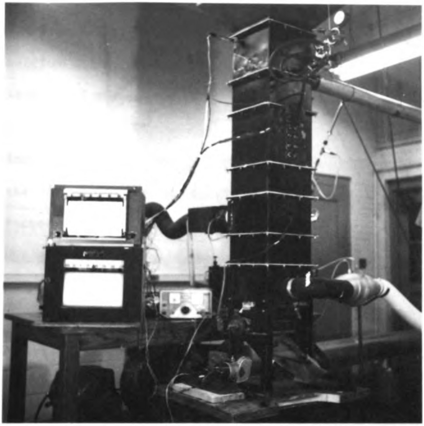


FIGURE 2.21A ASSEMBLED DRYER WITH INSULATION REMOVED

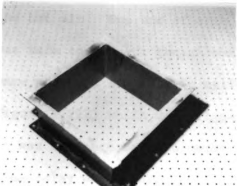


FIGURE 2.21B
BASIC SECTION

FIGURE 2.21C
GRAIN STORAGE TANK

The original design called for a storage tank of one foot by one foot cross section and three feet long. It was found that this did not give sufficient grain storage for a test. An alternative was to mount a rotary airlock feeder on top of the storage tank and refill the tank during testing. The cost of these units proved detrimental to the idea. Therefore, the larger tank as described above was constructed and was quite satisfactory.

The hot air inlet was made by modifying a basic section. The modifications consisted of adding three steel chambers to the inside so that the grain flow was divided into two streams, each of which had one sixth the cross sectional area of the basic section. This restriction caused a flow velocity of three times the velocity in the basic section. The restriction chambers served as an entrance for the heated air above the grain (See Figure 2.21D). The sides of the chambers were hinged and could be swung from side to side to spread or level the grain. It should be noted that these chambers were made of solid steel sheets (as opposed to perforated) to prevent exposure of the grain to the hot air. One end of each of the chambers was cut out and an adapter was made to connect the chambers to a four inch stove pipe. The spreaders were moved by a pneumatic cylinder operated by a reversing valve (See Figure 2.21E) which was triggered by a microswitch and stepping relay. It was not necessary to operate the spreaders continuously, so a variable time delay was incorporated at each half cycle.

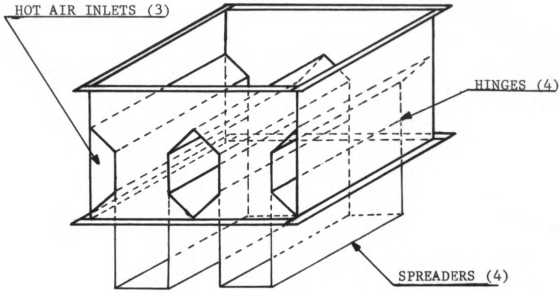


FIGURE 2.21D HOT AIR INLET WITH ADAPTER REMOVED
(not to scale)

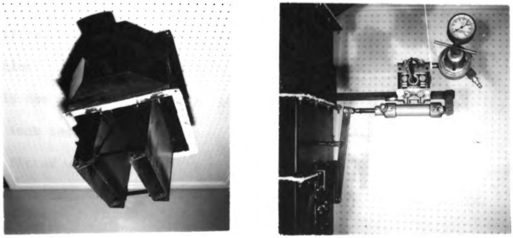


FIGURE 2.21E HOT AIR INLET WITH SPREADER, VALVE AND CYLINDER

This oscillating spreader was constructed because the first hot air inlet section was not capable of spreading the grain. The lack of spreading caused the grain to form a ridge under each of the two flow streams (See Figure 2.1A). This proved to be undesirable since a streamline of heated air was observed below the center of the troughs.

The drying section consisted of a one foot long basic section which was drilled to allow samples to be taken (See Figure 2.21F). The sample holes were one inch diameter and spaced at two inch intervals along a vertical line in the center of one side. The drying section could be made any length by merely adding or removing different length basic sections.

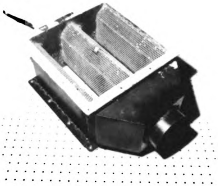
The exhaust section was a modified basic section very similar to the first hot air inlet section, the distinction being that the chambers were constructed of perforated steel plate and were equipped with perforated bottoms to prevent some of the fine particles from being exhausted with the air. The flow streams in this section had a cross sectional area of one fourth the cross sectional area of the drying section. This resulted in twice the flow velocity in this section as in the basic section. The perforated plates had 1/8 inch holes spaced 1/4 inch center to center in 60 degree rotated planes. The section was fitted with an adapter similar to the hot air inlet adapter except that the exhaust adapter was designed for a five inch stove pipe (See Figure 2.21G).

The cooling section was made from a basic section which was six inches in length. Sampling holes were not cut into these sections but could have been added at any time if it were necessary to use one of these sections to lengthen the drying section or if samples from the cooling section were desired. In Tests 1 through 5C, two six inch sections were used to form a one foot cooling section. Test 6 used only one six inch section.

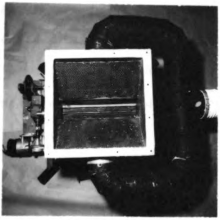
The cool air inlet and unloader section was a six inch long basic section except that it had only one connecter ring. Two perforated plates were installed inside at 45 degrees from the horizon to form a typical hopper bottom with a three inch wide by one foot long opening. Steel plates were welded into the remaining space in the horizontal plane containing the opening. A hole was cut in each of the sides of the section enclosed by a perforated plate and a bottom plate. This hole was fitted with a four inch stove pipe connecter (see Figures 2.21H, J and K).

The unloading mechanism was constructed from a one foot long piece of four inch standard wall steel pipe to which was welded sixteen steel bars (one half inch by one eighth inch by twelve inch) equally spaced radially on the outside (see Figure 2.21K). The fluted wheel just described was turned true axially and both ends were faced true. A piece of steel plate was rolled to a two and three quarter inch radius through an arc of 125 degrees to form the back plate of the rotary airlock. This acted as an airlock since more than two flutes of the wheel were in contact with the back plate at all times. The front piece of the airlock was originally constructed similarly but was later changed to include a piece of sheet rubber to provide a better seal. Each fluted segment of the unloading wheel had an approximate volume of four and one half cubic inches (1/2" x 3/4" x 12").

F. DRYING SECTION



G. EXHAUST SECTION



H. COOL AIR INLET (top view)

I. AIR FILTERS

J. COOL AIR INLET AND UNLOADER

K. UNLOADER CONSTRUCTION

FIGURES 2.21F through 2.21K

Sixteen segments per revolution gave 72 cubic inches or approximately two pounds of shelled corn per revolution depending on the moisture content.

The first fluted wheel was made of three and a half inch steel pipe (4" O.D.) with one inch by one eighth inch steel bars welded radially to form eight segments. The flow rate of such an unloader was much too great for this dryer due to the large volume of grain removed per revolution. To obtain the desired flow rates, it was necessary to turn the wheel very slowly. This slow speed resulted in step flow which could not be considered continuous. Ready made rotary airlock feeders are available but only with flow rates above those desired for these tests.

