THE PHYSICO-CHEMICAL MECHANISM OF SEAWEED DRYING

A thesis presented by

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SUMMARY

Drying of seaweed is desirable to reduce transport costs, to prevent decomposition and to permit easy compounding in feeding stuffs. Drying and grinding may be a preliminary stage in the extraction of algal chemicals. In all cases it is essential that drying is cheap and efficient, and this work is concerned with the investigation of this problem.

The main seaweed studied was Laminaria cloustoni which is one of the commonest sublittoral species around British shores. L. digitata is also common and was compared with L. cloustoni: L. saccharina received less attention.

The principal parts of these seaweeds are the stipe or stem containing 83-86% water and the fronds or blades with 75-90% water. A coating of mucilage on the fronds causes adhesion of cut pieces.

The physical properties of these parts made it probable that dryers of the rotary-louvre, pneumatic and through-circulation types would be the most suitable for seaweed drying, and tests were made on each of these.

It was shown that minced L. cloustoni stipe was readily dried in a rotary-louvre dryer, but that the sticky frond did not dry uniformly. A radioactive tracer technique was devised to measure the retention time of the frond in the dryer drum. A large-scale pneumatic dryer dealt easily with chopped stipe and whole plant, but again frond drying was unsatisfactory. A through-circulation grass dryer yielded a high quality dried seaweed meal from chopped frond.

From these tests it was decided to make a detailed investigation of the drying characteristics of seaweed in a laboratory through-circulation dryer.

The experimental procedure for cut stipe was established by preliminary tests on the effects of initial water content, interruption of

drying and repeatability. The principal factors studied were :-

Bed depth, (0.5 - 7 in),
Air temperature, (120 - 340°F),
Air mass velocity, (3 - 9.5 lb per sq.ft. per min),
Slice thickness, ($^1/16$ - $^5/16$ in).

The effect of agitation was studied, and the static pressure differences of air passing through layers of dried and wet seaweed were measured. The variables have been related to the drying times and constant ratio by empirical equations.

RESULTS

Bed depth is probably the most critical factor: for stipe the output rises to a maximum value as bed depth increases while for frond an optimum output occurs at a critical bed depth. This effect appears to be independent of the shape of the particles.

It has been shown that the optimum drying time for a frond bed is equal to twice the time required for a single layer of the material to dry, and this finding probably applies to vegetable material generally. Frond exhibits a marked seasonal variation in drying time which has been related to chemical constitution.

Agitation of the frond bed during drying proved advantageous particularly in the later stages of drying.

Drying rates of seaweed beds have been shown to be approximately proportional to the wet-bulb depression of the inlet air, irrespective of the air dry-bulb temperature: the maximum safe air temperature for L. cloustoni stipe or frond is about 225°F.

The constant-drying rate has been found to be directly proportional to air velocity, and at velocities of 8 - 9 lb/(sq.ft.)(min) the drying times tend toward constant values for both stipe and frond.

It was found that the physical differences between stipe and frond had more influence on drying time than the differences between the seaweed species.

A graphical design method has been devised applying the wet-bulb depression evaporation coefficient to the design of large-scale multistage through-circulation dryers.

PUBLICATIONS

Part of the work described in this thesis has been published in the following papers :-

(1) 'Through-circulation drying of seaweed' :-

Part I : L. cloustoni stipe

Gardner, R.G. & Mitchell, T.J., J. Sci. Food Agric., 1953, 4, 113.

(2) Part II : L. cloustoni frond

Gardner, R.G. & Mitchell, T.J., J. Sci. Food Agric., 1953, 4, 237.

(3) Part III : L. digitata stipe and frond L. saccharina frond

Gardner, R.G. & Mitchell, T.J., J. Sci. Food Agric., 1953, 4, 364.

(4) 'A radioactive tracer method of estimating the retention time of seaweed in a rotary-louvre dryer',

Gardner, R.G., Mitchell T.J. & Scott, R., Chem. & Ind. 1952, p.448.

(5) 'Large scale drying tests on a Pehrson dual-process type grass dryer',

Gardner, R.G., Scottish Seaweed Res. Ass. Rept. 145, 1951.

CONTENTS

1. HISTORICAL INTRODUCTION.

Seaweeds range in size from the tiny, brightly-coloured plants found in rock pools at low tide, to the giant kelp Macrocystis pyrifera, which has the distinction of being the largest plant in the world (1).

A method of classifying seaweeds or marine algae that is often employed is determined by the habitat of the plant in relation to the tides. Algae which are uncovered by the tides are known as "littoral" or rock weeds, whilst the plants which are revealed only by very low neap tides are the "sublittoral" seaweeds. Some species can even exist in the splash zone, which as the name implies is just above high water mark.

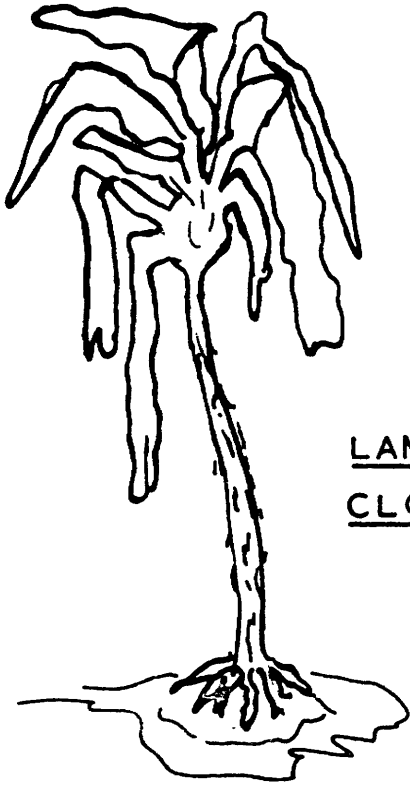
Common examples of British littoral weeds include Ascophyllum nodosum or bladder wrack, Rhodomenia palmata (dulse), Chondrus crispus which is carrageen or Irish Moss, and Chorda filum known as "sea bootlaces".

The sublittoral seaweeds, as distinct from the rock weeds, may be considered as having three distinct parts; the stipe, frond and holdfast.

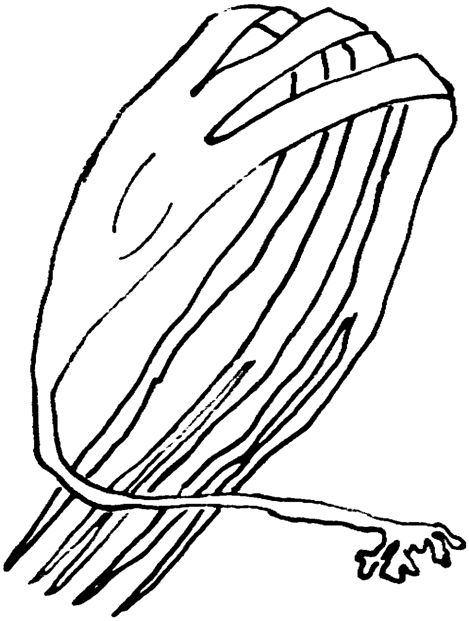
The stipe is the rigid stalk which enables the plant to stand upright, and corresponds to the stem of land plants. In mature seaweeds the stipe has almost a constant composition since comparatively little photosynthesis takes place. The frond on the other hand, which can be compared with leaves, is shed every spring and is the part of the plant where growth is most vigorous. The chemical composition of the fronds varies considerably during the year depending on the stage of growth.

The holdfast resembles in appearance the roots of ordinary plants, but the resemblance ends here as the function of this part is to anchor the plant to a rock or other suitable object.

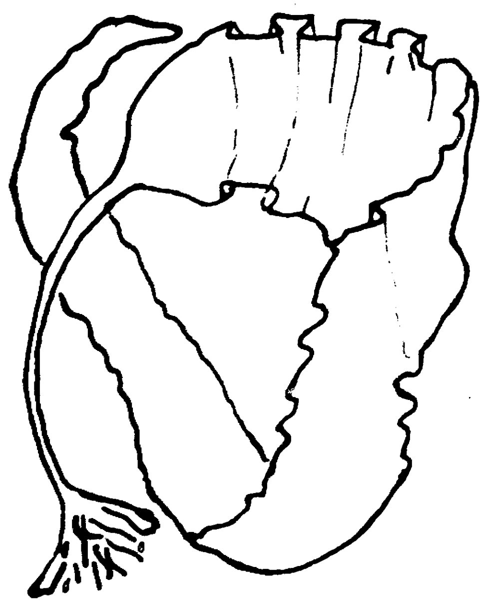
Proceeding from the water's edge to the sea, the first underwater species that would be encountered is Laminaria digitata - the "Tangle o' the Isles". This plant (Fig.1) has a smooth oval stipe



LAMINARIA CLOUSTONI.



LAMINARIA DIGITATA.



LAMINARIA SACCHARINA.

FIG. I.

terminating in a flat frond divided into fingers which gave it its name. Next in order would be found Laminaria saccharina, a species which has a crinkled ribbonlike frond. Finally at depths of 5 to 7 fathoms L. cloustoni would appear with its rough, sturdy, stipe often several feet long. This latter species is the commonest sublittoral plant indigenous to Scottish shores.

Seaweed growth does not continue indefinitely as the water increases in depth, as might be supposed, but beyond 8 or 10 fathoms the growth diminishes rapidly as the sunlight cannot penetrate to the sea bed.

1.1 USES OF SEAWEEDS

Past and present uses of seaweeds may be divided into two categories depending on whether the weed is used (a) directly in its fresh or dried state or (b) as raw material for the extraction of chemicals.

Crofters in Scotland, Ireland and Wales have used seaweeds as food for centuries, and during the occupation of the Channel Islands by the Germans in the recent war, the Islanders were obliged to use carrageen to thicken their soups (2). In Japan, seaweed has long been part of the people's diet and some seaweed varieties are regarded as delicacies by gourmets.

Seaweed has also been used as a manure for potatoes and as feeding stuff for poultry and stock. In the Shetlands, hardy sheep sometimes revert to a seaweed diet when there is a scarcity of pasture. The value of seaweed meal as a feeding stuff is undoubt--edly enhanced by the iodides and trace elements contained in the plants.

1.1.1. Chemicals from Seaweed.

Industries using seaweed as a source of chemicals probably originated with the Hebridean kelp burners who extracted soda from the ashes of the incinerated plants. At one time this was a flourishing trade, as kelp was the principal source of sodium carbonate for soap and glass-making, and in one year 20,000 tons were sent to Glasgow from the Western Isles. From that time onwards, however, the fortunes of the algal chemical industry alternately boomed and slumped.

Seaweed was seriously challenged as a source of soda by imports of Spanish barilla soda followed by the discovery of the Leblanc process and the repeal of the salt tax which ended the kelpers' prosperity. The industry revived again when Courtois discovered iodine in seaweed ash which he used in saltpetre manufacture, and Dr. Ure of Glasgow was the first to make iodine from the kelpers' harvest. Thirty years later, however, Lembert discovered iodine in Chile saltpetre and the kelpers no longer held the monopoly of this commodity. The Haber process for synthetic ammonia also affected seaweed interests indirectly, since the Chilean nitrate industry felt the competition on their main product and turned to increased production of iodine to offset their trading losses. This in turn stimulated research into improved methods of iodine extraction from algae, but in spite of this the seaweed iodine industry slowly declined.

The modern algal chemical industry had its foundation laid as far back as 1883 when E.C.C. Stanford of the North British Chemical Co. discovered alginic acid in brown marine algae (3). This discovery was not utilised until 1934 (4) when C.W. Bonniksen, a lecturer in London University, founded a company to manufacture Cefoil - a transparent wrapping paper similar in appearance to Cellophane. During the war when supplies of jute became scarce the Ministry of Supply conducted an intensive search for a substi--tute fibre suitable for military camouflage material. Alginate yarns provided the answer to this quest as they had the desirable qualities of weather and fire-resistance and could not be detected by infra-red photography.

1.2. THE WORK OF THE INSTITUTE OF SEAWEED RESEARCH.

At the end of the war the Scottish Seaweed Research Assoc--iation (S.S.R.A.) was formed to determine "whether the possibility existed of creating a stable Scottish seaweed industry which could compete with these of other countries and at the same time provide a considerable part time crofter industry in the Highlands and Islands" (5). Initially the S.S.R.A. was supported both by private industry and the Government but in 1951 the Scottish Sea--weed Research Association was dissolved and its place taken by the Treasury-financed Institute of Seaweed Research.

Scotland was selected as the headquarters of the Institute partly because of its long association with a seaweed industry but also because a large percentage of Britain's seaweed grows around Scottish shores.

1.2.1. Botanical Survey.

A fundamental requirement for the establishment of any industry is a knowledge of the quantity and quality of the raw materials on which it is to be based.

Accordingly one of the first tasks the Institute undertook was a botanical survey of the seaweed growing around the 5,300 miles of Scottish shores.

1.2.1.1. Littoral Survey. The survey of the plants growing in the zone between high and low water mark was relatively straightforward, as the density of growth could be measured by weighing the seaweed obtained from one square yard of rock. The predominating species were *A. nodosum* followed by *F. vesiculosus*.

This survey by Walker (6) revealed that there were approxi--mately 180,000 tons of rock weed around Scottish shores, of which nearly one third grew in the vicinity of Loch Maddy, North Uist.

1.2.1.2. Sublittoral Survey. A preliminary indication of the location of sublittoral weed beds was obtained by a study of

Admiralty charts, which eliminated areas of mud and sand on which seaweed will not grow. Observations on beaches near rocky areas showed if appreciable amounts of weed were torn adrift by winter storms. Aerial reconnaissance was also used to give some idea of the extent of the beds.

The laborious task of estimating the tonnages and species of seaweed in one such bed was carried out by the quadrat method. A survey boat took up position at a depth of 1 fathom, when a spring grab was lowered overboard. This grab closed as soon as it touched the sea bed and collected all the plants growing on half a square yard.

When the seaweed in this sample had been weighed and classified, the ship moved out at right angles to the shore until the two-fathom point was reached and a second sample was taken. This procedure was repeated at one-fathom intervals until the seaweed growth dis--appeared. The boat then moved 200 yards along the coast and the cycle of operations was repeated on a line parallel to the first. In this way an accurate estimate of the yield of seaweed in a bed was obtained.

A more rapid method was developed with the aid of the R.A.F. which enabled seaweed beds to be photographed in detail from fast flying aircraft. Years of boat work were thus saved as only occasional confirmatory samples were now required.

Results of this survey have indicated that Scottish coastal waters contain approximately 10,000,000 tons of sublittoral seaweed, of which L. cloustoni constitutes about 90%. Four million tons of this total is readily accessible, so that, as the sublittoral plants require about 4 years to grow to a reasonable size, a four-year harvesting cycle of one million tons per year has been suggested.

1.2.2. Chemical Survey.

Chemical analysis of the common sublittoral seaweeds has been reported by Black (7-10).

Samples of seaweed taken at monthly intervals over several years showed the seasonal variation in chemical constituents which can be expected and has enabled the potentially available quantities of algal chemicals to be assessed.

In addition to the alginates mentioned previously, sublittoral seaweeds also contain mannitol, laminarin, fucoidin, iodine, proteins, and small amounts of sterols, pigments, and vitamins.

Alginic Acid, the main structural carbohydrate of brown seaweeds, is a polymer of beta-D- mannuronic acid with a molecular weight of the order of 185,000.

Mannitol was first detected in *L. saccharina* by Stenhouse (11) and is known to be common to all brown seaweeds. This hexahydric alcohol is apparently in solution in the cell sap, for if a living plant is immersed in distilled water the mannitol diffuses outwards through the cell wall. Commercial mannitol is at present synthesised by the electrolytic reduction of fructose.

Laminarin in marine algae is considered to be reserve food material and is analogous to the role of starch in land plants.

Laminarin, which was first identified in seaweeds by Schmiedeberg (12), occurs principally in the fronds of the *Phaeophyceae.* The molecule consists of a chain of about 20 beta-D- glucopyranose units linked in the 1:3 positions (13,14). An interesting feature of this compound is that laminarin extracted from *L. cloustoni* is water insoluble whereas another form prepared from *L. digitata* and *L. saccharina* fronds is soluble in water. So far, no satisfactory explanation of this has been advanced.

Fucoidin is another cell-wall constituent and is a polysaccharide mono-sulphate ester based on fucose. It was first described by Kylin (15,16) and the constitution has been largely evaluated by Percival & Ross (17).

Proteins occurring in seaweed have recently been studied by Channing & Young (18) who detected leucine, valine, alanine, and glutamic and aspartic acids in the hydrolysates of A. nodosum and L. saccharina.

Pigments present in the brown algae include chlorophyll-a (19), fucoxanthin (20), and beta-carotene (21). Heilbron, Phypers & Wright (22) isolated fucosterol and its constitution was evaluated by MacPhillamy (23) and Hey, Honeyman & Peal (24).

Vitamins B_1, B_2 and C are present in the Phaeophyceae (25,26) but vitamin A is absent.

1.2.3. Harvesting of Seaweed.

With the quantity and quality of the seaweed established the next requirement is an economic method of harvesting the material. Collection of littoral seaweed presents no serious obstacles.

A large-scale harvesting test at Loch Maddy (27), indicated that the most effective procedure was to follow the receding ebb tide down the beach and continue cutting the seaweed from the rocks until low tide. At this stage the cut weed was forked into nets with a capacity of $\frac{1}{2}$ ton of wet seaweed and the net openings were secured. Cutting and netting was continued, in this case working in front of the advancing tide. On completion of the day's work the nets of seaweed were floated off the beach and towed to a central processing station by a small motor-launch. Up to 24 half-ton nets of seaweed can be transported in this manner. Harvest--ing rates of 15 cwt. of weed per man hour were consistently maintained during the test. If the rocks are not entirely denuded of seaweed, the plants will recolonize the area.

The problem of harvesting sublittoral seaweed is much more complicated.

L. cloustoni, the predominant sublittoral plant around Scottish shores, prefers rocky sea beds for its natural habitat. As it seldom grows at depths exceeding 8 or 10 fathoms, it is apparent that harvesting must be confined to hazardous inshore waters. In addition, these seaweed plants are invisible from the boat, and are denser than water. This is in contrast to the Californian species M. pyrifera which floats to the surface when cut, making its collection a simple matter.

A simple and effective harvesting gear developed by the Institute is the intermittent grapnel, which can be operated from small motor-boats or fishing vessels. These grapnels (Fig.2) are dragged along the sea bed for about two minutes, then hoisted on to the boat by a derrick and unloaded.

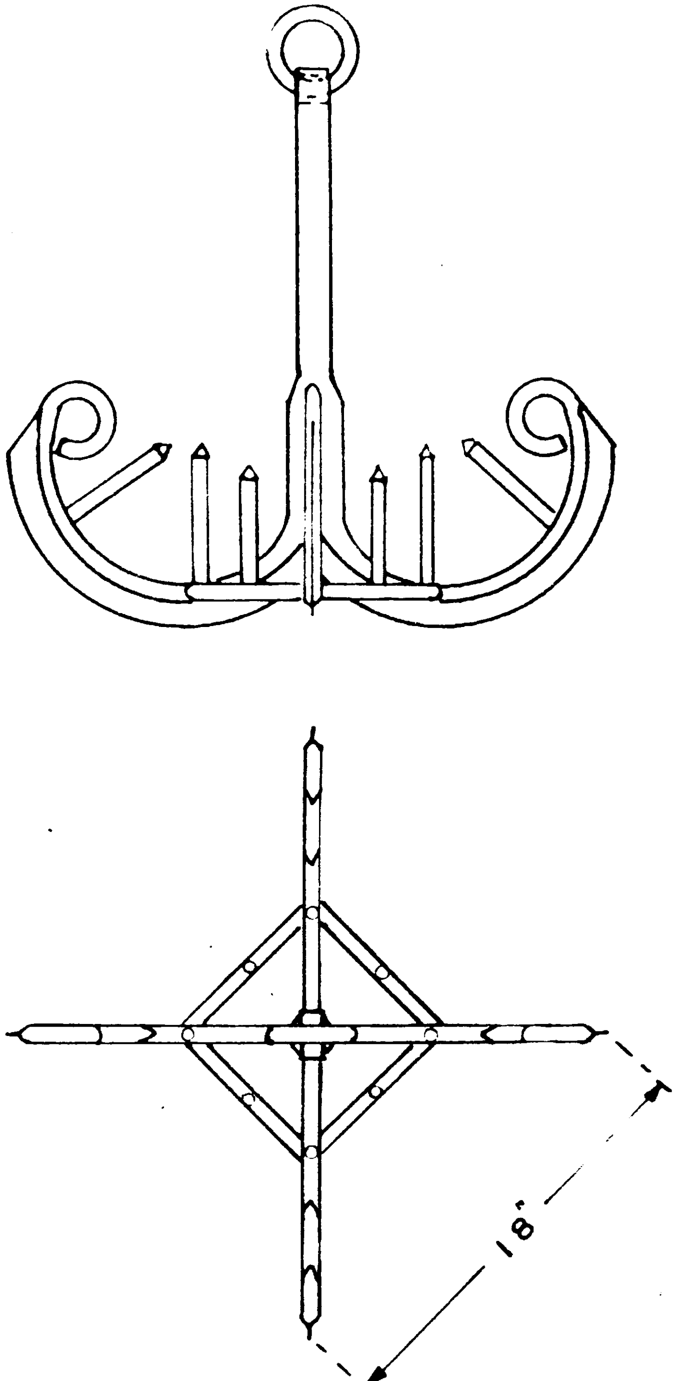
Mackenzie & Jackson (28) tested three sizes of these grapnels on weed beds off the Argyllshire coast and Table 1 lists the quantities of seaweed obtained from a 75 yards drag (based on 120 tests in each case).

TABLE 1.

Grapnel Size	1 ft 6 in	2 ft 3 in	3 ft 0 in
Average Weight/Drag, lb	161	233	328
Maximum Weight/Drag, lb	328	506	620

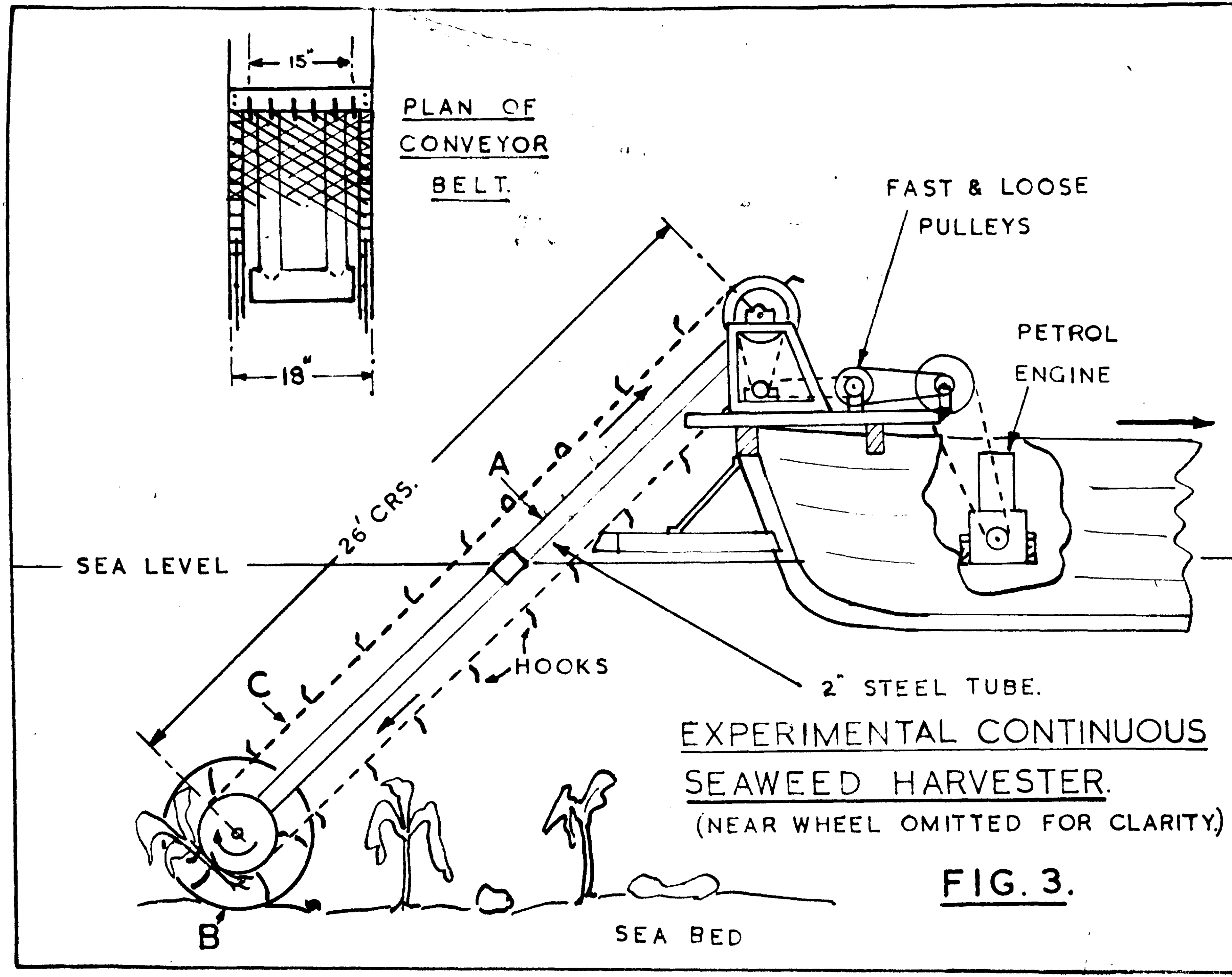
Grapnels are useful for part time harvesting work on account of their robust construction and low cost, but they are unsuitable for large-scale collection of seaweed because of their intermittent operation.

