CRITERIA FOR FLAT - BED RICE DRYING WITH ENGINE WASTE HEAT

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ABSTRACT

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By

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Flat-bed drying tests were conducted with depths of 6, 12 and 24 inches. Airflow rates of 10 and 30 cfm/ft^2 were used for air at 95, 110 and 125 degrees F and 0.016 lbs/lb absolute humidity (to simulate conditions in tropical areas). Rice obtained from the field at 20 percent moisture (w.b.) was dried to 14 percent. Various combinations of (a) uninterrupted drying, (b) periodic airflow reversal, (c) periodic stirring of the bed, (d) short-duration tempering were used and (e) combination of (c) and (d). Rates of moisture removal were measured and moisture contents as well as milled rice and head rice percentages were determined for samples taken throughout the bed at the end of the drying operation.

Air delivery characteristics were determined for two engine-fan combinations (single cylinder engines with propeller- and centrifugal-type fans) with all waste heat directed into the airstream. These corresponded approximately to the 95 degree F air condition, while the higher temperatures were those that might be obtained with the use of additional heat.

It was found that (a) air reversal and tempering were of little value, (b) high airflow rates or low air temperatures resulted in more uniform distribution of moisture content throughout the bed, (c) use of low air temperatures resulted in prevention of decreases of head rice percentages -- particularly at low airflow rates, (d) high air temperatures at high airflow rates produced rapid drying, but tended to cause reductions in head rice percentages, (e) these reductions were minimized by combining periodic stirring with increased bed depths, (f) when using such practices to minimize reductions in head rice percentages, the amount of rice dried with a given investment in equipment could be maximized by adding heat to the drying air beyond that provided by heat energy emission from the engine powering the fan.

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I. INTRODUCTION

Indonesia is a tropical rice producing country with an average temperature of 85°F and a relative humidity of 80%. Traditionally only one crop of rice has been grown each year during the rainy season. Harvest thus, came at the end of or after the rainy season so the high moisture paddy rice was generally sun dried on the ground or floor.

Recently, new high yielding rice varieties have been introduced and better water control for dry season irrigation development. These technological improvements are making it possible to grow rice continuously on a year round basis. The resulting two or three crops per year, each with heavier yields, increase the problem of drying, handling and storage. Natural sun drying is becoming more difficult in some cases due to the large quantities of rice harvested. Also, multiple cropping of rice means that some of the harvest periods fall during the rainy season and sun drying is quite unsatisfactory, if not impossible. Therefore, artificial drying must be considered.

Some small (approximately one metric ton) mechanical, fixed-bed type dryers have been introduced in Indonesia from Japan. They all use a supplemental source of energy for heating the drying air. According to Toshizo Ban (1960) the Japanese dryers are designed to operate with a drying air temperature of 9 to 27°F higher than the atmosphere temperature. Inexperienced operators tend to increase the supply rate of supplemental energy in order to speed up the rate of drying. The result is an increase in the drying air temperature which does cause faster drying, but also may bring about over drying and excessive rice cracking. The checks and cracks caused in the rice kernels are generally not visible until after processing.

Rice is mostly planted and consumed in the tropical areas. However, most equipment for grain handling, drying and storage comes from the industrial countries of the temperate regions of the world. As a result, most equipment is designed and built specifically to meet the requirements of the temperate regions. An all too common approach has been to transport such equipment directly to the tropical regions of the world for direct application and operation without modification. The results have often been disastrous.

II.1. OBJECTIVE

The objective of the research reported in this thesis was to establish rough rice mechanical drying parameters for utilizing the engine waste heat under the humid tropical conditions that typefy Indonesia.

II.2. RESEARCH STATEMENT

Research was carried out on the following topics:

1. Waste heat utilization from the internal combustion engines used to operate fans for the fixed-bed grain drying system.
2. A model of a fixed-bed rice dryer was operated at three temperature levels of 90°F, 110°F and 125°F; three grain depths of 6, 12 and 24 inch; and two drying air flow rates of 10 and 30 c.f.m./ft^2.

The following treatments were evaluated in an attempt to minimize the overdrying problem of the bottom layer and thus increase the head yield:

a. Uninterreputed drying (continuous air flow drying) similar to conventional fixed-bed drying systems
b. Periodic stirring
c. Short period tempering
d. Periodic air flow reversal
e. Short duration of tempering followed by period air flow reversal.

III. REVIEW OF LITERATURE

Considerable research has been done on rice drying as a review of the many publications confirmed. Angladette (1964) compiled a review of research that had been done in developed and developing countries.

Much effort in the United States has been directed toward increasing the head yield after processing. In the developing countries where rural rice consumption is high and the research support is low, the efforts directed toward improving the milling process has been limited. Proper drying by either sun or artificial means is critical for high head rice yields. Studies conducted in India (Wimberly, 1972) showed that mechanically dried rice had a higher head rice*, yield as well as total yield. Esmay (1972) stated that the cost, size and complexity of modern rice dryers make most of the units impractical for developing countries, particularly at the farm and the village level. Khan (1972) noted that the benefits from modern rice drying and processing have not been shared by the farmers.

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*Head rice. The kernels of milled rice which are full sized or three-fourths of full size or larger.

Head yield. The amount of head rice obtained by milling a given amount of paddy rice and may be expressed in percent of paddy rice.

$$\text{Head yield} = \frac{\text{wt of head rice}}{\text{wt of paddy rice}} \times 100$$

Total yield. The amount of milled rice (head rice and brokens) obtained from a given amount of paddy. It is expressed as percent of paddy rice by weight.

$$\text{Total yield} = \frac{\text{wt of milled sample}}{\text{wt of paddy rice}} \times 100$$

Different types of simple grain dryers for developing countries have been investigated by many research workers. Conduction drying of rice has been studied by Chancellor (1965) and conduction drying with heated sand is still in the developmental stage by I.R.R.I. (International Rice Research Institute) Khan et al (1970). Boyce (1956) in Malaysia and Esmay (1972) in Michigan studied a dryer that would utilize waste heat from the internal combustion engine for supplementary heating of the drying air. Huysmans (1971) proposed the utilization of the heat produced by an air cooled diesel engine. Da Padua (1970) developed a fixed-bed dryer with a higher drying capacity for use at the village level in the Philippine Islands. Batch dryers with small capacities of 1-2 metric tons are being investigated in India and at I.R.R.I. (1970).

III.1. DRYING OF RICE

Rice must be dried after harvesting in order to maintain in good condition throughout storage without loss in quality of quantity. Proper drying is one of the several requirements to maintain good quality. Different rice drying methods in the developing countries are discussed here briefly.

III.1.1. SUN DRYING

Sun drying is the most common and conventional method in the developing countries. This low capital cost method has been and is still practiced by the small producer where climatic conditions are favorable at harvest time. Although the method is the lowest cost in capital outlay, there are control limitations. According to Esmay (1969) the sun drying method may allow cyclic wetting and drying phases, which can cause kernel checking and breaking.

Angladette (1964) reported that several studies on the sun drying of rice have been conducted in Vietnam and Madagaskar with different depths, with stirring and on different types of drying surfaces. He also reported a study on sun-drying when the rice was not exposed directly to the sun. The rice dried in the shade had a higher milling outturn. Less cracked grain is normally the main factor that accounts for an increased milling yield. Chancellor (1963) studied the effect of hourly stirring on sun drying rice in Malaysia. He found an increase in the drying rate of up to 67%. He also concluded that the rate of moisture evaporation was proportional to the exposed areas. Baily and Williamson (1965) found that the heat utilized for grain drying in a covered solar dryer with uncontrolled air flow was similar to that for direct sun drying on the ground. Heat utilization for drying was considerably improved when the air flow was controlled and directed downward through the grain.

III.1.2. FIXED-BED DRYING

III.1.2.1. UNINTERRUPTED DRYING

The fixed-bed batch-type dryer is the simplest mechanical system. Catambay (1960) suggested that the flat-bed dryer has a great possibility for the Philippine farms. Wasserman (1970) found in the Philippine Islands that an improperly operated mechanical dryer resulted in a low yield of whole kernels. Considerable kernel checking can occur during the drying and cooling phase of an uncontrolled intermittent drying process. Often the grain is overdried in the heated air phase and subjected to overcooling in the moist air after drying. He suggested that a fixed-bed dryer is most easily controlled and simplier for farm level operation than the phase dryer.

According to Matthes (1972) the flat-bed dryer has the following advantages:

1. Grain handling is minized.
2. Drying is sufficiently slow to minimize checking and cracking from internal stresses.
3. Initial dryer cost is low compared to the continuous flow type drier.
4. Drying bin may also be used for other agricultural crops.

5. The simple flat-bed dryers can be utilized at the village level.

Shove (1967) studied the temperature gradient in the bed of drying grain. He observed that the factors that affected the bed drying were as follows:

1. Initial moisture content of grain.
2. The air flow rate.
3. Initial air condition.
4. Drying characteristic of the grain.
5. Treatment of the grain previous to drying.

Heat energy is required to evaporate moisture from the kernel. Heat energy can be obtained by convection heat transfer from the atmosphere air or from artificially heated air. When heated air is passed through the damp rice, moisture is evaporated. The air supplies the energy required for evaporation and provides a medium for carrying away the water vapor. In a fixed-bed dryer, heated air tends to dry the rice and drying occurs until an equilibrium moisture content is obtained. In an updraft dryer, the grain in the bottom layer dries first while the top layer dries later. It has been observed that the grain drying process in a fixed bed dryer takes place in a thin layer or "drying zone" which progresses from the point of heated air entrance to the air outlet.

According to Matthes (1972) fixed-bed drying is a continuous process with simultaneous changes in moisture content, air and grain temperature and air humidity occuring at the drying zone level of the bed. The drying zone changes vary with the different drying parameters and at different locations in the bed as limited by air temperature. When the air temperature is above the equivalent moisture content of the desired optimum moisture content for dry grain, there is the possibility of overdrying the bottom layer, while the top layer is still too moist. Lower air temperature, however, means slower drying. Several attempts have been made to overcome the overdrying problem by mixing or intermittent drying (Woodforde, 1965).

Many fixed-bed dryers are used in the temperate region of the world. The temperate climatic conditions are generally less humid and more seasonal. Often unheated air is used for drying. The same overdrying possibilities exist but have not been serious as only low drying air temperature are used. Operating instructions and recommendations from the dryer manufacturers will normally provide the farmers and grain elevator operators with specific information for optimum drying.

In developing countries the inexperiened dryer operators have a tendency to increase the drying rate by increasing the drying air temperature and thus, overdrying results. The heat energy supply is easy to modify by the dryer operator and a lack of understanding the undesirable consequences leaves the natural tendency open for increasing the drying rate.

Continual monitoring of temperature and moisture levels throughout the grain bed is difficult and inconvenient for operational purposes. Some relationships between the drying air temperature, the air flow rate and the depth of grain in a fixed-bed dryer were developed by Henderson (1966). Several formulas have been developed by various researchers to predict the time required to dry grain in a thin layer or in a fixed-bed for a given air flow rate, drying air temperature, grain depth and climatic condition. (Allen, 1960, Henderson and Henderson (1967).

Matthes (1972) made a heat balance analysis of a thin layer and developed an equation to predict the time required to dry a given depth of rice in a fixed-bed dryer. He made several assumptions and simplifications so the final formula could be applied to the farmer. He proposed that a fixed bed of grain be considered as a series of thin layers, and assumed that all the grain in a thin layer was dried at a uniform rate. Several other analytical methods have been developed for fixed-bed drying based upon the application of several thin layers. If for a short period of time the condition in any thin layer is considered to be constant, then by a reiteration arithmetical process the moisture change from layer to layer throughout the bed, may be determined throughout the drying period. Henderson and Henderson (1967) developed a computational procedure for a deep-bed drying analysis. Bakker-Arkema, et al (1967), Thompson (1968), Thompson (1970) developed a simulation model for determining the moisture change in the grain bed during the drying process.

III.1.2.2. PERIODICAL STIRRING

One of the disadvantages of fixed-bed drying, particularly at the higher drying air temperatures, has been previously pointed out as overdrying of the bottom layer. When the desired average moisture content of a fixed-bed of grain is reached, there still remains under most drying conditions a temperature and moisture gradient from the bottom to the top of the grain bed. The magnitude of these gradients depends upon the air flow rate, drying air temperature, depth and initial moisture content of the grain.

It has been a common practice for farmers and grain elevator operators in the United States to blend the high moisture grain from the top with the lower moisture grain from the bottom to obtain a mixture at or near the desired average moisture level. In many developing countries where sun drying has been a common practice, grain was stirred periodically to increase the drying rate and to minimize the temperature and moisture gradient.

Some studies have been conducted on the effect of rice depths, drying air temperature and moisture gradient in uninterrupted drying. These results can be tabulated as follows:

Researchers	Depth inch	Drying Temp. °F	Drying Time hrs	c.f.m.	m.c. gradient between top and bottom
Allen (1960)	18	80	10.0	-	9%
Catambay (1960)	17	120	4.33	22	5%
		140	4.08	22	7.3%
		160	3.25	22	8.2%
Manalo (1970)	12	110	9.0	15	3.0%

Rice and many other grains have an optimum range of moisture content between 12 to 14% wet basis for the maximum milling yields. If the moisture content is lower or higher, the head yield is reduced. According to Wasserman (1965), the more times the rice has been exposed to drying air and the lower the drying air temperature, the higher the head yield.

Work done by Fairbrothers (1929), on mixing the higher and low moisture content wheat, indicated that the low moisture wheat remained at a lower moisture content than the higher moisture wheat. Fisher and Jones (1939) concluded with reference to the mixing of wheat, that total equalization of moisture content between kernels is never obtained by mixing even after the grain has been held in storage for a long time.

Hart (1967) reported that a mixture of overdried shelled corn and undried corn having a mixed mean moisture content of 15.5% was more likely to become moldy than was unmixed samples at the same 15.5% moisture level. White (1972) studied moisture content with 40, 70 and 100°F air temperatures. He concluded that the higher the mixture temperature, the smaller the difference between the high and low moisture content. The speed at which moisture equilibrium took place was found to be temperature-dependent, but independent of mixture portion. He found that the initial rate of moixture exchange was higher for the moist corn as compared to the drier fraction. Woodforde (1965) found on his studies on mixed wheat, that the drying rate of mixed wheat was slightly lower than unmixed wheat.

III.1.2.3. PERIODICAL AIR REVERSAL

Several research workers have attempted to increase the drying rate and reduce the overdrying by intermittent drying, cycling of heated and unheated drying air through the grain.

Browning (1971) used alternately heated and unheated air in the batch-in-bin drying of corn. Three, four, six and twelve minute cycles were used and the same total Btu's were added as for the controlled drying test. During the air cycling tests the increase in temperature was 55°F.. Later Brooker et al (1971) analyzed the Browning results and found that there was no advantage in heat utilization by the cycled heat drying over continuous drying.

Kenyon (1969) studied cyclic drying by alternating hot and cold air through a column of wet corn. The increased temperature generated by the heating period was employed as a source of energy for moisture removal from the product during the subsequent cooling period.

IV. DESCRIPTION OF APPARATUS

IV.1. DRYING EXPERIMENT

A line drawing of the experimental apparatus is shown in Fig. 1, and a picture of the experimental set up is shown in Fig. 2. The high moisture rice (A) was placed in a removable grain box (B) mounted on a plenum chamber (C) which rested on a platform scale (D), that indicated weight changes of less than 1/2 lb. Water removal was thus indicated on a continuous basis without disturbing the drying system.

The drying box was constructed from 1/2 inch internally painted plywood and had dimensions of 16x16x12 inches. The rice was supported on the screen wire which formed the plenum chamber below. A screen was also placed over the rice to

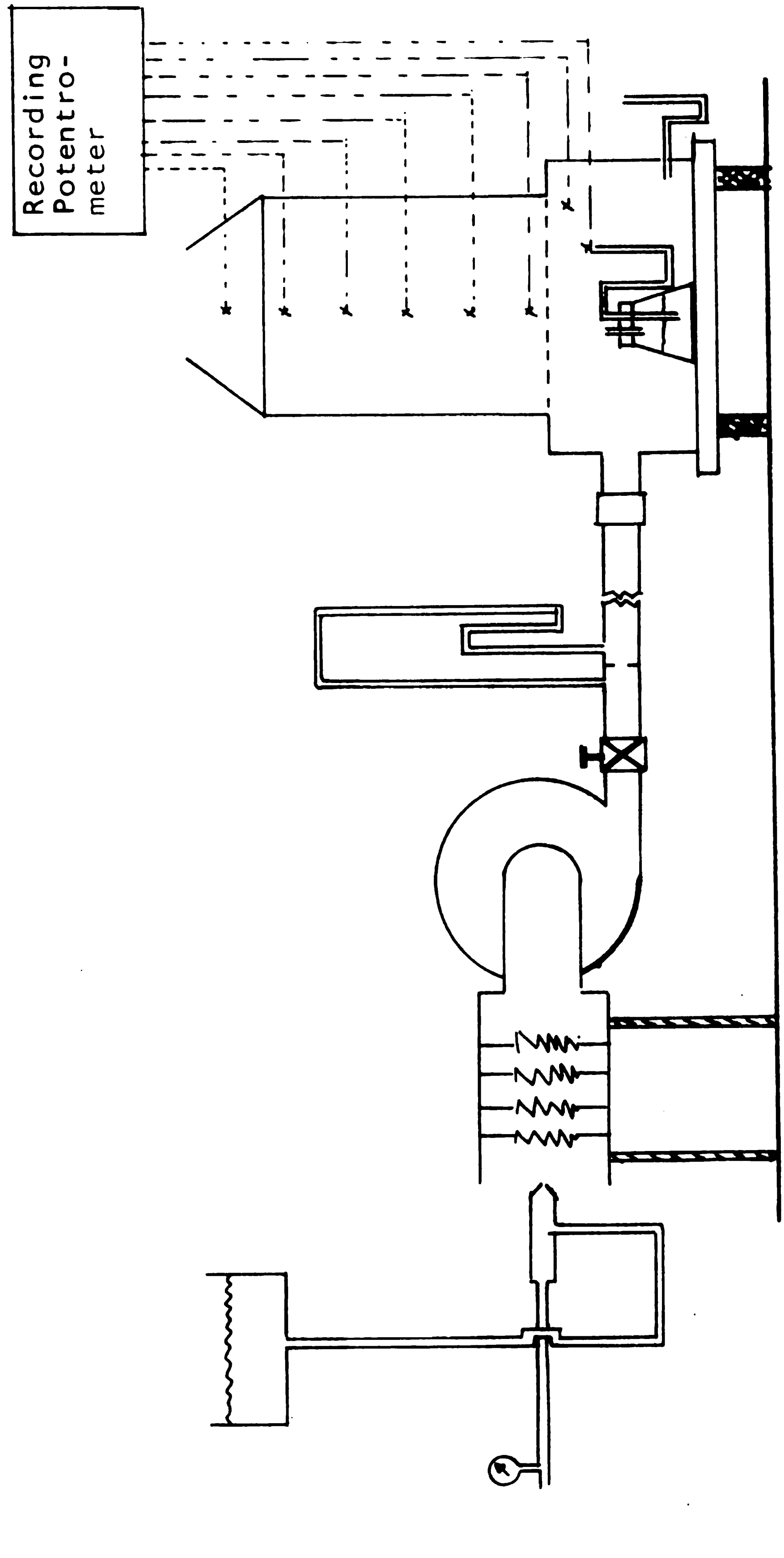

Figure 1. Lime drawing of the drying experimental apparatus.

