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DEVELOPMENT OF A THREE STAGE SOLAR DRYING SYSTEM FOR COFFEE

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ABSTRACT

The traditional practice of sun drying arabica coffee on tables is proving inadequate during the peak processing periods in some cooperative factories in Kenya. A three year programme to develop a solar drying system capable of maintaining a daily throughput of 3t of dried parchment coffee is described. The system consists of three separate stages: initial skin drying, intermediate sun drying on tables - mandatory for Kenyan coffee - and final drying. The skin trying and final drying stages take place in a purpose-designed building which incorporates a solar collector within the roof. Power is provided by a diesel-driven engine directly coupled to an axial-flow fan capable of maintaining an air flow of 8 m^3s^{-1}. Waste heat from the engine is used to heat the air thereby enabling drying to proceed in all but the worst weather and at night. The solar collector performed well within design specification with a collection efficiency of nearly 50%. In routine operating conditions system-dried coffee equalled that of control batches dried by the traditional method under ideal conditions.

INTRODUCTION

Coffee has long been the major cash crop and export earner from the agricultural sector of Kenya. Current annual production is about 100,000 tonnes of clean coffee. Smallholder farmers are members of cooperative societies and their produce is processed in communal factories. The capacity of individual factories varies from 250 tonnes of (coffee) cherry or less each year to between 500 and 1000 tonnes per annum. One tonne of cherry yields approximately 200 kg of dried parchment which, in turn, yields about 160 kg of clean coffee.

In the factories the coffee is processed from freshly-picked cherry to dried parchment and then transported to warehouses for dehusking, sorting, grading and packaging before sale and export. The factory processing operations carried out include pulping/grading, fermentation, washing and drying.

Traditionally wet parchment is dried on wire-mesh tables. There are two distinct parts to this operation termed skin-drying and (for the purpose of this paper) bulk-drying, the drying of parchment from skin dry to fully dried. In the former operation wet parchment with a moisture content of 50-55% (all moisture contents quoted are on a wet-weight basis) is spread directly on to wire-mesh tables and sun dried with frequent stirring by hand until skin-dry, a moisture content of approximately 45%. It is then spread on hessian sacking on bulk-drying tables where it remains until dry at a moisture content of 10-11%. Skin drying can take from one hour to one day and bulk drying anything from 7-28 days depending on many factors including the degree of loading, weather, and amount of hand stirring. Both operations are labour intensive.

As well as removing the moisture from the parchment the table drying operation is essential to allow the exposure of the parchment to sunlight for the equivalent of four (sunny) days (McCloy, 1979) and hence correct flavour development. Exposure to light is especially important at moisture contents between 20% and 32% (Gibson et al. 1972).

An appreciable number of cooperative factories experience operational constraints due to table shortages during the peak processing periods (Whitaker and Roe 1985). In these periods up to 40% of the annual intake of cherry can occur in a single month which unfortunately invariably occurs within the rainy season. This period of maximum activity also coincides with other farming operations and the farmers find it difficult to fulfil their labour commitment to the factory. This general shortage of labour at the critical time counteracts a seemingly obvious solution - that of increasing the number of drying tables which in any case would be difficult due to shortage of land.

The estate sector faced similar problems, but with greater financial and technical resources have in many cases invested in large scale mechanical dryers over the last 10-20 years (Ghosh 1966, 1968; McCloy, 1979). Such dryers have been investigated for their suitability for cooperative factories (Kamau, 1980). High capital and operating costs and technical sophistication has meant that very few have been installed at cooperative factories.

In recent years efforts have been successfully directed towards increasing the smallholder production of coffee. In view of the potential escalation of the drying problem already being experienced by cooperative factories, the (Kenyan) Coffee Research Foundation (CRF) in collaboration with the Tropical Development and Research Institute undertook to re-examine the problem.