One more problem was encountered with the unloading mechanism. By studying movies made of the plexiglas half scale model, an off-center hopper bottom unloading was noted. As mentioned above (see Figure 2.1E), the flutes on the unloading wheel would fill up with grain from the back of the dryer (when viewing the unloading grain broadside) (see Figure 2.1F). This caused a stall area along the front of the dryer which was undesirable. By narrowing the opening from the back side and by using the sixteen segment fluted wheel described above, the unloading was successfully moved to the center of the dryer.

The unloader drive was constructed from a 1963 Ford windshield wiper motor (12 volt D.C.) which was modified to give rotary motion instead of reciprocal motion. This was connected to an eleven to one gear reducer which in turn was connected to the fluted wheel shaft by sprockets and a chain (See Figure 2.21J). This combination gave an overall gear reduction of forty to one which allowed flow rates up to five pounds per minute for shelled corn. The direct current motor was capable of variable speeds by varying the input voltage using a variable D.C. voltage power supply. This system proved to be very satisfactory and easily controlled.

The entire dryer was placed on a table so that the outflow could be collected in a container placed on a scale giving continuous monitoring of the flow rate.

2.22 Control and Monitoring Equipment

Constant air flow rates and air temperatures were required at both the hot air inlet and the cool air inlet. Also, it was necessary to maintain constant relative humidity of the cooling air at the cooling air inlet. The grain flow rate and the hot air temperature were the primary variables. The air flow rates were secondary variables. Both primary and secondary variables were monitored continuously and were corrected whenever any variance occurred.

Hot air temperature was controlled by two means -- the gas regulator and the air damper. The heat output of the burner was directly related to the fuel consumption, ergo the pressure regulator. If a lower temperature was desired than was available with the smallest orifice and lowest pressure, the air damper was used. This routed some of the heated air into the room rather than into the hot air inlet. The five foot length of pipe between the damper and the inlet provided a cooling effect. It was possible to maintain the inlet temperature within five degrees of the desired value.

Due to the problems involved with higher temperature air measurement, it was desired to use an orifice plate. To accurately measure the air flow rate at four or five hundred degrees Fahrenheit, it was recommended that a six inch steel pipe be used with an orifice plate containing a three and a half inch bore. The size and weight of such a system eliminated it as a possible flow measuring device. Therefore, a pitot tube was used to determine the hot air flow rate. The pitot tube was calibrated using a laminar flow element and variable speed fan. Pitot tube differential pressures were measured with a micro-manometer which could be read to 0.001 inches of water.

Chromel/Alumel thermocouples were placed in the hot air chambers to give an indication of the air temperature just above the grain. These thermocouples were connected to a pen recorder to give continuous monitoring of the inlet temperature.

Values of cooling air temperature and relative humidity were maintained constant by the use of an air conditioning unit and were intermittently recorded during tests as a precautionary measure. The air conditioning unit was equipped with a variable speed fan to allow increasing or decreasing the cooling air rates.

The relative humidities of the cooling air and the exhaust air were monitored continuously with electric hygrometer indicators. Values from these were periodically recorded in the log book.

Two methods were used to determine the cooling air rate. In the earlier tests (1 through 5) a pitot tube was used to measure the hot air rate and a laminar flow element was used in the exhaust line so that a mass balance could be used to calculate the cooling air rate. This procedure was followed since it was initially desired to use room air for cooling and, by using a fan on the hot air line and in the exhaust line, no cooling air fan was necessary. A second method was used in test 6 and will be employed in the tests to follow. This method required the laminar flow element to be installed in the cooling air line. This was a more direct means of obtaining the cooling air rate. Maintaining the air flow rates was easier with this method since clean air was passed through the laminar flow element and the filters could be removed. The air filters were necessary with the earlier method to prevent plugging of the laminar flow element.

Copper/constantan thermocouples were positioned in the drying section when the first tests were run. After more than an hour at high temperatures, the insulation on the thermocouple wires began to melt. However, the wires remained insulated and true readings were still recorded. For safety, chromel/alumel thermocouples with a fiberglas and asbestos insulation were installed in the upper portion of the drying section. For test 6, the thermocouples were again changed to copper/constantan to take advantage of the better accuracies. The thermocouples were located in columns, each column located three inches (one fourth of the diameter) from two adjoining sides. With this configuration, and with more than one thermocouple at each depth, it was possible to average the thermocouple readings. This was done for both test 6A and 6B (See

Table 3.1F). Future tests will also have more than one thermocouple at each cross section to give a better indication of the air movement through the grain.

Copper-constantan thermocouples were positioned in the center of flow in the cooling section for all tests. Consecutive readings were recorded and five of these consecutive readings were averaged for cooling section data.

The exhaust fan was equipped with a variable diameter pulley and the fan speed was controlled by changing the distance between the motor and the fan. The hot air fan was a constant speed fan of the vane axial type. The cooling air fan was driven by a variable speed motor. By varying the speeds of the latter two fans numerous combinations of air flows were available. These were monitored continuously by use of manometers connected to the pitot tube and the laminar flow element. The laminar flow element required clean air and this necessitated the installation of air filters in the exhaust line. The filters (see Figure 2.21I) were custom made and were in three stages, each successively smaller up to the third stage, a furnace filter, which eliminated the fines. It was not necessary to use the filters when the laminar flow element was used in the cool air line (as in Test 6).

The grain flow rate, as mentioned previously, was controlled by varying the voltage to the unloader motor. The grain output was collected in a container which was on a scale, thus, continuous monitoring of the grain flow was available.

2.23 Summary of Control and Monitoring Equipment

1.* HEATER: Aerovent supplemental heater model SH 12, equipped with a 1/16 inch spud for 90,000 btu/hr output.

2. PITOT TUBE: Meriam model M-168 with 1/8 inch ram hole.

3. MANOMETER: Meriam micro-manometer model 34FB2 (to 0.001 inch H_2O).

4. THERMOCOUPLES: Chromel/Alumel (type K $\pm$ 5°F), 20 gauge.

5. RECORDER: Texas two pen, model P502W6A, accuracy $\pm$ 2° F, linearity $\pm$ 0.3° F.

6. THERMOCOUPLES: Copper/constantan (type T, $\pm$ 0.5% or $\pm$ 1.5° F), 24 gauge.

7. RECORDER: Texas twenty-four point, model FMWT6B, accuract $\pm$ 0.75° F, linearity $\pm$ 0.3° F.

8. AIR FILTERS: Custom made at Agricultural Engineering, M.S.U.

9. LAMINAR FLOW ELEMENT: Meriam model 50MC2-4P, accuracy $\pm$ 0.5% of calibration curve.

10. MANOMETER: Meriam model 40GD10WM-6 (to 0.02 inch H_2O).

11. EXHAUST FAN: Clarage Fan Co. size 3/4, with 9 inch squirrel cage rotor, driven by 5 hp General Electric motor by variable diameter pulley.