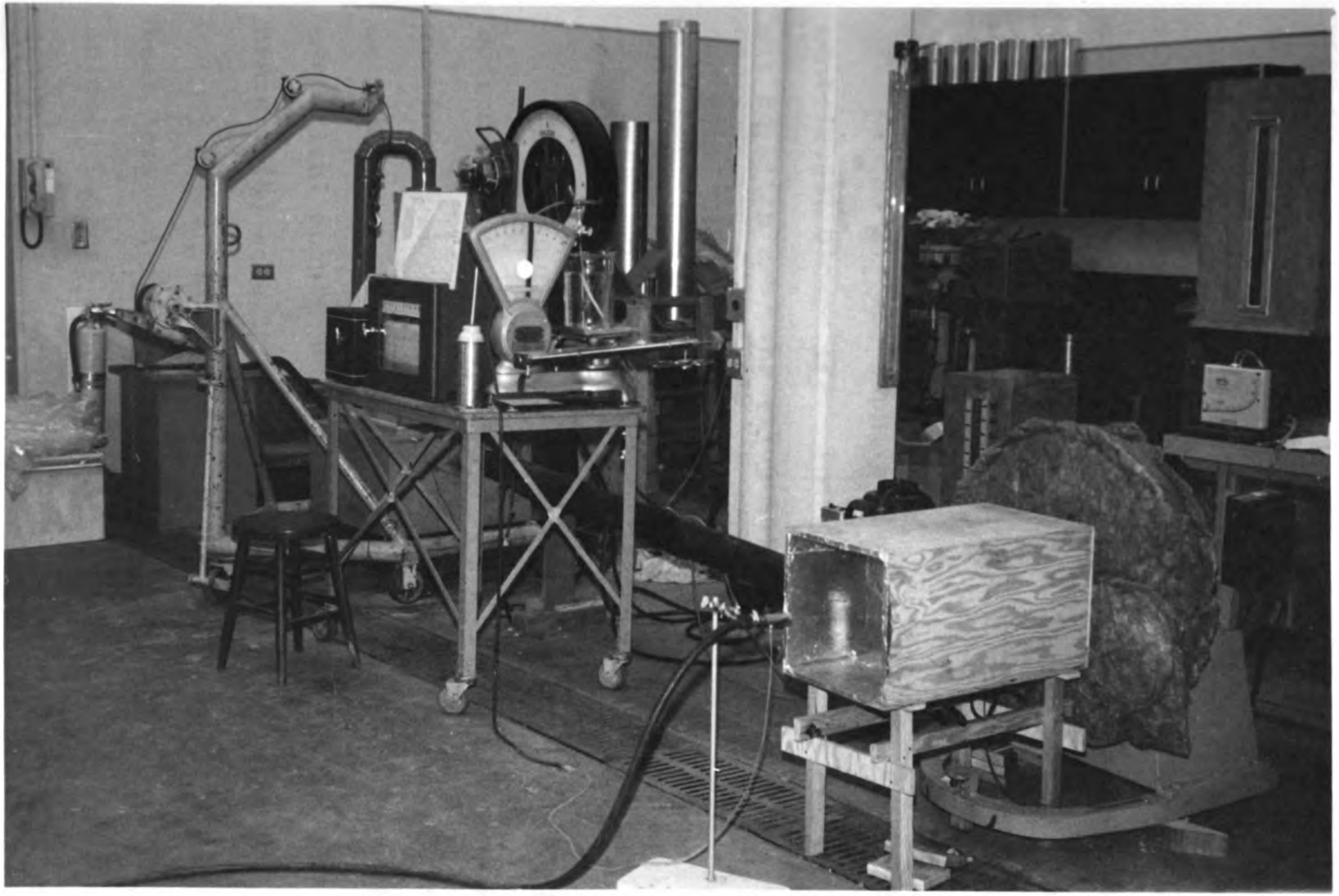

Figure 2. Experimental rice drying set up.

to permit turning of rice for some tests. A small crane was used to turn the drying bin upside down. The turning operation was accomplished in from 30 to 60 seconds. A 16x16x24 inch plywood box was used for the 24-inch depth tests. No attempt was made to turn the 24-inch depth box. The plenum chamber had a dimension of 24x24x12 inches and was insulated on the inside with fiberglass. A static pressure tap (E) was made in the plenum chamber and a tube was connected to the incline manometer.

Heated air was supplied to the plenum chamber from a centribugal blower (F). The airflow to the plenum chamber was adjustable by the valve (G) on the outlet side of the fan tube. The air measuring tube embodies an orifice plate (H) with a connection to the incline manometer having a range from 0-3 inches in 0.1 inch increments.

The fan pulled air from the inlet duct system (I). The duct consisted of a 12x12x24 inch plywood box insulated with aluminum foil on the inside. Four 500 Watt electric heaters were located inside the box and connected to a 20 AMP. 110 V. electrical supply through a variable voltage regulator. The heaters (K) were thus adjustable from 0-2000 Watts.

A damper was located at the incoming air to minimize heat loss. A spray nozzle (J) was also located in the air inlet. Controlled amounts of water were sprayed under high pressure into the air. The spray nozzle provided the humidity control. Distilled water was used for the water spray to to avoid the mineral deposit on the fan blade. A 60-80 p.s.i. pressure was maintained by an air compressor on the water spray. The water flow was adjustable with two valves, one main control and the other a mist fineness adjustment. The amount of water needed to reach the desired wet-bulb temperature in the plenum chamber was based on psychrometric chart calculations. A 5000 c.c. jar placed on a small scale provided the measurement for the exact amount of waterflow to the spray nozzle.

A recording potentiometer with 12 thermocouple connections was used to record the temperature during the tests. One cycle of recording took 2-1/2 minutes. Two thermocouple were located in the plenum chamber. For the 6-inch depth of rice, 3 thermocouples were used, while for 12 and 24-inch depth of rice, 5 thermocouples were needed. Wet-bulb temperature was measured by a wet bulb thermocouple, see Figure 4. Dry and wet-bulb temperatures in the plenum chamber were recorded continuously on a recording potentiometer. A continuous indicating potentiometers was also used to detect the slight changes in the dry and wet-bulb temperatures in the plenum chamber. The dry and wet-bulb temperatures in the plenum chamber were controlled by adjusting the heaters (K) and the spray nozzle (J) at the duct inlet (I).

IV.2. ENGINE WASTE HEAT UTILIZATION

The selection of engines and fans used for the experiment was based on the availability of equipment at the Agricultural Engineering Department at Davis, California. It was realized that each fan has a specific performance according to the rpm and hp in order to obtain the optimal efficiency. Two engines were available for the test. One was a 2-1/2 hp Clinton air cooled gas engine and the other was a 7-1/2 hp Briggs & Stratton air cooled gas engine. The governor system of the Clinton engine did not function properly. Some adjustments were needed on the engine speed during the test. The maximum rpm of the engine was checked before the experiment. A plate with a hole in it was placed between the carburator base and the intake manifold, to prevent the engine from running at maximum rpm continuously. The hole was sized so that 80% of the maximum torque was obtained. This adjustment will allow the engine to have a longer useful life without lowering its efficiency. By trial and errors the size of holes were found to be 9/32 inch for the Clinton engine and 7/16 inch for the Briggs & Stratton engine. The exhaust gasses of both engines were directed toward the fan during the test.

A propeller type 18 inch diameter fan with 6 blades was directly connected to the Clinton engine's drive shaft (see Figure 3). A centrifugal blower with 6 blades, 16 inches in diameter and 6 inches wide, was operated by the Briggs & Stratton engine through a belt pulley system. The rpm of both engine and fan were determined with a "Strobotac" rpm counter. The gas tank was removed from both engines and placed on a scale. The rate of fuel consumption was recorded on a weight basis per unit time. The average time period used for each test was 15 to 20 minutes.

The duct for airflow measurement was 8 ft. long and had a diameter of 15 inches. It was made from 22 gauge sheet metal. A Pitot tube was located one-fourth of the distance from the outlet for measuring the air flow rate. Airflow measurements were taken at several cross sectional area locations to obtain a representative average. The measurement method was based on Henderson (1966). Both static and dynamic pressures were taken. The Pitot tube was connected to a 0-3 inch inclined manometer for measuring airflow from the fan on the Clinton engine. For the blower and the Briggs & Stratton engine, the Pitot tube was connected to a 0-7 inch inclined manometer. A five feet length and 15 inch diameter canvas was placed between the fan outlet and the intake measuring tube. The canvas acted as a vibrator absorber from the engine. At the outlet of the measuring tube there was a sliding gate. By opening and closing the sliding gate the static pressure was varied (see Figure 4).

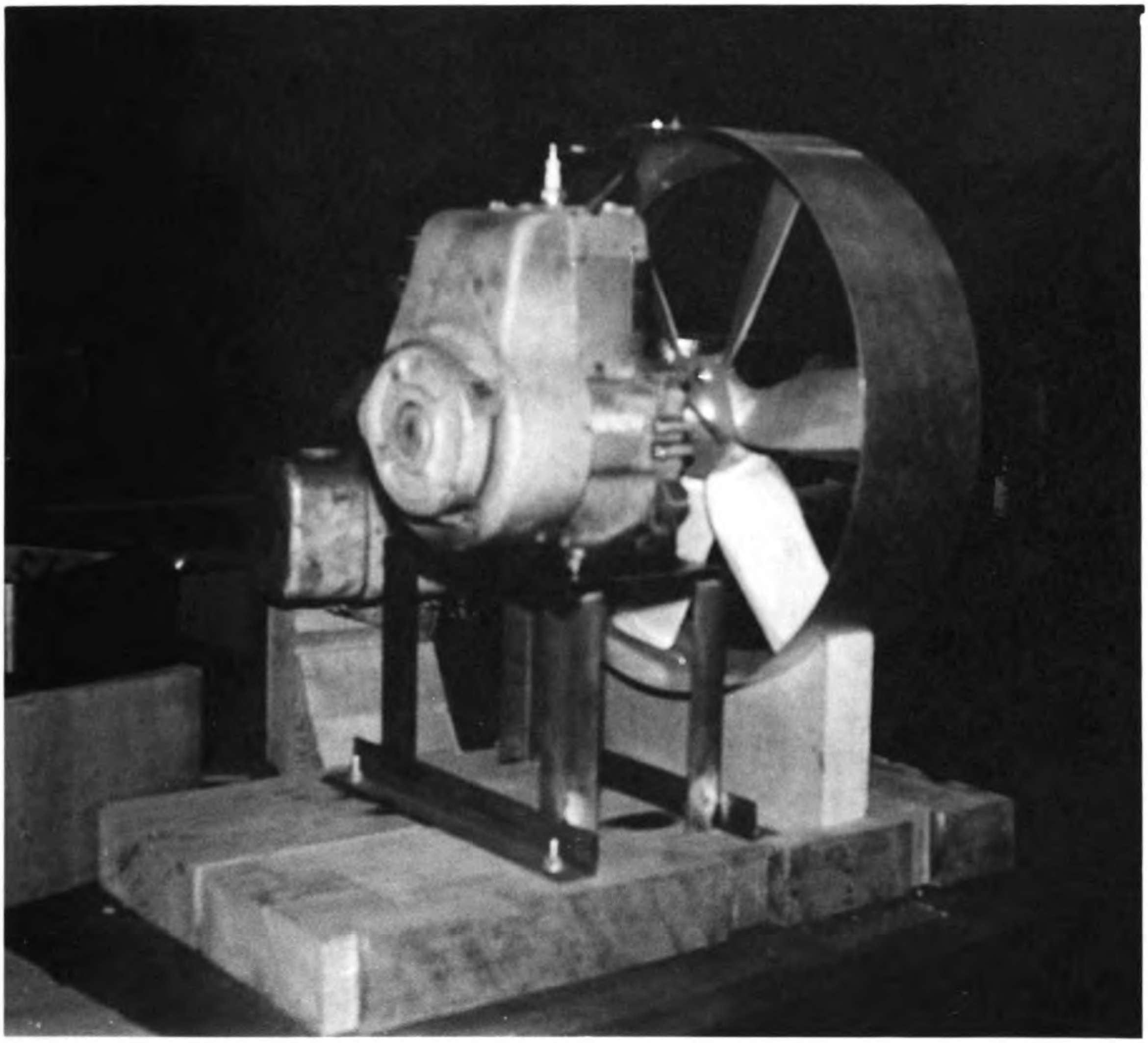

Figure 3. Direct connection propeller fan to the Clinton engine. A tube and plate ring were placed around the propeller housing to direct the airflow and reduce the turbulence of airflow.

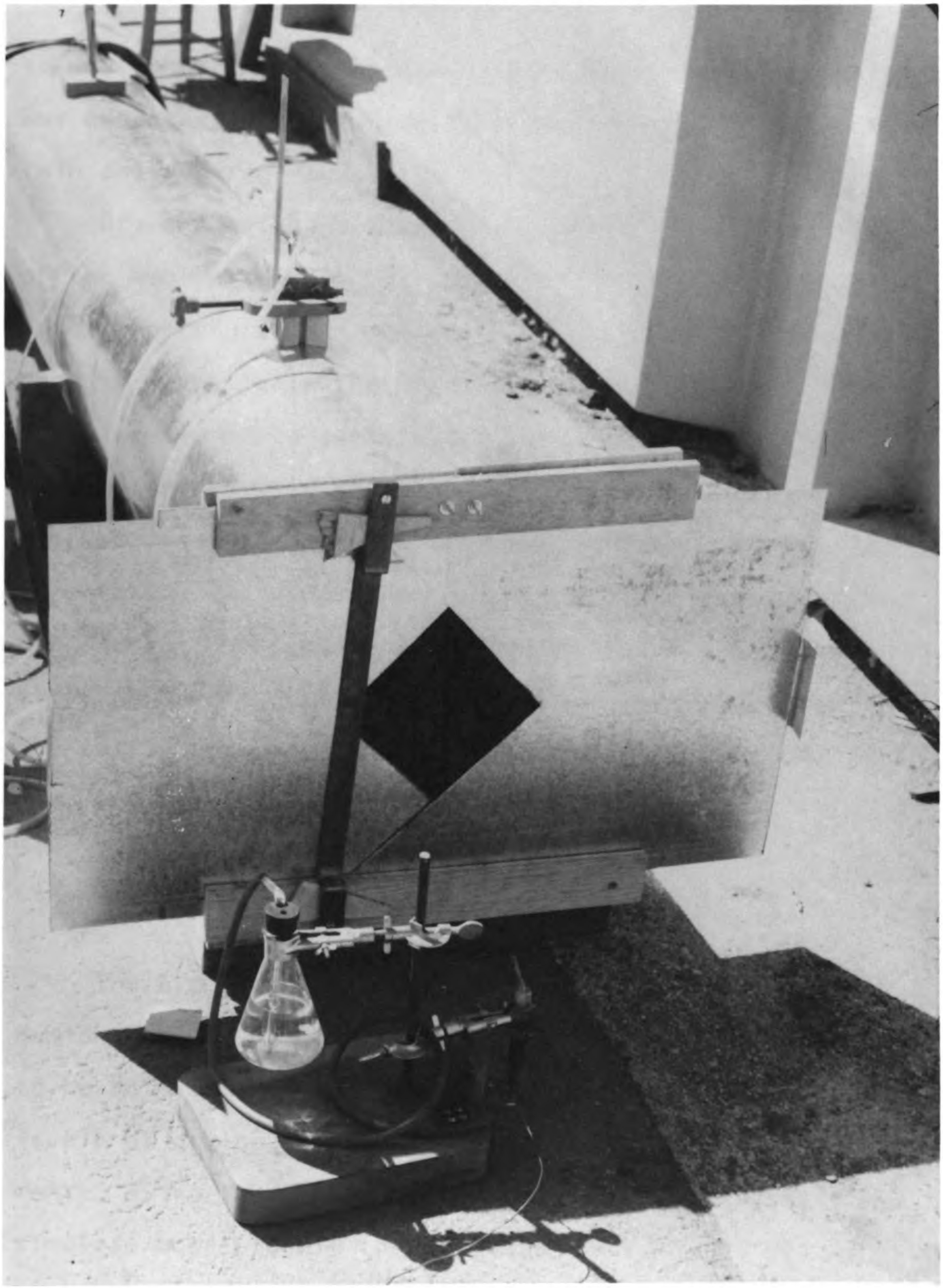

Figure 4. Wet-bulb temperature measurement and the sliding gate at the outlet of the measuring tube. By opening and closing the sliding gate the static pressure was varied.

It was found for the Clinton engine that a speed adjustment was necessary when the static pressure was changed to maintain the desired rpm.

Dry and wet-bulb temperature measurements were taken of the ambient air and at the outlet of the measuring tube. Some temperature readings were taken also along the measuring tube to investigate the heat loss or gain of the system. There was found to be only a slight difference in the temperature between the middle and the outlet. Dry and wet thermometers with an aspirator for measuring the ambient temperature was used. The waste heat from the engine was measured at the tube outlet with dry and wet bulb thermocouples connected to a continuous reading potentiometer. The set up for measuring the waste heat is shown as Figure 5.