One solution to the problem of harvesting seaweed continuously has been provided by Hay (29) who designed a continuous short-hook grapnel. This apparatus (sketched in Fig.3) consists of a tubular frame A attached at its upper end to the stern of the boat and supported on the sea bed by a pair of rubber wheels B. Sprocket wheels at either end of the frame carry a wire-mesh conveyor belt C which has sets of hooks fixed across its width at regular intervals. In operation, the boat moves slowly forward and the belt is driven in the direction shown. As the belt contacts a bed of seaweed,



No. 1. GRAPNEL (18")

FIG. 2.



EXPERIMENTAL CONTINUOUS SEAWEED HARVESTER.
(NEAR WHEEL OMITTED FOR CLARITY.)

FIG. 3.

the plants are compacted into a 9 in layer until a set of hooks pulls the stipes from the rocks and conveys them to the boat. If the hooks catch on a large rock, the driving belt momentarily slips until the equipment is pulled clear of the obstruction. The arrangement of the hooks is such that there is little danger of large boulders being lifted from the sea bottom and dropped into the motor vessel. In addition the framework is sufficiently flexible to enable the wheels to ride over most obstacles.

Further refinements have been made to the design and in several short duration tests near Oban, harvesting rates of about 5 tons/hr were obtained in dense beds of L. cloustoni (30). Hay estimated (31) that a rate of 17 tons/hr should be possible under ideal conditions using a continuous grapnel similar to the experimental unit but with a 2 ft 7 in wide belt.

A third system, at present being developed by the Institute, is based on the cutting and entrainment principle (32). Tests have shown that reciprocating reaper blades are capable of cutting off the stipes close to the sea bed with remarkably slight damage to the cutters. The severed whole plants are then hydraulically conveyed to the surface by a water injector and flexible piping.

1.2.4. Extraction and Utilisation of Algal Chemicals.

Alginic acid, the longest established organic seaweed chemical, can be readily isolated by treating the seaweed with dilute mineral acid followed by a water wash and extraction with sodium carbonate solution. This is essentially Stanford's original process and two modern variants are Green's 'cold' process (33) and le Gloahec-Herter process (34). The resultant solution of crude sodium alginate is then purified and evaporated to give a white starch-like powder. The concentration of the sodium alginate solution must be kept below about 0.1% during processing, otherwise the liquid becomes difficult to filter and may even form a gel.

The gel-forming property of alginate is used in foodstuffs for cream or table jelly manufacture, and to thicken soups, sauces, etc. Artificial cherries can be manufactured which withstand reasonably high temperatures and so do not melt inside a cake during baking.

Sodium alginate has a widespread application as an icecream stabiliser. The colloidal nature of the alginate prevents the growth of ice crystals and forms a homogeneous mix. Addition of sodium alginate to fruit squashes prevents the formation of a thick sediment of fruit particles.

The ability of alginate to form fibres was the main reason for their development during the war for camouflage netting. Alginate fibres made from the calcium salt or the free acid suffer from the great drawback of being soluble in weak alkali. This defect prevented their widespread adoption as a textile fabric, since the material disappeared during washing. Beryllium and chromium alginates are more stable in this respect, but are correspondingly more expensive. These apparently insuperable disadvantages of alginates were ingeniously turned to good use in textiles by the so-called 'scaffold' technique.

Very fine woollen yarns cannot be woven as the tension of the loom snaps the threads, but a composite fibre consisting of a heavy alginate filament twisted with an ultra-fine woollen one can be woven satisfactorily. When the resulting fabric is given the normal finishing scour, the alginates dissolve, leaving a light-weight cloth with the lightness of cotton but the feel and warmth of wool. Astrakhan and intricate laces can similarly be woven on a temporary backing of alginate yarn.

Soluble alginate fibres have also proved to be of value in medicine. Alginate swabs may be left in the human body to give temporary support to a delicate organ, since the body fluids eventu--ally dissolve the compound. Similarly, the healing of burns may be assisted by the application of an alginate film dressing. When the new skin has formed over the wound, the alginate layer can be removed by washing with dilute sodium bicarbonate solution. Sodium alginate solution is also a valuable haemostatic agent as the calcium in the blood forms an insoluble compound with the algal chemical.

The following fine chemicals present in seaweed have not so far been exploited on a commercial scale. Extraction procedures for most of the other major algal constituents have been devised at the Institute, and pilot batches have been prepared to enable possible uses to be found for them by interested industrialists.

Mannitol can be isolated from seaweed on the laboratory scale by extraction with alcohol or weak acid (35). Laminarin is separated from the acid extract and the mannitol is recovered from the evaporated filtrate by solvent extraction, precipitation, or the use of ion-exchange resins.

Pilot-plant work has shown that methanol extraction of dried and ground seaweed is the most promising commercial method of mannitol extraction (32).

Mannitol is at present employed in the manufacture of detonators, pharmaceuticals and in synthetic resin manufacture. It may also have some application as a sugar substitute in a diabetic diet.

Laminarin (insoluble form) can be easily prepared on the semi-technical scale by a single hot dilute acid extraction of *L. cloustoni*, followed by centrifugal clarification and precipitation. Water soluble laminarin is precipitated from the filtrate by alcohol at a concentration of 85% (36).

Blaine (37) has demonstrated that soluble laminarin has a possible outlet as dusting powder for surgical gloves. Adhesions or other after-effects can be caused by the use of non-absorbable dusting powders, such as talcum, but laminarin is free from this defect as it is absorbed by the body. Alpha-D-glucose and methyl alpha-D-glucoside can be prepared from laminarin.

Fucoidin can be prepared by extracting the dried milled seaweed three times with ten volumes of hydrochloric acid (pH 2-2.5) at 70°C. for one hour (38). The crude product is isolated by fractional precipitation with alcohol and a purer product can be obtained on treatment with formaldehyde. This chemical is so new that its market assessment is far from complete; but it may have some applications in the adhesives industry.

1.3. SEAWEED DRYING

In the preceding review of seaweed chemical production one important unit operation was omitted - the drying of the seaweed.

Although all the constituents can be extracted from the dried seaweed, it is not always essential to have the material in this condition. Alginic acid has been extracted from the fresh plants (39), although in Britain it is customary to dry the algae near the shore and send the dehydrated product to a processing factory. If organic solvents are used as extractants, it will probably be necessary to have the water removed from the seaweed, otherwise the extract will be contaminated with mineral salts. Another advantage of dehydration is that the required constituent is concentrated in the raw material so that extraction will usually be more efficient and less material will have to be handled for a given output. It should be noted also that the most satisfactory pilot-plant extraction processes at present devised for mannitol and fucoidin are based on dried milled seaweed.

Alginate production in this country appears to be based on cast seaweed which is collected and air-dried by crofters. This partly-dried seaweed is sold to a drying station where it is further dried and ground before being despatched to a chemical factory for extraction. Air-drying enables a substantial proportion of the water to be evaporated from the seaweed without the use of fuel, but long drying times are required. A severe disadvantage of air-drying is that frond cannot be satisfactorily dried in this manner as decomposition sets in, and a valuable part of the plant is lost. Air-dried stipe is suitable for alginate production, but most of the remaining constituents are leached out by the action of rain and sea.

As any future algal chemical industry will almost certainly be concerned with the production of the newer carbohydrate chemicals now being developed, in addition to alginates, it will be essential to have freshly-harvested seaweed available for the starting material. If this seaweed cannot be extracted immediately, it must be preserved with its constituents intact until it is convenient for the processing to be completed. Storage of the material in the dried and milled state is a satisfactory and convenient method of preservation.

It follows that there are two possible situations of factories for the production of algal chemicals (a) a chain of factories within easy reach of the main seaweed beds, using fresh weed, or (b) a few central factories operating on dried seaweed supplied by several drying stations situated on the coastline.

As the number of days suitable for seaweed harvesting in Scotland range from 100 to 200 per year (32), it is clear that any factory dependent on fresh seaweed would be liable to numerous stoppages unless buffer stocks of seaweed were held. An obvious method of storage would be by drying, but recent experiments (32) have indicated that fresh seaweed may be preserved by ensilaging. If no degradation of chemicals takes place, ensilaging would probably be preferred to drying on account of its lower cost.

If, as in case (b), the seaweed was to be transported for appreciable distances to inland factories, drying is a prerequisite. Sublittoral seaweed usually has a water content ranging from 83-90%, so that it would be poor economics to carry 5 to 9 tons of water along with every ton of seaweed solids; moreover the bulk density of dried seaweed meal is much greater than that of the raw material. In the event of bad weather prohibiting mechanical harvesting, the drying stations would also be liable to stoppages, but it would doubtless be possible to collect cast plants to keep the dryer in operation. This secondary product would at least be suitable for alginate production. If it eventually became necessary to stop production at the drying station for a period, it is probable that the financial loss would be smaller than that incurred by the closing down of an entire chemical works.

The preceding discussion has assumed that the seaweed was intended for chemical production. If, however, the seaweed is to be incorporated in animal feeding stuffs, it will require to be in the dried state. This outlet in itself could probably absorb Scotland's potential production of dried seaweed, as the annual manufacture of dried feeding stuffs in Britain is of the order of 15 million tons. Ensilaged seaweed would probably be suitable for stock feeding but it would have to be utilised locally as the transport costs will again be high.

As a result of the high water content of fresh seaweed, it is apparent that any dehydration process must involve the minimum cost. This in turn requires that the most suitable drying method be found for seaweed and that the dryer be operated at optimum conditions.

This present work on seaweed drying is concerned with the solution to the problem.

2. THEORY OF DRYING.

Drying is normally taken to mean the removal of a liquid (usually water) from a solid when the amount of liquid present is relatively small, thus making a distinction between drying and evaporation or distillation. Drying, in general, also implies the thermal removal of water to differentiate the process from the mechanical unit operations of filtration, centrifuging and pressing. Dehydration is a term which apparently was originally introduced by the dried fruit industry of the Western U.S.A. to distinguish between fruit which had been sun-dried in the open and fruit which had been dehydrated in tunnels under controlled conditions (40). Nowadays the two terms are almost synonymous.

The following review of drying theory is almost wholly that of adiabatic air-drying of solids; other possible methods have been briefly considered under drying equipment (Section 3).

When a water-saturated solid is exposed to a stream of air under constant conditions of temperature, humidity and velocity, the surface behaves as a free water surface and drying proceeds at a constant rate. As long as the gas/liquid interface remains saturated the constant rate will continue, but when the supply of water to the surface fails to meet this requirement a falling-rate zone ensues. The average moisture content of the solid at the changeover is defined as the critical moisture content.

The falling-rate period, which may in some instances be composed of two zones, then persists until drying is complete. The two principal mechanisms which have been postulated for water movement inside solids during drying - diffusion and capillarity - have been treated separately, together with a discussion on the drying of vegetable material.

The ultimate aim of most drying theories and formulae is to enable the drying times or rates for various solids to be predicted under a given set of air conditions. Water may be held in solids in a wide variety of ways, e.g. in the interstices between granules or fibres, inside cells enclosed by permeable or impermeable membranes, adsorbed on walls or in loose combination as water of hydration. Considering these possible numerous variations it is hardly surprising that there is no one solution to cover all conditions, and as a result of the complexity of the equations advanced so far, it is frequently much simpler and more accurate to conduct a drying test on the material in question to supply the information required.

2.1 THE EVAPORATION OF WATER

One of the earliest quantitative observations on the evaporation of water was made by John Dalton in 1802 (41). He found that the evaporation rate of water from small heated pans was proportional to the difference between the vapour pressure of the water and the aqueous vapour pressure of the ambient air, and that this relationship was independent of the air temperature.

Since this early observation, the film concept of evaporation has been developed which postulates the existence of a static gas film adjacent to the evaporating surface. The vaporizing liquid is transferred through the laminar layer by diffusion and becomes mixed in the turbulent stream beyond. Smith (42) states that at normal temperatures the rate of escape of molecules from a water surface would be about 1500 lb/(hr)(sq.ft.) according to the kinetic theory, but because of the resistance of the film practical rates are only 10^{-4} or 10^{-5} times as great.

Mass transfer through this gas film may be expressed (43) by the equation :-

$$dW/d\Theta = K\,A\,(p_w - p_a) \quad \ldots\ldots \text{Eqn.1}$$

where $dW/d\Theta$ = diffusion or drying rate, lb/hr,

K = film coefficient of diffusion, lb/(hr)(sq.ft.)(atm partial pressure difference),

A = drying surface, sq.ft.,

p_a = partial pressure of water vapour in air, atm,

p_w = partial pressure of saturated air at the water/air interface, atm, = vapour pressure of water at the surface temperature.

The humidity driving force may also be expressed as lb water/lb dry air using an appropriate film coefficient.

In any drying process there is a simultaneous heat transfer to the surface as the flow of heat must be equal to the latent heat of vaporization of the water. Thus the general heat balance for the evaporation becomes -

$Z\ dW/d\theta = Z\ K\ A\ (p_w - p_a) = h\ A_s\ (t_a - t_s)$ Eqn.2

where Z = latent heat of water at t_s,

A_s = surface area through which heat flows, sq.ft.,

h = mean film coefficient of heat transfer based on A_s, B.Th.U/(hr)(sq.ft.)(^oF),

t_a = air temperature ^oF,

t_s = temperature of surface through which heat is transferred, ^oF.

If a quantity of air at temperature t_a is brought into prolonged and intimate contact under adiabatic conditions with water at a lower temperature, the sensible heat of the air evaporates water until the air becomes saturated at the water temperature. This temperature (t') which is a characteristic property of the air, is known as the tempera--ture of adiabatic saturation (44). The difference between t_a and t' is a measure of the evaporative capacity of the air.

If now a small water surface is inserted in a stream of air, it will assume a temperature t_w resulting from the dynamic equilibrium between heat supply and water evaporation. This equilibrium tempera--ture t_w is the wet-bulb temperature of the air. Fortunately, for water/air systems at moderate temperatures the wet-bulb temperature and adiabatic saturation temperature are numerically very close, so that for adiabatic evaporation the drying rate is proportional to $t_a - t' = t_a - t_w$ = wet-bulb depression.

Equation 2 represented the general case, but for adiabatic conditions where there is no heat transferred by radiation and where $A_s = A$, a simplified equation may be used :-

$dW/d\theta = h_c\ A\ (t_a - t_w)/Z$ ..... Eqn.3.

where h_c = heat-transfer coefficient by convection and conduction.

The heat and mass-transfer coefficients depend principally on the film thickness which is controlled by the direction and velocity of the air stream relative to the surface. This was clearly demonstrated by Shepherd Hadlock & Brewer (45) who correlated the data of several workers and expressed the transfer coefficients for constant-rate drying in terms of the air mass velocity :-

$$K = 0.0512\ F^{0.75} \text{ and } h_c = 0.017\ F^{0.76} \quad \ldots\ldots \underline{\text{Eqn.4.}}$$

where F = air flow parallel to surface, lb/(sq.ft.)(hr).

In the above equations, drying was assumed to occur at the wet-bulb temperature.

Sherwood & Comings (46) found that the initial evaporation rates for a wide variety of materials was substantially the same for a given set of air conditions, demonstrating that the constant rate was a function of the surface film and was independent of the material characteristics. In addition the rate of drying per unit of surface area was unaffected by shrinkage and is independent of the thickness of the solid.

2.1.1. Mass Transfer from Single Surfaces

For non-adiabatic evaporation where heat is not supplied to the surface solely by the air stream, the surface temperature will be higher than the wet-bulb temperature.

Powell & Griffiths (47) studied the evaporation of water from a wetted surface maintained at a constant temperature in a tangential air current. They derived the expression :-

$$dW/d\theta = 2.12\ \ 10^7\ x^{\ 0.77}\ y(p_w - p_a)(1 + 0.121\ U^{\ 0.85}) \quad \ldots\ldots \underline{\text{Eqn.5.}}$$

where x & y = length and breadth of the surface, cm,

U = air velocity, cm/sec.

The local evaporation along the length of the surface decreased from the leading edge so that the evaporation was not directly proportional to the area. Powell (48) later showed that for all solid shapes the rate of evaporation per unit area increases as the surface area diminishes, and that large surfaces approach a common value regardless of the shape of the object. A sphere gave the highest rate of evaporation for a solid of specified area.

While transfer coefficients have the advantage of simplicity, they cannot be easily related to the properties of the gas film, but this has been overcome by employing dimensionless groups.

Film properties which affect heat transfer are the heat capacity (C), viscosity (μ) and thermal conductivity (k). If these three quantities are combined, i.e. $C\mu/k$, a dimensionless parameter is obtained, known as the Prandtl number (Pr) which includes all the relevant factors. The corresponding group for mass transfer is the Schmidt number (Sc) = $\mu/\rho D$ where ρ is the gas density and D the diffusivity of gas in the film.

Colburn (49) developed the dimensionless j factors to simplify the correlation of heat and mass transfer data. The factors are defined by the following equations :-

For heat transfer, $$j_h = \frac{h\ (Pr)^{0.67}}{CG}$$ ..... Eqn.6.

For mass transfer, $$j_d = \frac{k\ p_{gf}\ M(Sc)^{0.67}}{G}$$ ..... Eqn.7.

where p_{gf} = log mean partial pressure of inert gas over the gas film,
M = mean molecular weight of gas.

The air velocity can be expressed as a dimensionless group by using the well known Reynolds number $Re = Vd\rho/\mu$ where V = air velocity and d = diameter of duct. Colburn (49) showed that the transfer coefficients should not be plotted against Re since this was equivalent to plotting a variable against itself, and that this error could be avoided by using the j factors.

Maisel & Sherwood (50) studied the effect of turbulence in the air stream on the mass transfer of water from single spheres and cylinders. Turbulence is characterised by its scale and intensity. Scale is the size of the eddies whereas intensity is related to the local fluctuations of velocity at a given point in the stream. Maisel & Sherwood showed that the turbulence intensity increased the mass transfer sharply but the size of the eddies had little effect.

They concluded that the intensity of the turbulence reduced the laminar layer where molecular diffusion controls, but that the scale has little effect on the overall transfer since the eddy diffusion in the turbulent core represents only a small fraction of the total resistance to mass transfer.

Data on the evaporation of water, carbon tetrachloride, and benzene into streams of air, carbon dioxide, and helium have been reported by Maisel & Sherwood (51). The results were successfully correlated as a logarithmic plot of j_d versus Re.

Linton & Sherwood (52) investigated the solution rate of tubes, cylinders, plates and spheres of benzoic acid, cinnamic acid and beta-naphthol into water streams. With these materials the Schmidt numbers were in the range 1000 - 3000. It was found that the exponent of the Schmidt group used in the definition of the j_d factor was - 0.67 as had been predicted by Chilton & Colburn (53).

2.1.2. Mass Transfer from Beds of Solids

Gamson, Thodos & Hougen (54) investigated the constant-drying rate of beds of spherical and cylindrical catalyst pellets and presented their data as a single line on a logarithmic plot of j_d and j_h versus Re. They defined the effective particle diameter (D_p) of a cylinder as that of a sphere with the same surface area.

Wilke & Hougen (55) extended the data of Gamson *et al.* for turbulent flow to the streamline region. Taecker & Hougen (56) evaluated transfer factors for the evaporation of water from Raschig rings, partition rings and Berl saddles in a packed tower. The packings had a high porosity and capillarity to enable a long constant rate period to be obtained. Taecker & Hougen correlated j factors with a Reynolds number in which D_p was replaced by A_p (A_p = total surface area of particle) as it was difficult to visualise the significance of the diameter of a Berl saddle. The data for each of the tower packings gave straight lines, but were displaced from the lines obtained by Gamson et al. for other shapes. As the internal surfaces of the rings were less accessible to the air stream, the j factors for these shapes were lower than the common line for spheres and cylinders.

Hobson & Thodos (57) obtained mass-transfer data for organic liquids which had been absorbed on spherical pellets and were then extracted by a water stream passing through the bed. The systems were methyl ethyl ketone/water and isobutyl alcohol/water. Hobson & Thodos were able to correlate data on the basis of j factors which agreed with the general line of Gamson et al. even although the Schmidt number showed a 2000-fold variation. McCune & Wilhelm (58) likewise obtained a similar correlation for the system beta-naphthol/water.

Gamson (59) attempted to consolidate the existing data on cylinders, spheres, partition rings, Berl saddles and flakes on to a single line. He introduced a new Reynolds number by converting the particle diameter of a sphere to a specific surface by the relationship :-

$$D_p = \frac{6\,(1-E)}{a} \quad \text{so that} \quad \frac{D_p\,G}{\mu(1-E)} = \frac{6\,G}{a\,\mu}$$

where a = effective area per unit volume of bed, E = void fraction. A plot of $j_d/(1-E)^{0.2}$ versus $6\,G/a\mu$ gave a single line for all the available mass transfer data for spheres in fixed or fluidised beds. Other shapes when plotted on the same graph gave straight lines which were displaced below the line for spheres. This was attributed to portions of the particle surfaces in the bed being unavailable for mass transfer owing to contact with adjacent objects. In the case of spheres, the total surface is available as the particle-to-particle contact is at a point only, so that the maximum transfer will be obtained. Data for other commercial packings were made to fall on the plot for spheres by inserting a shape factor (ϕ) in the Reynolds number, i.e.

$$Re(M) = \frac{6\,G}{a\phi\mu}$$

where the shape factor equals the fraction of total surface available for transfer. Values of ϕ ranged from unity for spheres to 0.67 for partition rings.

The resulting general equation for j factors for a fixed bed of solids at Re(M) above 100 now becomes :-

$$j_d = 1.46 \left[\frac{6\,G}{a\phi\mu}\right]^{0.41} \cdot (1-E)^{0.2} \quad \ldots\ldots \underline{\text{Eqn.8.}}$$

2.2. MOVEMENT OF WATER BY DIFFUSION IN A SOLID DURING DRYING

Diffusion may be defined as the spontaneous intermixing of molecules or very small particles. This mixing, according to the kinetic theory, is caused by random thermal motion of the particles concerned. Diffusion tends to take place from regions of higher concentrations to areas of lower concentrations, and this diffusion potential is increased as the concentration gradient is increased.

The general differential equation for variation of water content in a solid with time and distance for unidirectional flow is

$$\frac{\partial T}{\partial \theta} = D\left(\frac{\partial^2 T}{\partial x^2}\right) \quad \text{..... Eqn.9.}$$

where T = water content subject to diffusion (dry basis),

θ = elapsed time,

D = diffusivity of the liquid through the solid,

x = distance measured from mid-plane of solid in the direction of diffusion.

The general differential equation for diffusion can be integrated for various boundary conditions only.

In 1921, Lewis (60) derived a formula for the falling-rate period of drying for sheet material. This formula was based on the simplify--ing assumptions that (a) the water-content gradient from the centre line to the surface of the sheet was linear, and that the diffusion rate of water to the surface was (b) proportional to the difference between the average water content of the sheet and the surface value and (c) was inversely proportional to the distance to be traversed.