12. RECORDER: Brown twelve point, model 153X65P12-X-2F, accuracy $\pm$ 1.2° F.

13. AIR CONDITIONING UNIT: Aminco-Aire model 4-5580, capable of maintaining constant temperature ($\pm$ 1° F) and relative humidity ($\pm$ 3% r.h.) equipped with variable speed fan motor.

14. HYGROMETER: Hygrodynamics electric hygrometer-indicator, model 15-3001, accuracy $\pm$ 1.5% r.h.

15. POWER SUPPLY: Electro D.C. power supply model EB, 0 to 32 volts, 4 amp maximum.

* See Figure 2.23A

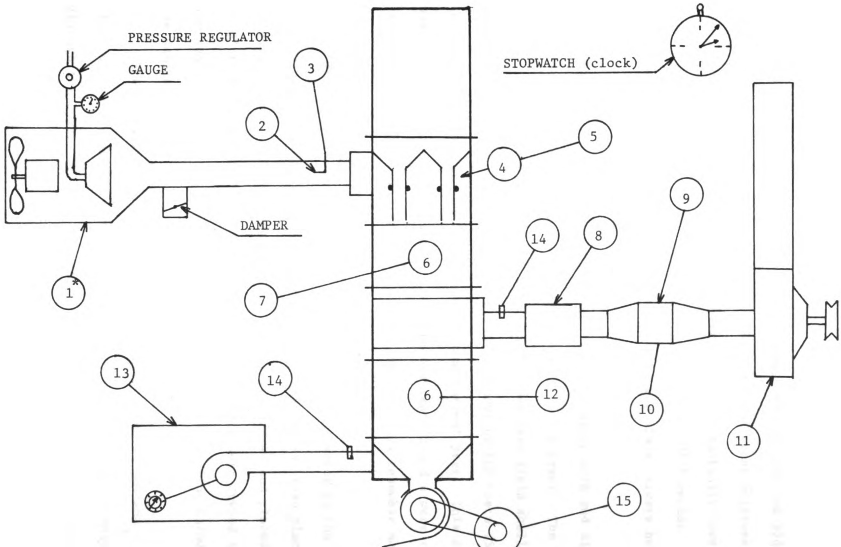


FIGURE 2.23A CONTROL AND MONITORING EQUIPMENT

(see Section 2.23 for identification of components)

2.3 TESTING PROCEDURE

Tests were based on two heating air temperatures, 450 and 220 degrees Fahrenheit. Grain flow rates were changed to get different moisture removal rates. The initial grain temperature was substantially lower than room temperature because the grain was kept in a 40° F cooler. This was a desired condition since corn temperatures are almost always below 80° F during the fall harvest.

Pretest procedures included rewetting the shelled corn and allowing it to temper and running an operational checkout of the dryer. The corn used in the first series of tests (1 through 4) had been field shelled in the Fall of 1969. The corn used in the remainder of the tests (5A through 6B) was picked and crib dried the same harvest year. This corn was shelled and cleaned less than a week before tests 5 and 6 were run. It was believed that this latter corn would more closely resemble new corn. New corn was not available at the time of testing.

The samples to be dried were rewetted by adding water to the corn and mixing the mixture in a cement mixer. The mixture was then placed in galvanized steel trash containers. These were covered and placed in a 40° F cooler for at least 36-42 hours. The contents were dumped and remixed after 12 hours to give a more uniform moisture content throughout the sample.

The operational check out of the dryer included an ambient air check of the thermocouple readings and a check with cooling air moving through the dryer. All thermocouple outputs were compared to a standard millivolt source at 32° F and at 80° F when first installed in the dryer. The thermocouples were not rechecked at 32° F unless there was a noticeable deviation during the operational checkout with ambient and with cooling air. This procedure was followed because of the extreme difficulty involved in positioning the thermocouples in the dryer.

The unloading rate was approximated by measuring the rotation rate of the fluted wheel. The actual unloading rate was slightly less than this initial approximation due to the increased load on the drive motor under test conditions. Next, the air filters were cleaned and the manometers were zeroed. The air conditioning unit was started and allowed to stabilize at operating conditions. The dryer was then filled with corn. The lower sections of the dryer were filled with dry corn to provide more rewetted corn for the test. The wet corn was again mixed prior to filling the dryer and samples were taken.

After the dryer was filled, the grain storage tank was sealed to prevent air movement upward through the stored grain. This procedure was necessary to maintain steady state inlet conditions during testing. The recorders and the unloader were started prior to lighting the burner. This was done to get a good representation of the starting conditions. The cooling air and exhaust air fans were also started at this time. The final steps in starting a test were lighting the burner, starting the clock, and adjusting the grain flow rate. Steady state conditions were reached after approximately 1/2 hour, the exact time depending on the moisture content of the grain and the unloading rate.

After steady state conditions were reached (indicated by a constant grain temperature at a position over a period of time), there was a time delay before output samples could be taken. It was necessary to unload at least 130 pounds of grain to allow the grain just entering the drying section when steady state conditions were reached to pass completely through the dryer.

After the delay, samples were taken and tested for moisture content. At this time, if the dryer contained sufficient grain, a second test could be run as was done in tests 3, 5, and 6. Whenever the thermocouples in the drying zone began to indicate higher temperatures, the burner was shut down since this indicated a lack of grain in the storage tank. Emptying the dryer and shutdown of equipment concluded the test.

III. RESULTS AND DISCUSSION

3.1 OUTPUT OF DRYER

A summary of the tests run, including output moisture contents, is given in Tables 3.1A through 3.1D. The output moisture content was for grain which had passed through both the drying and cooling zones. The amount of drying done in the cooling zone was considered to be only slight compared to the amount done in the drying zone but no attempt was made to prove this point. Since the dryer was of a one square foot cross section, grain and air rates can be compared to other dryers on a square foot basis.

The effect of grain spreading on drying air temperatures can be seen in Figure 3.1A (values listed in Table 3.1E). The testing was accomplished by merely stopping the spreaders at their center position and noting the air temperatures in the drying zone for a period of time and then comparing these to the values recorded during the next period of time when spreading was used. At steady state conditions, the air temperatures in the top eight inches of the drying zone were lower when spreading was used compared to the same test with no spreading. The final destination of the grain will determine whether spreading is essential. For instance, if the grain were used for seed, the higher air temperatures from not using spreading could cause considerable seed damage.

The drying air temperatures at various depths in the drying zone for tests 3A, 6A and 6B are listed in Tables 3.1F and 3.1H and are shown graphically in Figure 3.1B.