V. EXPERIMENT PROCEDURE

V.1. DRYING

The experimental procedure was designed to simulate a humid tropical climate. The ambient temperature was assumed to be 80°F and the relative humidity 75%. Three different levels of drying air temperature were chosen for the experiment: 95°F, 110°F, and 125°F. The 95°F was selected to simulate most closely the possible availability of the waste heat from a small internal combustion engine for the supplemental heating of the drying air. The 125°F level was used

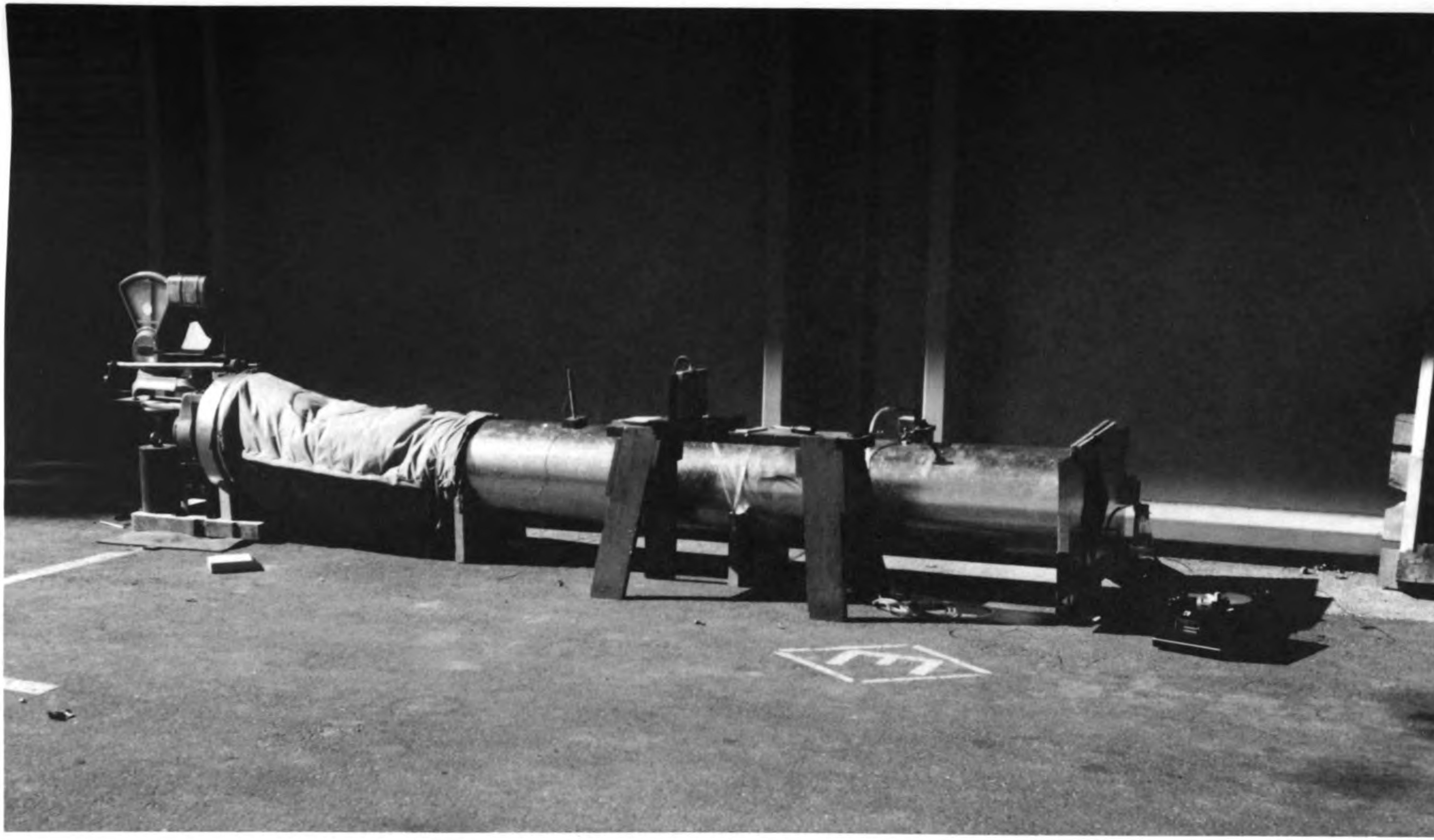

Figure 5. The experimental set-up for utilization of waste heat from engine. A Pitot tube was located one-fourth of the distance from the outlet for measuring the airflow rate.

to evaluate the potential of faster drying with supplemental heat. Air flow rates through the rice of 10 and 30 c.f.m./ft^2 of drying area were used. The 30 c.f.m./ft^2 was considered to be optimal and the 10 c.f.m./ft^2 a minimal air flow rate for drying rice. The range for air flow rates for rice drying is interrelated with the drying air temperature and the depth of rice.

The experimental deptsh of rice were selected as 6, 12 and 24 inches. The 6-inch depth provided an assumed lower limit for fixed bed druing and was readily adaptable to stirring. The 12-inch depth was used for most of the tests to evaluate the different drying techniques of; uninterrupted drying, periodical stirring, periodical air flow reversal, short duration of tempering and a combination of short duration tempering and periodical air flow reversal. The 24-inch depth was only evaluated for uninterrupted drying as it was too deep to stir or turn conveniently.

The controlled variables for the complete experimental procedure then consisted of 2 air flow rates (10 and 20 c.f.m./ft^2), 2 temperature levels (95^{o}F and 125^{o}F) and 3 depths (6, 12 and 24 inch). A few of the tests were run at an intermediate temperature of 110^{o}F.

Two levels of drying air temperature of 95^{o}F, 125^{o}F and two depths of 6 inch and 12 inch were used for the grain mixing experiment. The air flow rate for all grain mixing was 1 to 2 minutes. During the short mixing periods, the heated drying air was cut off to prevent blowing of rice husks.

For the air flow reversal experiments the grain box was reversed every 30 minutes. The time required for turning the box 180 degrees was from 30 to 60 seconds. Two experimental air temperatures of 95°F and 125°F were selected for drying 12 inch of rice with an air flow rate of 30 c.f.m./ft^2.

The short duration tempering was applied only with the higher temperature of 125°F. The grain was subjected to heated air for 30 minutes and no heat was added for 60 minutes periodically. The grain depth was 12 inch and the air flow rate was 30 c.f.m./ft^2.

The combination of short duration tempering and periodic air flow reversal was conducted also at the 125°F level with 30 c.f.m./ft^2 air flow rate. The grain depth was 12 inches. Heated air was supplied for 30 minutes and followed by tempering for 60 minutes. After tempering the grain box was reversed 180 degrees and heated air was added for 30 minutes.

V.1.1. PREPARATION OF THE SAMPLE

Some 1200 lbs. of rough rice, Early Rose variety, was used for these experimental evaluations. Early Rose is the early maturing variety in the Sacramento Valley area of California. First the rice was trucked by the farmer from 60 miles distance to the dryer plant at Woodland, California, then it was transported to the Davis Campus. When the rice arrived at the dryer plant, the moisture content was measured and found to be 24% wet basis. It was also found that the rought rice contained a lot of chopped stalks, empty grain hulls and weed seeds; so it was passed through the grain cleaner at the Davis Campus. The moisture content was taken again after cleaning and found to have dropped to between 19.5 to 20.5 and the average was 20%. The cleaned rough rice was placed in 25 lb. (approximately) double plastic bags and stored in a refrigerator at 40°F.

Prior to drying, the bags of rice were taken from the refrigerator and allowed to warm in the room temperature of 80°F before they were opened. At an average time of from 8 to 12 hours, the grain temperature reached 70°F. The rice moisture content was determined on sample basis from each bag with a "Motomco" moisture tester and the oven method at 130°F for 16 hours. The numbers of whole grains, empty grains, chopped stalks, weed seeds and broken rice were also determined from the sample by a weight percentage method before testing.

Rice samples of 2000 grams were taken from 3 to 5 different layers of the fixed drying bed after each test and placed in the double plastic bags. These samples were kept in the refrigerator for milling test purposes. For the 6-inch depth tests, 3 samples were tkane; 1 inche from the bottom, in the middle and 1 inch from the top. For the 12-inch fixed-bed depth of rice, 5 samples were taken; 1 inch, 3-1/2 inches, 6 inches, 8-1/2 inches and 11 inches from the bottom. For the stirring method only one sample was taken from each drying test.

Four 2000 gr control samples were taken. These were air dried by spreading at room temperature. The control samples were dried to a moisture content of 14%. Moisture content determinations were made with a "Motomco" moisture tester and by oven method. Milling tests of all drying test samples and control samples were made by the U.S.D.A. Grain State Laboratory in Sacramento, California.

V.1.2. RELATIVE HUMIDITY CONTROL

Several attempts were made to increase and control the relative humidity of the drying air. The average room temperature during the experimental studies was 80°F and the relative humidity was 40%. For the experimental drying studies 80°F temperature and 75% relative humidity was required. Considerable moisture had to be added to increase the relative humidity from 40% to 75%.

The first effort was to use steam to increase the relative humidity. This method worked well at the higher drying air temperature of 125°F, but for the low 95°F temperature it was impractical. A lot of heat energy was stored in the steam, so the 95°F was always surpassed. One attempt was made by using a pressure indicator, 3 adjustment values and two condensation traps, but control was still difficult.

A spray nozzle under controlled high pressure and with a controlled water flow was successfully used to increase the humidity to the desired level. Sprayed water was passed through the adjustable heated inlet duct. Water from the nozzle was evaporated by the heater and mixed with the incoming air. The desired relative humidity and drying air temperature at the plenum chamber were controlled through the variable heaters and the amount of water flow. Water pressure was maintained by an air compressor for all tests at 70 p.s.i.

The amount of water needed for the increase of the relative humidity was calculated from a psychrometric chart based on the temperature, air flow rate and the desired relative humidity. For example, room dry-bulb temperature was $80^{o}F$ and wet-bulb temperature was $61^{o}F$. This was a relative humidity of 32% and absolute humidity of 0.007 lbs H_2O/lb dry air. The specific volume of air at that condition was 13.75 ft^3/lb. dry air. The absolute humidity difference was 0.0168-0.007 = 0.009 lb. H_2Olb dry air. The absolute humidity of the drying air was to be maintained along the 0.0168 absolute humidity line of the psychrometric chart no matter what temperature and air flow rate was used.

The experimental air flow rates were 10 and 30 c.f.m./ft^2, and the temperature was $95^{o}F$, $110^{o}F$ and $125^{o}F$. The area of the dryer was 16x16 $inch^2$ = 1.78 $ft.^2$. For the 10 c.f.m./ft^2

and 95°F dry-bulb temperature and the incoming air was maintained at 0.0168 lb. H_2O/lb dry air absolute humidit, which is a wet-bulb of 78°F and relative humidity of 48%. The specific volume of air was 14.35 ft³/lb. dry air. For 1.78 ft² area of the system, the amount of the water needed for one minute:

$$= \frac{10 ft^3/min \times 0.0098\ lbs.H_2O/lbs\ dry\ air}{14.35\ ft^3/lb.\ dry\ air} \times 454\ gr/lb \times 178.$$

$= 5.53$ gr. H_2O/min.

The amount of the calculated water needed in grams/minute was as follows:

c.f.m./ft² \ Dry and wet temperature °F	95/78	100/81	125/85
10	5.53	5.35	5.20
30	16.59	16.05	15.60

In actual applications the amount of water needed was 25-30% higher than calculated. The lower the temperature and the lower the air flow rate the more water is needed. Some condensation for the low temperature might be contributing to the requirement for more water. Once the desired absolute humidity had been reached and inasmuch as the room temperature and ambient humidity were constant, only slight adjustments were needed in the flow of distilled water throughout the tests. The controllability of the relative humidity in the system was confirmed to be a function of the temperature and water flow.

V.1.3. TEMPERATURE CONTROL

The blower used in this experiment was powered by 1 hp electric motor. In order to reach the low air flow rate, the adjustable valve G (see Fig. 1) on the outlet side of the fan tube was almost closed. A heat of friction was also developed in the fan system. Some of the air heat energy was absorbed by the system and stored in the blower housing, the pipe and in the plenum chamber. In some preliminary tests at low air flow rates, the heat energy obtained from the system only (without additional heat) was 20^{o}F. With the room temperature at 80^{o}F it meant that the air was 100^{o}F when it got to the plenum chamber. On the other hand, for the high temperature and air flow rate, four 500 Watt heaters were used and a longer time was required to reach the 125^{o}F under the 0.0168 absolute humidity.

Fiber glass insulation was put around the blower housing and the pipe was wrapped with rubber insulation to reduce the heat loss from the system. This provided a better control temperature in the system. The dry and wet-bulb temperatures in the plenum chamber was observed to check the consistency of the 0.0168 lb. H_2O/lb. dry air absolute humidity. The temperature and the water flow rate were adjusted to maintain the 0.0168 absolute humidity.

V.2. WASTE HEAT UTILIZATION

Several measurements were made of the possible waste heat pick-up from two different engines and fans. A Pitot tube connected to an inclined manometer was used for measuring static and dynamic pressure. Static pressure developed in the system was controlled by closing and opening the sliding gate at the tube outlet. For the Clinton engine that was connected directly to a propeller fan, the static pressure level were controlled at 0.25, 0.50 and 0.90 inches of water. When the sliding gate was opened fully, the static pressure of the system was 0.10 inch. While on the Briggs & Stratton engine which powered a squirrel cage type blower, the static pressure level maintained were 1, 2, 3 and 4 inches.

As soon as the static pressure was obtained, the dynamic pressure measurements were taken. Dynamic pressure measurements were taken based on Henderson (1966). The average of ten different locations in vertical and horizontal positions of the duct cross section were measured for each static pressure. The velocity was determined from the formula

$V = 18.3\ P/8$

where V = air velocity, ft/min

P = dynamic pressure, inch of water

γ = specific weight of air lb/ft^3

The area of the experimental duct was 1.24 ft^2, so the air flow rate in c.f.m. was calculated for each static pressure level. The r.p.m. of each engine and fan was indicated with a "Strobotac" r.p.m. counter. When the static pressure was experimentally increased by closing the sliding gate valve in the duct, the r.p.m. of the engine also increased. The r.p.m. of the Briggs & Stratton engine was adjusted automatically by the governor to maintain a speed under all loads, while the Clinton engine was adjusted manually. Temperature at the outlet and the amount of fuel needed per minute was measured for each static pressure for both engines.

A propeller type fan was directly connected to the Clinton engine's drive shaft, although this method was not recommended by the fan manufacturers (see letter at the appendix). The direct connection to the engine shaft was to reduce the cost and the material needed such as: bearing, shaft, belt, pulley, etc. In the direct connection method, the balance of the fan blades is very critical. For these tests it was found, in fact, that the propeller was out of balance so some weights were added to the blades.

A 19-inch diameter and 5 inch long tube was placed around the propeller housing to direct the air flow. A plate ring with an 18-inch diamter was placed 1 inch away and in front of the fan to which the air duct was attached. This ring reduced the turbulence of the air flow (see Fig. 3).

It was found during the preliminary tests that there was no benefit derived from a shrouding box placed around the Clinton engine. All of the air moved past the engine without the shrouding, thus no benefit.

A centribugal blower was operated by the Briggs & Stratton engine through a belt pulley system. The speed reduction between the blower and the engine r.p.m. was 10 to 8. The blower air inlet was 8-1/2 inch by 7-1/2 inch. A shrouding box was placed around the engine and the blower.

VI. DISCUSSION AND RESULTS

VI.1. CODIFICATION OF SAMPLES

Each test involved four independent variables. The variables were controlled as follows:

1. Air flow rate (10 and 30 c.f.m./ft^2)
2. Drying air temperature (95°F, 110°F and 125°F)
3. Grain depth (6, 12 and 24 inch)
4. Method of drying or treatment

   U = uninterrupted drying

   S = periodical stirring

T - short periodical tempering

R = periodic air flow reversal

T&R = short tempering followed by periodic air flow reversal.

The treatments conducted during the experiment were tabulated as follows:

Air flow cfm/ft^2	Temperature °F	Depths (inch) 6	12	24
	95	-	u	-
10	110	-	u	-
	125	-	u	-
	95	u,s	u,s,r	u
30	110	-	u	-
	125	u,s	u,s,t,r,t&r	u

The drying air dry-bulb varied as the absolute humidity was maintained constant for all drying air temperature at 0.0168 lb H_2O/lb dry air. With the dry-bulb temperature of the drying air controlled at 95°F, 110°F and 125°F, the wet-bulb temperatures of the drying air were 78°F, 81°F and 85°F, respectively. The code used for all experiments is represented by the example: 30-125-12s which represents 30 c.f.m./ft^2

air flow at 125°F dry-bulb drying air temperature, a 12 inch depth of rice and the treatments is periodical stirring.

VI.2. DRYING

Although there were five different drying treatments studied, the discussion emphasis was the uninterrupted drying.

The only combination of variables for which five different treatments were run was the 30-125-12 level. Figure 6 shows that the drying rate was the highest for the periodic stirring and tempering treatments. This only differed slightly (15% higher) from the uninterrupted drying.

From the average head yield shown by Table 1, only the stirring, air flow reversal and combination of tempering and air flow reversal treatments represented the actual average. The average head yield was the highest for the stirring treatment and did not differ from the tempering and air flow reversal markedly, while the air flow reversal treatment was the lowest.

The top layers of the uninterrupted and tempering treatments were still moist, and additional drying was done for milling test purposes. The average head yield of the tempering treatment as shown in Table 1, was slightly higher than the uninterrupted drying.