As a first step about 25 factories were visited and it was concluded that any improved drying system would have to satisfy the following requirements:

i. A daily throughput of 3 tonnes of dried parchment.

ii. Carry out both skin-drying and bulk-drying.

iii. Accommodate the essential requirement of exposure to light during part of the drying process on sun drying tables.

iv. Independent of external power supplies since 90% of cooperative factories are not connected to grid electricity.

v. Minimum consumption of fossil fuels.

vi. Total cost of the system excluding drying tables should not exceed 300,000 Ksh (US$ 20,000) (at November 1982 prices).

vii. Due to the general shortage of land the system should not increase the area required for drying.

viii. Construction and subsequent operation should be as simple as possible. Construction should be carried out by local contractors using materials that are locally and easily available.

SYSTEM DESIGN FEATURES

Taking into account the criteria stated above, a drying system was designed with three distinct stages:

a. Skin drying, in which the moisture content of the wet parchment is reduced from 50-55% to 42-45%.

b. Table drying, in which the skin dried parchment is spread on tables in the traditional manner and allowed to dry in the sun. The controlling factor for this stage of drying is the period of exposure to sunlight rather than the time to achieve a certain reduction in moisture content. However, after such a period of table drying, parchment will have dried to 15-20% moisture content.

c. Final drying, in which parchment is dried in bins to 10-11% moisture content.

Skin and final drying are carried out within the same building as shown in Figure 1. A simple bare plate solar roof collector provides the principal source of heating during daylight hours. Additional heat is provided continuously by a moisture extraction unit (qv).

A diesel engine directly coupled to an axial-flow fan is used as an independent power source to move air through the final drying and skin drying bins. The engine and the fan unit, collectively termed a moisture extraction unit (MEU), is designed such that the fan draws air over and around the engine block thereby further heating the air and cooling the engine. The heated air is utilised twice for maximum utilisation of its drying capacity; it is first used for final drying and then for skin drying.

With the exception of the MEU, the system incorporates no mechanical parts thus minimising risks of breakdown. No instrumentation is required except for a thermometer.

SYSTEM BUILDING

The flow of air through the system building is shown schematically in Figure 2. Air can either enter at one end of the collector and be drawn into the fan house or it can enter the fan house directly via the open fan house doors. In both cases it then passes over the MEU into the manifold duct from which it is directed into any or all of the five final drying bins, or by means of the by-pass duct, directly to the skin drying bin. In the latter the air, after passing up through the final drying bins under the bin covers to the skin drying bin, passes down through the bed of parchment before venting to atmosphere.

The quality of parchment may be impaired at temperatures above 35°. Hence the temperature of the air to the final drying bins is controlled by opening the fan house doors. This lowers the ambient air temperature in the fan house and reduced the flow of air through the collector. Air temperature is measured by a filled-system thermometer within the manifold duct.

The bare plate solar collector is an integral part of the roof of the building. It consists of black-painted corrugated iron sheeting under which is positioned a wood "ceiling" so forming a wide duct running the length of the building. The angle of the collector to the sun's rays and the orientation of the building are of obvious importance for optimising the collector performance. At CRF's Rukera farm near Ruiru, the location of the prototype system, the sun is to the south during the peak processing period of November-December. The collector was therefore designed running East-West and facing due South with a slope of 20°.

The flow of air through the collector is from end-to-end rather than from side-to-side because of the inherent difficulties in maintaining an even flow of air across a very wide duct with a fan centrally positioned along one side.

Buelow (1958, 1961, 1962) established that an increase in the flow of air through a collector of fixed dimensions leads to an increase in collection efficiency (ratio of energy gathered by the air flowing through the collector to the insolation incident upon the collector) but a decrease in temperature elevation of the air. Some loss in potential collection efficiency has to be tolerated therefore in order to obtain an air temperature that will ensure a satisfactory drying rate. Collection efficiency is dependent upon the heat transfer characteristics of the system (Whillier 1964). These in turn are a function of the air velocity through the collector. The velocity for a fixed volumetric flow rate is inversely proportional to the cross-sectional area hence the maximum collection efficiency would be obtained with a duct of minimum cross-sectional area. However, the greater the velocity the greater the pressure drop developed in the duct and the more powerful the fan required to move the air through the collector.