Grain temperatures in a continuous flow dryer are difficult to measure and, therefore, theoretical temperatures are of significant importance. Bakker-Arkema et al.(1970) have obtained theoretical values of grain and air temperatures for concurrent flow drying (see Figure 3.1C). The significant point of this figure is the peak in the grain temperature curve. The overall shape of the curve is important for high temperature tests since the grain temperatures appear to be very high if the curve is superimposed onto Figure 3.1B for test 3A. Also, by superimposing this curve onto Figure 3.1A, one can see that grain spreading will greatly reduce the peak grain temperature. This fact is very important in maintaining grain quality, since the grain temperature approaches but never equals the heating air temperature. The grain temperature increases at a high rate and at the same time the air temperature decreases rapidly in the first few inches of the drying zone. The grain temperature peak will be influenced by the initial grain moisture content, the air flow rates, the air humidity, and the initial difference between the air and grain temperatures. Thus, for a given grain temperature there is a maximum allowable heating air temperature to keep the peak grain temperature low. The length of time that the grain is kept at a given peak temperature will have the greatest effect on the quality of the grain. Thus, there is also a relationship between unloading rate at a given heating air temperature and quality.

Cooling air temperatures at various depths in the cooling zone are given in Table 3.1G. These values are plotted in Figures 3.1D and 3.1E for both high and low temperature tests, respectively (see Tables 3.1A through 3.1D for details of tests). Little or no cooling took place in the cooling section for the low temperature tests and the need of the section under such conditions is doubtful.

The cooling air conditions could, under certain circumstances, actually cause rewetting of the grain. Under these conditions the addition of supplemental heat at the cooling air inlet could prove invaluable if the cooling section were used at all.

Due to the location of the exhaust hygrometer sensor, difficulty in recording values of the exhaust relative humidity was encountered. Wide fluctuations in the readings were caused by the fact that the cooling and heating air exhausts were not mixed when passing the sensor. Both exhausts were at nearly the same temperature but were greatly different in humidities. Because of this difficulty, the exhaust relative humidity was calculated by a water mass balance of the heating air, fuel water, cooling air and moisture loss of the grain (see Table 3.1D). An example of such a calculation is outlined in Section 3.11. The fuel water mentioned above is a product of combustion and is only a factor when direct fired burners are used as in these tests. Fuel water amounts will vary depending on the composition of the fuel, the heating value of the fuel and the air flow rate. The inclusion of fuel water in the heating air results in an equivalent specific humidity which is higher than for air heated indirectly to the same temperature.

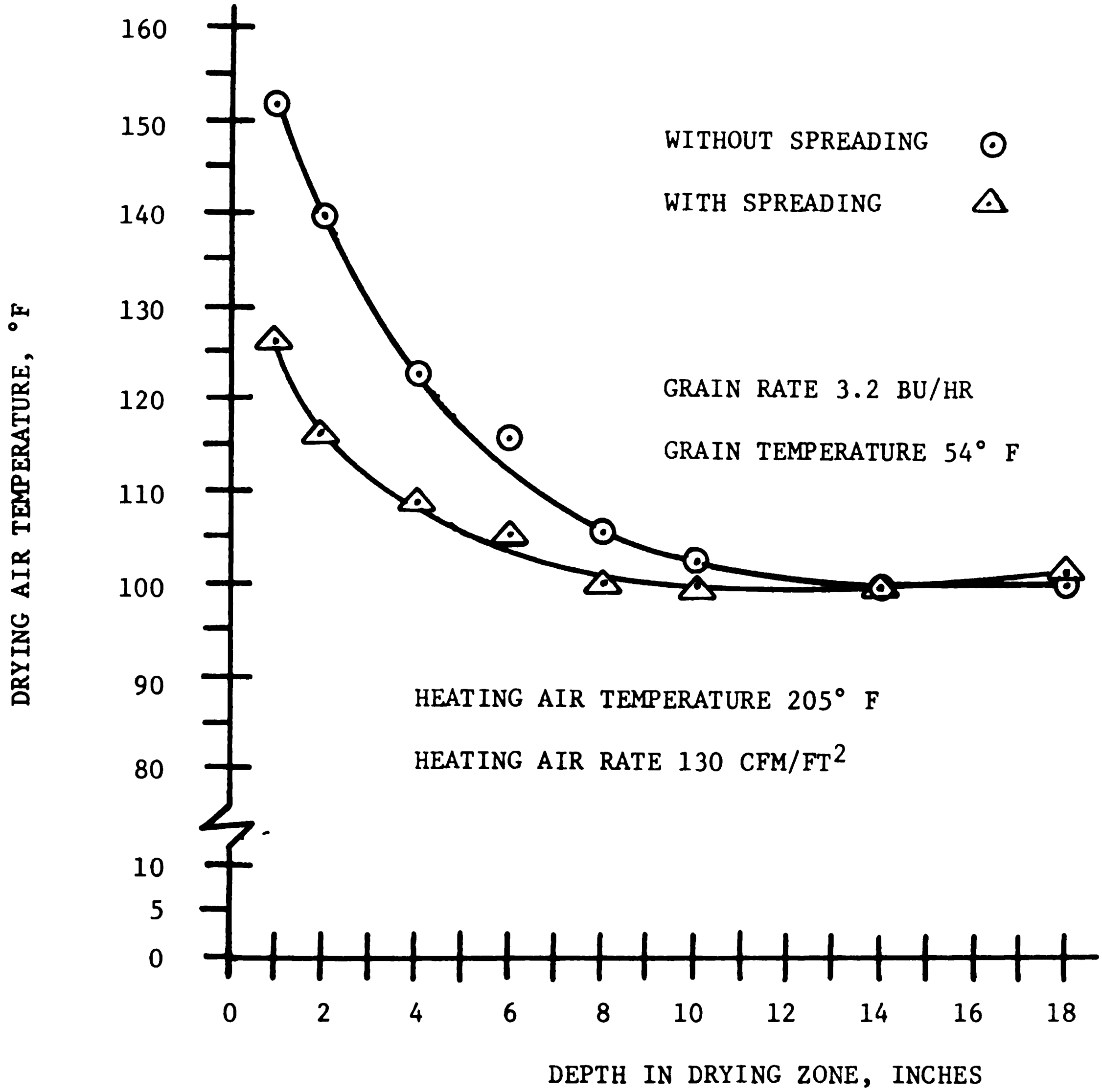


Figure 3.1A Effect of Spreading on Drying Air Temperatures.