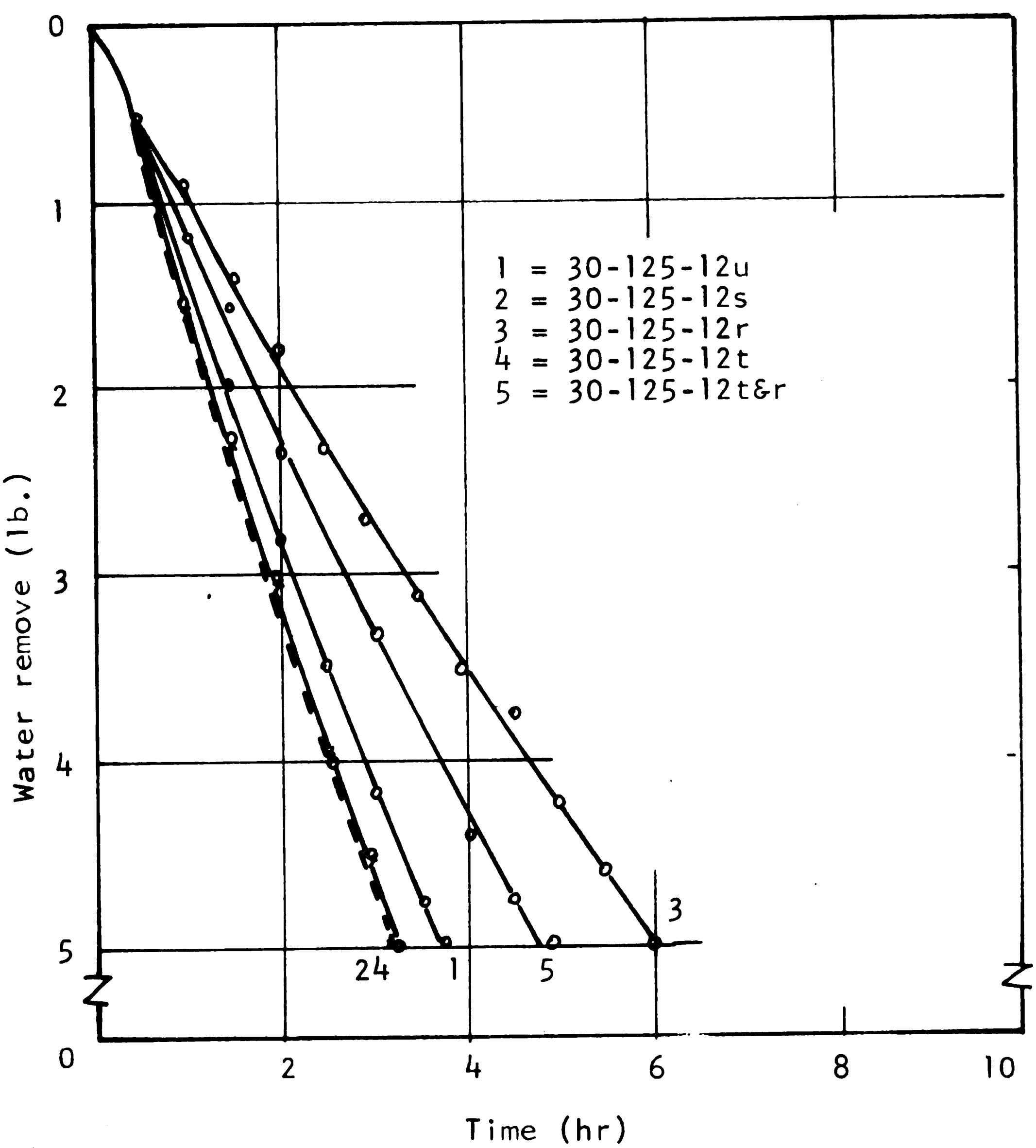

Figure 6. The effect of drying treatments on the drying rate of rice (Drying time only)

VI.2.1. UNINTERRUPTED DRYING

VI.2.1.1. TEMPERATURE EFFECT

Temperature is one of the most critical factors in fixed-bed drying. There is an interaction between the initial moisture content, and length of time the grain is exposed to the maximum allowable drying air temperature. The highest drying air temperature used in this research was 125^{O}F. The 125^{O}F was higher than the recommended drying air temperature of 110^{O}F in the United States (Hall, 1967), but still below the transition temperature of 139^{O}F (Arora, 1972) where the linearity of percentage broken kernels with temperature was lower than above the 139^{O}F.

Table 2 shows the effect of temperature on the drying rate, moisture content at the bottom layer, temperature and moisture gradient and the head yield. It was found that by increasing the drying air temperature up to 125^{O}F, the bottom level moisture content decreased and the top level moisture content increased. The higher drying air temperature thus caused greater temperature and moisture gradients between the top and bottom of the bed. The higher drying air temperature also increased the temperature of all grain layers. The temperature gradients were higher with the low air flow rate of 10 c.f.m. as compared to 30 c.f.m. At the end of the drying period for the 10-125-12u treatment there was a

Table 1. The effect of five different drying treatments on temperature and moisture gradients in the bed of rice, drying rate and milling yield of head rice.

Treatment	Bottom layer		Middle layer		Top layer		Gradient top & bot.		Drying rate	Av.head (1) yield
	Temp. °F	m.c. %	Temp. °F	m.c. %	Temp. °F	m.c. %	Temp. °F	m.c. %	lb/hr	%
30-125-12u	120	9.4	144	13.2	100	18.1	20	8.7	1.33	37.25 (2)
30-125-12s	-	-	108	14.1	-	-	-	-	1.53	39.0
30-125-12r	120	10.8	103	15.0	92	12.8	28	2.8	0.90	32.0
30-125-12t	120	9.9	109	10.9	94.5	18.3	25.5	8.4	1.53	39.25 (2)
30-125-12t&r	120	9.6	90	15.0	94	11.9	26	2.6	1.12	38.5

(1) The average head yield = $\frac{A + 2B + C}{4}$

A = head yield at the bottom layer
B = head yield at the middle layer
C = head yield at the top layer

(2) All rice samples which had moisture content higher than 15% W.B. were redried again at room temperature to 14% for milling test purposes. The actual average head yield may be lower than listed above.

$30^{o}F$ temperature gradient in a ten inch depth of grain (temperatures were taken one inch from the top and bottom of the 12 inch depth of grain).

Table 2. The effect of the drying air temperature on the temperature and moisture gradients and on the drying rate

Treatment	Bottom layer Temp. °F	Bottom layer m.c. %	Top layer Temp. °F	Top layer m.c. %	Gradient Temp. °F	Gradient m.c. %	Drying rate lb/hrs
30-95-12u	94	11.9	90	14.7	4	2.8	.49
30-110-12u	108	11.2	99	15.9	9	4.7	.85
30-125-12u	120	9.9	100	18.6	20	9.0	1.33
10-95-12u	90	11.2	84	17.5	6	6.4	.21
10-110-12u	107	8.9	87	19.1	10	10.0	.36
10-125-12u	118	8.5	88	19.4	30	11.0	.48

Figure 7 and Table 2 show that the rate of moisture removal increased with higher drying air temperatures. The drying rate was maximum with the higher drying air temperature and high air flow rate. An increase in the drying air temperature from $95^{o}F$ to $110^{o}F$ and then to $125^{o}F$ at the 30 c.f.m./ft^2 air flow rate increased the drying rate 1.7 and 2.7 times the $95^{o}F$ level. The low 10 c.f.m./ft^2 air flow rate increased the drying rate 1.6 and 2.6 times the $95^{o}F$ drying air temperature level. The length of time the

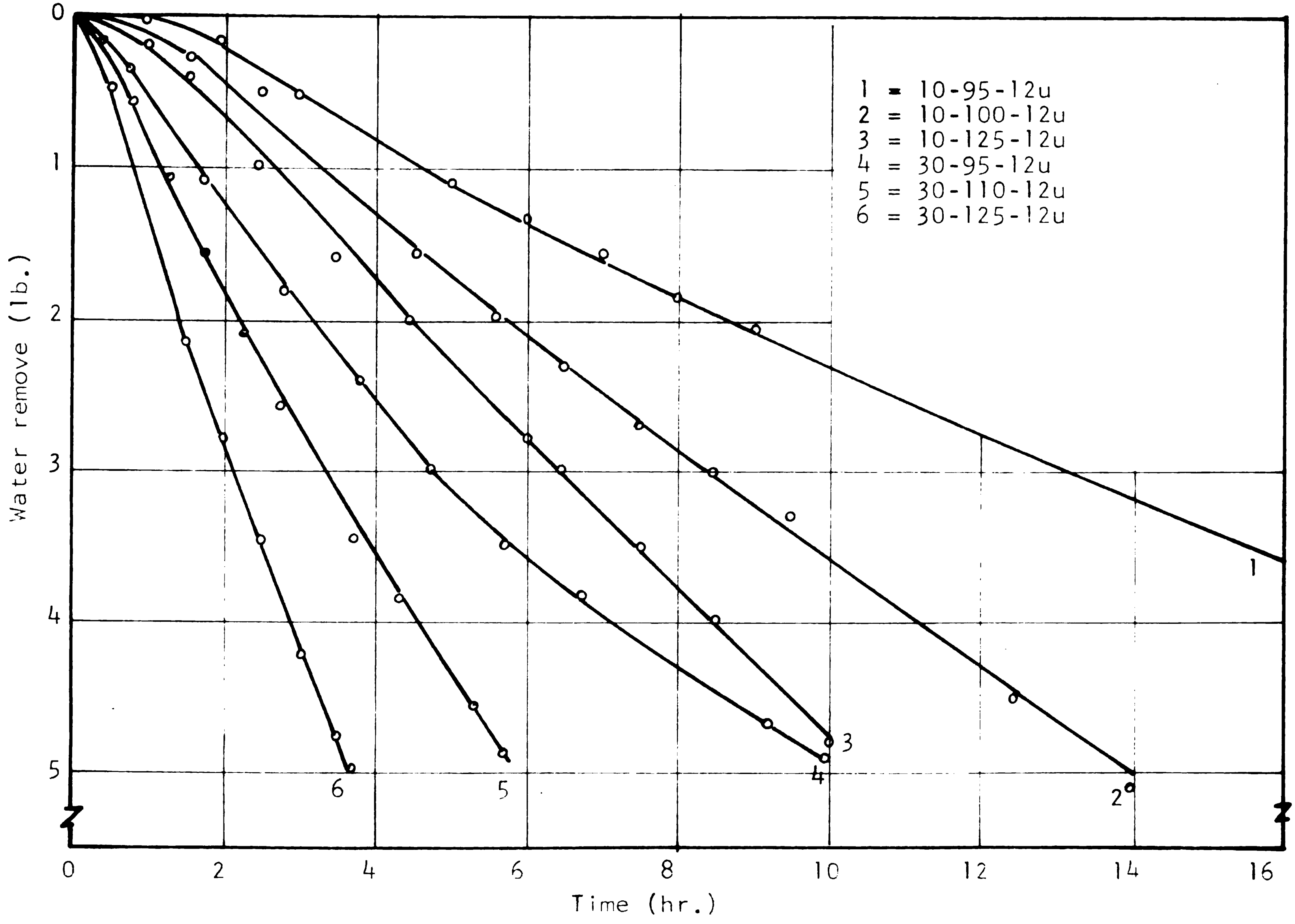

Figure 7. The effect of temperature and air flow rate on the drying rate of rice.

grain was exposed to the drying air during the drying process did not appreciably affect the grain temperature of the bottom layer, however at 125°F drying air temperature the head yield decreased with exposure time. At low drying air temperature of 95°F there was no difference in head yield of the bottom layer with exposure time (see Table 3).

Table 3. The effect of the duration the grain was exposed to 125°F and 95°F on moisture content and head yield at 1 inch from the bottom

Treatment	Drying time hrs.	Drying rate lb/hr	m.c. %	Head yield %
30-125-6u	2.0	1.15	11.75	23
30-125-12u	3.75	1.33	9.45	14
30-125-24u	6.50	1.52	9.30	11
30-95-6u	6.60	.35	12.3	42
30-95-12u	10.0	.49	11.9	41
30-95-24u	13.0	.77	10.0	42

VI.2.1.2. AIR FLOW EFFECT

Two levels of air flow were used in these experiments. It was difficult to isolate the effect on air flow only, since many factors were involved. An increased air flow rate resulted in a faster drying rate (see Fig. 7). Table 2 shows that the air flow rate of 30 c.f.m./ft^2 at 95°F, 110°F and

125^{o}F increased the drying rate 2.2, 2.4 and 2.8 times over the 10 c.f.m./ft^2 air flow level. Figure 8 and 9 also indicate that the heat utilization was more affected by the air flow rate than by the drying air temperature. The heat utilization lines at the same air flow rate and at different temperatures were almost parallel, and decreased as the drying air temperature was increased.

At low air flow rates, the heat utilization was very efficient. Figure 9 shows that at 10-92-12u and 10-110-12u the efficiency never dropped below 100%. This meant that there was still heat potential available when the drying period was over. The higher the temperature and air flow rates the less efficient was the heat utilization.

VI.2.1.3. THE DEPTH EFFECT

Three depths of grain in the drying bed were evaluated in these experiments. The 10 and 30 c.f.m./ft^2 air flow rates were, however, only compared at a 12 inch depth of grain. Increased grain depths from 6 to 12 and then to 24 inches increased the drying rate by 1.1 and 1.4 times at the 125^{o}F level, and 1.4 and 2.2 times at the 95^{o}F level (see Table 3).

The water removal rates for the 6 inch, 12 inch and 24 inch depths at the 125^{o}F temperature and 30 c.f.m./ft^2

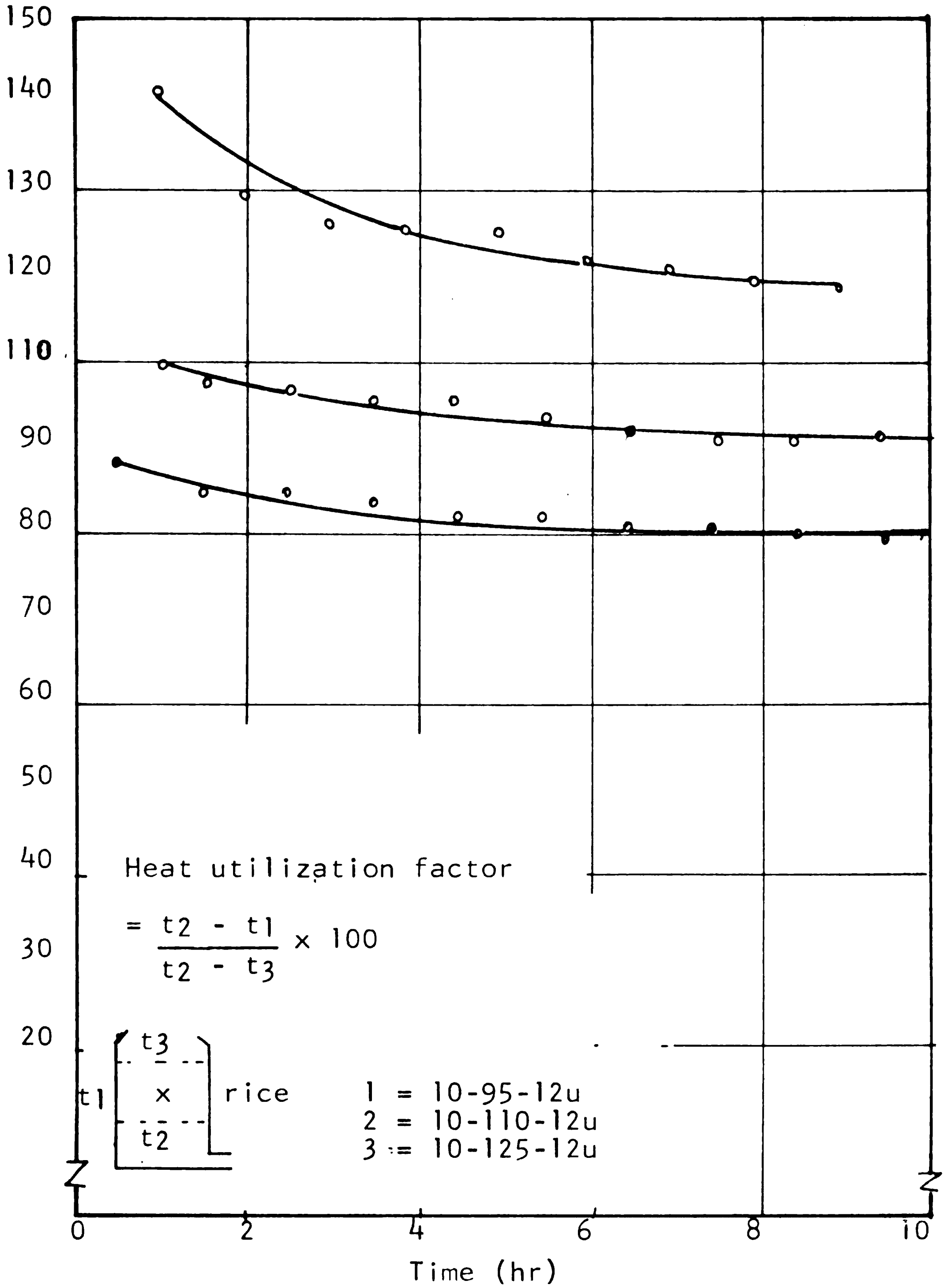

Figure 8. The effect of drying air temperatures on the heat utilization factor at 10 c.f.m./ft^2 air flow rate

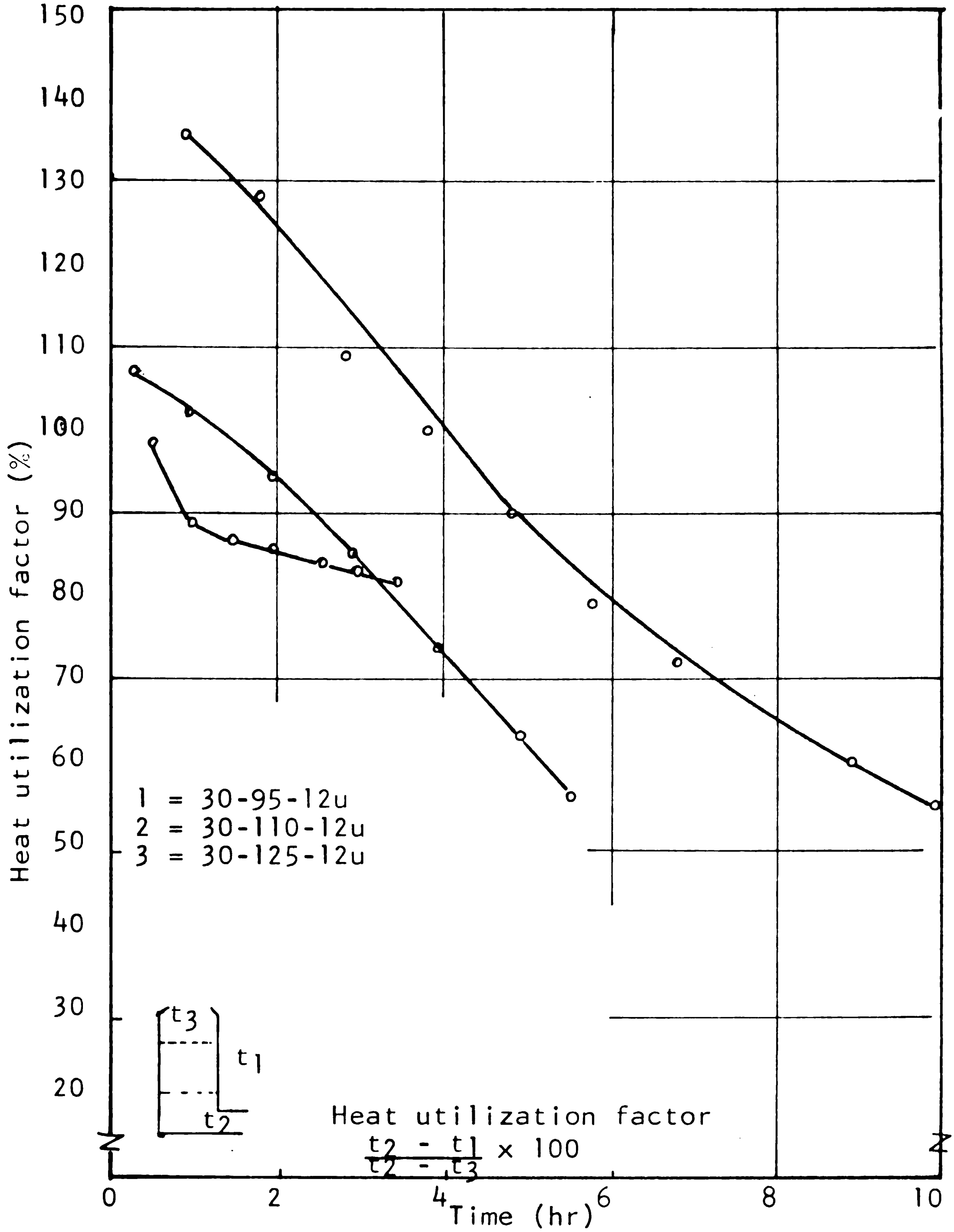

Figure 9. The effect of drying air temperatures on the heat utilization factor at 30 c.f.m./ft^2 air flow rate

air flow rate were the same (see Fig. 10). Increasing the depth of rice for the low drying air temperature caused a definite increase in the drying rate. The heat utilization improved also as the rice depths were increased both at 95°F and 125°F. (see Fig. 11 and 12).