Lewis showed that :-

$$\frac{-dT}{d\theta} = \frac{8\,A\,r\,T}{a(4A + ra)} \quad \text{..... Eqn.10.}$$

where T = total water content (dry basis),

θ = elapsed time,

A = proportionality constant,

r = coefficient relating evaporation to surface water content,

a = thickness of sheet.

If the air conditions are constant and the initial water content is sufficiently high the evaporation rate is constant, so that

$$\frac{8\,A\,r\,W}{a(4A + ra)} = \text{a constant } K = \text{the drying coefficient.}$$

On integration,

$$\log (T - E) = - K\theta + \text{a constant},$$

or,

$$\log \left[\frac{To - E}{T - E}\right] = \log \frac{Wo}{W} = K\theta \quad \ldots\ldots \underline{\text{Eqn.11.}}$$

where To = water content at zero time,

E = equilibrium water content of material,

W = free water content at any time = T - E,

Wo = initial free water content.

W/Wo is called the unaccomplished moisture change.

This means that if the drying rate is linear with respect to free-water content, the time in the falling-rate period is proportional to the fractional reduction of free-water content, irrespective of the value of the free-water content.

It follows that where internal diffusion rate is high compared with the surface evaporation rate, the drying coefficient K approaches $2r/a$, whereas if diffusion is slow the constant becomes $8A/a^2$.

Confirmation of these conclusions was obtained by Lewis from results of drying experiments on these two classes of material. Data for heelboard (ground leather and paper) showed that K was inversely proportional to the sheet thickness. Cord was dried by passing it over a heated drum and it was demonstrated that the effect of air velocity was small as internal diffusion controlled the evaporation rate for this material. The drying rate was found to be proportional to the inverse square of the twine diameter.

Where internal diffusion is very slow in a thick layer of material (soap or wood) so that the diffusion gradient is not rapidly established, Lewis found that the drying time was proportional to the square of the thickness and to the square of the loss of water from the start :-

$$\theta = \frac{a^2}{4A}\left[\frac{T_o - T}{T_o - E}\right]^2 \quad \text{..... \underline{Eqn.12.}}$$

Sherwood, in the first of a series of papers on the mechanism of drying, postulated (61) four general ways in which water (in liquid or vapour form) moved out from a solid during drying.

Case I Evaporation at the solid surface: resistance to internal diffusion small compared with the resistance to removal of vapour at the surface.

Case II Evaporation at the surface: internal resistance large compared with the surface resistance to vapour removal.

Case III Evaporation in the interior of the solid: resistance to internal diffusion small compared with the total resistance to vapour removal.

Case IV Evaporation in the interior: internal resistance great compared with the total resistance to the removal of vapour.

In a later publication (62) he withdrew Case III as it did not occur in practice. He considered that evaporation takes place inside a solid because the resistance to liquid diffusion is high.

For Case II relating to an infinite slab of thickness 2a, Sherwood provided a solution of the diffusion equation by assuming that (a) Newton's law of diffusion held for this case, (b) liquid diffusivity was constant, (c) diffusion took place in a direction perpendicular to the surface, (d) initial liquid concentration was uniform, and (e) the resistance to diffusion at the surface was negligible, i.e. the surface was dry or at its equilibrium water content. The solution is given on Fig. 4, Eqn. $\overline{\underline{I}}$.

Equation $\overline{\underline{I}}$ relates W/W_o to $D\theta/a^2$ for a given slab. Sherwood plotted W/W_o versus θ on special scales to force the relationship into a straight line and enable the diffusion coefficient D to be found by comparison of the slopes of the theoretical and experimental lines. The ratio of the two lines (on a semilog plot) gives the quantity D/a^2. As 'a' is known, D can be evaluated.

When drying times are large, Eqn. $\overline{\underline{I}}$ may be simplified to :-

$$\frac{W}{W_o} = \frac{8}{\pi^2} e^{-D\theta\left(\frac{\pi}{2a}\right)^2}$$

and hence

$$\frac{dW}{d\theta} = -\frac{\pi^2 D W}{4a^2} \qquad \ldots\ldots \quad \underline{\text{Eqn.13.}}$$

In other words, when diffusion controls over a long period, the drying rate is directly proportional to the free water content and the liquid diffusivity. This holds only when W/W_o is less than about 0.6.

Sherwood (63) next classified the two distinct falling-rate periods (obtained when drying paper pulp, whiting and clay slabs) into (a) the zone of decreasing wetted surface and (b) zone of internal diffusion controlling.

For zone (a), he considered that evaporation took place at the surface after the constant-rate period was finished and the decrease in drying rate resulted from dry patches appearing and reducing the water surface from which evaporation took place. He arrived at this conclusion from experiments which showed that the heat-transfer coefficient during the first falling-rate period was substantially the same as the value during the constant-rate period. This reason--ing was confirmed by the fact that the humidity of the drying air

EQN. I. $$\frac{W}{W_0} = E = \frac{8}{\pi^2}\left[e^{-D\theta\left(\frac{\pi}{2a}\right)^2} + \frac{1}{9}e^{-9D\theta\left(\frac{\pi}{2a}\right)^2} + \frac{1}{25}e^{-25D\theta\left(\frac{\pi}{2a}\right)^2} + \cdots\right]$$

EQN. II. $$\frac{T - T_E}{T_0 - T_E} = \frac{4}{\pi}\left[\cos\frac{\pi X}{2a} e^{-D\theta\left(\frac{\pi}{2a}\right)^2} - \frac{1}{3}\cos\frac{3\pi X}{2a} e^{-9D\theta\left(\frac{\pi}{2a}\right)^2} + \cdots\right]$$

EQN. III. $$T - T_E = T_M - T_E \sum_1^\infty 2e^{-\left(\frac{D\theta}{a^2}\right)\beta_n^2} A_n \cos\frac{\beta_n X}{a} - T_M - T_E \sum_1^\infty 2e^{-\left(\frac{D\theta}{a^2}\right)\beta_n^2} B_n \cos\frac{\beta_n X}{a}$$

WHERE $$A_n = \frac{ha}{[(ha)^2 + \beta_n^2 + ha]\cos\beta_n}, \quad B_n = \frac{2\beta_n^2 + ha\beta_n^2 - 2ha}{\beta_n^2[(ha)^2 + \beta_n^2 + ha]\cos\beta_n}$$

EQN. IV. $$\frac{W}{W_c} = E' = \frac{24 T_s}{\pi^2(T_s + 2T_M)}\left[e^{-p} + \frac{1}{9}e^{-9p} + \frac{1}{25}e^{-25p} + \cdots\right] + \frac{192(T_M - T_s)}{\pi^4(T_s + 2T_M)}\left[e^{-p} + \frac{1}{81}e^{-9p} + \frac{1}{625}e^{-25p} + \cdots\right]$$

WHERE $$p = \frac{D\pi^2\theta'}{4a^2}$$

EQN. V. $$T_0 - T\left(\frac{D\rho}{Ma}\right) = \left[\frac{(X-a)^2}{2a^2} - \frac{1}{6} + \frac{D\theta}{a^2} - \frac{2}{\pi^2}\sum_1^\infty \frac{(-1)^n}{n^2} e^{-n^2\pi^2\frac{D\theta}{a^2}} \cos n\pi\frac{(X-a)}{a}\right]$$

FIG. 4

influenced the drying rate in this region.

The zone where internal movement of liquid controlled the rate of evaporation was characterised by the heat-transfer coefficient (from the mid-plane of the solid to the air stream) decreasing sharply after the constant-rate period. In addition, air velocity and humidity had little influence on the drying rate which was inversely proportional to the slab thickness.

Moisture distribution curves measured in the solid after drying for various times showed a zone adjacent to surface which had a uniform moisture content lower than that of the interior. This suggested that subsurface evaporation occurred as the flow of liquid was insufficient to maintain evaporation at or near the surface. Sherwood further showed that the locus of evaporation depended on the nature of the material, e.g. for porous material like paper pulp subsurface evapora--tion was more likely to occur than in the case of less porous material such as brick clay.

Newman (64) made a useful contribution to the theory of drying by providing equations which he showed were solutions of the differential equations for diffusion. Making the same assumptions as Sherwood (61), Newman showed that Eqn.$\overline{\text{II}}$, Fig.4. was a solution for the infinite slab where T, T_E and T_O are respectively the water contents in the solid at any time, at equilibrium and initially. The equation enables the moisture content at any position X after time θ to be evaluated. Since for drying calculations the average water content at a given time is more useful than the moisture distribution curve, Newman integra--ted Eqn.$\overline{\text{II}}$ and obtained an expression giving the average water content as a function of time. This equation was identical with that given by Sherwood (Eqn.$\overline{\text{I}}$, Fig.4.).

Newman provided similar equations for the cylinder and sphere. All the equations embody the dimensionless ratio $D\theta/a^2$ which can be plotted against the ratio of initial to final free water content, giving a characteristic curve for each of the three solid shapes.

In a second paper (65), Newman criticised Sherwood's postulate that the water content at the solid surface remained in equilibrium with the air. He argued that if this were strictly true, the drying rate would be zero, since there would be no driving force to cause evaporation.

Newman made the alternative suggestion that the rate of surface evaporation at any instant during the falling-rate period, is proportional to the free water content at the surface. He provided diffusional equations for the cases where the initial water distribution in the solid was (a) uniform and (b) parabolic.

Eqn. $\overline{\text{III}}$, Fig.4, gives the solution for the parabolic distribution

where $h = \frac{M}{D}$,

M = surface evaporation rate lb/(sq.ft.)(hr) when surface concentration is 1 lb/cu.ft.,

$ha = Ma/D$ = a dimensionless ratio,

Tm = water content at the mid-plane, $\cot \beta n = \beta n/ha$.

The integrated form of Eqn. $\overline{\text{III}}$ may be represented simply as

$$W - T_1 = (Tm - T_1)\,A - (Tm - Ta)\,B.$$

Newman tabulated values of A and B for different values of ha and $D\theta/a^2$ for the slab, cylinder and sphere. From these equations the diffusivity can be calculated and the relative resistances of the surface film and internal diffusion evaluated (66).

Sherwood (61) had previously given an equation for an infinite slab where internal liquid diffusion controlled the drying rate on the assumption that the initial moisture content distribution was uniform. This was true where liquid diffusion controlled from the start of drying, but if there was an initial constant-rate period, the water distribution would be non-uniform. Sherwood showed theoretically (67) that in the latter case the water-content distribution would be parabolic at the end of the constant-rate period. This has been confirmed by the experimental evidence of Troop and Wheeler (68) on drying clay cylinders.

Using this finding, Sherwood modified a solution of the basic diffusion equation by Carslaw (69). Sherwood's solution is given as Eqn. IV , Fig. 4.

where T_s = water content at the surface.

Previous data on brickclay (61), plotted on specially-scaled paper, gave an initial curvature due to the non-uniform water distribution at the end of the constant-rate period. When the fraction of the critical free-water content was plotted against $D\theta'/a^2$ (θ' = elapsed time from critical moisture content) for Eqn. I on special paper, the line still had a marked curvature. Sherwood considered that this departure from the theoretical curve might be due to a change of D with water content.

Sherwood and Comings (46) carried out tests on clays, sands and porous plate and obtained drying curves with a constant rate and two falling-rate periods. Sherwood and Comings concluded from this that surface evaporation controlled at first, then liquid diffusion became the vital factor, and that their data did not support Newman's view (65) that there was a finite surface resistance during drying in the second falling-rate zone. They differentiated Newman's curves to obtain $\frac{dE}{d\theta} \cdot \frac{a^2}{D}$ which they plotted against E for values of ha ranging from 0.1 to 10 ($E = \frac{W}{W_o}$). This plot of drying rate versus moisture content gave curves which were concave upward in the first falling-rate period and linear in the second falling-rate zone. This required the drying rate to be a function of ha and hence air velocity at very low water ratios which was just the reverse of experimental findings. Sherwood and Comings concluded that Newman's theory of the relative magnitude of internal and surface resistances to drying did not explain the two falling-rate periods satisfactorily.

In an earlier paper (67), Sherwood had shown theoretically that the moisture content distribution in a slab of material at the end of the constant-rate period would be parabolic, provided internal diffu--sion controlled the movement of water at the critical point. The time required for a parabolic distribution to be reached depends on the nature and thickness of the slab and on the value of the constant evaporation rate. Gilliland and Sherwood (70) derived an expression (Eqn.$\overline{V}$, Fig.4) relating the critical moisture content of a slab to the surface evaporation rate and the liquid diffusivity. Gilliland and Sherwood presented Eqn.$\overline{V}$ as a plot of $\frac{(T_0 - T) D\rho}{aM}$ versus $\frac{D\theta}{a^2}$ for various fractional thicknesses.

Where M = surface evaporation rate

ρ = mass of dry solid per unit volume.

Hougen, McCauley & Marshall (71) sounded a note of warning on the indiscriminate application of diffusional equations to drying problems where other mechanisms of water movement were operative. They adopted as a criterion the shapes of the water-content/distance curves as determined experimentally, and showed that the shape of the distribution curves calculated from the diffusion equations did not agree with the observed shapes, although the average moisture content of the material, after a given drying time, had been reasonably accurately predicted by the equations.

Hougen *et al.* concluded that diffusion of liquid water in solids during drying occurred when bound water was being evaporated, i.e. where the equilibrium moisture content was below the point correspond--ing to atmospheric saturation. These conditions were approached in the last stages in the drying of clays, textiles, paper and wood. If the solid and water were mutually soluble (as in the case of soap, glue, gelatines or pastes) they considered that diffusion took place. Hougen *et al.* suggested that calculations made for these cases should allow for the variation of diffusivity of the material with water content, temperature and density. Where the water is contained in cell cavities and interstices or is present on the surface, Hougen *et al.* concluded that gravity and capillarity controlled the liquid movement.

Van Arsdel (72) considered that the movement of water in vegetables in the low-moisture region (below 0.2 lb water/lb B.D.S.)

corresponded to a system in which liquid diffusion controlled. He suggested that the failure of predicted drying curves to agree with experimental results was due to assuming that (a) the liquid concentration difference is the driving potential and (b) the diffusivity is independent of moisture content.

Van Arsdel devised an approximate numerical method of calculation based on mass balances over small finite solid thicknesses for small time increments. As the study was confined to nearly dry material, shrinkage and temperature gradients were neglected.

In diffusion studies, the conductivity of the solid to moisture movement is referred to as permeability when the driving force is vapour pressure, and diffusivity when the potential is water content. The diffusibility (D) is related to the permeability (P) by the expression

$$D = \frac{P\,dp}{s\,dT}$$

where $\frac{dp}{dT}$ is the moisture-content/vapour-pressure isotherm of the material.

The general diffusional equation for variable permeability is

$$\frac{\partial T}{\partial \theta} = \frac{1}{s} \cdot \frac{\partial}{\partial x}\left(P.\frac{\partial p}{\partial x}\right) \quad \ldots\ldots \text{ \underline{Eqn.14.}}$$

where s = weight of dry solids per unit volume.

Permeability is usually expressed as a function of the moisture content of the material, but it can also be related to the vapour pressure via the equilibrium moisture content curve. If consistent units are used the solution of the basic diffusion equation will be the same whether the driving potential be vapour pressure or concentration, although the intermediate points may differ if the permeability and diffusivity are assumed to be constant in their respective equations.

By assuming a constant permeability in a sample of carrots, Van Arsdel obtained sigmoid moisture distribution curves which had hitherto been considered to be inconsistent with the behaviour of diffusion in slabs (73).

Van Arsdel assumed in his calculations that (a) negligible error is introduced when the flow of water in the first increment is based on the initial potential gradient (b) the time interval selected was sufficiently small to neglect errors due to the effect of other increments, apart from those immediately adjacent and (c) the size of the element was small enough to enable the moisture content to be based on the potential at its centre.

By this method the change of partial pressure was plotted through the solid and the corresponding water contents were calculated from the vapour pressure isotherm. Van Arsdel investigated the effect of the change of permeability with water content on the shape of the drying rate curves, and found that the curves were comparable with typical experimental results. No simple relationship was found between the shape of the permeability function and the form of the drying rate curve.

It has also been shown that the drying rate is inversely proportional to the square of the thickness, provided the surface film resistance is negligible, irrespective of the form of the permeability function. This is a confirmation of the classical theory of diffusion.

2.3. MOVEMENT OF WATER BY CAPILLARITY IN A SOLID DURING DRYING

In the preceeding section, the theories of diffusional movement of water inside solids during drying were considered. Where the solids are granular, as in the case of sands, clays, whiting, etc., other mechanisms may govern the movement of water. Water movement in such instances may be caused by absorption, gravitational or surface tension effects.

Haines (74, 75) studied extensively the moisture distribution in unsaturated beds of granular solids, using for simplicity, small equally-sized spheres arranged in closest packing. Haines concluded that the movement of water in such a bed was produced by a suction resulting from the interfacial tension, and he distinguished three forms of water distribution in a bed of spherical particles.

In the first state - the pendular state - the water is present as separate lens-shaped rings round the points of contact of the spheres. The funicular state occurs when the water content is increased until all these rings link up, forming a continuous network of water around the air pockets. Lastly, the capillary state results when all the interstices of the bed are filled with water. The moisture contents for these three distributions can be calculated from a knowledge of the shapes and sizes of the interstices formed by the six regular methods of packing spheres.

The mechanism of water movement postulated by Haines is as follows :-

As the water is evaporated from a saturated bed of spheres, the water surface in the waists between two particles in the top layer is depressed into the opening, and a suction is developed which increases until eventually air is drawn into the pore. The value of the suction at this instant is the entry suction, which is a measure of the force tending to draw water from the interior to the surface.

The value of the entry suction is given by the formula

$$p = \frac{C\,\gamma}{r\,\rho\,g} \qquad \ldots\ldots \text{ Eqn.15.}$$

where C = a constant ranging from 12.9 for rhombohedral packing to 4.82 for cubical packing

Y = surface tension

g = gravitational constant

ρ = density of liquid

r = radius of pore.

In a bed of random packed spheres, the most open pores (cubical) will have the lowest entry suction, and will therefore be the first to suck in air.

As drying proceeds, the water in these cubical pores is drawn to the surface by the higher capillary suction of the finer pore spaces at the surface. Cubical pores at increasing depths in the bed open successively until the suction at the surface is sufficiently high to open the next most open pore, the increased suction being provided by the slight retreat of the remaining menisci into the waists.

A pore situated h cm from the surface with an entry suction of p_h requires a higher surface suction to open it, as follows :-

$$p_s = p_h + h \quad \ldots\ldots \text{ \underline{Eqn.16.}}$$

The pores are progressively opened until eventually the suction potential is sufficient to open the finest surface pores (rhombohedral) when the surface evaporation ceases. The saturated water level then retreats from the surface of the bed and evaporation takes place by vapour diffusion from the centre of the bed.

Haines measured the suction potential of beds by using a Buchner funnel connected to a combined burette and manometer. The apparatus was filled with water and the saturated bed was placed in the funnel. By means of a two-way cock, water was run out of the burette in small increments, so that the bed had to support increasing heads of water. Eventually, some of the surface pores emptied and the water which drained out was measured, together with the suction head.

Ceaglske & Hougen (73) applied the suction potential theory to the drying of sand. From the suction-potential/moisture-content curve they calculated moisture content distributions for sand beds of various depths which compared well with direct experimental determinations. Water distribution curves calculated from diffusion equations did not agree with the experimental data as the water flow was independent of the liquid concentration.

Ceaglske & Hougen concluded that during the constant-rate period the wetted surface area was maintained at a constant value by the capillary flow of water from the interior. When the menisci at the surface eventually receded into the slab, the constant rate ended as the wetted surface diminished rapidly and the first falling rate period occurred. The second falling rate period ensues when the surface becomes dry and evaporation takes place from the isolated nodoids of the pendular state when vapour diffusion becomes the controlling mechanism.

Pearse Oliver & Newitt (76) extended Haines' work to include gravitational and frictional effects by the use of a modified Poiseuille equation for the resistance to flow through a bed. Thus if the flow to the surface is to be maintained, the surface suction is given by :-

$$p_s = p_h + h + H \quad ..... \quad \underline{\text{Eqn.17.}}$$

where H = the frictional resistance through distance h.

Frictional effects appeared to be most important for particle diameters of 0.1 microns and below, whereas capillary forces largely controlled the flow in the size range of 1 - 10 micron.

Pearse _et al._ showed experimentally that (a) where gravity and capillarity controls, the critical moisture content is independent of the drying rate, but varies with bed depth; (b) capillary forces control where the critical moisture content is independent of both bed depth and drying rate, and (c) where the critical moisture content is proportional to the drying rate and bed depth, capillary and frictional forces control.

Some anomalies in the experimental data for the finer sizes suggested that internal vaporization may have occurred as a result of the high suctions which were developed.

Oliver & Newitt (77) continued the work described in the preceding paper by devising an apparatus for measuring higher suction potentials during drying. The improved apparatus utilised an unglazed porcelain suction head which was embedded in the material to be dried. A mercury manometer was used to measure the suctions.

The suctions developed by beds of 47 micron diameter silica flour were reduced by increasing temperature and porosity. The suction-potential measurements were verified by using them to calcul--ate the moisture distributions inside the bed and comparing these predicted values with the experimental results. Experiments on silica flour (15 micron dia.) had previously shown that some variable other than capillary forces and drying rate affected the duration of the constant-rate period. Tests carried out at different temperatures and humidities proved that the temperature of the bed greatly influenced the value of the critical moisture content.

Oliver & Newitt further showed that when high suctions are used the air dissolved in the water filaments in the pore spaces will come out of solution and will eventually fill the pore and break the continuity of the thread. They classified the beds into three groups, depending on whether the liquid movement is (a) independent of, (b) greatly influenced by, or (c) partly influenced by this vaporization effect. They demonstrated that the suction potential curves for 5 micron silica flour agreed with group (b) since the suction reached a maximum at 900 cm water and at this point the constant rate period ceased, showing the inability of the bed to draw liquid to the surface. It was also suggested that the variation of critical moisture content with temperature for 15 micron silica (group C), was due to this vaporization effect interfering with the mechanism of water movement when higher temperatures were employed.

The suction potential technique was used by Newitt & Coleman (78) to study the drying mechanism of china clay. As the particle sizes of china clay are lower than the silica flour studied previously (77), Newitt & Coleman considered that a high percentage of the water was adsorbed on the surface of the silicates, and that the capillarity theory was no longer adequate for china clay.

Support for this hypothesis was afforded by the fact that the critical moisture content for china clay coincided with the cessation of shrinkage of the clay piece. Shrinkage of clay is directly proportional to the volume of water evaporated, and it is generally accepted that the clay particles are initially separated by films of water, and these films are reduced in thickness as drying proceeds until the particles are in direct contact and no further contraction is possible. Capillary suction was apparently unable to maintain a constant rate in the normal way and this was attributed to the water being immobilised by adsorption across the very fine pores and passages. This view was subsequently confirmed by suction potential measurements carried out with a balancing-pressure technique. It was also shown that the most important variable affecting the critical moisture content of a wide range of granular solids is the specific surface, which implies that adsorption plays a large part.

Newitt & Coleman considered that the osmotic imbibition hypothesis gives a satisfactory explanation of the phenomena. This theory postulates that the clay particle is surrounded by a cluster of cations which osmotically hold several molecules of water. This imbibed water has been related to the base exchange capacity of the clay which, in turn, is related to its degree of dissociation (79).

The absence of capillary effects in clay was demonstrated by using Teepol solution to reduce the surface tension of the water when preparing the plastic clay. No alteration in the normal suction-potential/moisture-content relationship of the clay was observed in contrast to the suction potential curve for 15 micron silica which varied in direct proportion to the surface tension. Conversely, the presence of osmotic imbibition in clay/water mixtures was demonstrated by the addition of sodium silicate and hydrochloric acid which respectively reduced and increased the suction for a given moisture content, probably by varying the degree of ionic dissociation.

As a result of drying rate and moisture distribution studies, Newitt & Coleman postulated that because of the adsorbed nature of the water in the clay structure, the water movement in the falling rate period was by vapour diffusion. Vaporization is restrained (a) by the resistance of the interstices to vapour flow, and (b) by the reduction of vapour pressure at lower moisture contents; these two forces are self-compensating, so that at any instant the evaporation rates at all parts of the bed are equal.