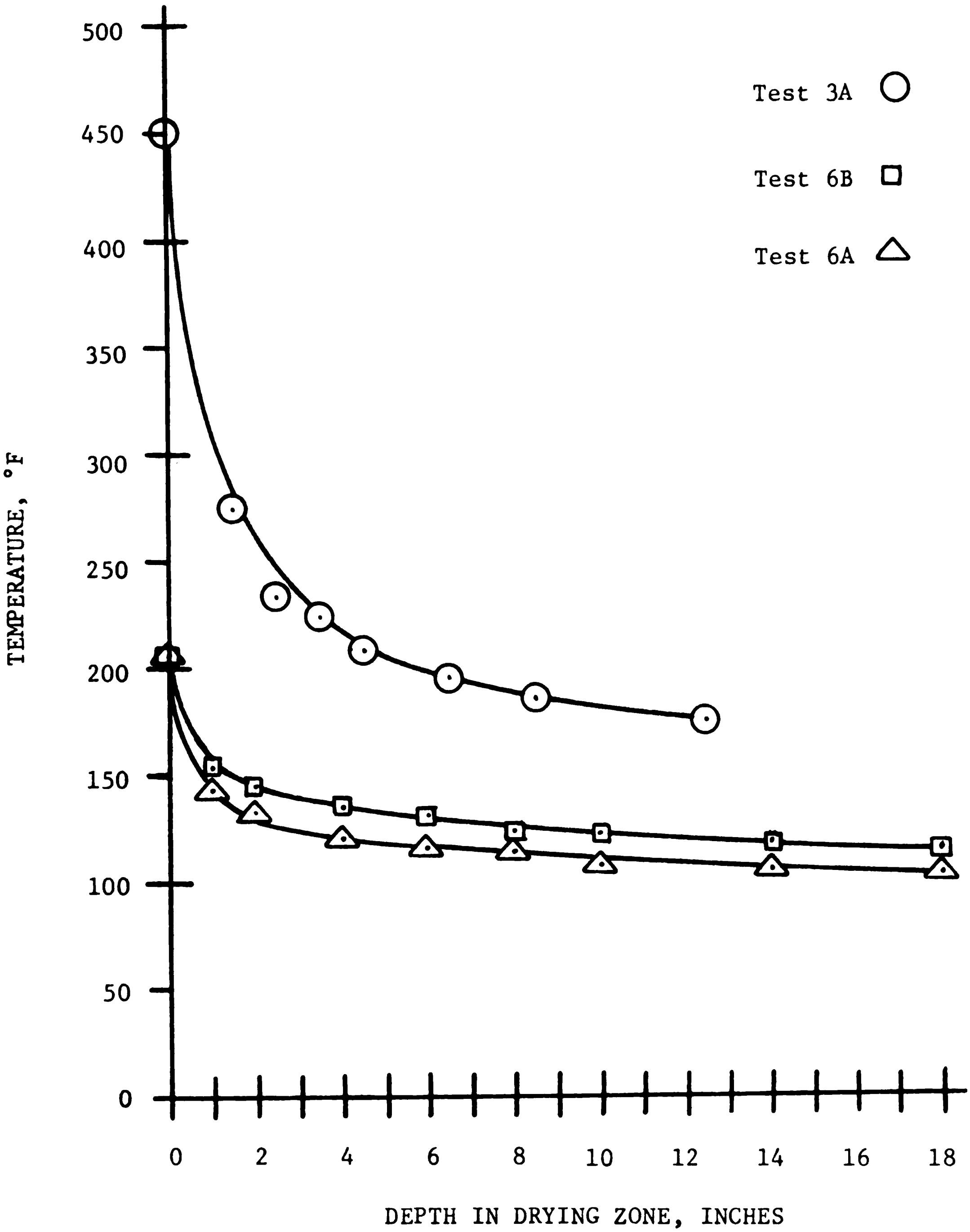


Figure 3.1B Drying Air Temperature Versus Depth for Several Tests.

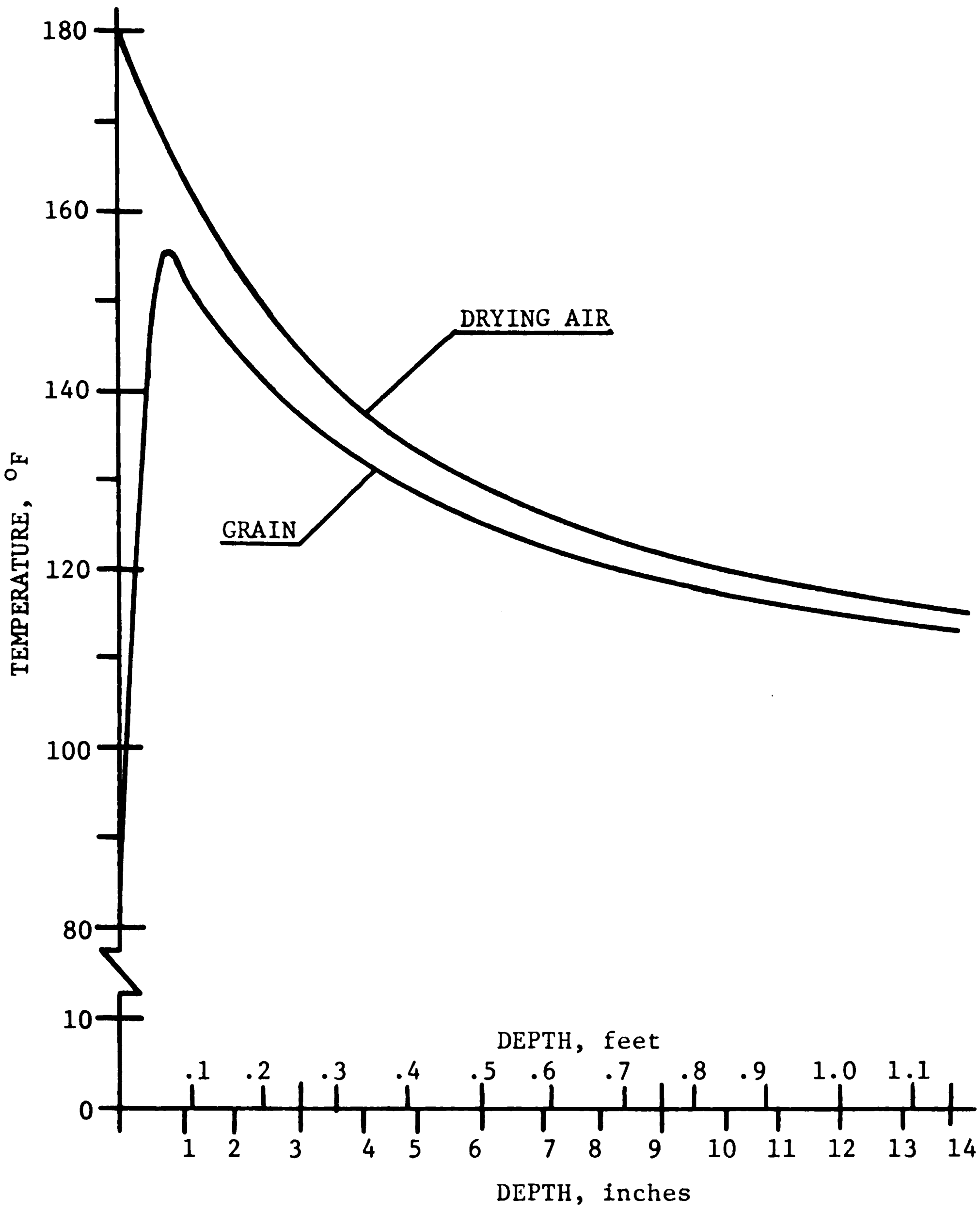


Figure 3.1C Theoretical Air and Grain Temperatures (from BAKKER, 1970)