The dimensions of the collector are therefore a compromise between the conflicting demands of the collection efficiency, pressure drop and temperature elevation. For this application the collector was approximately 27m long and 7m wide with a spacing of 300mm between the roof and the ceiling.

There are five final drying bins within the system building positioned side-by-side alongside the manifold duct (Figure 1.) Each bin is 2.75m square and 1.20m deep and with a capacity of 4 t (dry) of parchment. The bins are rendered concrete block and have a perforated tray of wire mesh supported on wooden legs affixed to the concrete base of the plenum chamber. The flow of air to each bin through the inlet port is regulated by a wooden shutter raised by a chain from the catwalk above the manifold duct. The bins are covered by plywood sheeting supported at the side-walls of each bin but not at the end-walls. The bins are loaded from sacks through 0.9m square openings in the covers closed by wooden shutters. The parchment is unloaded from the bins into sacks via a discharge chute regulated by a wooden shutter.

The skin drying bin, likewise constructed, is positioned at one end of the line of final drying bins and separated from them by a by-pass duct. The bin is 6.40m long and 2.75m wide and can also hold 4 t of parchment. Air enters this bin either from the final dryings bins and/or the by-pass duct and flows down through the parchment bed. The air vents to atmosphere via ports in the end- and side-walls below the bin floor. Loading of the bin is likewise through openings in the covers and unloading through two discharge chutes as for the final drying bins.

The MEU is a commercially available machine (R A Lister Farm Equipment Ltd, Cirencester, UK) widely employed for the drying of tropical crops. The unit selected for the system uses a three-cylinder diesel engine with a shaft power output of 18 kW. The fan can provide an air flow of 8 m^3s^{-1} against a pressure of 500 Nm^{-2}. The MEU is mounted on a concrete plinth within the fan house (Figure 2). The fan casing is connected via a canvas coupling to the entrance of the manifold duct. Since it is imperative that the exhaust gases do not contaminate the parchment they are piped out of the fan house to atmosphere at roof level.

The roof of the manifold duct also acts as the catwalk for access to the drying bins. In addition, a concrete floor is laid on the far side to provide a clean and dry environment for unloading parchment and also a temporary storage area for full sacks waiting to be taken to the drying tables or store.

To prevent contamination of parchment the fuel drums for the MEU are positioned adjacent to the fan house wall with the fuel line running through the wall to the MEU.

SYSTEM COMMISSIONING

The system was commissioned over a 38 day period in which 23 batches of parchment were dried. Wet parchment from the washing channels was pumped, for reasons of convenience, into the skin drying bin early in the morning and dried for 20-22 hours. It was then manually loaded into sacks and taken to the drying tables and remained there until the necessary time of exposure to sunlight had been achieved. It was then removed from the tables and taken, again in sacks, to one of the 5 final drying bins where it remained until dry. The final drying bins were used in sequence thus providing a 5 day operating cycle.

Control batches of approximately 100 kg were dried on tables in the traditional manner as a basis for quality comparison.

During commissioning air temperature and humidities at pertinent points within the system building were continuously monitored using multi-point chart recorders (Anville Instruments Ltd, Chertsey, UK). Manometers (Air Flow Developments Ltd, High Wycombe, UK) were used to measure the duct pressure and pressure drop across the beds of parchment. Insolation and wind velocity were logged using a solar distrometer and cup anemometer (Casella London Ltd, London, UK), respectively. When batches were dry, samples were taken for oven moisture determination. Every batch, both system dried and control dried, was assessed for quality employing standard techniques by the Coffee Board of Kenya (CBK) after conditioning in sacks for 4-5 weeks.