2.4. THE DRYING OF VEGETABLE MATERIAL

When a piece of freshly cut vegetable is exposed to an air stream, the cut surface acts as a water surface. Results of experi--ments by Ede & Hales (80) have shown, however, that the evaporation rate of vegetables per sq.ft. of tray area is 3 to 4 times the value for a water surface under similar air conditions. This presumably is because of the larger vegetable surface area exposed per unit of tray area.

Van Arsdel (81) likened a piece of cut vegetable to a fine-grained sponge saturated with water and considered that in the initial stages of drying, water may be fed to the surface by capillary suction. When this method of transfer stops, Van Arsdel concluded that the water movement was by diffusion and that the diffusivity of the water in the solid, more than any other factor, controlled the drying rate of the vegetable. The application of diffusional equations is greatly compli--cated by the factors such as the shrinkage of the vegetable and by the fact that the water is not present in the pure state but as solutions of sugars, salts and other constituents. As drying proceeds, these solutes become concentrated in the cells nearer the surface and this concentration gradient sets up a driving force causing a movement of the dissolved solids towards the centre.

Because of the difficulties enumerated above, vegetable drying tests have tended to be semi-empirical, and drying design data have usually to be provided for each individual product.

Van Arsdel (81) considered that in the drying of fruit and vege--tables, capillary suction did not play a large part in the mechanism of water movement. In the case of wood drying or seasoning, however, capillary movement is much more important. Hawley (82) had previously shown that diffusion of water could not take place in wood when it was above the fibre saturation point, i.e. the moisture content at which the cell walls are just saturated.

Bateman, Hoff, & Stamm (83) concluded that there were three mechanisms of water movement occurring in wood during drying, (a) capillary movement (b) liquid diffusion (c) vapour diffusion. Capillary movement is the principal means of transfer when the wood is above the fibre saturation point and the cell cavities are com--pletely or partly filled with water. The bound water in the cell walls moves by liquid diffusion through transient cell capillaries which exist only in the presence of water. The water vapour which can exist in wood above and below its fibre saturation point diffuses to the surface under the influence of vapour pressure gradients. Bateman et al. found that the diffusivity of the water through the wood was increased by using humid air for drying since the resultant swelling of the wood enabled the bound water to diffuse more easily through the cell walls. Woods with high specific gravity tended to have lower diffusivities as the cell walls were thicker and the capillary volumes were lower.

Culpepper & Moon (84) made an extensive study of the effect of temperature, humidity, air velocity and particle size on the drying of Keiffer pears. The fruit was cut into segments which were then impaled on pins and supported in a horizontal air stream to ensure access of air to all the surface. Culpepper & Moon presented their data as percentage moisture (wet basis) versus time, but Smith (42) recalculated their results to the more convenient dry basis for comparison with other products. It was found that the drying times of different sized segments were approximately proportional to the specific surface and that very little drying took place from unpeeled areas. Drying times were inversely proportional to the W.B.D. and the rate per unit W.B.D. increased with rising temperature.

The dehydration of prunes was investigated by Guillou (85). He found that the drying time could be expressed by the equation

$$\theta_2 - \theta_1 = \frac{1}{K} \log \frac{W1}{W_2} \quad \text{..... Eqn.18.}$$

where θ = drying time, hr.

Guillou related the drying coefficient (K) to the temperature, humidity and velocity of the air stream by the expression

$$K = 0.2 \left[\frac{t}{165}\right]^4 \left[\frac{v}{600}\right]^{0.2} \left[\frac{100-H}{60}\right] \quad \ldots\ldots \text{Eqn.19.}$$

where t = air temperature, ^{o}F,

v = air velocity, ft/min,

H = relative humidity, %.

It was observed that the drying rate was independent of relative humidities below 40%. A design for a prune dehydrator was suggested, which embodied the findings of the experimental work.

A further study of the dehydration of prunes was made by Perry (86) who measured the internal temperatures of the fruit during drying. From the surface/air temperature difference, surface area, and drying rate he calculated the thermal conductivity of the prune surface.

He found that the surface temperature rose steadily during drying and did not remain at the wet-bulb temperature for any appreciable time largely because internal resistance to water movement was high compared to the surface permeability.

Perry also showed that the drying rates were unaffected by changes of relative humidity below 40% because the equilibrium moisture content of prunes did not increase appreciably until this humidity was exceeded. As the drying rate was proportional to the free water content, any increase in humidity would increase the equilibrium water and reduce the free water content so reducing the drying rate. Below 40% R.H. the equilibrium moisture remained substantially constant. Moisture distribution curves of the prunes during drying suggested that the moisture conductivity decreased with decreasing moisture content, so that diffusion equations were not applicable.

Reeve (87) studied microscopically the physical changes which occurred inside carrots and potatoes during drying.

In carrots there is an inner core of lignified cells separated from an outer ring of softer parenchymous cells by a cambium layer.

During the initial stages of drying, these outer cells formed a hard shell which opposed the shrinkage of the interior cells and caused some of the intermediate cells to be pulled open. Reeve found that if carrots were dried at temperatures exceeding 100°C there was a tendency for the internally trapped water to vaporize and generate sufficient pressure to rupture the internal tissues.

In potatoes it was observed that most of the cells contained starch grains which could be gelled on heating to a temperature of 65°C. When potatoes are blanched or scalded before drying, all the starch in the tissues is gelled and cell shrinkage is limited. Reeve dried samples of unscalded potatoes at 90°C and found that after $2\frac{1}{2}$ hours drying internal gelation had taken place to within 500 microns from the surface, whereas the surface cells still had intact starch grains. Starch grains were still present at the potato surface after $3\frac{1}{2}$ hours drying, thus indicating that evaporation near the surface regions had retarded the temperature rise of the material. It also follows that in this case, the water had moved to the surface in the liquid state and not as vapour, otherwise there would have been no evaporative cooling.

A drying problem with certain similarities to seaweed drying, was described by Rosin (88). The material was sugar beet tops which consist of leaves, stalks and crowns with widely different drying characteristics. Prolonged drying of the leaves had to be avoided owing to loss of proteins, so Rosin suggested that disintegration of the material before drying would reduce the disparity of drying rates; but this would incur loss of plant juices and the mash would be more difficult to handle in commercial crop dryers.

Alternative practices are to dry all the material at a low temperature (140°F) or in a selective pneumatic dryer which will separate the two components and give them different treatment times.

Cashmore (89) gave a general survey of the drying of agricultural products, with reference to the problems and requirements of the particular material being treated. He recommended the use of the specific consumption (B.Th.U/lb water evaporated) as a suitable basis for comparing the efficiencies of different types of dryers.

Tomkins (90) reviewed the difficulties encountered in the dehydration of soft fruits and vegetables and considered future developments, while Barker & Thomas (91) summarised current dehydration practice for vegetables and gave typical operating data for the various classes of dryer which are used for this purpose.

Bailey (92) presented a paper on grass drying in which he con--sidered the effect of the grass structure on drying rate. The effect of thermal damage on the chemical analysis of the grass was outlined together with the high-temperature and low-temperature drying techniques which have been introduced to minimise this thermal degradation.

Bailey & Hamblin (93) described the development of a standard procedure for testing grass dryers adopted by the National Institute of Agricultural Engineering. Their report included a summary on the theoretical characteristics of grass dryers together with the solution of several practical problems arising from the testing of grass dryers.

3. SURVEY OF DRYING EQUIPMENT

The selection of a suitable dryer for dehydrating seaweed was considered by surveying available designs of dryers and selecting the three most promising types.

Drying tests on these three representative commercial dryers indicated the most suitable drying system to use for seaweed. Extensive laboratory tests were then carried out to study the drying characteristics of the seaweed and to find the optimum operating conditions.

In this survey the seaweed feed has been considered under the headings of (a) stipe and (b) frond. The advantages and disadvantages of drying these two parts of the plant mixed or separated are discussed in Section 10. In view of the possibility of either stipe or frond being required alone, each part of the plant has been considered independently. Physical properties of the stipe and frond are described in Section 6.2.

3.1. CLASSIFICATION OF DRYERS

Friedman (94) suggested three methods of dryer classification: (1) by the mechanical method used to convey the material through the dryer, (2) by the type of material they can handle, and (3) by the means of transferring heat to the stock.

Examples of group (1) would be rotary, band or truck dryers but this definition is so loose that operating conditions can vary widely although the dryers may be of the same nominal class. This method has thus limited usefulness for dryer selection.

The second system groups dryers under their suitability for drying material of different physical forms, e.g. sheets, pastes, fine powders, slurries, etc., and can be used to eliminate dryers which are inapplicable to the problem.

Method 3, which was proposed by Marshall (95), is logical and has been widely used as it gives some indication of the operating conditions to be expected. Dryers in which heat is transferred to the material by convection from a stream of hot gases are called direct dryers. Indirect dryers are those in which heat is trans--mitted to the wet stock through a metal wall and the vaporized liquid is removed independently of the heating medium. An alternative name for this class is conduction dryers. A third division in which heat transfer takes place by radiation is represented by infra-red or radiant-heat dryers. A more recent method of drying is also included in this class, namely, dielectric or induction dryers.

Direct and indirect dryers can usually be further subdivided into batch and continuous units.

3.2. DIRECT DRYERS

3.2.1. Tray or Tunnel Dryers

In most tray dryers, the hot air is blown across the surface of the solid to be dried. This method is also called over-draught or cross-circulation drying.

Each dryer has a number of trays of wet material stacked above each other in trucks which are moved progressively through the tunnel in contact with the hot gases. The air flow can either be concurrent or countercurrent to the flow of material and a tunnel design due to Eidt (96) has a centre exhaust in which part of the air flows parallel to the material and part in opposition.

As the greatest part of heat and mass transfer takes place at the surface of the material layer, the bed depth of the stock has to be comparatively low (1 - $1\frac{1}{2}$ in) otherwise the air cannot penetrate to the lower strata and drying becomes unduly prolonged.

Air velocities used in tunnel dryers are of the order of 400 - 1000 ft/min to give rapid heat transfer and eliminate static air pockets. Ducting must be designed along wind-tunnel lines as poor air distri--bution across the trays results in a rapid fall in evaporating capacity. Tunnel dryers are widely used for fruit and vegetable drying, and extensive research work was carried out in this method during the recent war for the dehydrated vegetable programme. The experience thus gained in food dehydration was collected by the D.S.I.R. and Ministry of Food in Britain (97) and by the U.S. Department of Agriculture in America (81).

Tunnel dryers are suitable for almost any type of material and have a high drying-capacity for a given floor area.

3.2.2. Through-Circulation Dryers

In this class of dryer good gas/solid contact is achieved by blowing the drying air through a permeable bed of solids. The air flow may be upward or downward and in some designs both are used.

Granular, fibrous or flaky materials may be dried in this manner and pastes or powders can often be preformed to a suitable particle shape for a porous bed. Fine dusty materials are unsuitable for through-draught dryers.

Marshall and Hougen (98) showed that drying rates are high as a result of the large surface area exposed to the air, good contact with the air and short diffusion paths for the water in the solid.

Air temperatures used in through-circulation dryers do not exceed about 600^{o}F as lubrication problems for the moving conveyors become serious above this value. Normal size range of the conveyor belts are 2 - 9 ft wide and 16 - 160 ft long.

3.2.3. Rotary Dryers

3.2.3.1. Direct Single Shell. The simplest form of rotary dryer is a hollow metal cylinder supported on rollers and inclined at a small angle to the horizontal. Wet stock is added at the upper end and progresses to the discharge end by virtue of the rotation and slope of the drum. The hot gases can be blown parallel or countercurrent to the solids flow. This would be a direct single-shell dryer.

Other designs have more elaborate lifting flights inside the drum, intended to drop the solids in curtains through the hot gases to promote more rapid evaporation. The air may be heated by steam pipes; or gases from the combustion of oil, gas, or solid fuels can be used.

Rotary dryers are designed primarily for free flowing granular solids but sticky materials can sometimes be handled by using straight radial flights and fixing loose chains inside the drum. Knockers on the outside of the drum are also useful for dislodging sticky materials.

A special type of rotary dryer - the rotary louvre - blows the air through radial gas channels inside the rotating drum. Air is blown only through those channels which are covered by the material, so that the air passes through the bed of material.

3.2.3.2. Indirect - Direct. Indirect-direct rotary dryers have two concentric shells to enable the gases to heat the solids by conduction as well as by convection. The solids flow down the annulus between the shells and the air flows through the inner shell before contacting the solid stream on the outer surface of the internal shell. In this way the thermal efficiency of the installation is greater than the corresponding single shell unit. This dryer is unsuitable for thermally sensitive materials which tend to be overheated by the metal surfaces.

Temperatures used on rotary dryers range from 200 - 1400°F and efficiencies vary from about 55 - 75% for direct single shell dryers and 75 - 85% for indirect-direct dryers.

3.2.4. Pneumatic Conveying Dryers

In this system the solid is entrained by the hot gas stream so that maximum contact of the solid and air is obtained. This dryer works best with free-flowing solids which can be easily dispersed. Sludges and filter cakes can also be handled as disintegrators are frequently installed in the circuit. Pastes are sometimes modified by mixing with a proportion of the dried product. Shredded, sticky, or abrasive solids are generally unsuitable for pneumatic dryers (99).

These dryers find their greatest application for high evaporative rates (2000 lb/hr or more) and efficiencies range from 25 - 70% for low temperatures and 65 - 75% for high temperatures. Air temperatures are usually in the region of 300 - 1500°F and an average figure for the air velocity is 75 ft/sec.

Friedman (94) states that pneumatic dryers generally cost less than rotary dryers for the same evaporation rate.

3.2.5. Spray Dryers

Spray drying installations are designed primarily for liquid feeds. A nozzle or atomizing disc is used to spray a mist of liquid droplets into a stream of hot air. Drying times are very short and thermally-sensitive products can be treated with the minimum of deterioration.

Spray dryers are extensively used for dehydrating milk, eggs, purees, detergent solutions, etc., and generally if a material can be pumped it can be spray dried.

3.3. INDIRECT DRYERS

3.3.1. Vacuum Shelf Dryers

Materials to be processed in this class of dryer are placed on trays which rest on heated shelves. These shelves are contained in a rigidly-constructed chamber which can be subjected to a vacuum. These units are usually batch, although a continuous type is also available.

Vacuum dryers of this type are eminently suitable for heat sensitive or easily oxidised solids and have good facilities for solvent recovery. Thermal efficiencies of 60 - 80% can be obtained.

3.3.2. Agitated Pan and Vacuum Rotary Dryers

Agitated pan dryers consist of shallow, circular pans, steam jacketed on the bottom and sides, which can be arranged to operate under atmospheric conditions or under vacuum. Agitation is provided by stirrers mounted on a vertical axis.

Vacuum rotary dryers usually comprise a horizontal cylinder with an axial stirring shaft fitted with agitator blades. In both types of dryer a batch of material is added through a manhole, dried, and then discharged through a lower opening. These dryers are suitable for the types of materials described under vacuum shelf dryers which require mixing during drying.

3.3.3. Steam Tube Rotary Dryers.

The general arrangement of a steam tube dryer is similar to that of a direct rotary dryer except that the heat is transferred by conduction and radiation from longitudinal steam tubes. Vapors are removed from the drum by a natural-draught chimney so that carry over of dust is minimised.

Steam-tube dryers are suitable for drying granular materials that can withstand high temperatures but must not be contaminated by products of combustion. Efficiencies up to 90% are obtainable with this type of dryer largely because the steam is condensed only as required, thus giving a 'self-checking' effect.

3.3.4. Vacuum Freeze Dryers

This type of dryer operates at low temperatures and high vacua. The water is frozen, and under the high vacuum the drying occurs by sublimation. Water is removed from the system as ice, using surfaces cooled by solid carbon dioxide.

Because of the low temperatures used, losses of volatile constituents and denaturing of proteins are minimised.

4. PRELIMINARY SELECTION OF DRYER

4.1. DIRECT DRYERS

4.1.1. Tray & Tunnel Dryers

This class of dryer is clearly capable of producing a high--quality product, as they have been extensively used for food dehydration.

They have the advantages of simple construction, high efficiency and high drying capacity for a given floor area. They are, however, essentially factory installations and require more labour than most other dryers, because of the manual loading of the trays. Their unsuitability for high production rates (94) is a further disadvantage. High drying-costs can be justified for dehydrated foodstuffs where cost is of secondary importance to quality, but it is significant that grass dryers (which are designed for large throughputs and low-cost operation) do not use tunnel dryers extensively. Dried grass is a commodity of roughly the same value as dried seaweed meal (100).

Tunnel and tray dryers were, therefore, excluded from further consideration.

4.1.2. Through-Circulation Conveyor Dryers

If the seaweed is subdivided prior to drying, this type of dryer would be applicable.

Advantages of this dryer are that heavy bed loadings may be used, efficiencies are good as the air is brought into intimate contact with the solid, and drying times are short as a result of the smaller particle sizes which can be used. Sticky materials have been handled on this class of dryer, sometimes with the aid of a preforming device. Drying times and air temperature can be controlled accurately to suit variations in the wet feed.

Designs, ranging from simple mat dryers to more complex multi-stage recirculation dryers, are used extensively for grass drying.

It appeared that this system merited further investigation.

4.1.3. Rotary Dryers

This class of dryer has been used for vegetable material, e.g. sugar-beet pulp (101).

High temperatures and efficiencies have been obtained with heat-sensitive products but the indirect-direct rotary dryer is not suitable for vegetable materials.

Stipe should behave well in a rotary dryer but the frond will probably give trouble owing to its stickiness. It remains to be seen how severe this stickiness will be, and whether it can be controlled by devices normally used to remedy this trouble.

The rotary-louvre dryer has the combined advantages of intimate air/solid contact as in through-circulation dryers, and the mixing action of rotary dryers, so that it appeared to be a promising type for testing. Barker & Thomas (91) considered the rotary louvre to be the best type of rotary dryer for vegetables.

The rotary-louvre dryer was therefore retained for further investigation.

4.1.4. Pneumatic Dryers

Grass dryers using the pneumatic conveying principle are in common use, and can give high evaporative efficiencies.

One advantage of pneumatic drying is that a large amount of fines in the feed presents no problem as these flash drying systems frequently have integral grinders and dust collectors. It should therefore be possible to achieve rapid drying times by cutting the material finely. Stipe should be amenable to this treatment but frond may be difficult to disperse in the air stream and may also adhere to the interior of the ducting.

As these dryers are claimed to be less expensive than other designs at high production rates, it was decided to give this method of drying further consideration.

4.1.5. Spray Dryers

Spray dryers were not applicable to this problem, as the feed material is in the solid state.

4.2. INDIRECT DRYERS

4.2.1. Vacuum Shelf Dryers

Vacuum shelf dryers would undoubtedly give a high-quality product, but the low output and high operating and handling costs would prevent this process from being competitive.

4.2.2. Vacuum Freeze Dryers

This is probably the drying process par excellence for biological material, but industrial use is at present limited to valuable pro--ducts such as orange juice concentrates (102), blood plasma and penicillin.

4.2.3. Agitated Pan Dryers and Vacuum Rotary Dryers

Pan dryers were rejected as unsuitable because of their compara--tively low outputs.

Bate-Smith (103) experimented with a full-size vacuum rotary dryer for meat dehydration and found difficulty in preventing the nearly-dry meat from being scorched by the hot surfaces. This was largely a result of the high thermal capacity of the dryer walls.

Frond would almost certainly adhere to the conducting walls and reduce the heat transfer rate.

4.2.4. Steam-tube Dryers

Dryers in this category are attractive because of the very high efficiencies which may be obtained with steam-heated plant under suitable conditions, but this ~~dis~~advantage would largely disappear if there was not an existing boiler plant. Frond would very probably again cause unsatisfactory operation if the particles adhered to the steam tubes. Resultant scorching and charring would contaminate the remainder of the batch.

4.2.5. Infra-red Dryers

Infra-red dryers are at present mainly limited to surface drying, and are unsuitable for drying solids in which internal movement controls. Japanese workers (104) dried various thicknesses of fish by this method and concluded that infra-red drying was uneconomic for the dehydration of low priced products.

4.2.6. Dielectric Drying

Dielectric drying is a high-cost method which can be justified only for drying large irregular shapes that would otherwise require days to dry. The principle of the operation requires the solid to be an insulator so that it forms a capacitor when placed between the electrodes. As seaweed contains a solution of an electrolyte the system could not function effectively.

4.3. MISCELLANEOUS METHODS

The following alternative methods have been proposed for drying seaweed.

4.3.1. Drying by Distillation in a Solvent

A similar process was attempted during the War for the dehydration of potatoes by boiling in an immiscible liquid (105). Water was removed from the vegetable satisfactorily but traces of the solvent could not be removed from the potatoes which were rendered unpalatable. Similar difficulty would probably be encountered if the seaweed was intended for cattle feeding.

4.3.2. Drying by Plasmolysis

Walker (32) demonstrated that seaweed frond could be partly dewatered by immersion in a concentrated brine solution so that the cell liquids diffused outwards by osmotic flow. Further tests would be required to ascertain if losses of valuable constituents occurred. Apart from this, the process would be impracticable on the industrial scale as the maintenance of the concentrated brine would require either addition of salt crystals or evaporation of the diluted solution.

Final stages of drying would probably have to be accomplished in conventional apparatus where the excess salt might constitute an additional corrosion hazard.

4.3.3. Mechanical Dewatering Methods

When freshly harvested L. cloustoni stipe is minced in a meat mincer and the disintegrated material is allowed to drain in a receiver, a considerable amount of liquid separates out from the particles on standing. This free liquid was separated rapidly by centrifuging giving a weight loss of 25-30%, depending on the initial water content of the stipe. Analysis of this filtrate from one such test indicated that it contained 7% solids, 20% of which was mannitol.

Some of the advantages of mincing combined with centrifuging before drying are that the seaweed has a more uniform water content, the smaller pieces dry more rapidly and the evaporation load of the dryer is reduced. These advantages would probably be offset by the loss of chemicals in the expressed liquid as they would still have to be recovered by evaporation.

It was found that no liquid could be removed from L. cloustoni frond by mincing and centrifuging.

A test on a small hydraulic press in the Royal Technical College showed that liquid could also be pressed from minced L. cloustoni stipe by pressure.

At 700 lb/sq.in. pressure, a 27% reduction in weight was obtained using minced stipe (passing $\frac{1}{2}$ mesh) but only about 3% could be removed from $\frac{1}{8}$ in thick stipe slices. It would appear from this test that the crushing had occurred in the mincer and the hydraulic press merely served to separate off the liquid.

5. LARGE SCALE DRYING TESTS

From the preceding review of dryers, it was concluded that three types which merited further study were :-

(a) through-circulation,

(b) rotary-louvre,

(c) pneumatic-conveying dryers.

Seaweed drying tests on representative dryers of these three types have been carried out. A pilot-plant installation was utilised for the rotary-louvre dryer tests and commercial grass dryers were used for the two remaining trials. These latter tests also gave parallel information on the suitability of existing grass dryers for seaweed dehydration and provided reasonable quantities of dried seaweed for the extraction of chemicals. Pneumatic drying was represented by the initial stage of a Pehrson dual-process crop dryer while through-circulation drying was represented by a Templewood double-pass conveyor grass dryer.

The final selection of a dryer for seaweed was made from the results of these tests.

5.1. ROTARY-LOUVRE DRYER TESTS

5.1.1. Introduction

This series of drying tests was carried out on a pilot-plant rotary-louvre dryer at the Institute of Seaweed Research, Inveresk.

The rotary-louvre dryer was first described by Erisman (106) who claimed that the efficiencies obtained with this dryer were greater than those of conventional rotary dryers, due to lower exhaust temperature. This dryer differs from the majority of other rotary dryers in that the air is blown radially through the moving bed of material instead of axially between cascades of falling particles. It can therefore be classed as a through-circulation dryer (107).

Goldstein (108) described the use of this dryer for granulated sugar. One advantage of the particles rolling instead of cascading was that the sugar crystals were not scratched or powdered to any serious extent.

Sewage sludge has also been dried in a rotary-louvre dryer (109).