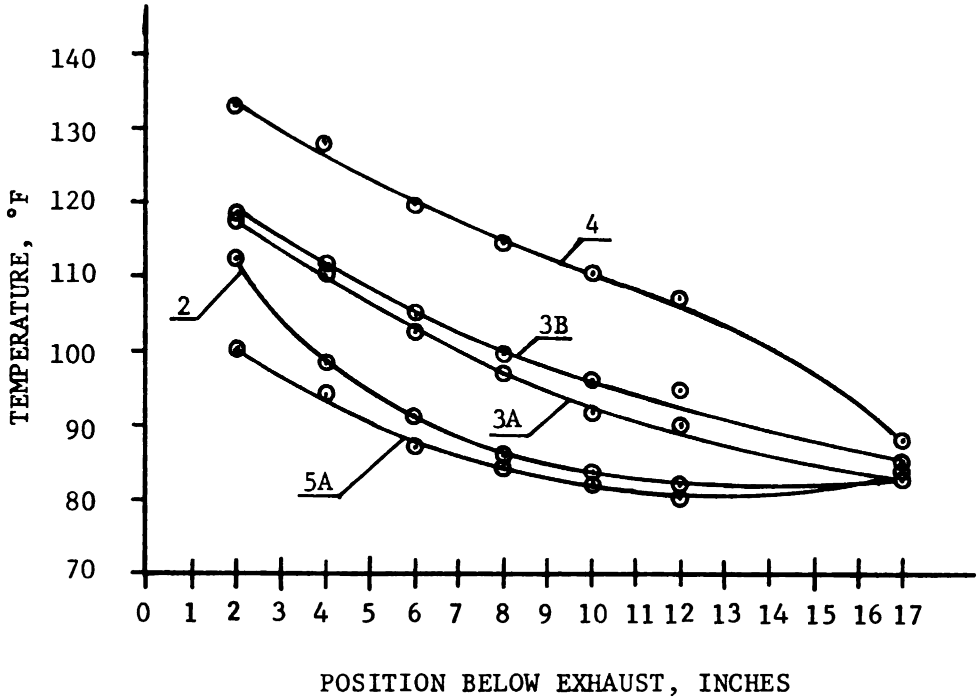


Figure 3.1D Cool Air Temperatures Versus Position (450° F Tests)

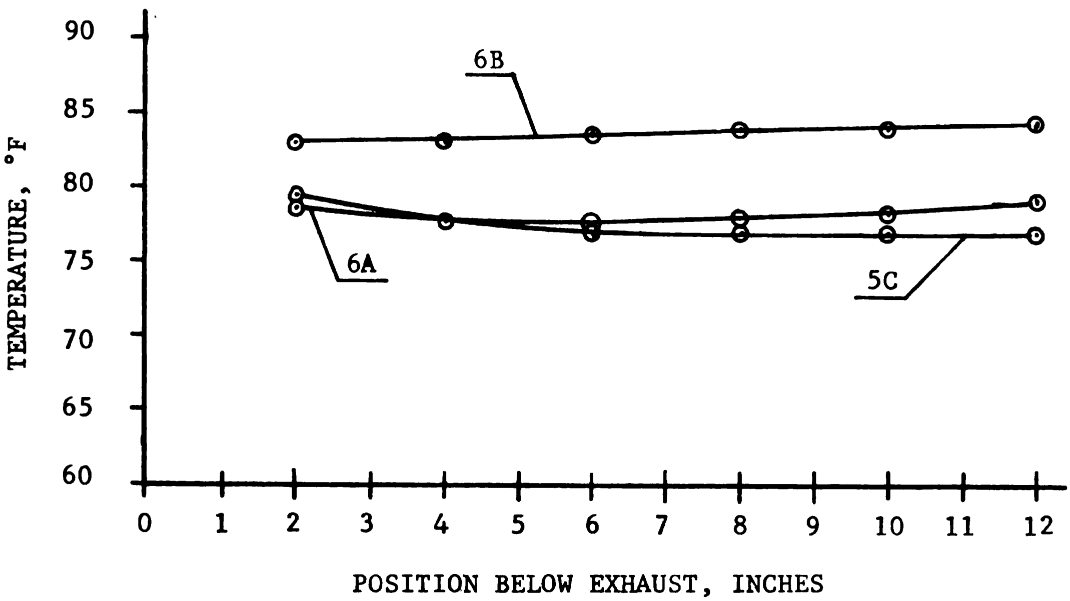


Figure 3.1E Cool Air Temperature Versus Position (220° and 205°F Tests)

3.11 Example of Mass Balance for Test 5A

Measured values:

Room (cooling air) temperature	83° F
Room (cooling air) relative humidity	55 %
Heating air temperature	450° F
Heating air rate at 450°F	96.5 cfm
Exhaust air temperature	118° F
Exhaust air rate at 118°F	153 cfm
Grain temperature at inlet	50° F
Grain rate at inlet	3.2 bu/hr
Grain moisture content at inlet, MC_{in}	37.3% d.b.
Grain moisture content at outlet, MC_{out}	26.5% d.b.

Values dependent on above values:

Density of moist air at 83° F	.072	lb/ft^3
Density of moist air at 450° F	.04324	lb/ft^3
Density of moist air at 118° F	.0658	lb/ft^3
Specific humidity for cooling air, H_{cool}	.0137	lb water/lb d.a.
Specific humidity at burner inlet, H	.0137	lb water/lb d.a.

Known values:

Specific heat of air, C_p	.24	BTU/lb °F
Heating value of fuel[1], HV	19,200	BTU/lb
Water to fuel ratio (grams water from grams fuel)	72/44	

---

[1] See Smith (1952)

Calculated values:

G_{aw} for heating air (rate x 60 x density)	250.3 lb/hr
G_{ad} for heating air $[G_{aw}/(1+H)]$, excluding fuel water	246.9 lb/hr
Water carried in heating air $(G_{aw}-G_{ad})$, no fuel water	3.4 lb/hr
Heat needed to warm heating air (ΔT x G_{aw} x C_p)	30000 BTU/hr
Fuel needed (Heat needed/HV)	1.56 lb/hr
Water of combustion (Fuel x water to fuel ratio)	2.56 lb/hr
Total water in heating air	5.96 lb/hr
Moisture content change $(MC_{in}-MC_{out})$	10.8 % d.b.
Dry matter grain rate [rate x 56 x $(1-MC_{out})$]	131.7 lb/hr
Water removed from grain (d.m. rate x MC change)	14.22 lb/hr
Equivalent specific humidity for heating air (Total water in heating air/G_{ad})	0.024 lb/lb

Mass balance:

Two mass balances are needed, one for the dry air and another for the water vapor. Since the exhaust relative humidity was not a valid measurement, it was necessary to solve both balances simultaneously to obtain the exhaust humidity. The dry air balance was:

$$G_{ad\ cool} = G_{ad\ exhaust} - G_{ad\ hot}$$

The water vapor was a summation as follows:

$$Water_{exhaust} = \text{Water in hot air} + \text{water in cool air} + \text{water from grain}$$