VI.2.2. PERIODIC STIRRING

All periodic stirring treatments were conducted at the 30 c.f.m./ft^2 air flow rate with two levels of drying air temperature, 95°F and 125°F at 6 inch and 12 inch depths. The stirring was done manually every 30 minutes. The stirring results indicated more benefit at the 6 inch depth as compared to the 12 inch. Stirring required from 1 to 2 minutes. The graphical presentation of Figures 13 and 14 show that the continuous drying rate for all periodic stirring treatments was somewhat better than for the uninterrupted drying treatments.

The total average drying rate for stirring increased only slightly at the 95°F drying air temperature level for both the 6 and 12 inch depths of grain (see Table 4). Periodic stirring at the 125°F drying air temperature level compared to the 95°F level produced a great increased drying rate at both the 6 and 12 inch depths of grain (15% @ 6 inch depth and 20% @ 12 inch depth).

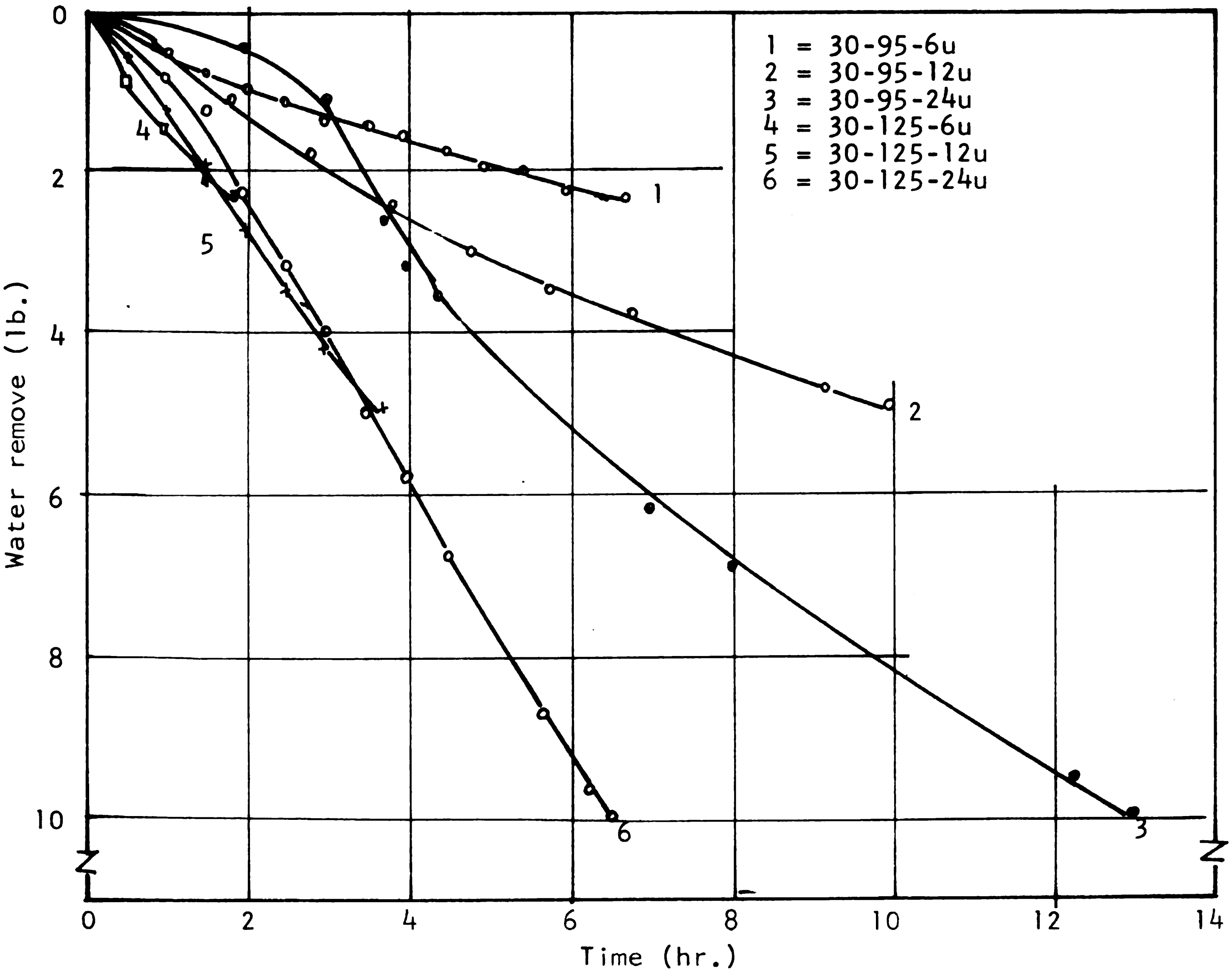

Figure 10. Drying rate of rice at 3 depths of 6 inch, 12 inch, and 24 inch, and two drying air temperatures of 95°F and 125°F.

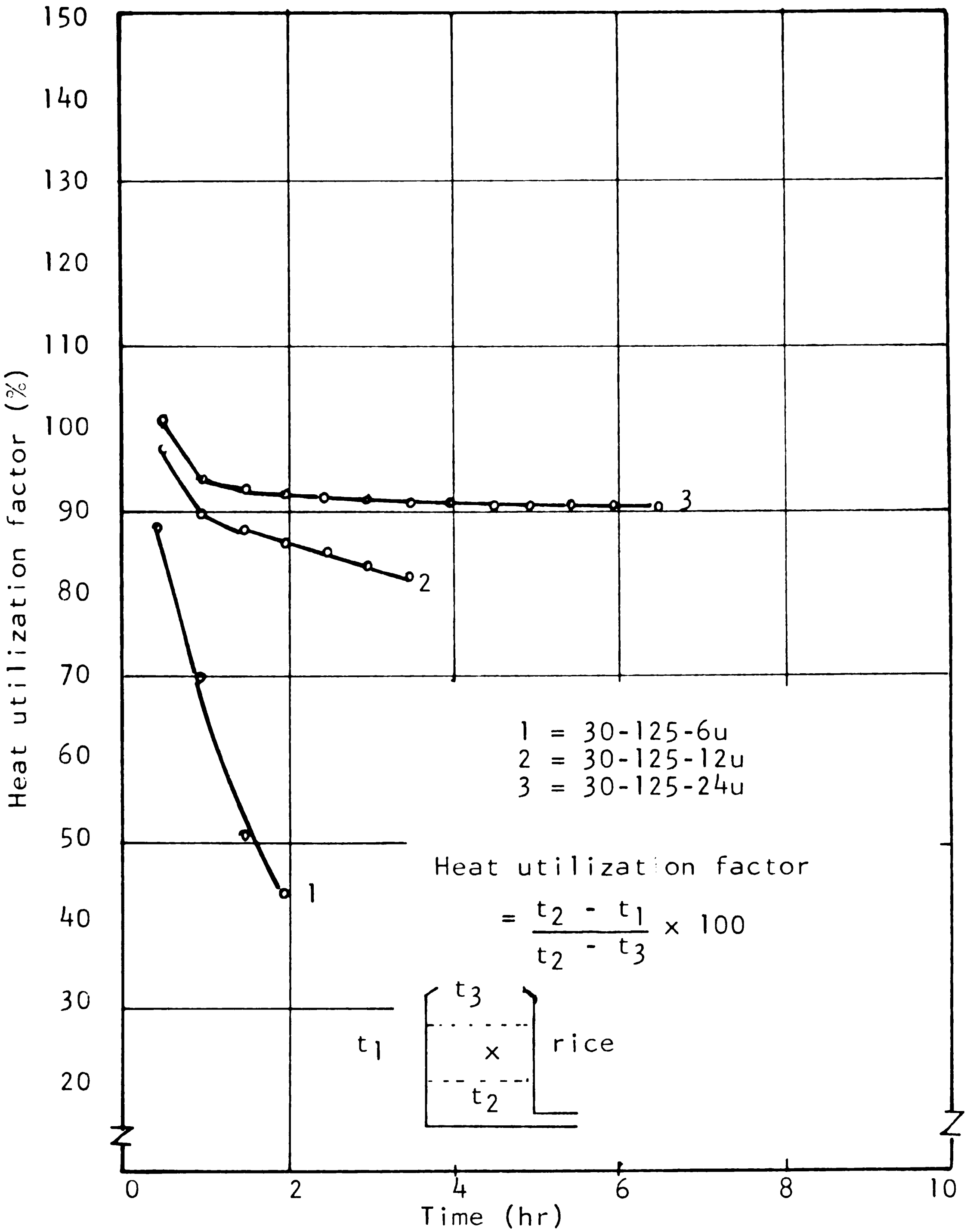

Figure 11. The effect of grain depths on heat utilization factor at 125°F.

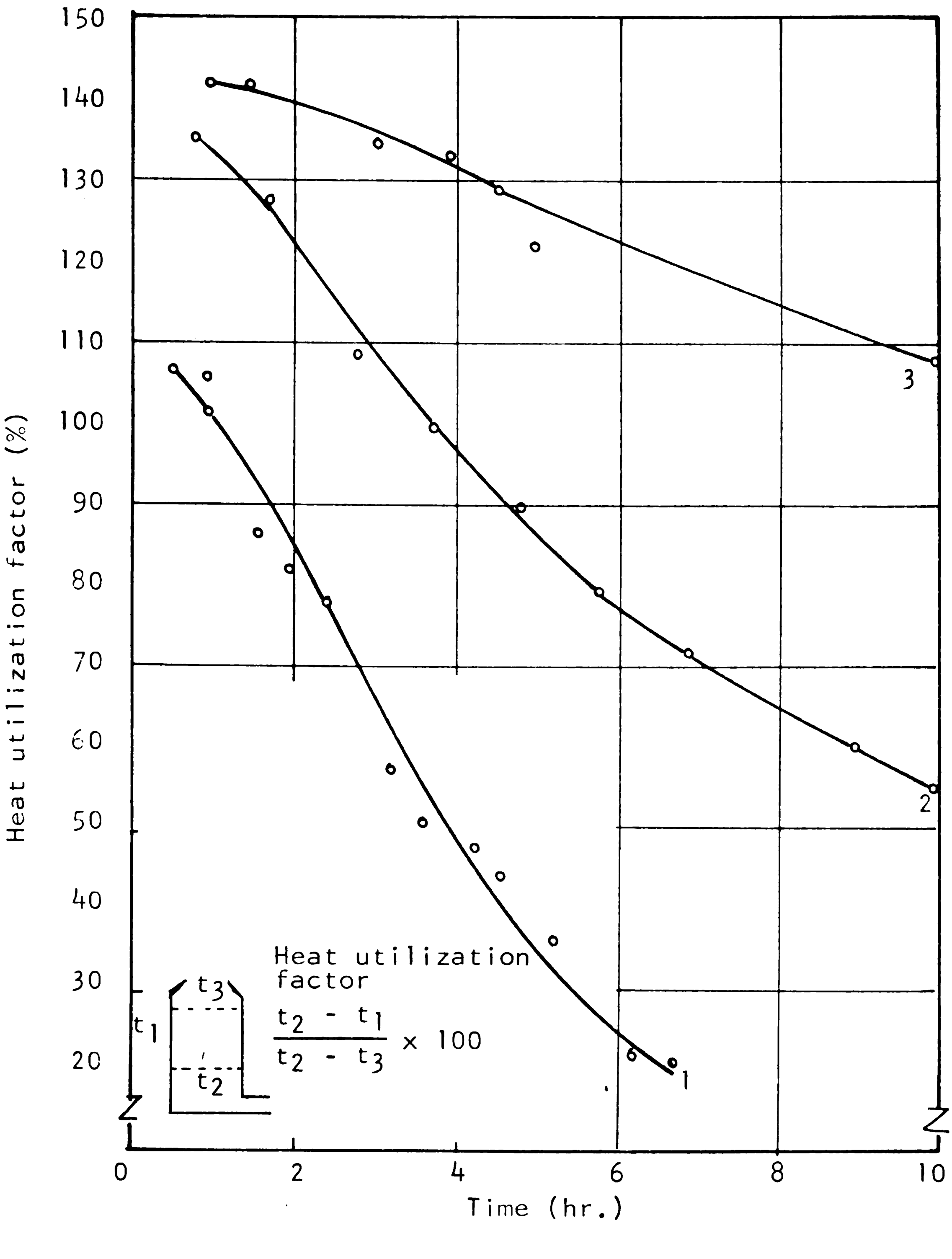

Figure 12. The effect of grain depths on the heat utilization factor at 95°F.

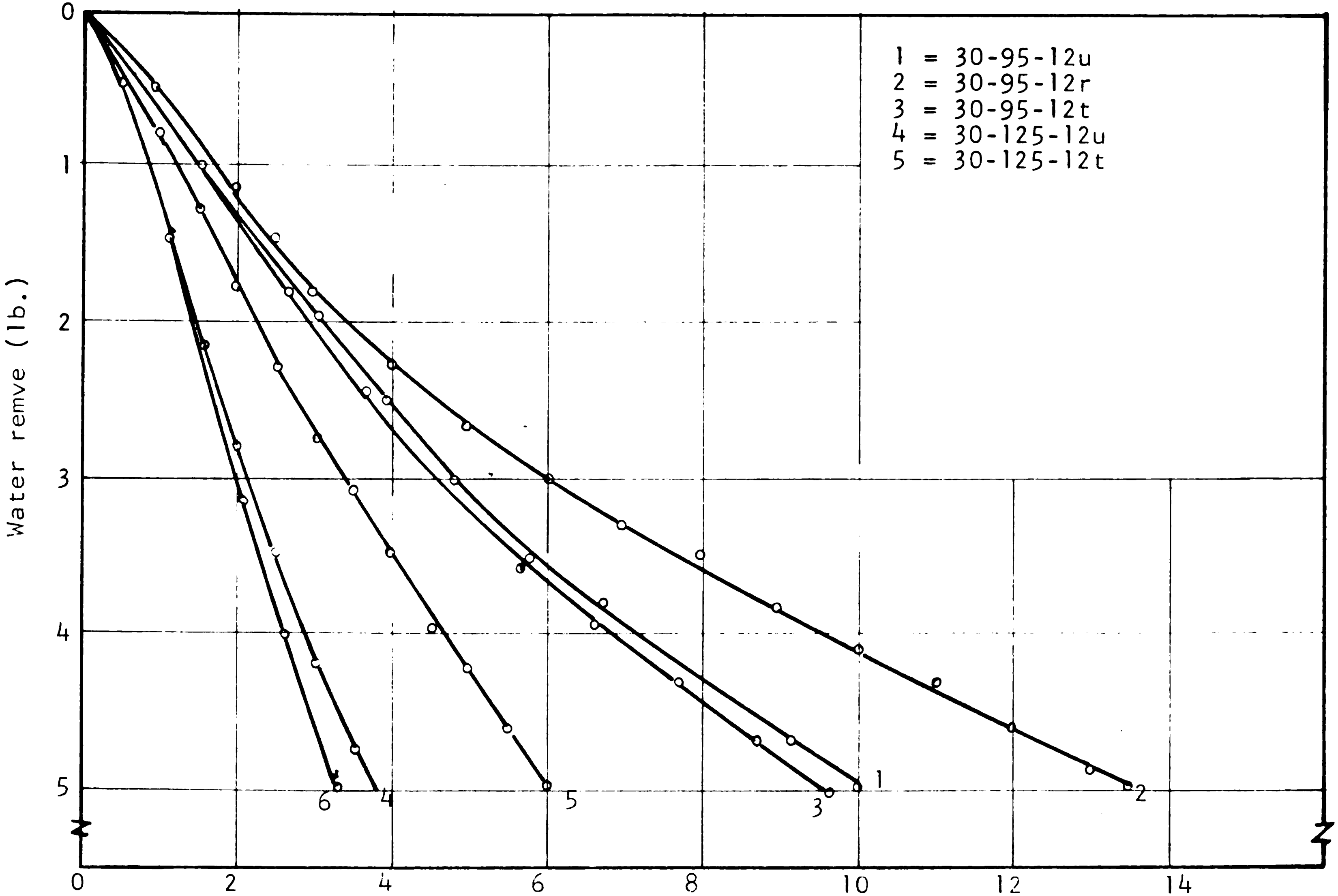

Figure 13. The effect of drying treatments on the drying rate of rice at 95°F and 125°F drying air temperatures.