Earlier seaweed drying tests on a rotary-louvre dryer have been reported by Jackson (110), who used Ascophyllum nodosum and L. saccharina (stipe, frond and plant mixed) which had been soaked in fresh water until the moisture content was approximately 50% (70% for L. saccharina stipe). This water content approximated to that of air-dried seaweed. With an inlet air temperature of 570°F, efficiencies of 53-62% were obtained when drying to a final water content of 2-3% (10% for L. saccharina stipe). The drying of stipe and frond spearately gave higher drying efficiency than using the mixed plant. The tests showed that the later stages of drying seaweed can be accomplished reasonably efficiently on a rotary-louvre dryer.

5.1.2. Other Tests on Rotary Dryers

Drying tests on a "Buell" rotary dryer with A. nodosum and L. digitata (stipe) have been carried out (111) in which dried seaweed was soaked to an initial water content of 47%. This type of dryer has a rotating drum equipped with "Büttner" type cruciform shelving which is claimed to give even distribution of material and even gas velocity throughout the drum cross section.

A "Williams" cutting machine (112), designed to subdivide whole seaweed plants, was tested in conjunction with the dryer.

The average inlet air temperatures were 418 and 479°C for the A. nodosum and L. digitata respectively with a thermal efficiency of 28% in each case. This low figure was partly caused by the tests being conducted primarily to assess the suitability of the Williams' cutter as a method of size reduction for a dryer, and not to determine optimum drying conditions.

Kraybill (113) described a method of drying cooked minced meat in a rotary dryer. The dryer drum was equipped with louvre-like vents to allow the air to pass through the tumbling mass of meat. The drum was 7 ft 11 in diameter x 24 ft long and using air at 300°F the meat was dried from 50% to 10% water in two hours with a product rate of 1000 lb/hr. It was not stated specifically in the paper if the dryer was a rotary louvre or a conventional type rotary dryer, but the high velocity (800 ft/min) suggests that the dryer was of the cascading type with axial air flow.

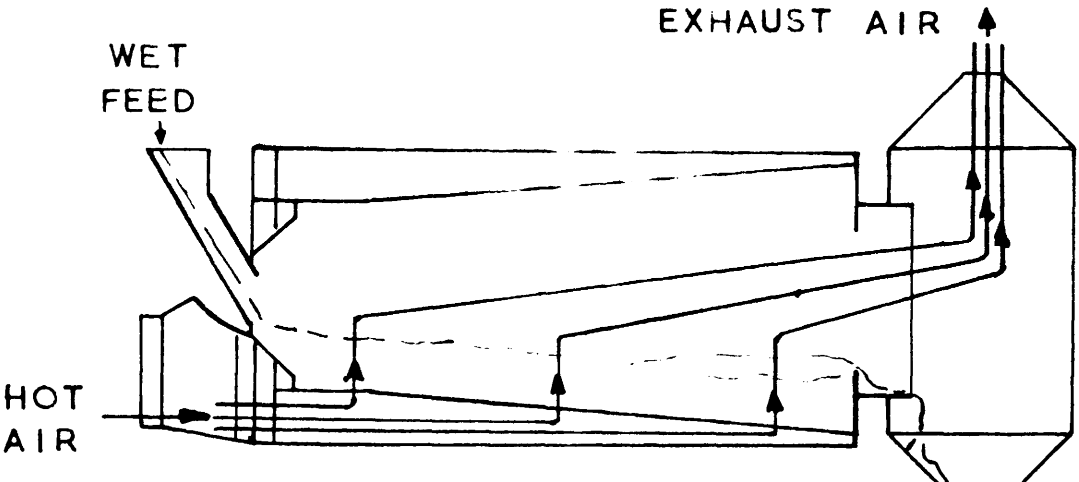
Clark, Pratt, Coleman & Green (114) described a method of drying Macrocystis pyrifera, a seaweed found off the Californian coast. The chopped M. pyrifera (87% water) was fed into a rotary dryer with an inlet air temperature of 1200-1800°F and was discharged after 20 minutes with a water content of 40-65%. The seaweed was further dried to 5-15% moisture content on a conveyor-dryer by means of air at 200-260°F and a retention time of 30 minutes. The depth of the seaweed bed was 2-3 in.

5.1.3. Description of Rotary-Louvre Dryer

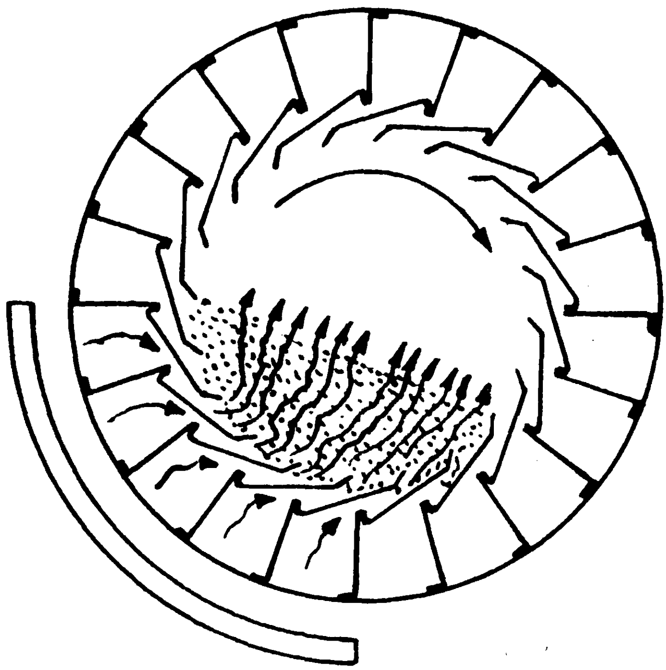
This dryer consists of a horizontal drum with a series of radial plates fitted to the internal circumference of the shell, forming gas channels into which hot air is blown by a fan. These channels taper in depth from inlet to discharge so that the quantity of heat available is in proportion to the evaporation load. Tangential louvres are attached to the radial plates in such a way that the air can pass through the material, without allowing the solids to fall into the gas channels (see Fig. 5). The drum is supported by rollers and is rotated by an electric motor with sprocket chain drive. Wet material is fed into the conical inlet end through a small feed hopper and, maintaining a constant angle of repose, travels to the discharge end as a result of the rotation of the drum and the increasing internal diameter. The particles roll gently over each other when the angle of repose is exceeded and should always form a bed over the inlet gas channels. A manifold on the stationary head at the feed end admits hot gases only to those channels underneath the charge of material while the other channels are isolated from the inlet. The depth of the bed of material and its time of retention in the drum for a given rate of feed can be varied by altering the diameter of the discharge opening. Exhaust gases are carried away from the drum through the vaned discharge end and collecting hood. The discharge section consists of open vanes which allow the exhaust to pass from the drum to the hood at a relatively low velocity, thus preventing material from being carried over. A small Perspex observation window on the end door of the discharge hood and an internal electric lamp enabled the seaweed bed to be observed during drying without disturbing the air conditions. The length of the drum is 7 ft 6 in which includes the 1 ft 6 in long discharge portion. The outlet gases are removed from the dryer by an exhaust fan, and pass through a cyclone separator which collects any entrained dust. Dampers in the ducts before each fan enable the air volume to be varied and the air flow can be measured by an orifice plate in the inlet duct.

Figs. 6 & 7 show the general layout of the pilot-plant rotary-louvre dryer used in the tests.

Hot gases for drying are drawn from an oil-fired furnace which

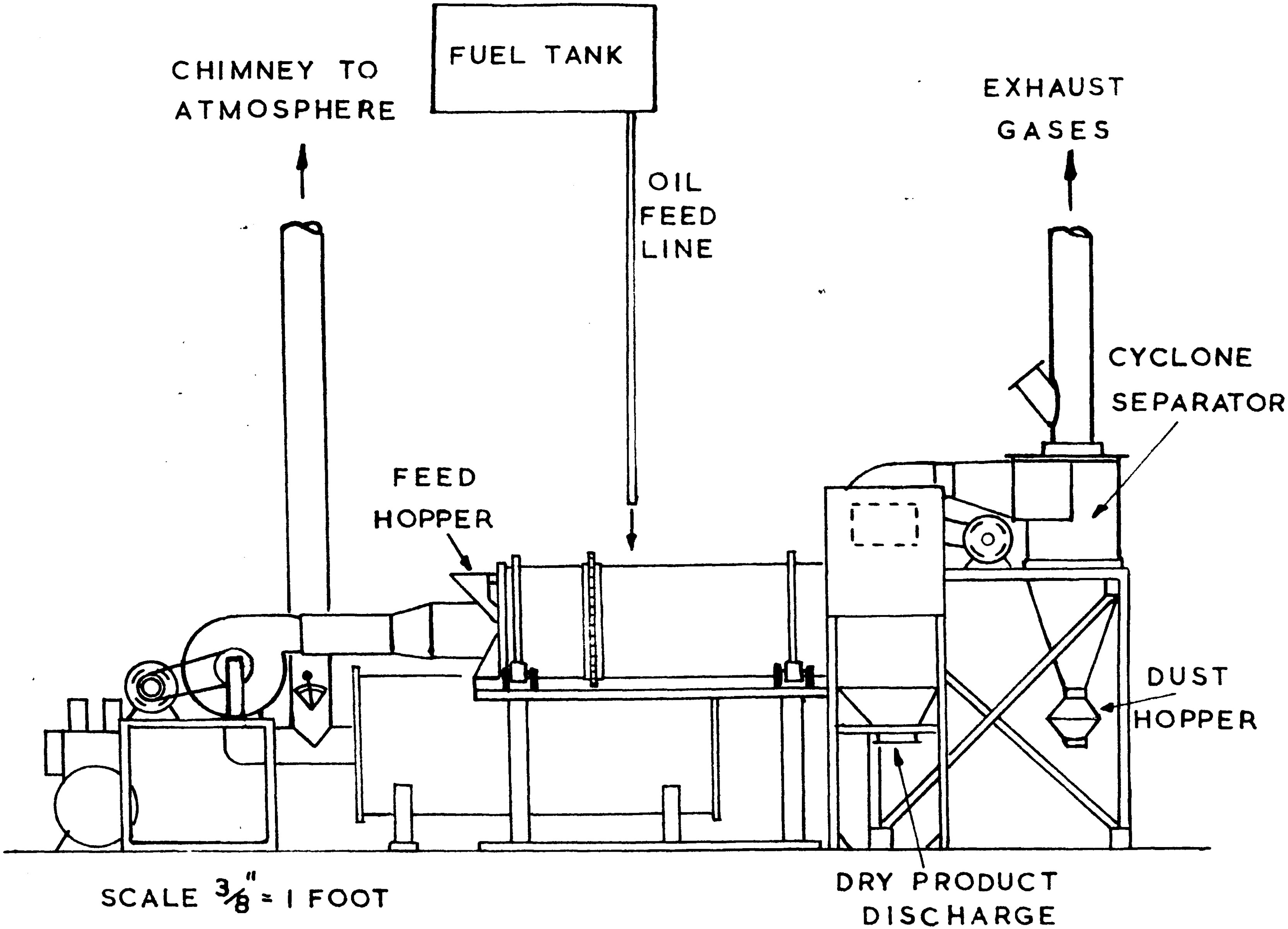


AIR AND MATERIAL FLOW
THROUGH ROTARY-LOUVRE DRYER.



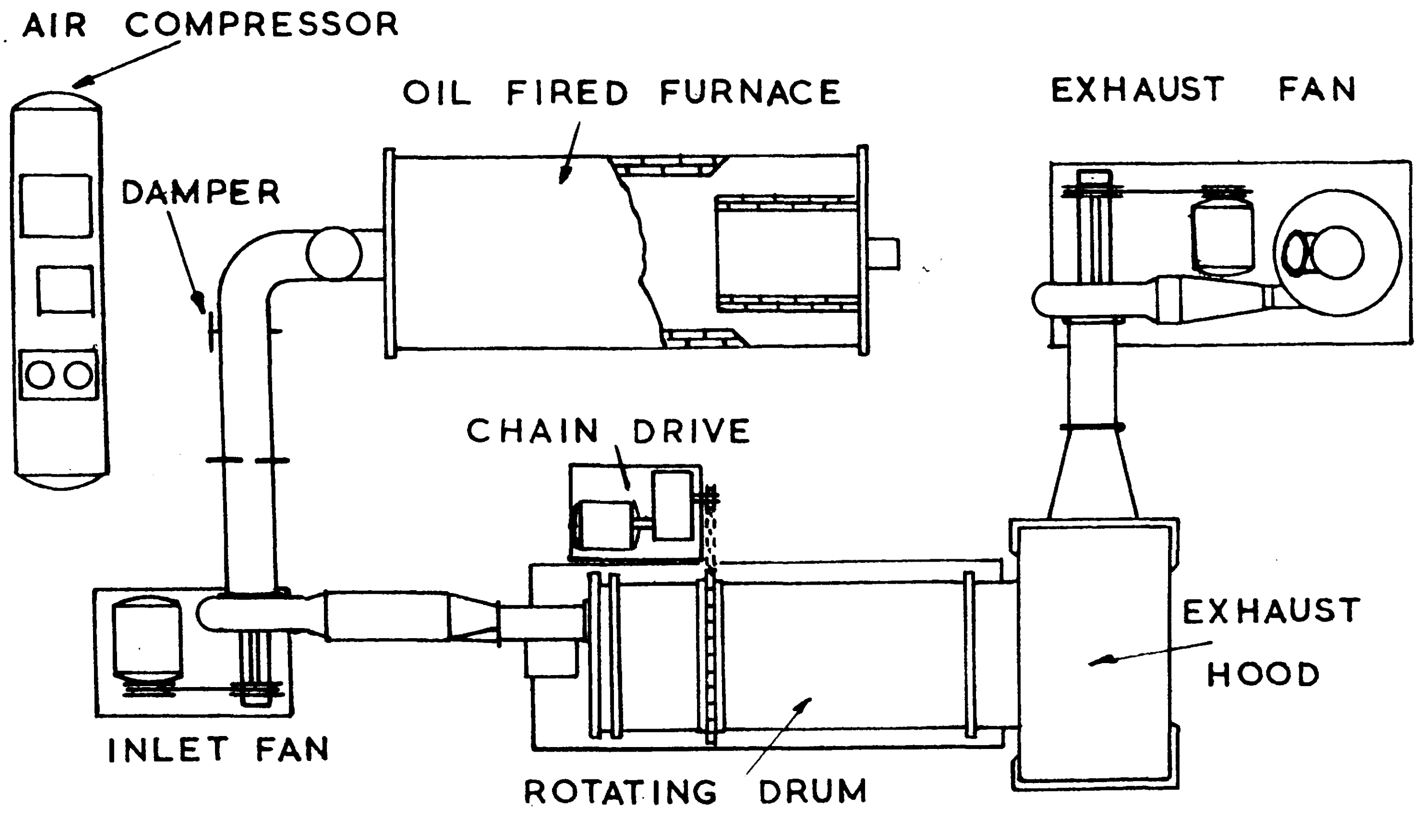
CROSS SECTION OF DRUM.

FIG. 5.



SCALE 3/8" = 1 FOOT

ROTARY - LOUVRE DRYER FIG. 6.



ROTARY - LOUVRE DRYER

SCALE $3/8'' = 1$ FOOT

PLAN VIEW

FIG. 7.

burns gas oil supplied by gravity from an 80-gallon tank situated 12 ft above the furnace. The furnace consists of a mild steel cylinder lined with refractory bricks with a smaller concentric combustion chamber of the same material. Primary air was supplied to the burner at 5 lb/sq.in. and secondary air for combustion enters through three shuttered openings in the furnace end. A chimney leads to the atmosphere from the duct at the end of the furnace, so that the flue gases during the heating up period may be diverted from the dryer. A cut-out is provided to stop the oil supply should the burner go out.

The air temperature in the inlet duct is automatically regulated between 212-930°F by a Negretti & Zambra pneumatic recorder-controller which operates a diaphragm valve in the oil supply line to the burner. A by-pass valve is also provided in the oil pipe to prevent the burner from being extinguished when the control valve is closed. When the relative flow of oil through the two valves is correctly adjusted, the controller will maintain the air temperature within four Fahrenheit degrees.

5.1.4. Experimental Procedure

5.1.4.1. Raw Material: *L. cloustoni* plants harvested in the Firth of Forth near Granton during the first fortnight of February 1952, were used throughout the rotary-louvre tests.

The seaweed not immediately required for the tests was stored on a concrete path outside the laboratory and covered with a tarpaulin.

Most of the seaweed was dried 2 or 3 days after harvesting, but little decomposition was observed in plants which were 7 days old - presumably a result of the frosty weather.

Fronds were minced in a power mincer using a cutter-plate with $\frac{3}{8}$-in dia. holes as some form of size reduction was necessary to allow the material to enter the dryer and form a uniform bed. This type of mincer was apparently unsuitable for fresh frond as the exudation of mucilage tended to increase so that the individual pieces of frond were connected with an adhesive jelly, almost forming a sticky paste. The parts of the frond adjacent to the stipe were more free of mucilage and helped to make the material less sticky.

The stipes were chopped into approximately 1-in lengths and minced to pass $\frac{3}{8}$-in holes. As mincing caused a considerable amount of water to separate from the stipe on standing, the material was centrifuged before drying.

The centrifuge had a removable steel basket 12 in dia. x $6\frac{1}{2}$ in deep with a capacity of 16 lb of wet stipe.

Two minutes centrifuging at 1500 r.p.m. (gravity ratio = 384) gave a product with a water ratio of about 4 lb water/lb bone-dry solids.

5.1.4.2. Material Sampling: Samples of wet and dried seaweed were taken at the end of each run and Table 2 shows that the run-to-run agreement of the initial water content was quite close.

Moisture contents of the material at different positions along the dryer drum were estimated from samples taken from the bed at the end of the test. The air was shut off, the drum was stopped and samples were collected using a long-handled sampling cup. The handle was marked off in 12-in lengths for convenience in measuring.

Moisture contents were determined by drying the samples in an electric oven at 220°F for 15 hours. The samples were dried in the minced condition as the water contents were too high to allow the seaweed to be ground.

5.1.4.3. Drying Runs: The furnace was lit and the refractories allowed to heat up for an hour or two before the test. When this was accom--plished the damper was set to pass the air through the rotary drum.

The recorder/controller was adjusted to the required temperature and the instrument reading verified by a mercury thermometer inserted into the inlet duct. As soon as the air entered the dryer, seaweed was fed at the inlet end to form a bed over the louvres.

The air velocity was adjusted to give a prearranged reading on the orifice meter and the dampers regulated to give a slight positive pressure in the dryer.

After a bed had been formed "buffer" seaweed was fed in at regular intervals corresponding to the desired hourly input rate. When the product was being discharged in a steady stream the quantitative test was commenced.

Laboratory air temperatures and humidities were obtained from sling psychrometer readings. The water content of the inlet air was calculated indirectly from the laboratory humidity with an addition for the water generated by combustion of the oil. Exhaust air humidity was measured by dry-bulb and wet-bulb thermometers situated in the outlet duct.

Gas oil for the furnace was fed by gravity from the main supply tank to a subsidiary 10-gallon drum equipped with a sight glass. The oil volume was measured to an accuracy of about 0.05 ± 0.02 gallons.

Wet and dried seaweed was collected in bins and weighed on a $\frac{1}{2}$-ton balance to an accuracy of $\frac{1}{4}$ lb. The product was weighed as discharged from the dryer, i.e. unground.

A small hopper was supplied with the dryer to guide the wet stock into the drum. This device was quite unsuitable for minced fresh frond, however, as the material choked the narrow throat of the hopper. For all the tests described, the hopper was removed and the seaweed was fed into the open end of the drum with a small scoop.

The duration of the test was limited by availability of seaweed and time required for preparation, but was in most cases one hour or more although the material was usually fed into the dryer for double this time.

Air velocities used were the maximum that could safely be employed without causing lifting of the bed or blowing particles out of the dryer. Prior to and during drying runs, the bed was observed periodi-

-cally to ensure that no blowholes had occurred.

There appears to be an optimum feed-rate for seaweed particles for this dryer. If the material was added too slowly, the rotation of the drum and shrinkage of the material caused a gap in the bed near the feed end, with the result that the air short-circuited the material. On the other hand, if the seaweed feed rate was too rapid the material was displaced through the drum in too short a time and drying was insufficient. The feed rates used (70 - 80 lb/hr) appeared to be near the optimum value.

Table 2 shows that drying was only partially complete. The only remaining variable that can be altered on this particular dryer is the drum rotation. Throughout these tests the rotation was 4 r.p.m. as the drive at the time of testing could not readily be reduced. If the rotation were to be reduced, the retention time of the material would be increased with a corresponding reduction in final water content.

5.1.5. Results

Principal data for the ten tests are set out in Table 2. The evaporation rate was calculated from the feed rate and the terminal moisture contents. From the evaporation rate and the initial and final air humidities the mass air flow was calculated. The calculated air flow was higher than the rate measured by the orifice plate presumably because of the unsuitable position of the instrument. Table 3 is a heat balance for one of the stipe runs. This heat balance was based on the gross calorific value of the oil, which means that the heat used to vaporize the water formed by combustion is wasted. A more practical comparison may be made by using the net C.V. so that this term disappears. The specific evaporation for Test 8 would then become 1,660 B.Th.U/lb and the efficiency 63%.

When the frond was added to the rotating drum the material tended to "ball up" at first and stick to the metal louvres. In some instances

TABLE 2.

ROTARY-LOUVRE DRYER TESTS

Drum Rotation 4 r.p.m. Species: L. cloustoni

Run No.	1	2	3	4	5	6	7	8	9	10
Material	F	F	F	F	DF	DF	S	S	S	F
Inlet Air D.B.T. °F	212	212	212	302	302	212	212	212	392	302
Outlet air D.B.T. °F	124	111	107	142	158	147	117	102	144	126
Outlet air W.B.T. °F	91	90	91	102	101	89	90	90	110	109
Inlet water ratio	5.10	4.93	4.72	5.45	2.09	0.38	4.08	3.98	4.25	5.28
Outlet water ratio	2.79	2.38	2.09	0.73	0.47	0.11	2.11	1.53	0.23	0.79
Feed rate, lb/hr	71.5	82.6	70.2	77.5	101.2	65.5	75.5	76.2	74.0	75.0
Discharge ring dia., in	11	8	5	5	5	5	8	5	5	5
Air flow, lb/hr	1730	2070	1660	2110	2580	1360	1710	1840	1420	1220
Evaporation, lb/hr	27.1	35.8	32.4	56.6	54.9	12.8	29.2	37.0	56.5	53.9
Specific evaporation, B.Th.U/lb	3030	2400	2530	2360	2430	5300	1860	1780	2520	2480
Retention time (calcd.) min	-	12.5	39.5	30	20	30	14	32	53.5	-
Drying time, (calcd.) min	-	9	29	14	13.5	24	11	23	36	-

F = Fresh frond (minced), S = Fresh stipe (minced and centrifuged), DF = Dried frond.

this adhesion was sufficiently strong to form a ring of frond particles sealing off the first few inches of the air ducts. Frond pieces did not roll but slithered and broke irregularly.

As drying proceeded the stickiness became less until on discharge it was practically negligible. The product however still contained numerous agglomerates of frond particles, so that the frond did not pass through the dryer in a regular manner and in the initial stages at least, did not form a very satisfactory bed.