Since the water exhausted can also be expressed as

$$Water_{exhaust} = G_{ad\ exhaust} \times H_{exhaust}$$

and since

$$G_{ad\ exhaust} = G_{aw\ exhaust} / (1 + H_{ex})$$

then, by substitution

$$Water_{exhaust} = H_{exhaust} \times (G_{aw\ exhaust} / (1 + H_{ex})$$

Equating the expressions for water exhausted and substituting the values for the water in the hot air and the water from the grain gives:

$$H_{ex} \times (G_{aw\ ex} / (1+H_{ex})) = 20.18 + H_{cool} \times [(G_{aw\ ex} / (1+H_{ex}) - G_{ad\ hot}]$$

Substituting in values for $G_{aw\ ex}$, $G_{ad\ hot}$ and H_{cool} and solving for H_{ex}:

$$H_{exhaust} = 0.0428 \text{ lb } H_2O \text{ / lb d.a.}$$

With this value, the remainder of the values were calculated:

$G_{ad\ exhaust}$	=	577.3	lb/hr
$G_{ad\ cool}$	=	330.4	lb/hr
Water in cool air	=	4.52	lb/hr
$G_{aw\ cool}$	=	334.92	lb/hr
Cooling air rate	=	77.5	CFM/ft^2
Relative humidity of exhaust air	=	56 %	

3.2 Quality

A very extensive series of tests is needed to determine the true value of grain dried at high temperatures for short periods of time. This value will be determined by the final destination of the grain, that is, feed, seed, milling, etc. Such tests were beyond the scope of this study but samples of grain from tests 5A and 5C were taken and germination tests were run. Test 5A exposed the grain to 450°F heating air with the grain travelling vertically downward at approximately 0.68 inches per minute. The grain was exposed to the hottest air for at least one half minute. Test 5C used 220°F heating air but due to the grain velocity of 0.37 inches per minute, the grain was exposed for at least one minute. The germination test results were:

SAMPLE	% GERMINATION
1, undried	59
2, Test 5A (450°F)	28
3, Test 5C (220°F)	51

If the results of Sample 1 are considered 100% then the results of Samples 2 and 3 are 47.5% and 86.5% respectively. It would have been invaluable to have had samples which were dried at the same conditions only without spreading to verify the theoretical grain temperatures for spreading compared to no spreading.

3.3 Computer Simulation

A working computer model is a invaluable tool for grain drying research. Once the model is proved to be trustworthy, parameters can be changed to find the effect of each separately. Without the computer model many hours of testing would be necessary to obtain an optimum design.

The type of dryer used in this research requires two computer models, one for the drying zone and another for the cooling zone. Elzinga (1970) developed a simulation model for the concurrent flow drying portion of the dryer used in this study. Evans (1970) developed a model for counter-current flow drying. This model must be modified for cooling since very little drying takes place in the cooling section of the dryer used in this research. For this reason the cooling section was ignored as far as moisture content changes. The model developed by Elzinga can be used to find the optimum length of drying zone. By modifying the Evans model, the optimum cooling section length could also be found with very little testing.

Grain temperatures are difficult to measure during grain drying tests without interrupting the testing. Air temperatures on the other hand, are relatively easy to measure. A computer simulation model can be used to determine both air and grain temperatures. If the air temperatures can be verified experimentally, it is safe to assume that the grain temperatures are also correct.

The use of these models will enable the achievement of the ideal concurrent - counter-current flow dryer design. Such models will also enable the designer to keep the grain temperatures below the established limits which will result in higher quality grain and the needed speed in drying.

IV. SUMMARY AND CONCLUSIONS

4.1 Summary

Continuous flow grain dryers using concurrent flow drying and counter-current flow cooling are capable of high moisture content removal at initially high rates which decrease as drying progresses. A grain spreading device at the top of the drying zone is necessary to maintain the grain temperature below the high limit when high temperature air, e.g. 400°F, is used for drying. From a moisture content only aspect, these dryers are an answer to the increasing drying demands. Further tests are necessary to determine the values of the limiting temperature-time relationship for grain drying, specifically grain damage limits. Once this limit is established, continuous flow grain dryers can be properly designed to do the best possible job.

4.2 Conclusions

1. The use of a grain spreading device is essential to assure high quality grain when using high temperature concurrent flow drying.
2. Direct fired burners significantly increase the absolute humidity of the heating air and thus affect the drying rate and optimum drying section length.
3. Good mixing and uniform distribution of the heating air above the drying zone is essential to uniform drying.
4. In the dryer used for these tests, exhaust air relative humidity was difficult to measure due to the high air flow rates and mixing problems.
5. Counter-current cooling prevents or at least limits the amount of stress cracks due to cooling warm grain.
6. The use of natural air (room air for these tests) effectively cooled the dried grain to an acceptable handling temperature.
7. The use of rotary airlock unloaders is satisfactory if the airlock is properly designed and positioned.

V. RECOMMENDATIONS FOR FUTURE STUDY

The most important recommendation for grain drying research in general is that tests be run using new field shelled corn to best approximate farmer and elevator drying conditions. Another recommendation is the recording of the average size of the kernels to aid in the study of moisture and heat transfer in relation to grain drying.

Testing is needed to determine the economic effect on drying rates of adding products of combustion to the heating air.

Recommendations that apply specifically to the type of drying described in this paper include: (1) providing smoother transitions at air inlets and exhausts; (2) testing both with and without spreading to determine its effect on grain quality; (3) testing concurrent flow drying with no cooling, and; (4) testing the cooling section knowing the temperature and moisture content of the grain at the top to determine the amount of drying that occurs in that section.

Also, the exhaust section should be separated to allow monitoring the temperature and relative humidity of both the exhausted cooling air as well as the exhausted heating air instead of monitoring the mixed exhaust air.

Further testing should be done to determine the exact limits of the temperature-time relationship needed to assure good quality grain. Other biological criteria should be established for grains of various final utilizations so that dryers can be designed for optimum capacity while maintaining quality standards.

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APPENDIX

TABLE 3.1A Grain Parameters for Tests 2 Through 6B

PARAMETER	TEST NUMBER							
	2	3A	3B	4	5A[1]	5B[1]	6A[1]	6B[1]
T_o, (°f)	60	46	46	48	50	58	46	46
Rate, wet bushels/hr.	2.1	2.45	5.0	5.2	3.2	1.8	3.4	1.75
G_p, lb d.m./hr.	98.4	108.8	2.0.3	238.0	131.7	79.7	154.0	83.0
MC_{in}, % d.b.	35.6	34.1	34.1	25.5	37.3	37.3	25.9	25.9
MC_{out}, % d.b.	17.9	24.3	29.9	20.6	26.5	24.2	21.0	16.3
MC removed, % d.b.	17.7	9.8	4.2	4.9	10.8	13.1	4.9	9.6
Water removed, lb/hr.	17.4	10.7	8.8	11.7	14.2	9.99	7.5	7.9

[1] With spreading in drying zone.