RESULTS AND DISCUSSIONS

Thermodynamic performance

Mean daily insolation was 21.9 MJ day^{-1} (compared with the seasonal mean of 20.3 MJ day^{-1}) and there was an average of 7.8 sunshine hours per day (compared with the norm of 6.4 hours). Such weather conditions resulted in high ambient air temperatures which necessitated the fan house doors to be open for long periods, on most days from 11.00 to 16.30. When the doors were open the flow of air through the collector was reduced by 50% to 4.0 m^{3}s^{-1}. Even though the collector outlet air temperature frequently rose as high as 44°C, after mixing with the cooler ambient air the temperature of the air flowing to the drying bins was within the required limits.

Table 1 summarises the collector performance over the commissioning period. Collection efficiencies were lower when the fan house doors were open compared with when all the air was drawn through the collector. This was to be expected since collection efficiency increases with increase in air flow even though temperature elevation may be higher.

The air heating performance of the collector is presented in Table 2 and meets design specifications. It is reasonable to conclude that the collector would be able to provide sufficient heat even during periods of more inclement weather likely to be experienced at other times. Opening of fan house doors proved effective as a means of regulating the air temperature.

From the data in Table 2 it can be calculated that on those days when the fan house doors were closed throughout, the collector provided 1800 MJ during the day time and the MEU 2400MJ over 24 hours, together supplying a total daily heat input of 4200 MJ. If an equivalent amount of energy was provided by electricity, a 50 kW heater would be required. Alternatively, if a direct-fired oil heater was used then approximately 120 litres per day of diesel oil would be consumed; more if for product quality reasons an indirect-fired heater were used.

Operating conditions for skin drying are presented in Table 3. The mean inlet air temperature for the 23 batches dried was 24.6°C and the outlet air temperature 17.7°C. The outlet air was for the most part saturated, ie at 100% relative humidity (RH), and never less than 90% RH. This indicates that the system was very effective in terms of utilising the capacity of the heated air to absorb moisture from the parchment.

Mean temperature of the inlet air to the final drying bins was 29.2°C and the outlet air temperature 24.8°C (Table 3). There was relatively little difference between the temperatures of the inlet and outlet air at night. This can be attributed to the inherently large heat capacity of the system. Particularly when a batch was almost dry the outlet air temperature was sometimes as high as 32° at 1800 hours and it can be taken that the parchment temperature was only a little lower. During the next few hours, even though drying continued, albeit slowly, the outlet air temperature was actually greater than the inlet air temperature, sometimes by as much as 5°C, due to the parchment and bin walls releasing heat absorbed during the day.

The MEU proved a very efficient and reliable machine. It was operated for nearly 800 hours with an average fuel consumption of 3.23 $\mathrm{l.h^{-1}}$. Since fuel consumption was somewhat greater, about 4.0 $\mathrm{l.h^{-1}}$, when the MEU was being "run-in", it would be expected to average 3.0 $\mathrm{l.h^{-1}}$ in subsequent operations. For the most part of the commissioning period when all the bins were fully loaded the MEU delivered a constant air flow of 8.0 $\mathrm{m^3s^{-1}}$ against a pressure of 400-500 $\mathrm{Nm^{-2}}$.

The mean weight of the 23 batches processed was 2.94 tonnes although there was considerable variation in batch size as would be expected in any cooperative factory. There were three days when parchment was not available; on these days the parchment already within the skin drying bin was given an extra day of drying.

The mean reductions in moisture content achieved for each of the three drying stages and the times required to effect these changes (Table 4) are all within the system specifications. The mean rate of evaporation of moisture during skin drying was 49 kg $\mathrm{h^{-1}}$ and that during final drying approximately 15 kg $\mathrm{h^{-1}}$. From these data the pick-up efficiency, the ratio of the moisture evaporated during the drying to that which the air is theoretically capable of evaporating under adiabatic conditions, was calculated. The efficiency of the system (61%) is satisfactory.