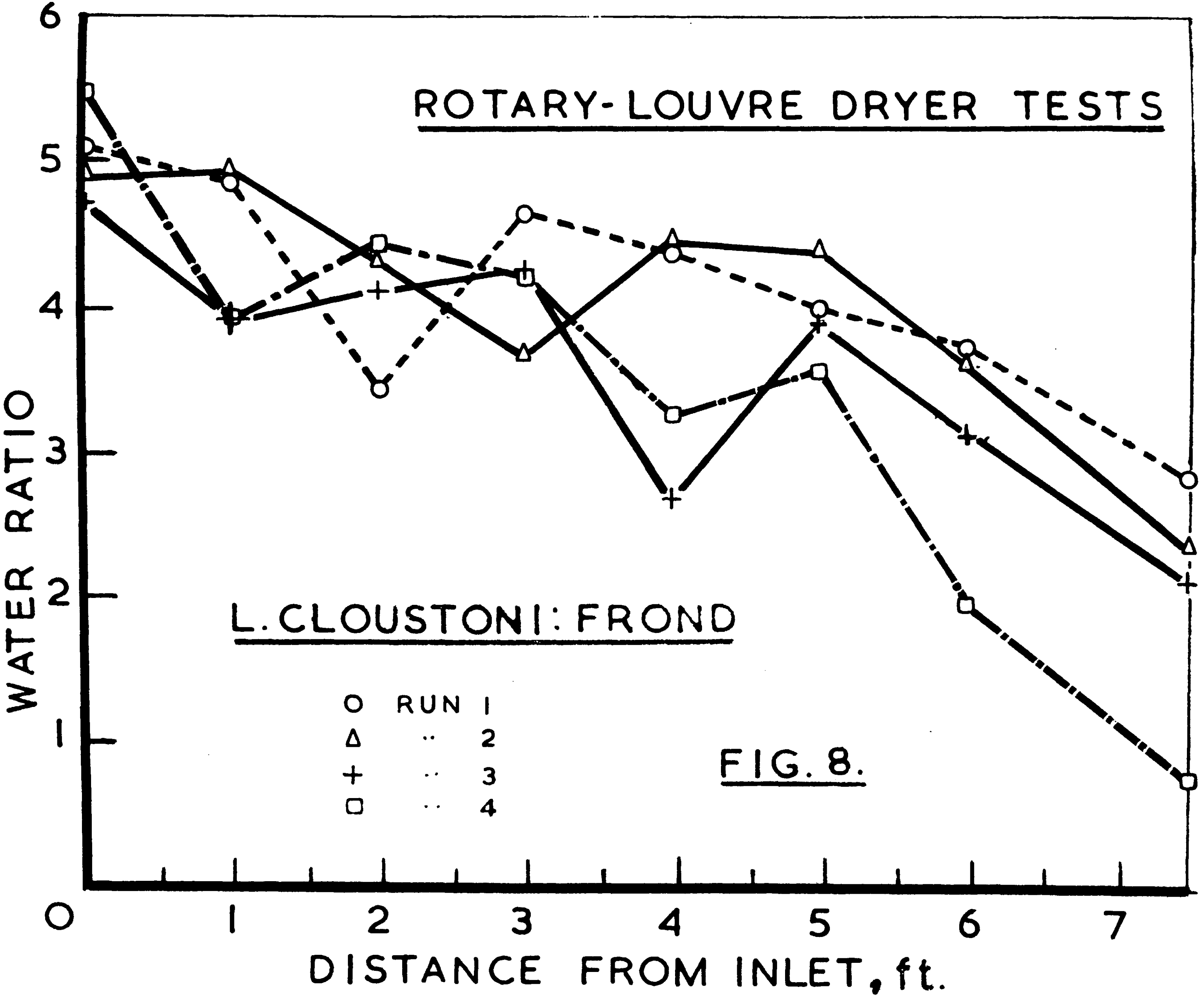
Minced and centrifuged stipe, in contrast to frond, gave a most satisfactory bed. Very little adhesion to the louvres was observed, and the particles rolled along smoothly, maintaining a constant angle of repose.

The marked differences in character of the beds formed by the stipe and frond are reflected in the final water content of the product. With air temperature of 212^{o}F the final water ratio for stipe was approximately 1.5 and for frond 2.1.

The curves of water content versus position in drum (Figs. 8 & 9) are much more regular in the case of stipe and predried frond than those for wet frond. This suggests that the stipe water content at any one cross-section of the bed was more homogeneous, and that the scattering of the data for frond resulted from samples which had adhered to the drum and received longer time of contact in the hot air.

If it is assumed that a given position in the drum is reached in approximately the same time for stipe and frond, it appears that stipe is drying more rapidly than the frond, presumably owing to better contact with the drying air. Although the water content of the frond feed was 25% higher than the stipe, this should not reduce the evapora--tion appreciably since water can be removed from seaweed more rapidly in the early stages of drying. The stickiness of the frond may have a much greater influence on the drying time than has the water content.

The frond tests, and to a much lesser extent, the stipe tests,


ROTARY-LOUVRE DRYER TESTS
L. CLOUSTONI : FROND
O RUN 1
Δ .. 2
+ .. 3
□ .. 4
WATER RATIO
DISTANCE FROM INLET, ft.
0
1
2
3
4
5
6
7
FIG. 8.

indicate (Figs. 8 & 9) that the discharge water content is lower than that at the entrance of the cooling section. This cannot entirely be dismissed as sampling error and it is quite possible that drying is taking place in the cooling zone, as a result of the exhaust air passing over the seaweed and also by conduction of heat from the main part of the drum.

Fig. 9 shows clearly the advantages of using a deeper bed with stipe. The material is dried more fully for the same air flow and temperature. The air is more effectively used with a deeper bed because of fewer gaps and longer contact time, but another factor is that the retention time will be increased as the particles have a longer mean path to travel in the bed.

A comparison of the input and output rates of bone-dry seaweed revealed that there was an average apparent loss of dry matter (a.l.d.m.) of about 15%.

There are four ways in which loss of dry matter could occur in these drying tests :-

(a) Physical loss due to test procedure.

(b) Physical loss due to the dryer itself.

(c) Chemical loss as a result of combustion of seaweed in the dryer.

(d) Chemical loss through biological changes in the seaweed.

There is a possibility of solids loss under the first heading especially with frond as this material was difficult to handle owing to its stickiness. It was estimated that the error in weighing was within 1%. Losses of dry matter characteristic of the dryer would mainly be the carry-over of small particles in the exhaust air. This was minimised by keeping the bed under observation and adjusting the air flow to a value which avoided fluidising the bed. For this reason the air flow used for the stipe tests was lower than that for frond runs. Solids recovered from the exhaust cyclone were negligible in

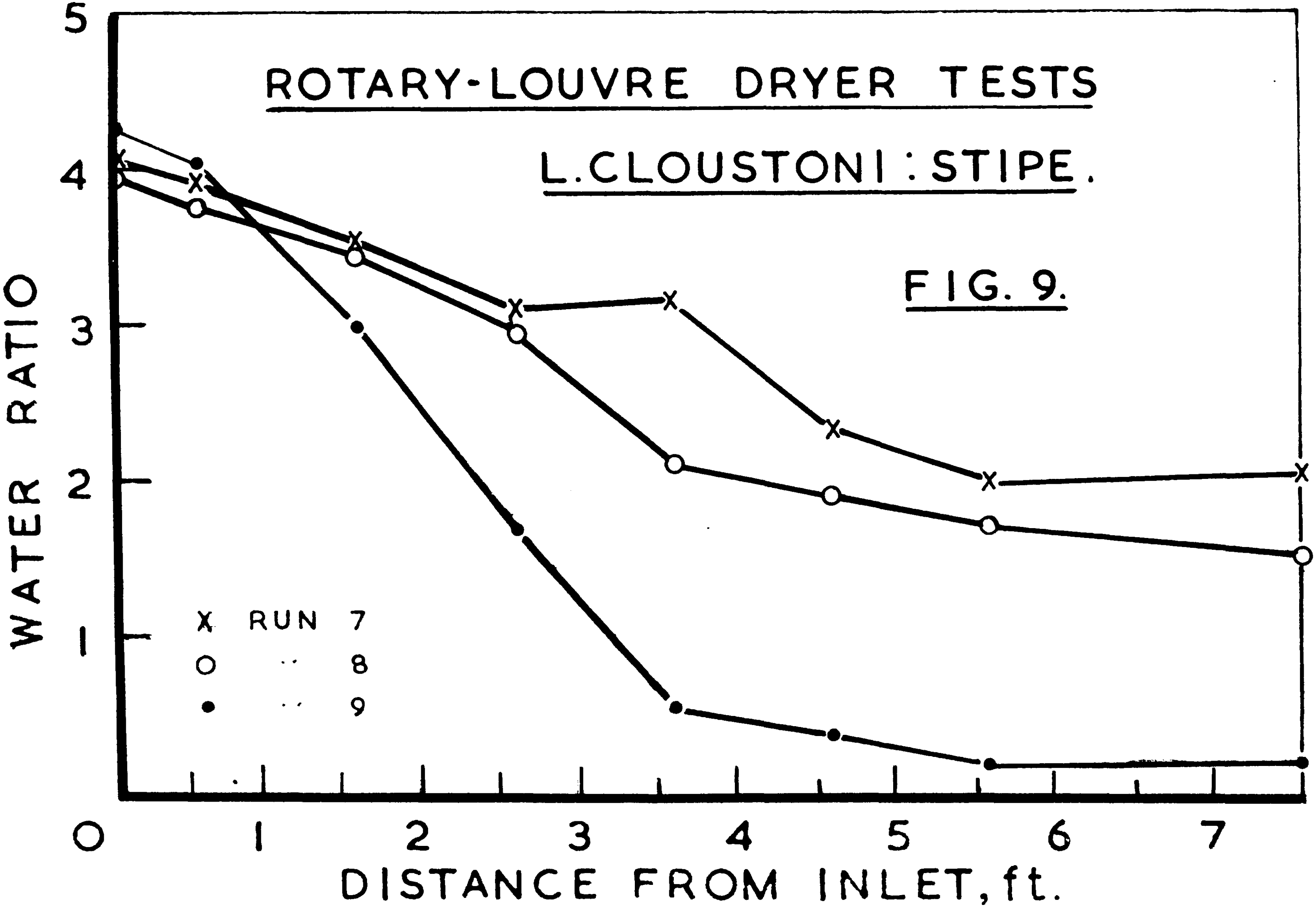

ROTARY-LOUVRE DRYER TESTS
L.CLOUSTONI : STIPE.
X RUN 7
O " 8
● " 9
WATER RATIO
0
1
2
3
4
5
6
7
DISTANCE FROM INLET, ft.

FIG. 9.

amount suggesting that this method of control was successful.

It is thought that the a.l.d.m. is mainly the result of the following two factors :-

(a) The dryer may not have reached stable drying conditions at the start of the quantitative test and as a result the seaweed would still be filling up inside the drum, hence the discharge rate would be less than the feed rate. This error would of course be minimised by using longer run times.

(b) Ideally, the input and output rates should be measured over similar time intervals separated by the time of passage of the seaweed through the dryer. As no estimate of the retention time was available until the end of these series of tests, it was decided to measure these rates simultaneously. This reduces any error in time measurement but subjects the output rates to considerable error if the earlier feed rates were not constant and equal to the rate used in the test proper.

Because of the apparent loss of dry matter, the evaporation rate was calculated from the feed rate and the terminal water contents.

5.1.6. Retention Time

An estimate of the retention time of the seaweed in the rotary-louvre dryer is useful as it enables drying rates in different types of dryers to be compared.

5.1.6.1. Previous Work: Sullivan, Maier and Ralston (115) gave the following formula for the retention time of granular solids in a rotating kiln :-

$$\theta = \frac{0.000517\ Lq^{\frac{1}{2}}}{S\ d\ N}$$

where θ = retention time, min,

L = kiln length, ft,

N = rotation, r.p.m.

S = slope, ft/ft

q = angle of repose of material, deg,

d = kiln diameter, ft.

Bayard (116) recorrelated the data of Sullivan *et al* into the expression :-

$$\theta = \frac{0.0000513\ (q + 24)L}{S\ d\ N}$$

The time of passage of material in a kiln was given by Ginstling Zilberman & Gvozdev (117) as :-

$$\theta = \frac{0.00783\ L}{S\ d\ N}$$

using symbols as above.

Johnstone & Singh (118) suggested that the effect of the lifting flights on the time of passage for rotary dryers could be corrected by applying the factor of 1.4 to the equation given by Sullivan *et al*. The equation for a rotary dryer would then be :-

$$\theta = \frac{0.00722\ Lq^{\frac{1}{2}}}{S\ d\ N}$$

From studies of the residence time of materials in a dryer 8 in dia. x 4 ft long, Prutton, Miller & Shuette (119) derived the formula :-

$$\frac{KL}{S\ d\ N} + mV$$

where V = air velocity ft/min,

K = constant, ranging from 0.0046 - 0.0053 for 6 to 12 flights,

m = constant, varying from -0.00025 to -0.00075 for parallel air flow and +0.00033 to +0.00133 for countercurrent flow.

Smith (120) gave the following formula for calculating the retention time of solids in a rotary dryer :-

$$\theta = \frac{kL}{S\ d\ N}$$

k = 0.0042 to 0.017 for counterflow, 0.0017 to 0.0058 for parallel flow dryers.

Friedman & Marshall (121) from an extensive study of rotary drying of a variety of granular materials (e.g. wood chips, sands, plastic granules) proposed the formula :-

$$\theta = \frac{0.23L}{S\ N^{0.9}\ d} \pm \frac{0.06\ BLG}{F}$$

where $B = 5(D_m)^{-0.5}$

B = a constant dependent on the material,

D_m = weight average particle size of material, micron,

F = feed rate lb dry material/(hr)(sq.ft. of dryer cross section). The plus sign is for countercurrent flow and the negative sign for parallel flow.

Saeman (122) gave a theoretical derivation of the retention time of solids in a lightly loaded kiln which agreed closely with the empirical formula of Sullivan et al. He derived a mathematical relationship to enable the bed volume and time of passage for heavily loaded kilns or rotary-louvre dryers to be calculated by trial and error from the physical data of the system.

Most of the foregoing equations given for retention time of materials in rotary dryers or kilns refer to granular free-flowing solids in cylinders set at a slight slope to the horizontal. In addition the dryers often have lifting flights designed to drop the material in curtains through the air stream. The problem in many cases has been simplified as no drying of the material was attempted.

Measurement of the retention time of seaweed in a rotary-louvre dryer is complicated by the fact that the particles are non-uniform in size, which shrink as they pass through the dryer, with consequent changes in bulk density. In the case of minced frond the fragments are covered with a mucilage which makes the feed material resemble a sticky paste.

In view of the nature of the frond, it was desirable to have a direct measurement of the time of passage and also to find the range of retention times encountered with this material.

The following radioactive-tracer method (123) was devised to measure the retention time of the frond in the dryer.

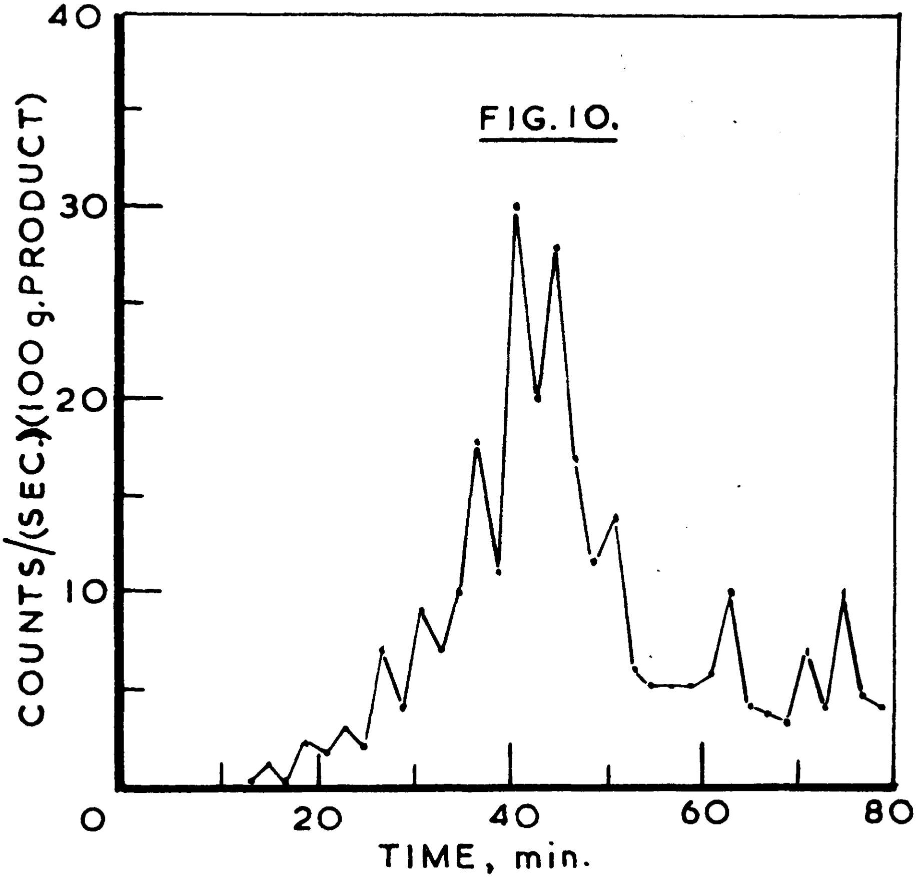
5.1.7. Radioactive-tracer Method of Estimating the Retention Time of Frond in a Rotary-louvre Dryer

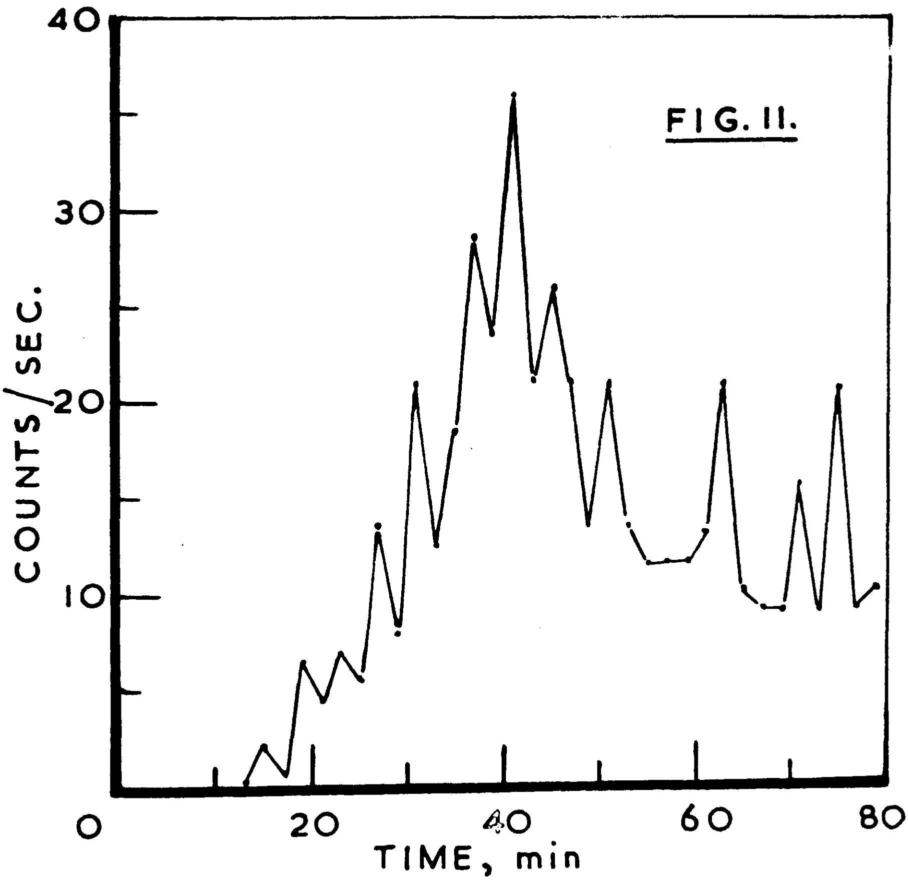
As small L. cloustoni plants were not available, the tracer material was prepared from young L. digitata plants which were collected and kept alive and healthy in a tank of aerated and illuminated seawater. It was considered that for the purposes of this test the physical differences between minced L. digitata frond and minced L. cloustoni frond could be disregarded.

For activation, 100 microcuries of radioactive orthophosphoric acid (P^{32}, half life = 14.3 days) was added to the seawater. During the first 24 hours, the plants absorbed 93% of the radioactive isotope and an additional 4% in the second 24-hour period. Phosphorus 32 was selected mainly because it was readily obtainable in a suitable form, was short-lived and was known to be absorbed. The small amount of minced stipe from the L. digitata should not vitiate the experiment. About one hour before the test, the treated plants were washed free of the radioactive seawater, allowed to drain and minced.

Drying conditions were stabilised on the rotary-louvre dryer by feeding wet L. cloustoni frond in small equal-volume increments (approximately 150 g every 15 seconds) for over one hour. The minced radioactive seaweed was then added (ca. 200 g) and regular feeding resumed with the original frond. The dried material issuing from the discharge end of the dryer was collected over two-minute intervals from the time the treated seaweed was inserted. Each sample was weighed before being placed in a reproducible position under a Geiger-counter tube connected to a radiation monitor type 1021 and the count per second minus the background count was recorded.

The results have been expressed (Fig. 10) as counts/(sec)(100 g of product) to allow for the irregularities in the discharge rates, but


COUNTS/(SEC.)(100 g. PRODUCT)
40
30
20
10
0
20
40
60
80
TIME, min.
FIG. 10.


COUNTS/SEC.
40
30
20
10
0
20
40
60
80
TIME, min
FIG. 11.

since this assumes that each product sample comes out of the dryer with a uniform concentration of radioactive seaweed particles, the results have also been plotted as counts/second versus mid-time of sample irrespective of the sample weight, as the count should be proportional to the actual number of tracer particles being discharged (Fig. 11). It appears that the modal retention time is of the order of 41 minutes, although radioactivity is still present at double this time. It is obvious that some of the weed has passed straight through the dryer, while some is still retained after 80 minutes.

The four peaks occurring after 50 minutes probably represent quantities of frond which had adhered to the louvres and become de--tached at a later period.

The dimensions of the dryer were :-

Drum internal diameter at feed end	-	7 in
Drum internal diameter at discharge end	-	11 in
Drum length	-	7 ft 9 in
Discharge ring opening	-	5 in dia.

The retention time of solids in a rotary dryer is defined as the hold-up divided by the feed rate. In the case of seaweed which has a high water content, the above quantities cannot be expressed on the basis of the wet material as the water is being continually evaporated from the seaweed as it passes through the dryer. If, however, the feed rate and hold-up are expressed on a bone-dry weight basis, the retention time definition becomes :-

$$\frac{\text{lb B.D.S. hold-up}}{\text{lb B.D.S. per hr feed rate}}$$

where B.D.S. = bone-dry solid.

When operating conditions are steady, the input B.D.S. rate must equal the output B.D.S. rate as required by the mass balance.

It follows from the above expression that the air temperature will have an effect on the retention time if the seaweed is not dried to a point where no further shrinkage occurs. As the stipe dries, the bulk density (lb wet/cu.ft.) decreases (Table 4), but the solids content increases so that the overall B.D.S. bulk density or "concentration" of solids (lb B.D.S/cu.ft.) increases as the seaweed becomes drier. Thus for a constant B.D.S. feed rate, higher air temperatures will result in greater shrinkage of material in the drum and will increase the hold-up of B.D.S. in the dryer.

TABLE 4.

BULK DENSITY OF SEAWEED

L. cloustoni Stipe (Minced to pass $\frac{3}{8}$" dia.)

Water Ratio	0.23	1.53	2.11	3.96	6.15
Bulk Density, lb wet/cu.ft.	23.0	27.2	30.5	34.2	44.6
Bulk Density, lb B.D.S/cu.ft.	18.6	10.7	9.9	6.9	6.2

This effect is illustrated by the stipe Runs 8 & 9. In each case a 5-in ring was used and the hold-up weights were approximately equal (27.5 and 25 lb respectively). Owing to the difference in the average water contents of the bed, however, the corresponding B.D.S. hold-ups were 8.05 and 12.45 lb giving retention times of 32 and 53.5 min respectively. It appears then, that the effect of increasing temperature in the retention time is partly cumulative - the higher temperature gives a drier product which in turn causes a longer retention time due to the larger hold-up of B.D.S.

The expression for retention time in terms of B.D.S. hold-up is probably true only for the dryer as a whole, as the relative residence times of the seaweed in different zones of the dryer drum are probably governed also by the bulk densities in adjacent increments of volume and by the mean radius of the particle path. In the cooling zone these variables are eliminated as the material is no longer shrinking and the bed cross section is uniform.

Heavier bed-loadings will obviously increase the hold-up and retention time of the dryer.

5.1.8. Retention and Drying Time:

The retention time in the present rotary-louvre dryer does not equal the drying time as the last 18 in of the drum is designed as a cooling zone and no hot air is admitted at this region.

Although the cooling zone is only one-fifth of the drum length, the bed cross section is larger and the hold-up of this part is greater in proportion.

An estimate of the retention time in the cooling zone may be obtained by calculating the area of the segment from the dimensions of the drum and discharge ring. As this zone is parallel the bed depth is assumed to be uniform, i.e. the droop of the bed as it nears the discharge is neglected.