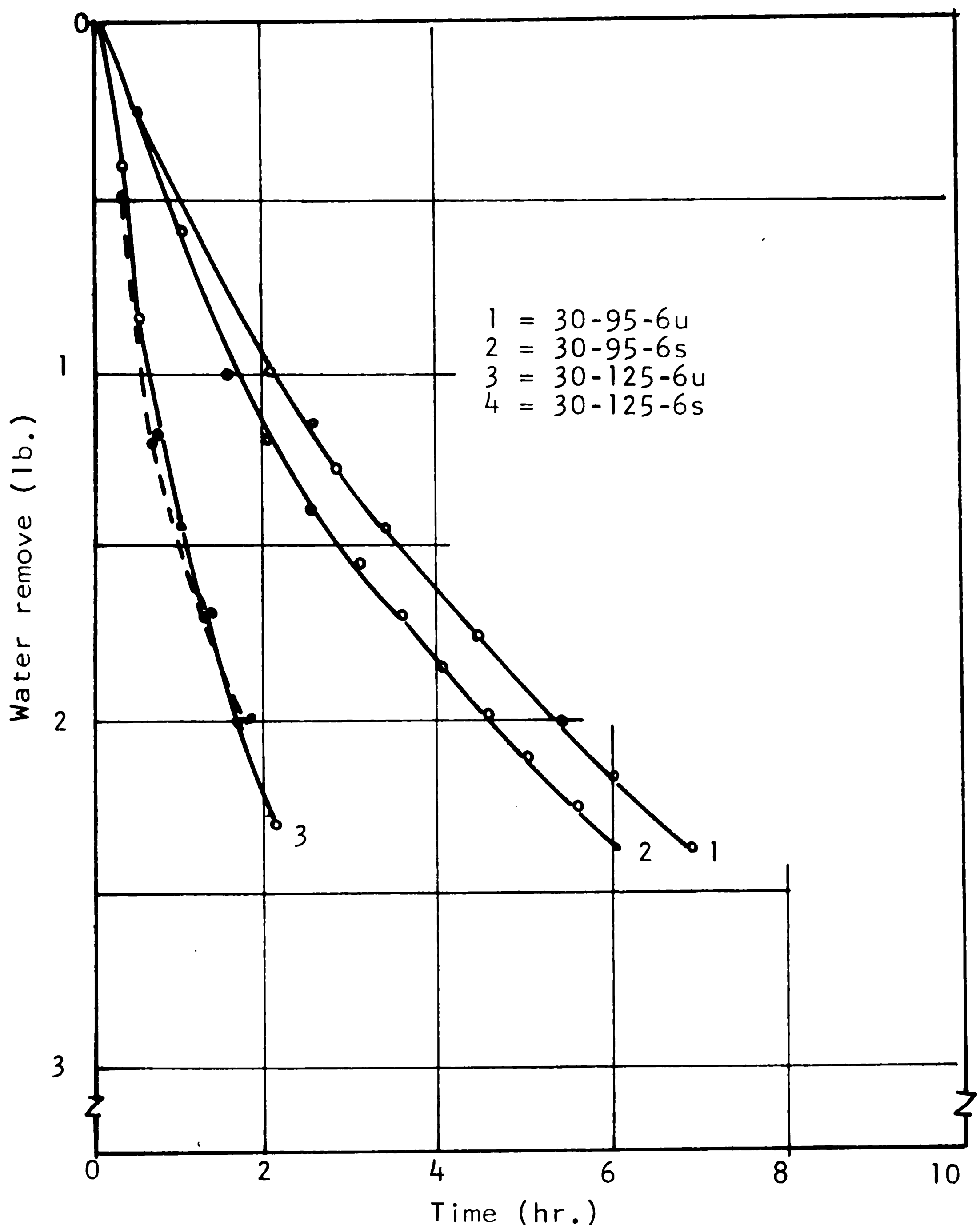

Figure 14. The effect of stirring on the drying rate of rice at the 6 inch depth.

The head yields increased appreciably with stirring for the 125°F drying air temperature while no change occurred at the lower temperature of 95°F.

Table 4. The effect of periodical stirring on the drying rate and average head yield at 95° and 125°F, and 6 and 12 inch depths

Treatment	Drying rate lb/hr	Average head yield[1] %
30-125-12u	1.33	37.25[2]
30-125-12s	1.53	39.0
30-95-12u	.49	41.5[2]
30-95-12s	.52	42.0
30-125-6u	1.15	32.5
30-125-6s	1.20	35.0
30-95-6u	.35	41.0
30-95-6u	.38	41.0

(1) Average head yield = $\frac{A + 2B + C}{4}$

A = head yield at the bottom layer
B = head yield at the middle layer
C = head yield at the top layer

(2) All rice samples which had moisture content higher than 15% w.b. was redried again at room temperature to 14% for milling test purposes. The actual head yield may be lower than listed above.

Some heat from the higher temperature grain transferred to the cooler, more moist grain after stirring and some undoubtedly escaped to the ambient air above the grain surface. The grain mixture temperatures as shown in Figures 15, 16, and 17 were always lower than the middle layer temperature as measured for the uninterrupted drying, with one exception at the 30-95-125. For this later treatment (Fig. 18) stirring was done only every 60 minutes as compared to 30 minutes for all other stirring treatments.

VI.2.3. PERIODIC AIR FLOW REVERSAL

Air flow direction reversal was tried as another possible means of preventing overdrying of the bottom layer for fixed-bed drying. Reversal of the direction of the heated air flow was accomplished by turning the complete box of grain 180 degrees without mixing. Turning was done manually and without turning off the flow of drying air to eliminate any need of additional equipment. The grain was packed full to minimize mixing during the turning maneuver.

The packing increased the grain bulk density by 10% which, in turn, increased the static pressure by 30%. It was hoped that the air flow reversal would reduce the overdrying at the bottom and the higher moisture grain at the top, and thus provide a more uniformly dried product. A low head yield and some moisture gradient between the top and the bottom grain layers, however, remained as shown in Table 5.

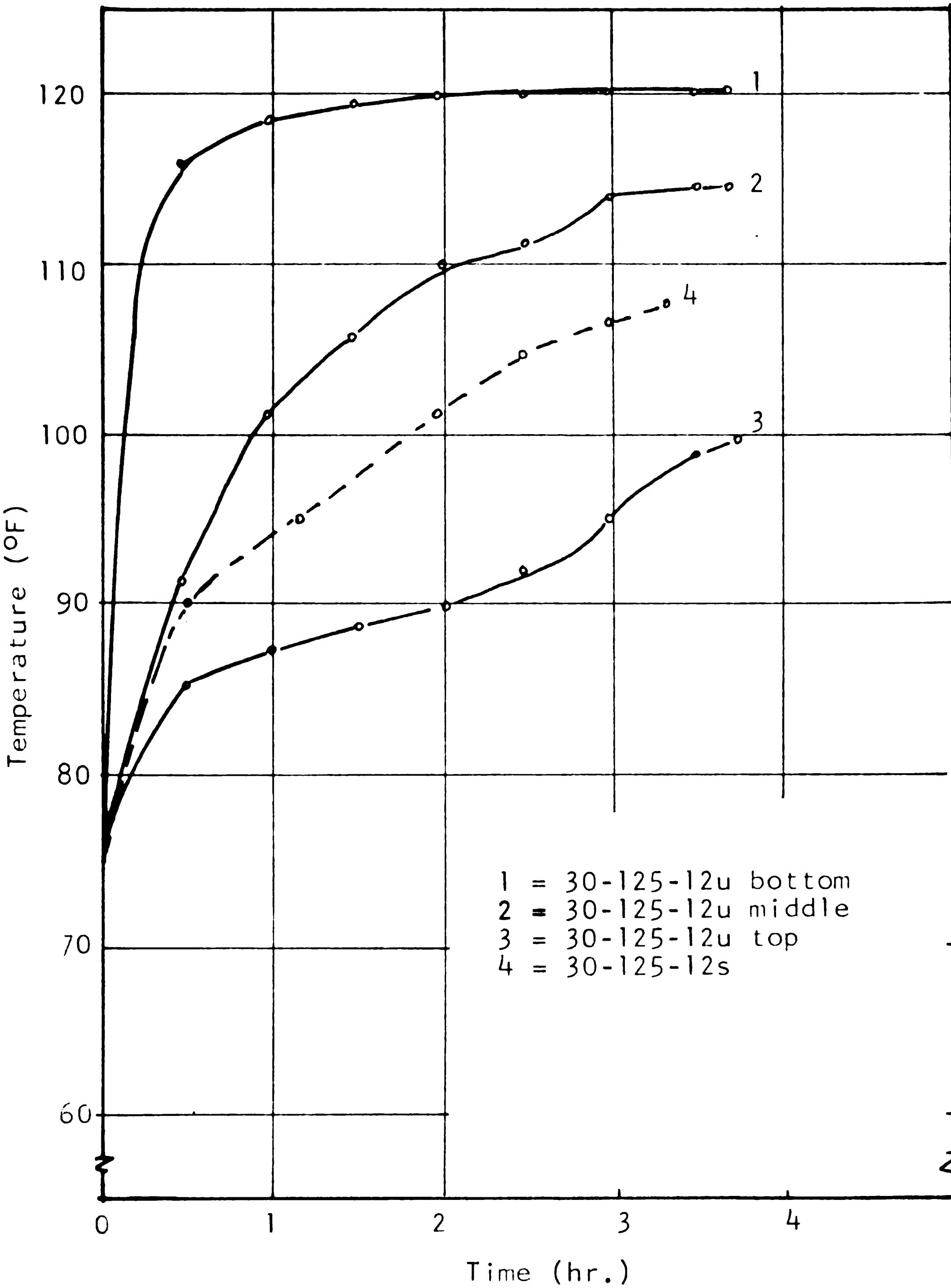

Figure 15. The effect of stirring at 125°F drying air temperature and 12 inch depth on the grain temperatures

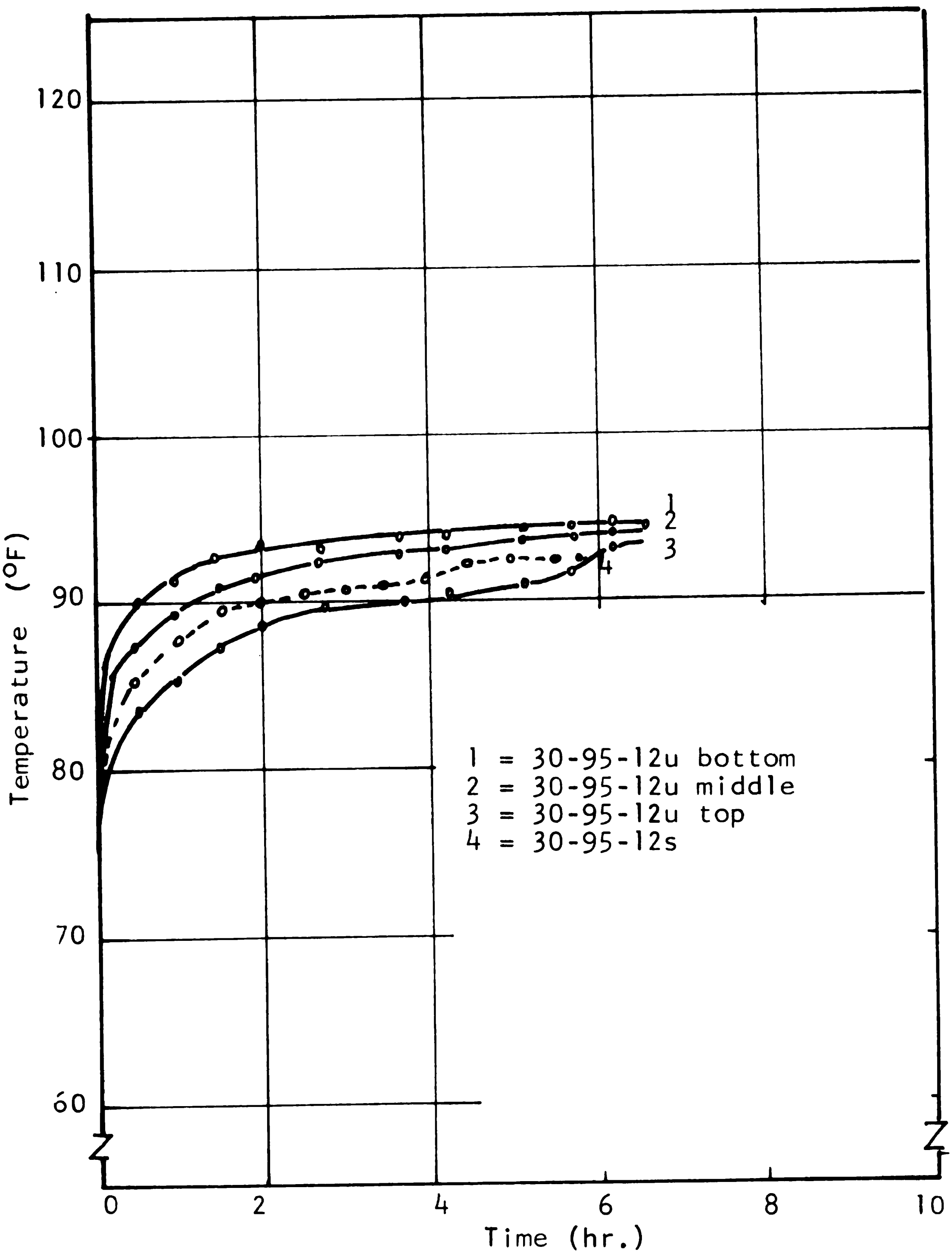

Figure 16. The effect of stirring at 95°F drying air temperature on the grain temperatures.

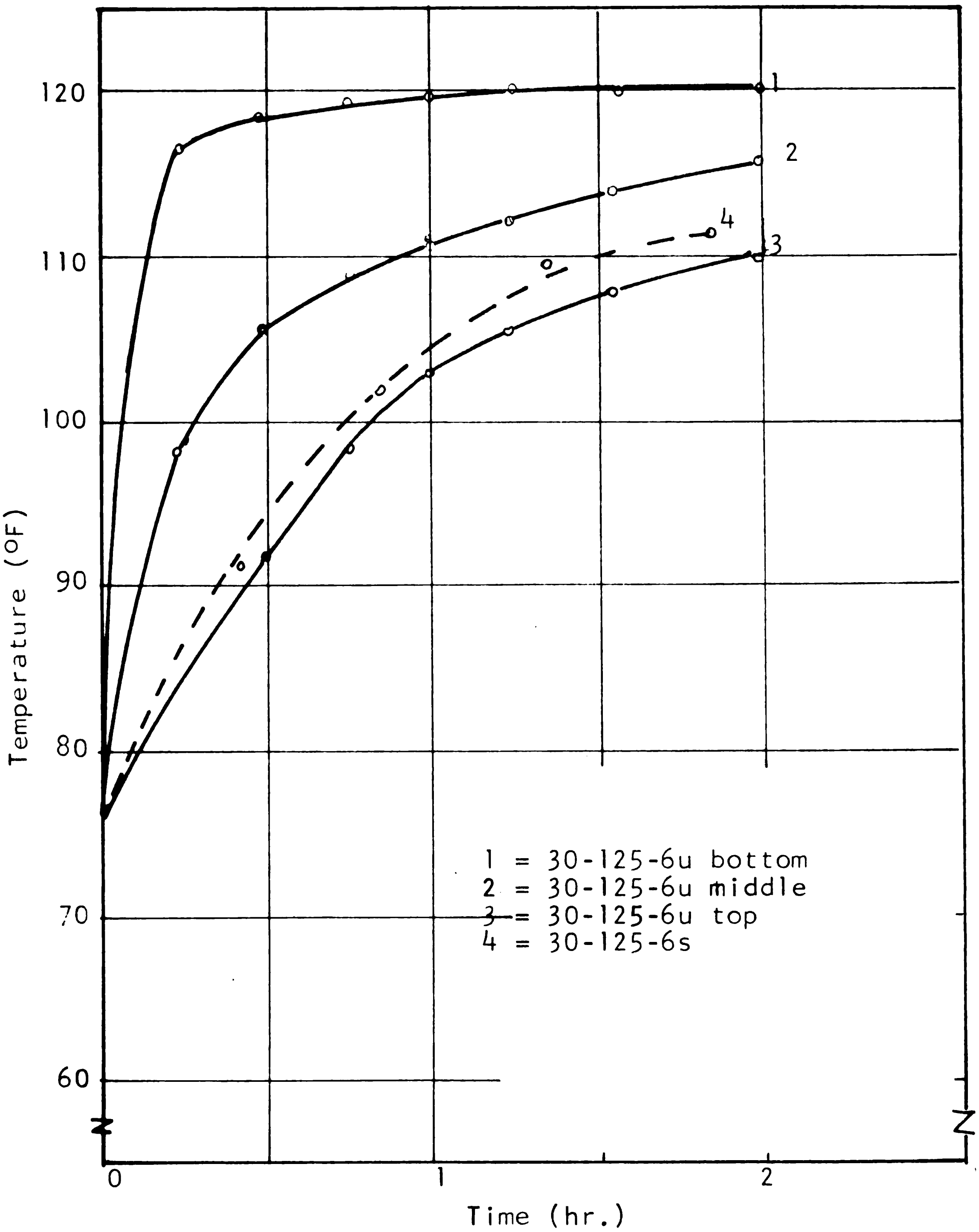

Figure 17. The effect of stirring at 125°F drying air temperature and 6 inch depth on the grain temperature