Because of the high moisture content moisture evaporation of the skin drying stage is rapid. This results in the air becoming saturated before it reaches the bottom of the bed. The parchment therefore tends to dry from the top down. To ensure even drying of the parchment it is necessary to thoroughly turn the bed twice during the day. This simple but very important procedure required two men for 20 minutes for each turning and proved very effective.

Because of the dry and sunny weather experienced during commissioning the necessary 30-35 hours of exposure of parchment to sunlight on the tables was invariably achieved within 5 days. Although there was considerable variation in the parchment loadings on the tables, 6.4-9.4 kg m^{-2}, the rate of drying remained essentially constant.

The system has the in-built capacity to final dry each and any batch for about 110 hours (5 days and nights less unloading and loading times). The mean final drying time of 83 hours indicates that the system has sufficient in reserve to cope with less favourable weather. However, slightly better skin drying performance was possible if the air inlet ports to the final drying bins were closed at night and the air ducted straight to the skin drying bin. Final drying times for parchment were not significantly increased. It was therefore concluded that optimum system performance in this respect would be achieved if parchment is final dried continuously for 3 days and nights and then only during daylight hours of the remaining 2 days.

A similar procedure would be adopted during rainy periods. On rainy days final drying would be effective until the moisture content reached 12-13%. During these periods it is recommended that batches that have had at least 3 days (and nights) of final drying be isolated until the rain ceases and the air humidity drops. Skin drying can of course be pursued under all likely weather conditions.

Although a moisture gradient within the final drying bins of 1-2% from bottom to top was initially established it gradually decreased as drying proceeded. By the time moisture contents of 10-11% were reached the moisture gradient had virtually disappeared. There was no evidence either of any variation in moisture content across the beds thus indicating that air flow through the beds was evenly distributed; a fact endorsed by direct measurement of the air flow.

Product quality

Regardless of how thermodynamically efficient the system or how fast parchment dries the most important feature for successful adoption of the system by cooperative factories will be the quality of the dried product. There was no significant difference in quality between the system dried coffee and the control samples. However, the system was commissioned over a sunny period which meant that the table drying conditions for the control batches were very favourable. It can be said therefore, that the system gave a product as good as that produced under ideal sun drying conditions. The quality of the dried parchment was not exceptionally good in absolute terms, Classes 4 and 5. (The lower the class number, the higher the quality.) However, data from CBK indicated that without exception this was not attributable to any effect of the drying process but to shortcomings in pre-drying operations such as poor pulping and fermentation operations.

System economics

From data gathered from the commissioning and from data of traditional drying practices (Whitaker et al. 1985) it has been concluded (Whitaker and Roe 1985) that nearly 10% of all cooperative factories in Kenya, 55 in total, would benefit financially if the system was integrated with their present drying facilities. These factories are mainly those with a shortage of drying tables which would have to purchase land to build more tables. The number of factories benefitting could well be greater. For this evaluation the potential of the drying system to prevent quality losses under congested factory conditions was ignored because of the uncertainty surrounding the extent to which this occurs. Also, the convenience of the system was not taken into account. Furthermore, in many districts there is an upward trend in coffee production in the cooperative sector (Whitaker et al. 1985) and increasingly more factories will be experiencing drying problems due to shortages of tables and/or land.

CONCLUSIONS

It has been demonstrated that the drying system is capable of efficiently drying 3 tonnes of parchment coffee and to a quality at least equivalent to that obtained under ideal sun drying conditions. The system building proved easy to construct by local artisans and labourers. The cost of the building and the MEU came within the budget specifications. The operation of the system proved simple and presented no problems to the factory staff. The economics of the operation are such that there are, at present, over 50 factories that could financially benefit from the system. There are also indications that this figure could increase if present production trends continue.