The B.D.S. hold-up can then be calculated from the water content and bulk density of the product and the volume of the seaweed bed. Thus for Run 9 the drying time is approximately two-thirds of the retention time.

5.1.9. Conclusions from Rotary-Louvre Tests

5.1.9.1. Frond: The handling characteristics of minced freshly harvested L. cloustoni frond render it unsatisfactory as a feed material for a rotary-louvre dryer. This is a result mainly of the mucilage on the frond surface which causes the particles to adhere to the drum interior, giving rise to uneven treatment times. This conclusion was confirmed by direct observation, by a tracer technique and by the measurement of moisture contents along the drum.

In addition to giving inefficient operation of the dryer, the adhesion of the frond to the dryer would probably give rise to scorching and contamination of the product.

5.1.9.2. Stipe: Minced and centrifuged L. cloustoni stipe has good physical properties for this kind of dryer and gives a product which may be described as a granular meal.

Tests showed that greater efficiency of evaporation was obtained with the use of a deeper bed, and the stipe was successfully dried in a single pass to a water content of 0.23 lb water/lb B.D.S. with a specific evaporation of about 1800 B.Th.U/lb and an estimated retention time of 54 min.

It is anticipated that with the use of deeper beds and possibly air recirculation on a full-scale dryer of this type, higher efficiencies will be obtained.

Evaporative efficiencies for stipe were invariably higher than those for frond, under similar operating conditions.

5.2. PEHRSON DUAL-PROCESS CROP DRYER

5.2.1. Introduction

The Pehrson dual-process crop dryer was developed in 1936 by the Ingeniorsfirma J.M. & R.V. Pehrson, Stockholm, Sweden, for drying heterogeneous mixtures of leaf and stem grass without reduction of nutritive value.

This particular dryer was erected at Kenton, near Stowmarket, Suffolk, by representatives of the Swedish firm in 1949-50 for the Eastern Counties Farmers' Co-operative Association Ltd. This Pehrson dryer (model P-750 + T-250), was the first of its kind to be erected in Great Britain and was one of the largest grass dryers in the United Kingdom. The rated output of the plant is 22 cwt dried grass per hour corresponding to an evaporation of about 8,000 lb water per hour.

During the grass drying season in 1950, the Eastern Counties Farmers' Co-operative Association cut, collected and dried grass from over 120 farms within a 20-mile radius of the drying station. A review of one year's grass drying at the Kenton station has been published (124). The cost of the complete drying station at Kenton which includes field equipment, dryer, buildings, etc., was stated by the manager to be about £60,000. The cost of the dryer (less furnace) given by the Grass Drying Mission to the Continent in their report (125) was £17,000.

Manufacturer's literature on the Pehrson dryer (126) claims that it is suitable for drying cast seaweed. Data given for lucerne (127) show that the specific evaporation increases from 1580 to 1750 B.Th.U/lb water evaporated as the initial water content is reduced from 85% to 70%

5.2.2. Description of the Dryer

The drying process in the Pehrson dryer is carried out in three stages - a pneumatic tower drying section and two rotary drum sections (Fig. 12). The chopped wet material is fed into the base of the tall duct by an endless bucket elevator with buckets 36 in

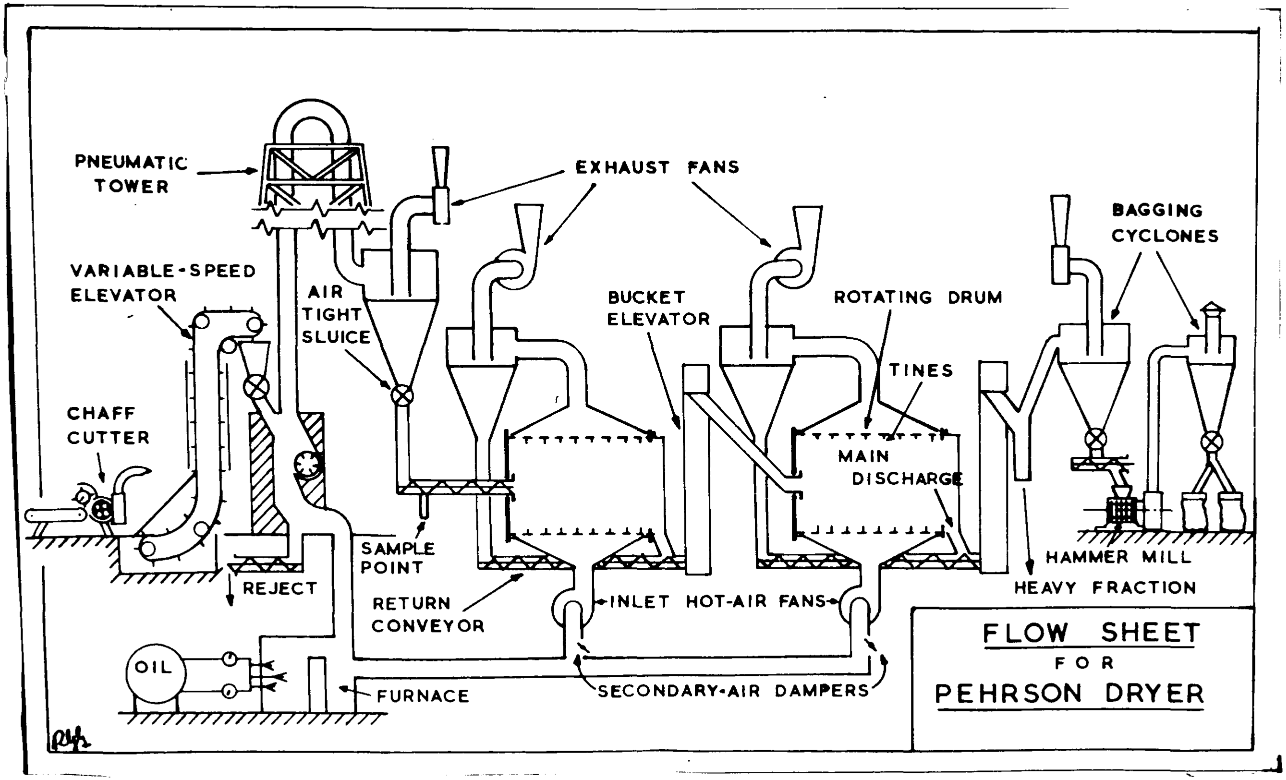

PNEUMATIC TOWER
VARIABLE-SPEED ELEVATOR
CHAFF CUTTER
AIR TIGHT SLUICE
EXHAUST FANS
BUCKET ELEVATOR
ROTATING DRUM
TINES
MAIN DISCHARGE
BAGGING CYCLONES
HAMMER MILL
HEAVY FRACTION
SAMPLE POINT
REJECT
RETURN CONVEYOR
INLET HOT-AIR FANS
OIL
FURNACE
SECONDARY-AIR DAMPERS
FLOW SHEET
FOR
PEHRSON DRYER

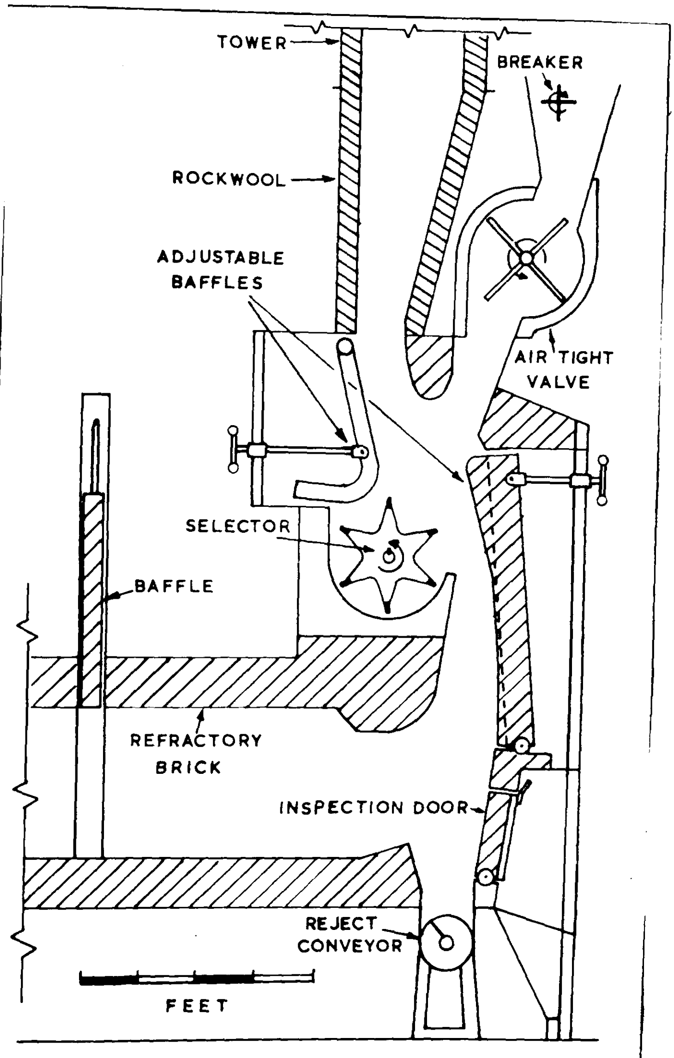
Fig. 12.

wide, 6 in deep, spaced at 6 in intervals. The feed elevator discharges the wet stock into a hopper fitted with a rotating breaker to prevent the feed from agglomerating before it passes through an air-tight sluice into the hot gas stream.

The hot gases (1800°F) used in the pneumatic tower are drawn from an oil-fired furnace which burns Shell Britoleum. The oil burners were manually operated throughout the tests.

When the wet feed is introduced to the gas stream in the tower, the smaller particles are swept upwards almost immediately whilst the heavier pieces fall into the "selector". This mechanism comprises a set of six bars mounted round a horizontal shaft by star-shaped end-plates and the whole assembly rotates in a corresponding cavity in the refractory lining of the tower base (Fig. 13). The heavier particles are continually exposed to the hot air blast by the rotating bars until they have lost sufficient weight to enable them to be carried upwards. Stones and the largest particles are eventually rejected and fall to the bottom of the tower, where they are removed from the system by a screw conveyor. The rate of evaporation in the tower is so high that the gases are cooled to a temperature of approximately 300°F. The partly-dried solids are removed from the air stream at the exit end of the pneumatic stage by a cyclone separator. The exhaust fan for inducing the air through the tower is sited on the roof of the cyclone.

The material now passes through an air seal and is fed by a worm conveyor into the first drum. This rotary dryer consists of a cylindri--cal steel drum about 8 ft 6 in diameter by 12 ft long which has a large number of "eyelid" perforations on the curved surface. Rotation of this drum (2 r.p.m.) imparts a rolling and mixing action to the pieces of material, while tines bolted to the inside of the drum prevent packing of the charge and the formation of gas channels, in addition to giving even distribution of heat and intimate contact between the air and material. Drying air to the drum is at a much lower temperature (550-750°F) than the air in the flotation section.



SELECTOR MECHANISM
AT THE BASE OF THE
PNEUMATIC TOWER
OF THE
PEHRSON DRYER.

RM.

Fig. 13.

The drying gases are blown transversely through the bed of material by a hot-air fan which draws gases through a brick duct from the furnace. Between the blower and the furnace there is a temperature-regulating/air-mixing box in which the gases are reduced to the required temperature by diluting with cold air. A damper is also fitted to this duct. As the smaller particles in the drum become dry, they are carried out by the exhaust gases and recovered in the cyclone or else fall through the perforations to the platform below. These fines are pulled into a central conveyor by a set of scraper blades but the bulk of the material flows through the drum and over an adjustable gate to the worm conveyor. A third balancing fan is used so that the drum is operated under a slight vacuum and the door may be left open to observe the material during drying. After the material has been discharged from the first drum, a bucket elevator passes it to a feed chute leading to the second drum. This drum is identical to the first, but operates at a lower temperature (300 - 500°F).

The dry product is raised to the mill cyclone by a second bucket elevator and a pneumatic conveyor. An adjustable damper is provided in this duct so that the air lift may be varied to allow only the lighter particles to be carried over. The product is then fed by gravity from the base of the cyclone to either of the grinders via an air seal and worm conveyor. The Christy & Norris "Briton" swing hammer mills operate at 3000 r.p.m. and are driven by individual 60 H.P. electric motors. The screen aperture used throughout these tests was 1.6 m.m. and the product passing through the screen was blown into a bagging cyclone.

5.2.3. Precutting

A Fox River chaff cutter was used to chop the seaweed prior to drying. This machine has a conveyor belt which guides the material under a spring-loaded feed roller. Serrated ridges pull the seaweed into the cutting cylinder which chops the material against a fixed blade. A delivery duct with a fan driven by a 40 H.P. Petrol engine incorporated in the machine enable the chopped product to be blown into any suitable

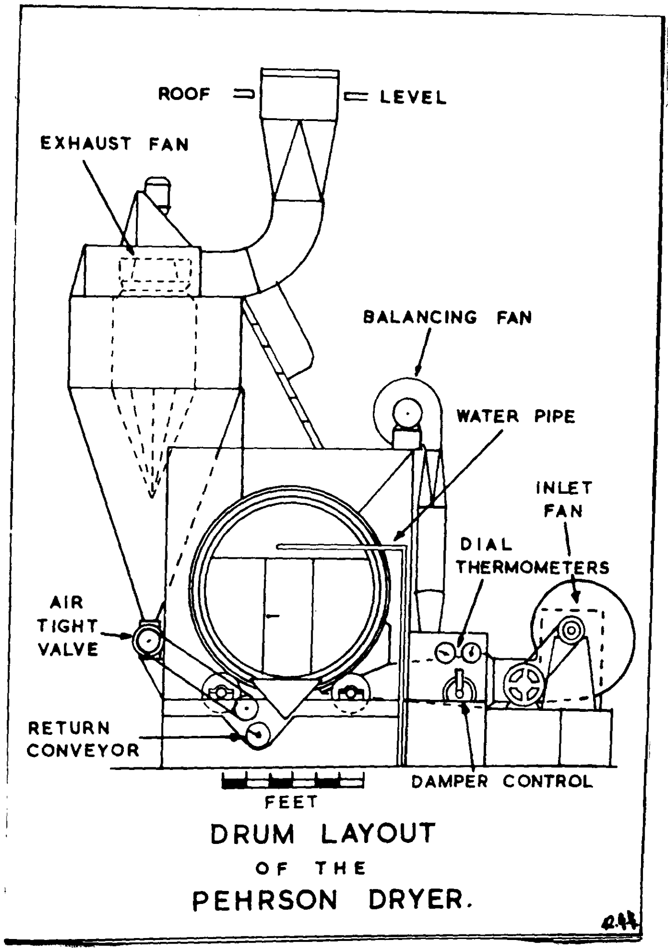

ROOF
LEVEL
EXHAUST FAN
BALANCING FAN
WATER PIPE
INLET FAN
DIAL THERMOMETERS
AIR TIGHT VALVE
RETURN CONVEYOR
DAMPER CONTROL
FEET
DRUM LAYOUT
OF THE
PEHRSON DRYER.

Fig. 14.

receptacle. The cost of this chaff cutter is about £1,200.

The capacity of the cutter was tested by passing 3,670 lb of fresh L. cloustoni stipe through at as great a rate as possible (with eight men loading the seaweed on to the conveyor). This weight of stipe required 21 minutes to cut, equivalent to a throughput of 5 tons of wet seaweed per hour. By varying the conveyor belt speed in relation to the cutter speed, the size of the piece can be regulated. In all these tests the machine was set to the smallest size which was nominally $\frac{1}{4}$ in. In practice the stipe pieces were about $\frac{1}{2}$-in cubes on the average and the frond pieces about 2-in squares. The quantity of over--size particles amounted to about 5% (based on the weight of material rejected from the selector in the dryer).

The general impression gained from this test was that the cutter was working well within its capacity. The fronds did not cut satis--factorily as they became very sticky and showed a tendency to choke the cutters. When the whole plants were tried, the stipes prevented the fronds from clogging the machine to any serious extent.

With a few modifications this type of machine would appear to be suitable for precutting seaweed. A screening arrangement, such as a trommel, to hold back larger pieces, would give a more homogeneous particle size for drying. The oversize pieces should be recycled through a smaller machine, perhaps of a different type, as it is unlikely that the Fox River cutter would further reduce short lengths of stipe effectively. If the air stream is used for size classification as in this dryer, the rejected fraction could be passed through a smaller cutter directly. This rejected fraction will contain stones and foreign matter from the feed, and adequate precautions should be taken to prevent these from entering the cutter.

5.2.4. Experimental Procedure

5.2.4.1. Material Measurement: The portable weighing machine used for the ingoing seaweed was designed and constructed by the National Institute of Agricultural Engineering for tests on grass dryers.

This weighbridge comprises a rigid platform supported at its corners by four low steelyards, each with a capacity of 4,000 lb by 1 lb. Ramps at either end of the platform enable trailers containing seaweed to be wheeled on to the machine.

Large wire nets had previously been placed in the trailer, so that the load could be dumped by opening the side doors and pulling out the nets. Each trailer has a capacity of about two tons of seaweed.

The seaweed was loaded into the bucket feed elevator of the dryer by a tractor equipped with a "Horn-Draulic" hydraulically-operated mechanical shovel. As the area surrounding the elevator was concreted, any small amounts of seaweed which fell off the mechanical shovel, etc., were easily swept up and fed to the dryer, thereby keeping the losses of weighed material to a minimum.

The dried seaweed meal was collected in paper bags and the contents adjusted to 56 lb net on a sack balance. The approximate filling time for each bag was noted for the second and third runs.

During a drying run, the material coming from the tower cyclone was frequently sampled for evidence of scorching, for measurement of material temperature and for moisture content. These samples were taken from the screw conveyor feeding the material to the first drum. By pushing up the valve handle in the sampling tube a handful of material was obtained. A large basket was placed underneath this sampling point and the contents were recycled periodically.

Losses of dry matter may have occurred in the filter bags of the hammer mill as it was impracticable to empty the bags before the tests. There may also have been small amounts of fines underneath the drums which may have escaped the scrapers. It was observed that a quantity of dried seaweed (circa 20 lb) was collecting at the bottom of the bucket elevators by being missed by the edges of the buckets.

One feature claimed for this dryer is that oversize and heavy material, such as stones, is rejected from the feed by the selector and is removed by a screw conveyor. This arrangement proved to be effective for the runs on stipes and whole plants, as chunks of stipe above about $1\frac{1}{2}$ - 2 in appeared in the worm exit. A very clean cut separation was achieved, and very few small pieces were ejected in this way. This seaweed was collected in bags and its weight deducted from the weight of feed. Although a certain amount of drying had probably taken place, the moisture content was assumed to be that of the raw feed.

With frond on the other hand, a large proportion of the feed (25 - 50%) was rejected immediately, although the sizes of individual pieces were well within the flotation limits. On opening the inspect--ion door under the selector, it was observed that the frond was falling intermittently in cascades which seemed to indicate that the material was sticking together and falling in agglomerates. At this stage a man was fully employed returning the whole of the reject into the feed elevator. Eventually the bulk of the frond was carried over, leaving only the heavier pieces of the seaweed plant adjoining the stipe. This final reject is the weight reported.

5.2.4.2. Temperature Measurement: The inlet temperature to the pneumatic tower was indicated by a dial thermometer and the exhaust temperature was recorded on a thermograph, as the latter value was important for control purposes. The rate of feed to the selector was adjusted to keep this exhaust temperature in the region of 320°F. Inlet and outlet temperatures to each drum were indicated by mercury/steel dial thermometers.

Wet-bulb temperatures of the air leaving each drum were measured by dial thermometers of the ether vapour type. The bulbs of these thermometers were kept wet by a piece of muslin which dipped into copper dishes (Fig. 15) suspended inside the drum. A length of rubber tubing

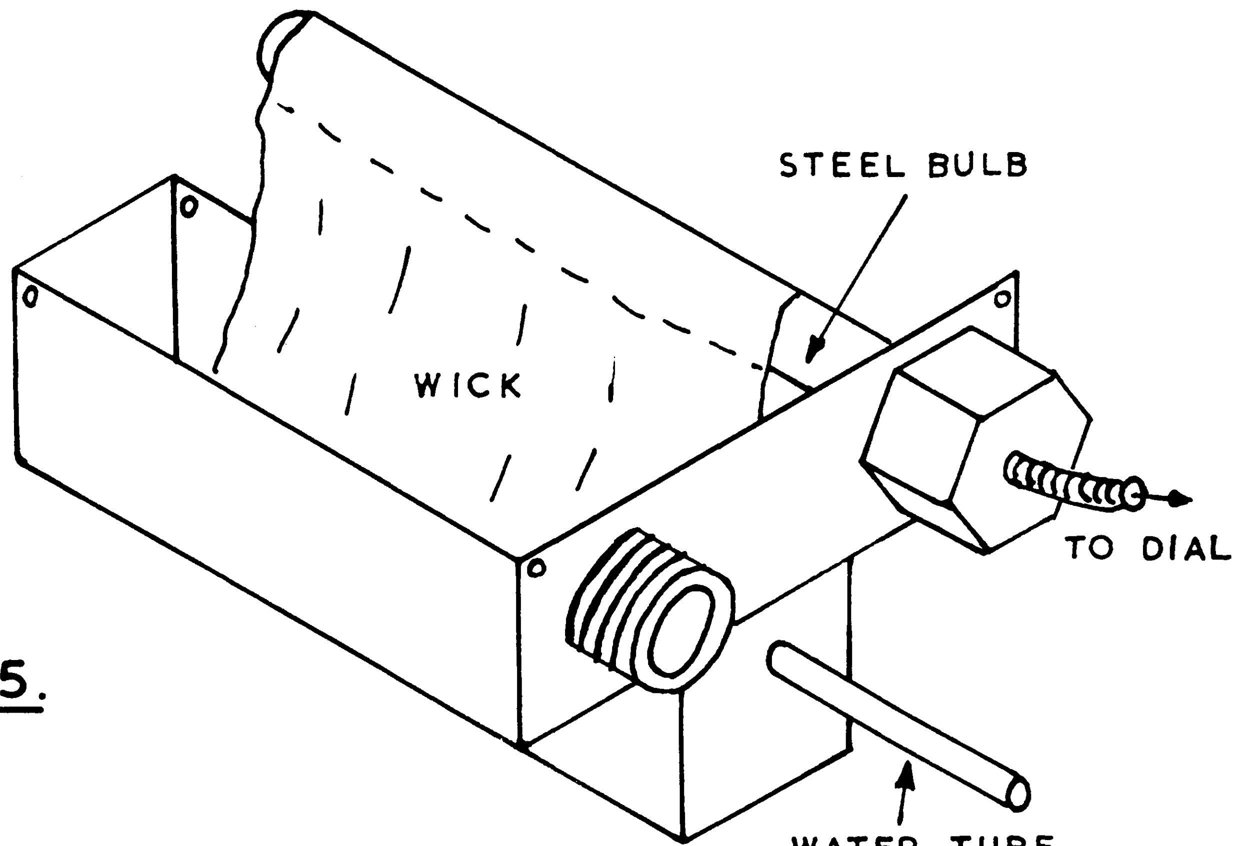


FIG. 15.

ISOMETRIC SKETCH OF
WET BULB RESERVOIR

was used to siphon water to the dishes from a pail placed on the roof of the dryer.

As the doors at the end of the drum casings were open throughout the tests, it is possible that the exhaust dry bulb temperatures recorded are low due to entry of cold air.

5.2.4.3. Material Temperatures: The temperature of material leaving the pneumatic drying stage was taken by obtaining a handful of the seaweed from the sampling tube at the base of the tower cyclone, and embedding a thermometer in it until the mercury reading was constant. Where the material was moving along the conveyor beneath the drums, the thermometers were suspended in the stream of material and read at ten-minute intervals.

5.2.4.4. Sampling: Samples of the seaweed were taken at five stages of the drying process, viz:-

(1) Wet feed - from the bucket elevator.

(2) After pneumatic tower - from sampling point (see flow sheet, Fig. 12).

(3) After drum 1 - from overflow at weir.

(4) After drum 2 - ditto.

(5) Milled product - small sample taken from each bag.