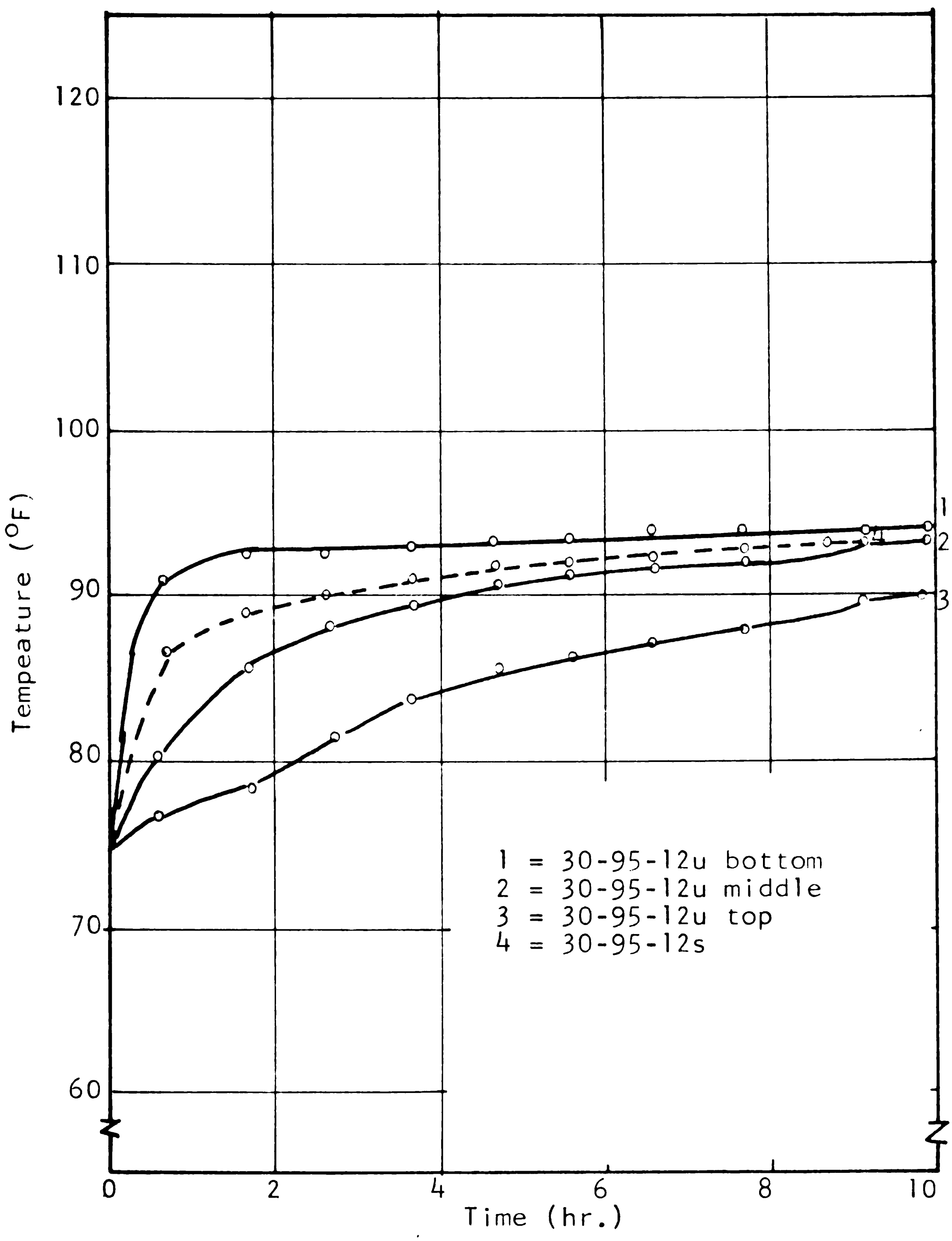

Figure 18. The effect of stirring at 95°F drying air temperature on grain temperatures (stirring for every one hour)

Table 5. The effect of air flow reversal on the head yield and drying rate

Treatment	Bottom m.c. %	Bottom Head yield %	Middle m.c. %	Middle Head yield %	Top m.c. %	Top Head yield %	Drying rate lb/hr
30-125-12u	9.4	14	13.2	40	18.1	41*	1.33
30-125-12r	10	18	15.0	42	12.8	26	.91
30-95-12u	11.9	41	13.1	42	14.8	41	.45
30-95-12r	12.6	44	16.2	42	14.0	43	.38

*Not actual head yield. All rice samples which had moisture content higher than 15% W.B. was redried again at the room temperature to 14% for milling test purposes.

Table 6. Temperature gradients between the top and bottom layer in uninterrupted drying and air flow reversal

Treatment	Temperature gradient 30 min. after drying	Gradient at final temp.	Gradient at final m.c.
	°F	°F	%
30-125-12u	30	19	8.7
30-125-12r	30	29	2.8
30-95-12u	15	7	2.8
30-95-12r	15	10	1.4

Table 6 and Figure 19 and 20 show the temperature gradient between the top and bottom layer, from one hour of drying

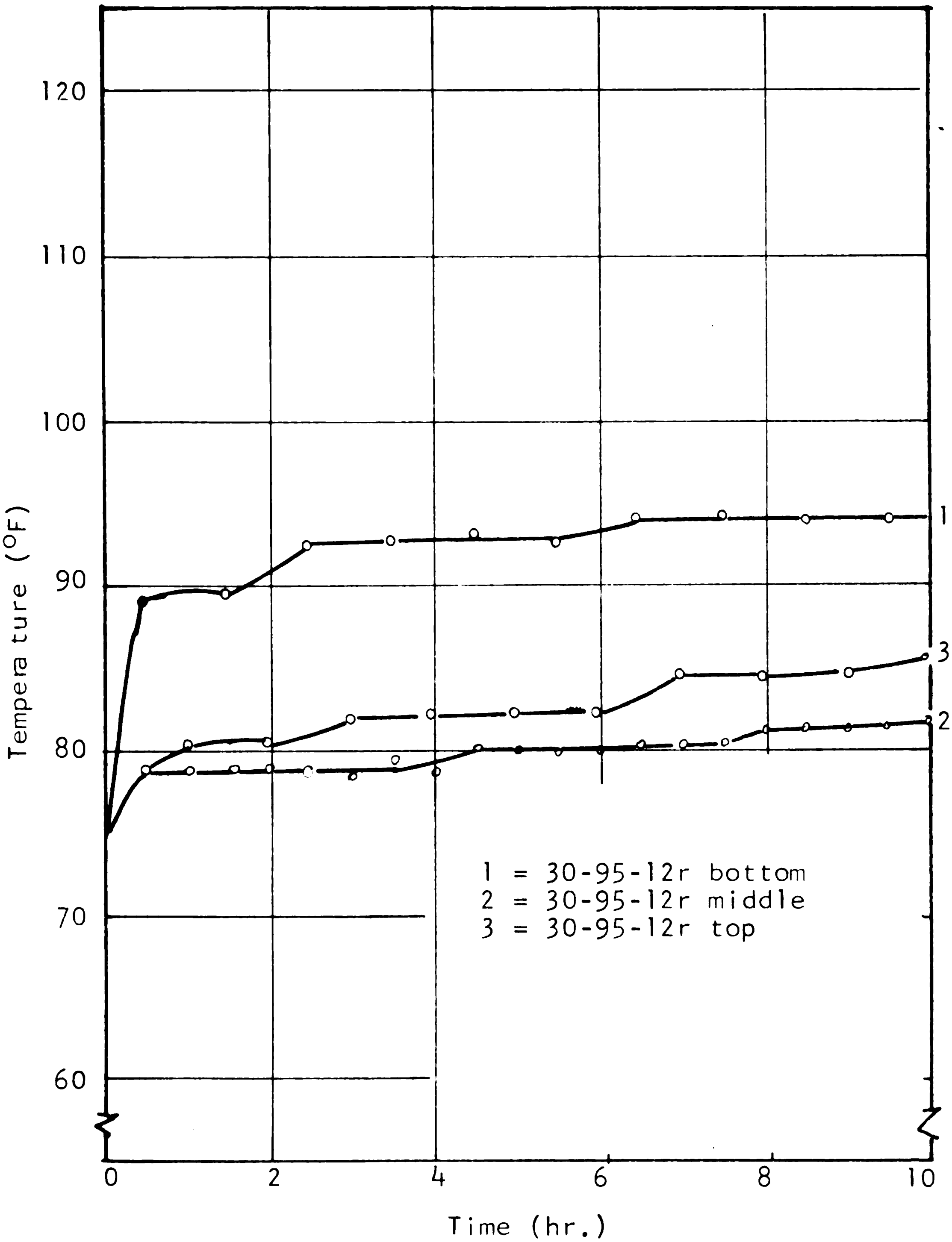

Figure 19. The effect of periodic air flow reversal at 95°F drying air temperature on the grain temperatures

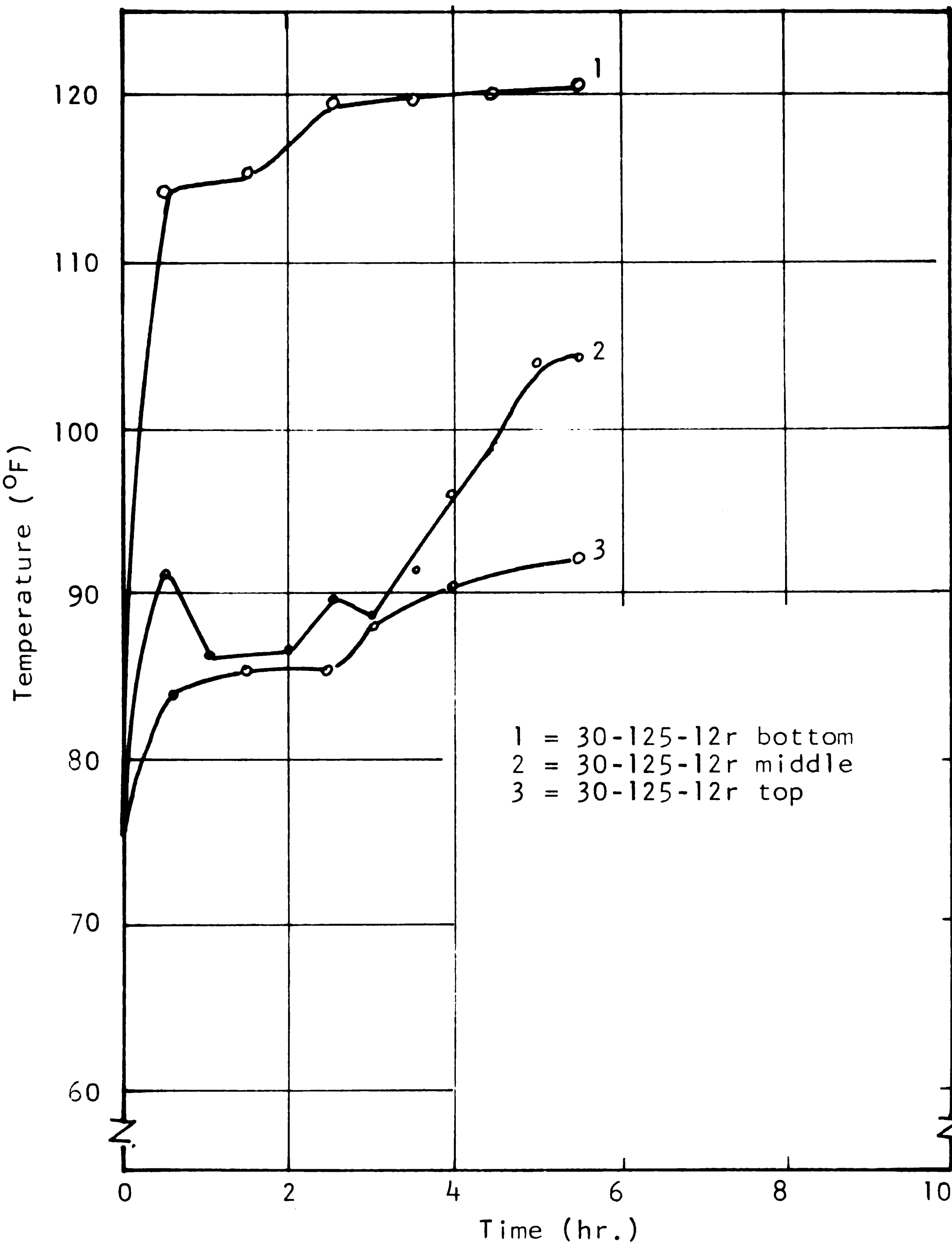

Figure 20. The effect of periodic air flow reversal at 125°F drying air on the grain temperatures.

until drying was complete, stayed quite constant for both reversal treatments. Middle layer temperature at the 95° drying air temperature run consistently below both top and bottom temperatures, while at 125°F it ran somewhat erratically above top level temperature.

Reversing the air flow caused a decrease in the drying rate. An appreciable quantity of heat escaped to the ambient air above the heated top layer of grain after each reversal. The heat utilization might be better if the air flow direction is changed rather than the reversal of the grain bed orientation. This actual air flow reversal would require more complicated equipment.

VI.2.4. SHORT DURATION OF TEMPERING

Tempering has been done usually in separate storage bins. The grain is first passed through the dryer where it is subjected to a fairly high drying air temperature for a short period of time.

Only one tempering test was conducted as a part of this research for comparison purposes. Only the 30-125-12 treatment was used and drying and tempering were accomplished while the grain was still in the drying box. The bottom layer was subjected directly to the drying air temperature of 125°F for 30 minutes followed by tempering periods of 60 minutes. In order to reach the desired average moisture content, the rice was subjected to seven 30-minute drying periods separated by six 60-minute tempering periods.

The effect of drying and tempering on the grain temperature throughout the bed is shown in Figure 21. The grain temperature of the top and middle layers were considerably lower where drying and tempering were alternated. The bottom and middle layer temperatures cycled somewhat below that for the non-tempering treatments. The top layer was affected only slightly by the drying and tempering process. The tempering treatment doubled the head yield of the bottom layer and improved it some at the middle levels as seen below.

Treatment	Head yield percentage			Drying rate
	Bottom	Middle	Top	lb/hr
30-125-12u	14	40	41	1.33
30-125-12t	28	43	44	1.53

As seen from the table above, the drying rate was 15% faster than the uninterrupted drying (the drying rate for this tempering treatment was compared on the basis of counting the drying periods and not the tempering periods). There was still a moisture and temperature gradient between the bottom and top layers. As seen from Figure 21, the final temperature of the top and middle layers for the tempering treatment was always lower than those of the uninterrupted.

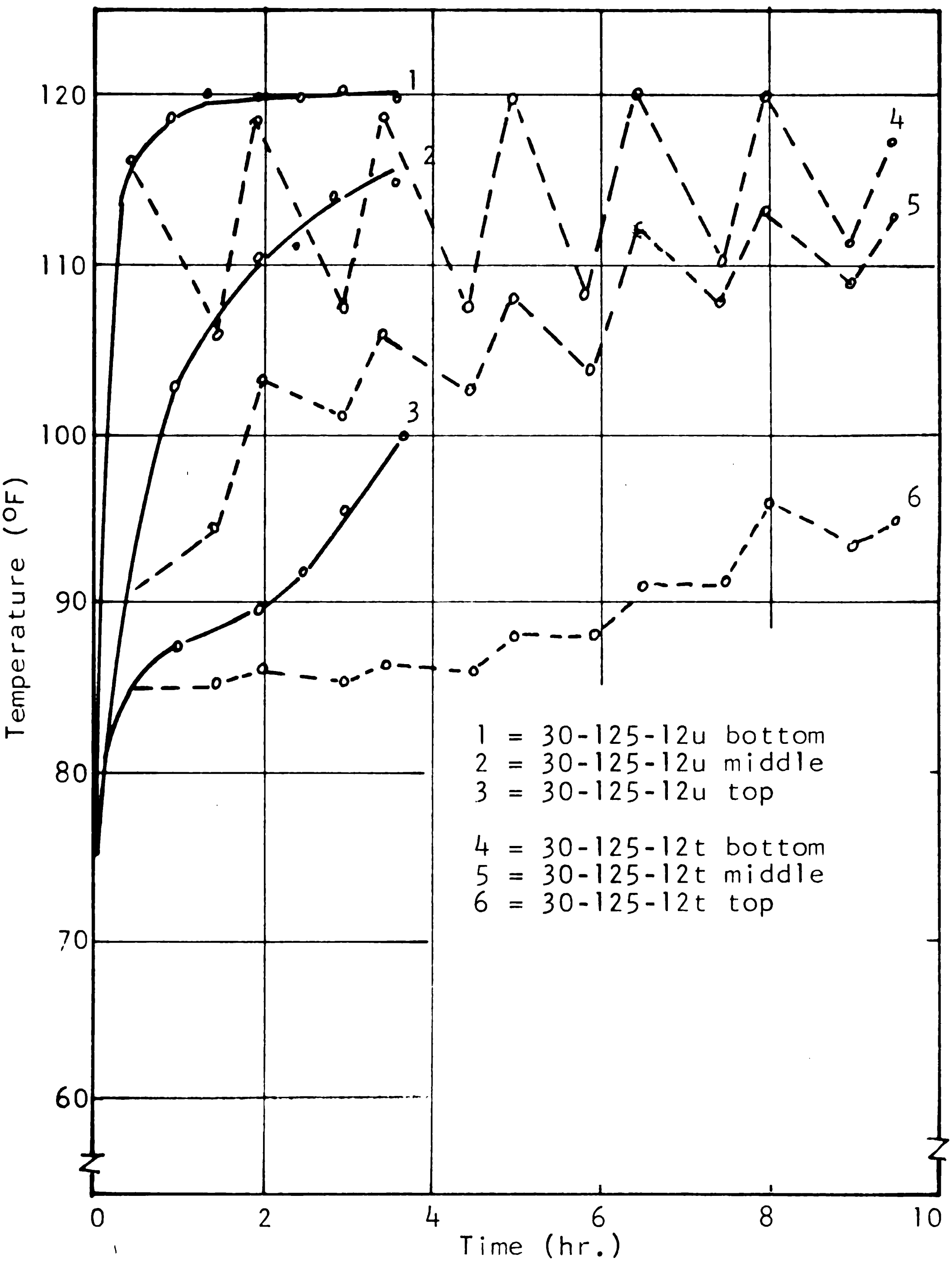

Figure 21. The effect of periodic tempering at 125°F drying air on grain temperatures

The heat utilization factor as shown in Figure 22 was increased slightly by the tempering treatment as compared to uninterrupted drying (heat utilization factor was counted during the drying time only).

VI.2.5. SHORT DURATION OF TEMPERING AND FOLLOWED BY PERIODICAL AIR FLOW REVERSAL

Short duration tempering still caused some temperature and moisture gradient between the top and bottom layers. Overdrying of the bottom layer resulted, although it was reduced as compared to the uninterrupted treatment. Periodical air flow reversal also resulted in overdrying of both the bottom and top layers by the time drying was completed. A combination treatment of drying 30 minutes and tempering for one hour then followed by airflow reversal was tried to study the possibility of reducing the overdrying problem. This was an exploratory treatment and only one test was conducted.

These treatements had prolonger the tempering period at the bottom layer and resulted in an increase of head yield as shown in table 7.