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TABLE 1: Solar Collector Performance

Position of fan house doors	Insolation MJ m^{-2} day^{-1}	Daily air temperature rise*, °C	Collection efficiency %
Open**	23.25	5.3	40.8
Shut	18.25	5.4	49.7

* Mean over the 12 hour period 06.00-18.00

** The fan house doors were only open for part of each day, approximately 11.00-16.30.

TABLE 2: System Air Heating Performance

Period*	Position of fan house doors	Air Temperature, °C			
		Ambient	After collector	Before MEU	After MEU
0800-1100	Shut	23.1	29.5	29.5	32.3
1100-1630	Open	28.9	39.8	34.4	37.1
1630-1800	Shut	26.4	29.5	29.5	32.8
1800-0600	Shut	18.7	18.7	18.7	23.1

* The period times are approximate; there was considerable variation in the times the fan house doors were open depending upon the weather.

TABLE 3: System Air Temperatures

Operation	Period*	Air Temperature °C Inlet	Outlet
Skin drying	0600-1800	27.1	18.7
	1800-0600	22.1	10.9
Final drying	0600-1800	34.3	25.3
	1800-0600	22.2	22.0

* The period times, particularly for skin drying are approximate; there was variation depending on the availability of parchment.

TABLE 4: System drying performance

Operation	Drying time, h	Parchment moisture content % (wb) At start	At finish
Skin Drying	21.2	53.2	42.6
Table Drying	33.5*	42.6	17.5
Final Drying	83.0	17.5	10.6

* The time for table drying is the period parchment was actually uncovered on the tables and <u>not</u> the residence time of parchment upon the table.