Table 3.1B Heating Air Parameters

PARAMETER	TEST NUMBER 2	3A	3B	4	5A[1]	5C[1]	6A[1]	6B[1]
T_o, °F	450	450	450	450	450	220	205	205
H, lb H_2O/lb d.a.	.0152	.0114	.0114	.0174	.0137	.012	.0136	.0127
Rate, cfm/ft^2	106	115	109	108	96.5	74.5	133	130
Rate, cfm/bu/hr	50.5	47	21.8	20.8	20	41.4	39.2	74
G_{aw}, lb w.a./hr	276	298	283	280	250	259	472	462
G_{ad}, lb d.a./hr	271.8	294.6	279.8	275.2	246.6	255.9	465.7	456.2
Length of zone, inches	13	13	13	13	13	13	19	19
Water added by air, lb/hr	4.2	3.4	3.2	4.8	3.4	3.1	6.3	5.8
Water added by fuel, lb/hr	2.83	3.05	2.9	2.87	2.56	0.79	1.45	1.42

1 With spreading in drying zone.

Table 3.1C Cooling Air Parameters

PARAMETER	TEST NUMBER 2	3A	3B	4	5A	5C	6A	6B
T_o, °F	83	82	82	82	83	84	85	87
H, lb H_2O/# d.a.	.0084	.0086	.0087	.0098	.0137	.012	.0136	.0127
Rate, cfm/ft^2	47.5	60.6	63.0	63.0	77.5	86.9	89.9	79.2
Rate, cfm/bu/hr	22.6	24.7	12.5	12.1	24.2	46.7	27.4	45.0
G_{aw}, lb w.a./hr	210.0	267.7	278.6	278.1	334.9	371.2	391.0	342.0
G_{ad}, lb d.a./hr	208.2	265.4	276.2	275.4	330.4	366.8	385.7	337.6
Length of zone, inches	15	15	15	15	15	15	9	9
Water added by air, lb/hr	1.75	2.27	2.4	2.7	4.5	4.4	5.2	4.3

Table 3.1D Exhaust Air Parameters

PARAMETER	TEST NUMBER 2	3A	3B	4	5A	5C	6A	6B
T, °F	142	132	120	130	118	92	90	93
G_{aw}, lb w.a./hr	507	580	573.8	544.9	602	641	871.8	813
G_{ad}*, lb d.a./hr	480	560.4	556	522	577.3	622.3	851.4	793.8
Rate, cfm/ft^2	135	150	145	141	153	150	200	188
Rate, cfm/bu/hr	64.3	61.2	29.0	27.1	47.9	83.3	58.9	107.0
H*, lb H_2O/lb d.a.		.035	.032	.044	.0428	.0294	.024	.024
RH*, %	35	30	40	40	56	89	76	71

* Calculated values from mass balance.

Table 3.1E Effect of Spreading on Drying Air Temperatures

LOCATION[1]	WITHOUT SPREADER °F				AVE.	WITH SPREADER °F				AVE.
1	188	134	153	130	151.5	130	128	132	116	126.5
2	158	135	146	119	139.5	122	109	128	106	116.2
4	135	121	121	112	122.2	114	102	112	105	108.8
6	122	NT	NT	110	116.0	110	NT	NT	101	105.5
8	NT	104	108	NT	106.0	NT	96	104	NT	100.0
10	107	NT	NT	98	102.5	104	NT	NT	96	100.0
14	NT	NT	100	NT	100.0	NT	NT	100	NT	100.0
18	104	NT	NT	96	100.0	105	NT	NT	98	101.5

1 Distance from top of drying section, inches.

Table 3.1F Drying Air Temperatures for Test 6A and 6B.

Test 6A						Test 6B					
Location from top in drying section (inches)	Thermocouple Column[1]					Location from top in drying section (inches)	Thermocouple Column				
	#1	#2	#3	#4	Ave.		#1	#2	#3	#4	Ave.
1	153.0[2]	132.8	147.8	136.8	142.6	1	162.8	147.6	155.8	147.4	153.4
2	142.0	125.8	143.8	118.8	132.6	2	151.6	138.6	150.4	136.0	144.1
4	126.4	114.8	123.0	118.0	120.5	4	140.6	130.2	134.8	135.2	135.2
6	120.4	NT	NT	110.4	115.4	6	132.8	NT	NT	126.0	130.4
8	NT[3]	116.8	111.8	NT	114.3	8	NT[3]	120.4	126.6	NT	123.5
10	113.4	NT	NT	102.2	107.8	10	126.6	NT	NT	116.6	121.6
14	NT	NT	105.2	NT	105.2	14	NT	NT	117.0	NT	117.0
18	106.4	NT	NT	97.4	101.9	18	119.0	NT	NT	109.0	114.0

1 Each column located three inches from two adjoining sides.

2 Average of five readings monitored during eleven-minute time intervals, ^{o}F.

3 NT; No thermocouple at this location.

TABLE 3.1G AIR TEMPERATURES IN COOLING SECTION

LOCATION*	TEST NUMBER							
	2	3A	3B	4	5A	5C	6A	6B
0	130.0**	112.3	113.0	132.6	102.4	83.1	83.7	84.5
2	112.3	118.0	118.3	133.3	100.1	79.2	78.5	83.0
4	98.3	110.1	111.7	127.8	94.1	77.6	77.6	83.0
6	91.0	102.3	105.0	119.9	87.7	76.8	77.5	83.5
8	86.0	97.0	99.3	114.4	84.4	76.7	77.7	83.7
10	83.6	91.5	96.0	110.2	82.6	76.7	78.0	83.7
12	82.0	90.0	94.6	107.0	80.1	76.6	78.8	84.0
INLET	82.6	83.0	85.0	87.9	84.0	86.1	86.2	86.0
Grain Rate bu/hr	2.1	2.45	5.0	5.2	3.2	1.8	3.4	1.75
Air Rate CFM/ft^2	47.5	60.6	63.0	63.0	77.5	86.9	89.9	79.2
LENGTH***	15	15	15	15	15	15	9	9

* Distance from bottom of exhaust chamber, inches.
** Average of five consecutive readings, degrees Fahrenheit.
*** Inches.

Table 3.1H Drying Air Temperatures for Test 3A

Depth*	Temperatures, °F, Consecutive Readings					Average
0	over 300**					
0.5	over 300**					
1.5	274	276	275	274	278	275.4
2.5	235	236	234	228	228	232.2
3.5	337	224	224	224	216	223.0
4.5	2.3	209	211	207	202	208.4
6.5	199	196	195	194	190	194.8
8.5	192	187	185	183	182	185.8
12.5	180	177	173	170	169	173.8

* Distance from top of drying zone, inches.

** Upper limit on recorder was 300° F.