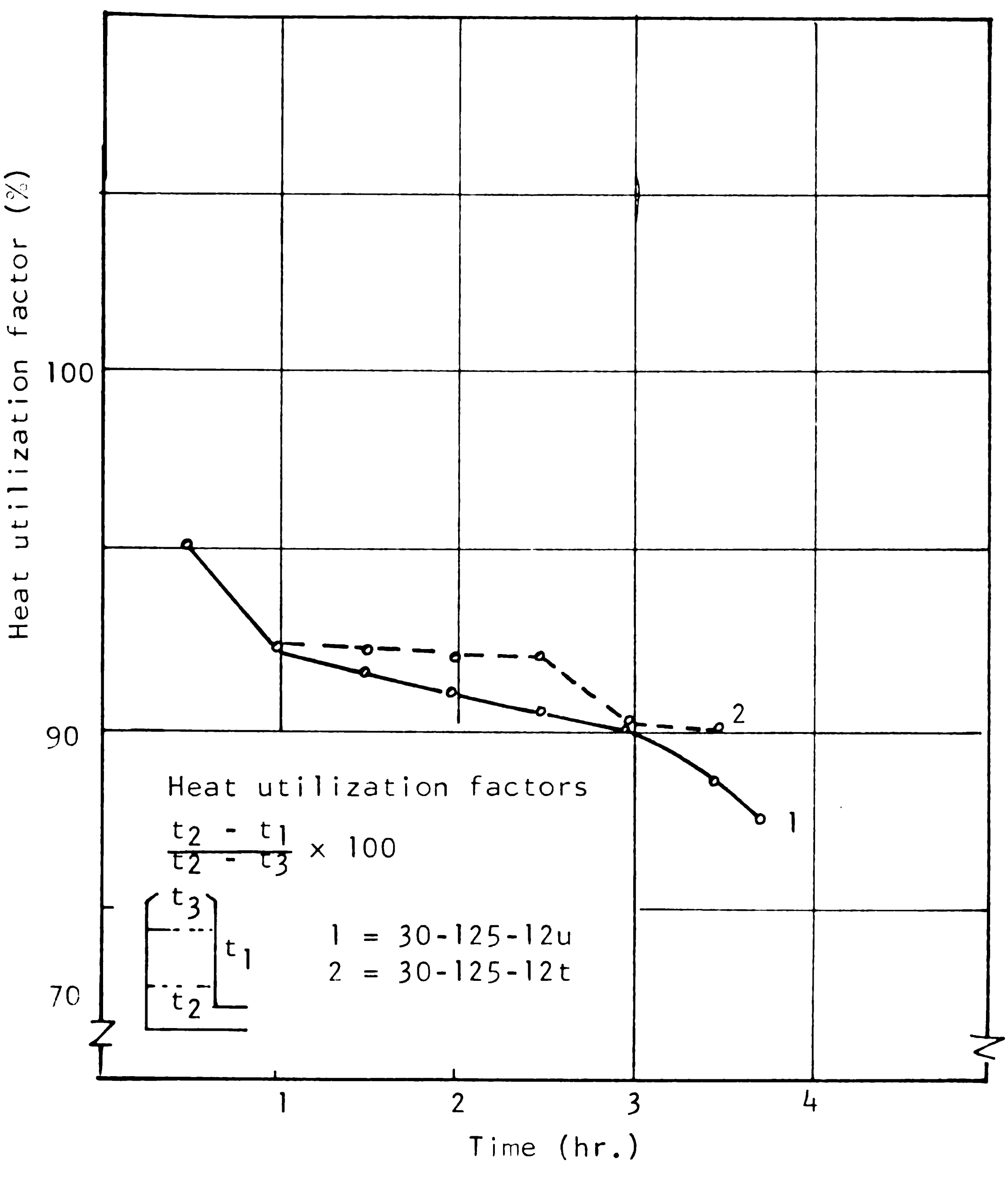

Figure 22. The effect of periodic tempering at 125°F drying air temperature on the heat utilization factor

Table 7. The effect of a combination of tempering and air flow reversal on head yield

Treatment	Tempering period hr.	Head yield percentage Bottom	Middle	Top	Drying rate lb/hr
30-125-12u	0	14	40	41*	1.33
30-125-12r	0.5	18	42	26	.90
30-125-12t	1.0	28	43	44*	1.53
30-125-12t&r	2.5	34	43	34	1.12

*The actual head yield will be lower, since the top layer was redried again for test purposes.

The combined tempering period and air flow reversal shows an increased head yield at the bottom and top layers as compared to air flow reversal only. While the average head yield increased 17% higher than airflow reversal treatment.

VI.3. WASTE HEAT UTILIZATION

The directly connected fan and engine were found to be unsafe during the preliminary test. The setscrews which were to hold the fan to the engine drive shaft would not stay tight initially. After some adjustment, this problem was corrected. A metal weight was placed on the engine stand to prevent moving due to the torsion effect of the engine and fan.

The waste heat utilization test on the directly connected fan and engine ran four hours continuously. Although these test runs were satisfactory, the engine and directly connected fan should be evaluated more intensively prior to being recommended. As previously stated, the exhaust gasses for these tests were released into the air stream. This might not be desirable for actual drying of food grains.

Table 8 shows that as the static pressure increased the temperature and fuel consumption also increased. The maximum temperature increase for the Clinton engine in this test was 15^{o}F. While for the Briggs & stratton engine, the greatest increase was 24^{o}F. At 1 inch static pressure for the fan operation the Briggs & Stratton engine developed 1848 Cfm, 5.9 hp and the temperature increase was 20^{o}F. The temperature increase was almost the same as found by Boyce (1956). He found a 20^{o}F temperature increase by using a 5 hp engine against a static pressure of 1.25 inch. The energy pick-up and energy consumed are shown also in Table 8. As the static pressure increased the thermal efficiency increased. The inconsistency of the thermal efficiency of the Clinton engine and fan was due partially to improper functioning of the engine governor.

The fans were of two different types so they cannot readily be compared as to heat utilization from two different

Table 8. Airflow rate, temperature increase and thermal efficiency at different static pressures

Engine	S.P. inch	R.P.M.	H.P.[1]	C.F.M.	ΔT^2 °F	h Btu/lb	Fuel gr/min	Energy[3] pick-up Btu/hr	Energy[4] consumed Btu/hr	Thermal[5] Eff. %
Clinton	.1	2490	1.31	1960	10	2.6	16	21,800	41,000	53
with	.25	2510	1.33	1325	13	2.8	18	15.700	45.000	35
propeller	.50	2660	1.40	1052	14	3.0	20	13,400	50,000	26.5
fan	.75	2760	1.45	1030	15	3.4	20	14,700	50,500	29
	.90	2820	1.50	1016	15	3.4	22	14,500	55,000	26.5
Briggs &										
Stratton	.25	2090	5.4	1975	17	4.2	26	30,000	64,000	45
with	1.0	2180	5.9	1848	20	4.8	30	37,500	76,000	49
centrifugal	2.0	2210	6.0	1694	21	5.0	32	36,000	81,800	44
blower	3.0	2300	6.2	1406	23	5.4	34	32,000	86,000	37
	4.0	2400	6.5	1030	24	5.6	35	24,000	88,000	28

[1]Theoretical hp = $\frac{D^2 \times S \times N \times rpm}{11.000}$

where O = bore of engine in use
S = stroke in use
N = number of clinders
rpm = rotation per minute

[2]ΔT = temperature increase as measured at the duct outlet

[3]Energy pick up = cfm × γ × h (Btu/hr)
where cfm = airflow rate (ft^3/min)
γ = air density (lb/ft^3)
h = cuthalpy (Btu/lb.dry air)

[4]Energy consumed = fuel used × heat content of the fuel
$= \frac{gr}{min} \times \frac{60\ min}{hr} \times \frac{lb}{45481} \times \frac{19,000\ Btu}{lb}$

[5]Thermal efficiency = $\frac{\text{energy pick up}}{\text{energy consumed}} \times 100$

that content of fuel = 19,000 Btu/lb.

engines. The fan must be selected for the static pressure and c.f.m. required for the system of rice drying to be used. The heat utilization is dependent upon the engine size, but temperature increase seems to be inversely related to the c.f.m. of air.

VII. APPLICATION

Waste heat utilization from the internal combustion enginer and the effectiveness of different drying treatments for the fixed-bed dryer were investigated. The study was directed toward the possibility of application at the farm or village level in developing countries. An acceptable dryer should be inexpensive thus have a low initial cost and be simple to operate. An economic feasibility study for the experimental dryers was not conducted.

Esmay (1972) had placed some constraints upon the development of a batch type dryer that would utilize waste heat from the internal combustion engine. He suggested also that the dryer should be easily operated in the developing countries.

The temperature increase derived from the waste heat of the Clinton engine and the static pressure developed by the propeller fan were of the same range as the static pressure and temperature increases studied during the drying experiments. The static pressures developed by the Briggs & Stratton engine and centrifual blower were higher than necessary for shallow bed type dryers. During the experiment the Clinton engine and propeller fan delivered 1960 c.f.m./ft^2 against a static pressure difference of 0.1 inch of water and the drying air temperature increase was 10^{o}F. When the static pressure was increased to 0.5 inch the fan delivered only 1052 c.f.m./ft^2 and the temperature increase was 14^{o}F. For example, if the atmospheric temperature was 81^{o}F and the relative humidity 75%, the waste heat derived from the Clinton engine at 1052 c.f.m. and 0.5 inch static pressure will dry 35 ft^3 of rice or 1260 lbs. at 1 ft depth within 10 hours. When the engine developed 1016 c.f.m. and 0.9 inch static pressure it will dry 2400 lbs at a 2 ft deep bed of rice in 13 hours.

As stated previously, the drying experiments were all conducted under controlled room temperature conditions and the drying air at the plenum chamber was maintained at a constant absolute humidity for each level of drying air temperature. In tropical countries like Indonesia, for example, there is little variation in temperature throughout the whole year. The average temperature difference between day and night is from 7 to 13^{o}F. The fixed-bed dryer designed to utilize the waste heat from the engine can increase the drying air temperature from 10 to 15^{o}F above the atmospheric temperature. High atmospheric temperatures and low humidities are most efficient for the low temperature, slow drying systems.

For 24 hours per day operation the dryer will be more efficient when located where diurnal variation is minimum.

VIII. SUMMARY AND CONCLUSION

VIII.1. SUMMARY

Research on fixed-bed dryers that utilize waste heat from the internal combustion engine had been initiated by some research workers, but application in the developing countries has been limited. An attempt was made to simplify the design of the waste heat utilization drying system in order to minimize the initial cost by connecting the fan directly to the engine shaft. Satisfactory results were obtained, but more intensive study of the design is required. The static pressure against which the fan operated was varied and the temperature increase was measured in order to study the variation in thermal efficiency. The fan must be selected for optimum performance at the desired static pressures.

Fixed-bed dryers are most adaptable for the slow drying process at low drying air temperatures. An incorrect belief of many inexperienced operators in the developing countries is that if a little heat is good, a lot of heat will be even better. This research was oriented towards the utilization of the low cost and simple equipment. Several simple methods which might be done by the operators without additional equipment such as periodical stirring, periodical airflow reversal, were studied in an attempt to increase the drying rate without lowering the head yield.

A variation in three temperature levels of 95°F, 110°F and 125°F, three depth levels of 6 inch, 12 inch and 24 inch, and two levels of airflow rates of 10 and 30 c.f.m./ft^2 were studied. The effect of those variables was evaluated on the head yield and the drying rate. All graphical figures were based on the observation only.

VIII.2. CONCLUSION

These conclusions are based upon the conditions and operations included in this research:

1. Waste heat from internal combustion engines can be utilized as a supplementary heat source for drying rice in a fixed bed. The Clinton engine with the propeller fan is more adaptable for village level operation; it was small, light and low cost compared to the larger Briggs & Stratton engine with the centrifugal type blower. Also the range of static pressure (0.1 inch up to 0.9 inch of water) against which the propeller fan operated efficiently,

and the temperature increase (10°F up to 15°F) were in the range required for the slow drying process with minimum rice cracking.

When 10 cfm/ft^2 airflow rate was used at 1 ft depth of rice, the static pressure measurement was 0.1 inch of water. The highest thermal efficiency from the engine waste heat experiment was at 0.1 inch static pressure, the airflow rate was 1960 cfm and the temperature increase was 10°F.

Assuming that the average air temperature in Indonesia is 85°F, the Clinton engine with the propeller fan when operated at 0.1 inch static pressure and 1960 cfm, will dry two to three metric tons of rice from 20% moisture content wet basis to 14% moisture content wet basis in 21 hours. The 24 hours or less drying period would be desirable under tropical weather conditions and with high moisture paddy rice.

2. At the low drying air temperature of 95°F, there was no overdrying problem at grain depths up to 24 inches. The deeper the grain, from 6 to 24 inches, the more efficient was the heat utilization. The drying rate increased 2.2 times from 6 to 24 inch depth. The head yield between the top and the bottom of the drying bin was not significantly different.

3. The higher drying temperature of 125°F increased the drying rate, but there was overdrying in the bottom layer. The head yield between the top and the bottom was significantly less than the head yield at the top (significant level F = 0.008). This overdrying can be reduced by periodical stirring. Periodical stirring under these conditions has also increased the drying rate up to 20%. A mechanical stirring device would be needed for depths of grain greater than 12 inches.
4. The tempering process at 125°F drying air temperature and 30 c.f.m./ft^2 airflow rate reduced the overdrying at the bottom layer thus increasing the head yield of that layer. A higher head yield of 16% resulted by extending the tempering period from 30 minutes to 2.5 hrs. The drying rate was improved by 15% by tempering with grain depths of 12 inch.
5. Airflow reversl by turning the grain box was carried out for the 12 inch depth only. The drying rate did not improve and some overdrying still existed at the top and bottom layers. A combination of tempering and periodical airflow reversal did not improve the drying rate.

VIII.3. SUGGESTION FOR FURTHER STUDIES

Based upon observations made during this research, further study is needed in the following areas:

1. The direct connection of a fan to the engine drive-shaft for fixed-bed drying purposes. This combination would simplify dryer construction and minimize the cost.

2. Further studies are needed on length of interval for stirring, airflow reversal and tempering for maximizing drying rate and head yield.

3. The waste heat derived from the internal combustion engine was limited. Further study of the utilization of rice waste product (straw and husks) as a heat source for the reduction of dryer operating cost for higher temperature drying of 100 to 125^{o}F.

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APPENDIX

Milling test of rice drying experiment

Sample	Top			Middle			Bottom			Drying time
	m.c.	tot. mil	head	m.c.	tot. mil	head	m.c.	tot. mil	head	
	%	%	%	%	%	%	%	%	%	hrs.
10-95-12u	15.4*	68.0	40.0	13.7	67.0	40.0	12.4	67.0	44.0	21.0
30-95-12u	15.3	67.0	41.0	14.0	67.0	42.0	11.5	67.0	41.0	10.0
10-110-12u	14.5*	69.0	45.0	12.0	68.0	43.0	8.9	69.0	41.0	14.0
30-110-12u	15.3	66.0	40.0	13.7	67.0	41.0	11.4	68.0	37.0	5.75
10-125-12u	14.6*	68.0	42.0	11.6	68.0	44.0	8.5	70.0	26.0	10.0
30-125-12u	15.1*	67.0	41.0	14.2	68.0	40.0	9.8	68.0	14.0	3.75
30-95-6u	14.2	67.0	41.0				12.6	67.0	42.0	6.66
30-125-6u	15.5	67.0	37.0				12.3	67.0	23.0	2.0
30-95-24u	14.7*	67.0	42.0	13.3	68.0	41.0	11.1	68.0	42.0	13.0
30-125-24u	14.7*	69.0	44.0	12.0	68.0	35.0	7.8	68.0	11.0	5.66
30-95-6s				14.4	68.0	41.0				6.0
30-125-6s				14.4	67.0	35.0				1.80
30-95-12s				14.3	68.0	42.0				9.75
30-125-12s				15.0	68.0	39.0				3.60
30-95-12r	13.4	68.0	43.0	14.8	67.0	42.0	12.5	68.0	44.0	13.5
30-125-12r	11.1	67.0	26.0	15.4	68.0	42.0	9.8	67.0	18.0	5.5***
30-125-12t	14.6*	68.0	44.0	12.0	68.0	43.0	9.0	69.0	28.0	3.25
30-125-12 t&r	9.8	68.0	34.0	14.5	68.0	43.0	10.7	68.0	34.0	5.0***
Control air dried**										
1				12.3	67.0	43.0				12.0
2				12.8	68.0	45.0				12.0
3				13.4	67.0	42.0				12.0
4				14.9	68.0	40.0				12.0

*The samples were redried again for milling test purposes.
**The controlled samples were spread on the floor.
***Drying time only, tempering period not included.

Hartzell ·PROPELLER·FAN·COMPANY

Manufacturers of Fans and Blowers
DIVISION OF CASTLE HILLS CORP.
PIQUA, OHIO, U.S.A.

August 9, 1972

University of California, Davis
Department of Agriculture Engineering
Davis, California 95616

ATTENTION: Mr. William J. Chancellor

Dear Mr. Chancellor:

Thank you for your request of July 31st. Enclosed herewith please find the duplicate copies of bulletin A-109-M covering our standard propeller type fans. Enclosed also please find in duplicate copy of our typical performance rating sheet FPR-67 covering the most common models of direct drive duct type fans used for agricultural purposes. To clarify the FPR model specifications, the first two digits in each instance indicate the nominal fan diameter. The third digit indicates the number of fan blades and the last one or two digits indicate the brake horsepower.

In your letter you've made mention of an engine shaft and we presume that you are speaking of an internal combustion engine. This being the case we would caution against the use of some of our props inasmuch as there is considerable amount of fatiguing stresses set up by any internal combustion engine when the prop is mounted on the crank shaft. In other words, we would not want to be held responsible for any failures which might occur.

If there is only one unit involved, I feel quite sure that we could arrange to furnish one of our props on a no-charge basis. However, if the experiment eventually leads to a production prototype we certainly would want to be in a position to furnish our complete fan units if at all possible.

Prices vary considerably from blade to blade inasmuch as the total casting weight and number of blades is the determining cost factor. We suggest that you look over the enclosures and decide on one or two models which best suit your present needs. On reply then we will submit prices. We trust that this meets with your approval.

Yours very truly,
HARTZELL PROPELLER FAN COMPANY

D. W. Johnston
Sales Engineer

DWJ/jr
Enc.