FIGURE 2: Air flow within system building

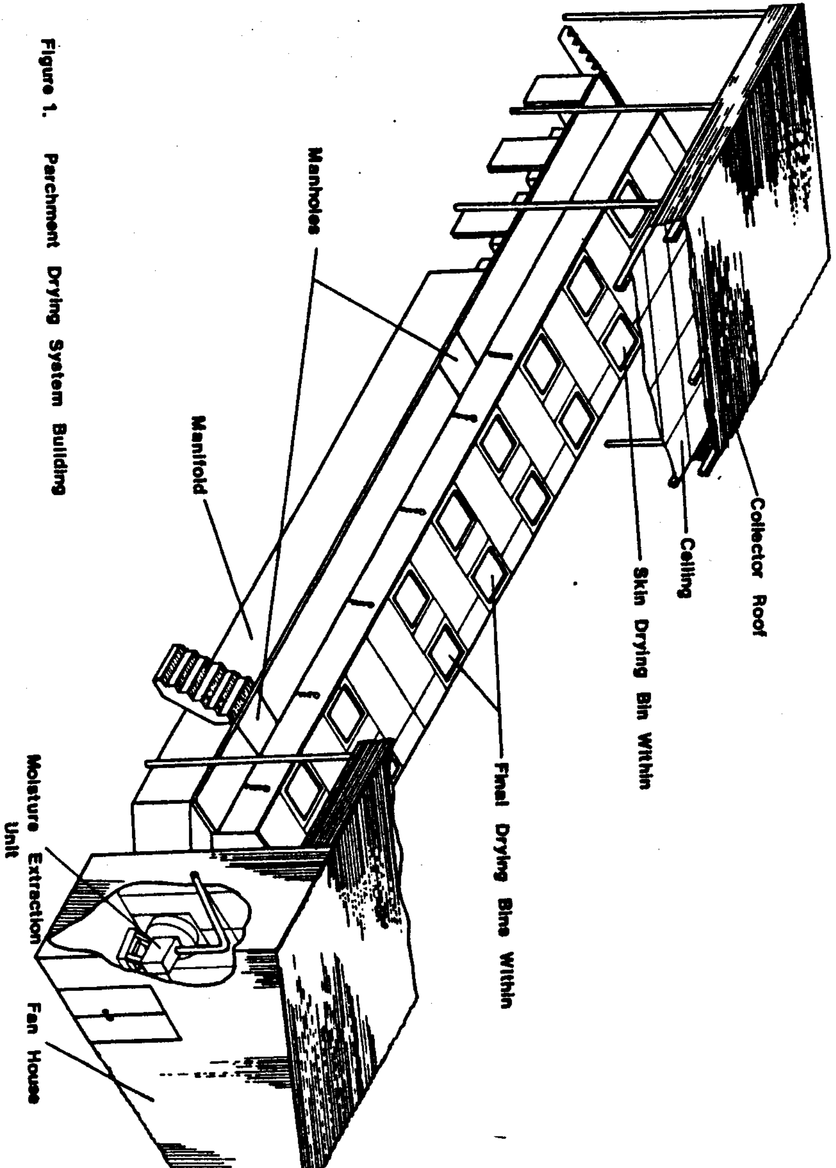
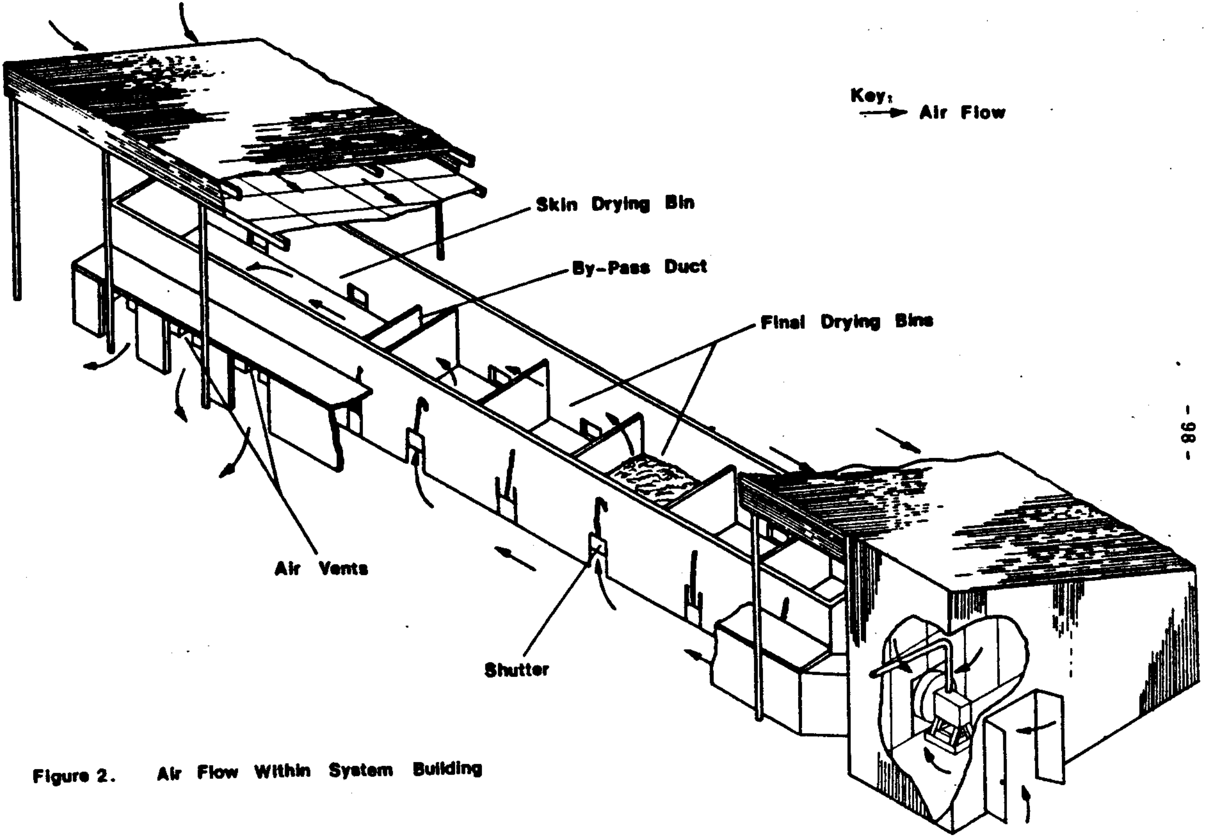


Figure 1. Parchment Drying System Building



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