At each sampling point, small increments were taken every ten minutes and the combined sample placed in a labelled 8-oz sample bottle and dispatched to the Institute of Seaweed Research by passenger train. On arrival at the laboratory, the contents of each bottle were cut into small pieces and the moisture contents determined by an oven method at 212°F. The results are set out in Table 4.

5.2.4.5. Fuel and Power Measurement: During the runs, the Kent oil meters were read at ten-minute intervals in addition to readings made at the start and finish of each test. The oil temperature was also noted.

The P-750 + T-250 type dryer has 19 electric motors with a total of 130 H.P. excluding furnace equipment, plus 60 H.P. for the hammer mill.

TABLE 4.

WATER CONTENTS OF SEAWEED SAMPLES

(Average Values)

SAMPLE POINT	STIPE		WHOLE PLANT		FROND	
	Wet Basis %	Dry Basis lb/lb	Wet Basis %	Dry Basis lb/lb	Wet Basis %	Dry Basis lb/lb
Wet Feed	83.8	5.17	83.5	5.38	80.8	4.20
Ex Tower	74.3	2.90	74.0	2.85	63.3	1.73
Ex Drum 1	49.8	1.0	44.0	0.78	41.1	0.70
Ex Drum 2	8.4	0.09	11.0	0.12	8.0	0.09
Product	9.3	0.1	11.6	0.13	9.8	0.11

TABLE 5.

AIR VELOCITIES

		Tower	Drum 1	Drum 2
Duct diameter, ft	...	2.39	3.28	3.28
Air velocity, ft/min	...	2,840	1,170	1,320
Air volume, cu.ft/min	...	12,750	9,900	11,150

The average power consumption for the drying plant was stated to be 140 k.w.h. (128).

5.2.4.6. Air Velocities: Two days before the seaweed test, the oil burners were started at low heat in order to warm up the furnace refractories and dry out the air ducts. This air at approximately 212°F was drawn through the tower and passed out to the armosphere. An approximate value of this velocity was obtained by traversing the fan outlet duct with an anemometer. In practice, the air enters the tower at 1800°F and is cooled to approximately 300°F before leaving, so that the velocity in the tower itself will probably be very much higher. Air above 300°F was not passed through the empty tower as there would be a risk of distorting the feed machinery.

On the day prior to the drying test, several tons of silage were dried which gave the observers an opportunity of seeing the dryer in operation and to perfect the testing technique. During the silage test, duct traverses were made to obtain the air velocities leaving the two drums. These measurements (Table 5) probably represent approximate working conditions since the resistance of the bed of material will have reduced the air flow. It was impracticable to measure air flows during the seaweed drying tests.

5.2.4.7. Raw Material: The seaweed for these tests (L. cloustoni) had been harvested during the previous week at Oban and stored in the sea in large nets. Two days before the test it was loaded on to two open-sided, roofed, cattle trucks and sent by road to Suffolk. One load of stipe and frond arrived on the afternoon before the test enabling the stipe to be chopped in readiness for the following day. This material was stored overnight on a concrete apron and was sheltered by the lean-to roof. The remainder of the seaweed was unloaded and left out in the open.

There were frequent showers of rain during the test which may account for the increase in moisture content of the frond from 80% at Oban to 81% at Kenton.

5.2.4.8. Drying Runs: As the behaviour of seaweed during drying in a dryer of this type was unknown, it was impracticable to operate the dryer under prearranged conditions. Air temperatures and volumes were altered to give a dry product which could be ground in the mills. The conditions had to be such that the evaporation loads in the drums were equal, otherwise heat would be wasted and scorching would take place. These restrictions partly account for the wide variations in the inlet drum temperatures (Fig. 16). If sufficient quantity of seaweed had been available for a prolonged test, no doubt a suitable set of conditions would have been found when the dryer had stabilized.

Due to the large cross section of the chopped seaweed particles in relation to grass, it was decided to reduce the feed rate to the minimum and give the material a maximum drying time. The overflow weirs at the ends of the rotary drums were also adjusted to give the maximum holdup volume.

When the wet feed for each run was finished, the pneumatic tower was isolated from the furnace by a refractory baffle, and the burners turned down. The seaweed was allowed to remain in the first drum until it was partly dried, then the fans were shut off and the drum allowed to empty. Lastly the remainder of the seaweed was brushed out from the rotating drum. This process was repeated for the second drum.

The time log-sheet for those various operations is illustrated in graphical form for the frond test run (Fig. 17) in which vertical distances are proportional to time.

5.2.5. Labour Requirements

For normal running, 5 men would be required :-

One chargehand who adjusts the controls, oil burners, etc., and operates the plant generally.

One man loading the chopped material into the feed elevator with the "Horn Draulic".

One man operating the Fox River precutter.

Two men bagging, weighing and storing the product.

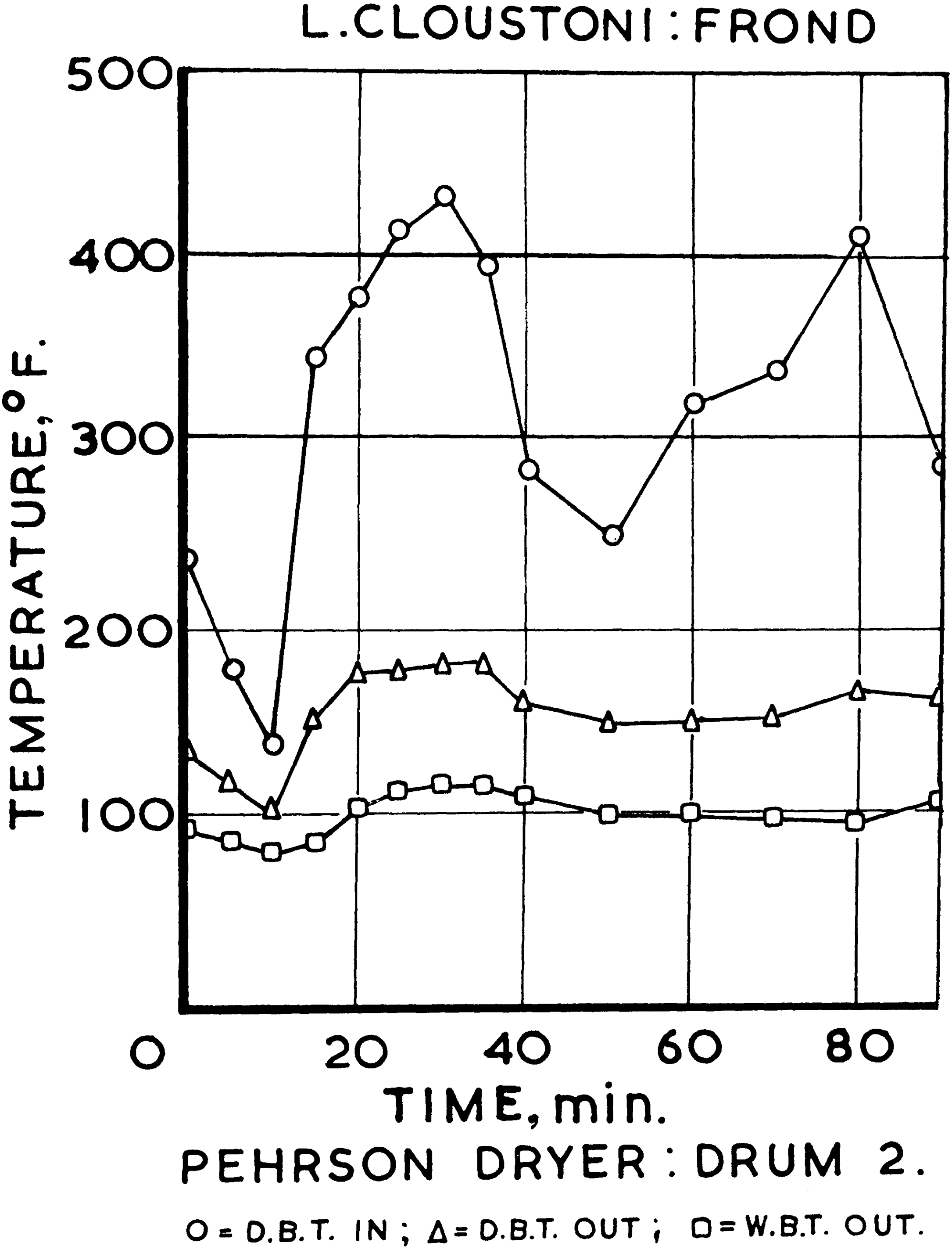

L.CLOUSTONI : FROND
TEMPERATURE, °F.
500
400
300
200
100
0
20
40
60
80
TIME, min.
PEHRSON DRYER : DRUM 2.
O = D.B.T. IN ; Δ = D.B.T. OUT ; □ = W.B.T. OUT.

FIG. 16.

This schedule excludes administration. It also assumes that the material is loaded on to the conveyor belt of the Fox River cutter. The test on the chaff cutter has shown that if mechanical handling is not available, this labour item may become excessive.

5.2.6. Contact Time

It was impracticable to measure directly the contact time of the seaweed particles in the pneumatic tower, but on starting up, it was observed that the first pieces arrived at the sampling point about one minute after the feed had entered the hopper. The figure given by the manufacturers of 5 - 10 seconds retention time in the selector before going over the tower would appear to be reasonable.

In the rotary drying stages, a rough estimate of the drying time was obtained from a study of the frond time log-sheet (Fig. 17). A trickle of fines started within 10 minutes from the beginning of the test, but steady filling of the bags was not attained till 45-50 minutes from the start. If the time of passage through the drum is assumed to be equal to the filling time, then the retention time in each drum would be of the order of 25-30 minutes.

5.2.7. Results

In the performance table of the dryer (Table 6) the feed times are quoted as 93, 60 and 71 minutes for stipe, whole plant and frond respectively. Owing to time lags in filling and emptying drums and the mill, the total times for these runs were 150, 120 and 90 minutes. This raises a difficulty regarding the correct time to use for calculating the output of the dryer. The alternatives are feed time, product time, or an average "steady conditions" time.

The latter could possibly be obtained for the frond run by selecting the period from 50-70 minutes from the start when the tower was in operation and the product was coming over at a steady rate. Unfortunately in the other runs the product rate did not steady until the feed was finished, and the product rate had been noted at intervals only. This method was not used as it seemed unwise to select a small portion of the

TIME LOG FOR FROND RUN. FIG.17.

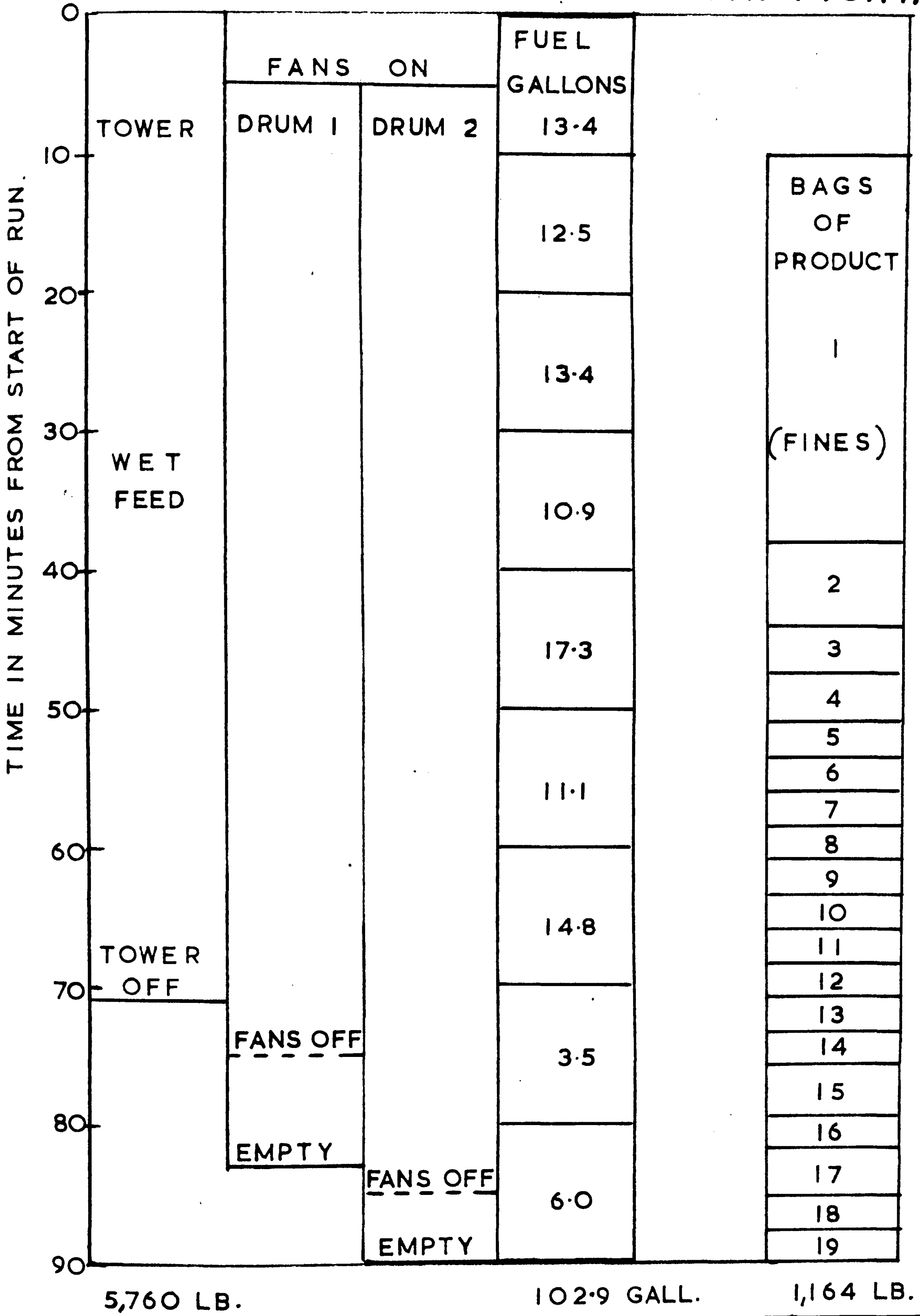


TABLE 6.

PERFORMANCE FIGURES FOR PEHRSON DRYER (P-750 + T-250)

OPERATING ON SEAWEED

L. cloustoni	STIPE	WHOLE PLANT	FROND
Water content of raw material, % ...	83.8	83.5	80.8
Water content of dried material, % ...	9.3	11.6	9.8
Weight of wet feed, lb ...	8809	6316	5799
Weight of feed rejected, lb	420	170	39
Net weight dried, lb ...	8389	6146	5760
Weight of dried product, lb	1365	1164	1064
Loss of weight, lb ...	7024	4982	4696
Loss of dry matter,* lb ...	120	+14	146
Net evaporation, lb ...	6904	4996	4550
Fuel consumption, gall @ 160°F	168	121	103
Gross calorific value of fuel, B.Th.U/gall @ 160°F ...	169,500	169,500	169,500
B.Th.U/lb water evaporated ..	4130	4100	3840
Feed time, min ...	93	60	71

* See Table 7.

test on which to base an output rate.

The next alternative, the time required for the product to collect is unsatisfactory as the rate is uneven at the beginning, and it may represent the minimum capacity of the dryer if the mill was choking or unable to handle the load.

In the circumstances it was decided to base the rates on the feed time. It may be argued that in normal running the drums and mill could handle the feed as fast as it came from the tower and eventually the weight of product being delivered would be equivalent to the weight of feed entering. The feed rate was also very nearly constant during the test run.

The outputs of dried product were 0.394, 0.52 and 0.398 tons/hr for stipe, whole plant and frond. From the moisture contents (dry basis) at various points in the dryer, the percentages of water evaporated in the pneumatic tower were 45%, 48% and 60% respectively. The higher percentage of evaporation in the tower for frond may be accounted for by the recycling of the rejected feed material. The makers claim that using grass, 60% of the moisture is removed in the tower. The maximum temperature of material leaving the tower was 127°F.

The net evaporation was obtained from the algebraic difference of the loss in weight of the seaweed in passing through the dryer and the apparent loss in dry matter. The dry matter loss was calculated from the inlet and outlet weights and moisture contents (Table 7).

5.2.8. Conclusions

The results show that the dryer was running well within its rated evaporation load. A possible reason for this was that the feed elevator was set at the lowest feed rate. It is probable that the feed rate could be increased and yet enable the dryer to deliver a suitable dried product, due to more efficient evaporation. Table 8 shows that in all cases the exhaust air had a relative humidity of less than 20%, so that the air could still take up more water, at least in the first drum. In the last drum, there is evidence of overheating as the material was at a temperature

TABLE 7.

APPARENT LOSS OF DRY MATTER

Run	Dry Matter Input lb	Dry Matter Output lb	Apparent Loss lb	% Loss
Stipe	1360	1240	120	8.8
Whole Plant	1015	1029	Gain 14	+1.4
Frond	1106	960	146	13.2

TABLE 8.

AIR HUMIDITIES

Material	Position	Air Temperature °F		Relative Humidity %	Absolute Humidity gr/lb
		Dry bulb	Wet bulb		
Stipe	Drum 1	180	113	14	346
	Drum 2	161	106	18	271
Whole Plant	Drum 1	158	102	16	231
	Drum 2	165	111	19	342
Frond	Drum 1	212	113	6	292
	Drum 2	154	104	19	260
Atmospheric Air		52	48	90	43

of 140-180°F. If the throughput of seaweed was increased there would be less chance of this occurring.

Considering the size of the dryer, the quantity of seaweed available for the three tests was insufficient to give the dryer time to reach stable conditions. Also the dryer had not been in use for several weeks previously so that the heat losses were probably exaggerated. The overall specific evaporation for the dryer on seaweed ranged from 4130 B.Th.U. per lb water evaporated for stipe to 3840 B.Th.U/lb for frond. The figure given by a firm of consulting engineers in Sweden on a recent test of a similar dryer using grass was 1580 B.Th.U/lb (125). This disparity may be due to different materials being used, although the agreement between frond and stipe - two materials with widely differing physical characteristics - seems to indicate that the difference lies in the dryer.

It is reasonable to assume that under steady conditions the specific evaporation will approach the value of 1580 B.Th.U/lb which means that the probable output will be 2 or $2\frac{1}{2}$ times the value obtained in this test.

Drying stipe and frond together (i.e. whole plant) gave a greater output than frond or stipe separately. This seems to be due to the cut stipe preventing the sticking together of the frond particles resulting in a more porous bed of material. It should be noted, however, that the average inlet air temperatures to the drums were the highest for this run (Table 9).

This dryer is technically capable of drying fresh L. cloustoni stipe or whole plant (after chopping) to a suitable condition for grinding. The dryer in its present form is unsuitable for drying frond, due to the present feeding arrangements for the pneumatic tower and to the adhesive nature of the wet feed. The ground seaweed meal obtained from this test was not of good quality as it had evidently been scorched and had an unpleasant "off" odour. This should not be entirely attributed to the dryer, however, since some decomposition of the wet seaweed may have

TABLE 9.

AIR TEMPERATURES

		PNEUMATIC TOWER		DRUM No.1.			DRUM No.2.		
		Inlet °F	Outlet °F	Inlet °F	Outlet °F	Mat'l °F	Inlet °F	Outlet °F	Mat'l °F
STIPE	Ave.	1740	310	667	180	-	401	162	-
	Max.	1900	375	828	198	109	585	201	140
	Min.	1650	284	550	171	-	212	95	-
WHOLE PLANT	Ave.	1740	293	797	158	-	415	165	-
	Max.	1830	320	842	163	125	500	203	158
	Min.	1650	275	694	147	-	280	131	-
FROND	Ave.	1810	284	518	212	-	311	154	-
	Max.	1920	338	657	241	154	428	181	181
	Min.	1760	248	302	167	-	136	102	-

occurred in transit to the drying station. The air temperatures in the drums were apparently too high and some of the larger stipe pieces had burst open, probably as a result of rapid internal vaporization of water.

The pneumatic drying section minimised the stickiness of the frond pieces, and enabled them to be dried more readily in the rotary dryers. It was not known if any of the seaweed frond adhered to the interior of the tower and was burned, but this possibility may account for the dry-matter loss for frond being the highest of the three runs.

5.3. TEMPLEWOOD GRASS DRYER

5.3.1. Introduction

The through-circulation conveyor dryer selected for testing was a Templewood Mk.2 Grass Dryer at Gilmerton Estates, Drem, East Lothian. This dryer has been described in the literature (129) and the prototype was tested by the National Institute of Agricultural Engineering (130).

Output of dried grass from this unit was rated at 4 cwt/hr when feeding grass with a water content of 80%. The dryer was designed to operate at a maximum air temperature of 300°F to avoid rapid scorching of the grass and consequent loss of digestibility in the protein content.

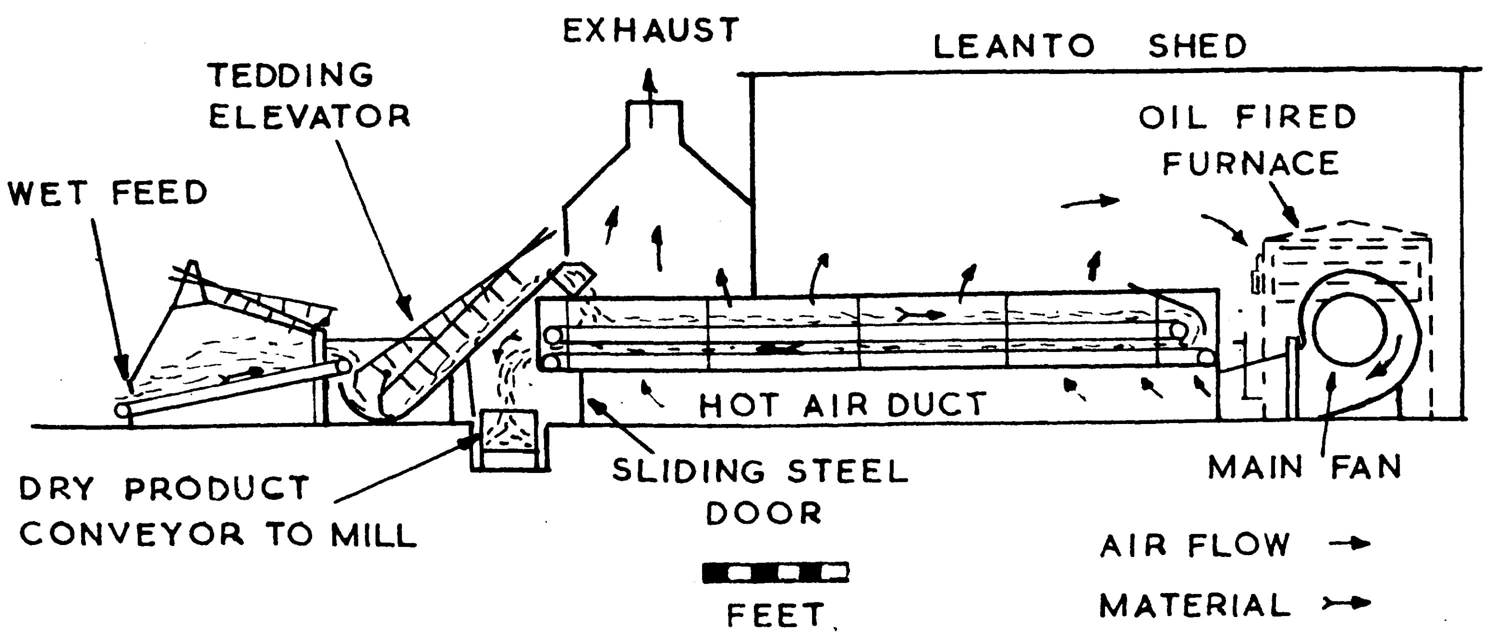
5.3.2. Description of Dryer

This dryer is a double-pass through-draught conveyor type grass dryer using low-temperature drying-air (300°F) with recirculation.

The wet grass is normally loaded on to a feed conveyor of the same width as the drying conveyors, which slopes upward from 1 ft above ground level and discharges into a curved trough at the foot of the feed elevator (Fig. 18). The grass is pulled up nine sloping channels by tined rods driven by a 9-throw crankshaft and is finally discharged on to the top drying conveyor which is approximately 6 ft above ground level.

The drying conveyor belts are each 25.1 ft long by 5.38 ft wide and consist of 16-in long panels of $\frac{3}{8}$-in link wire supported on each side by sprocket chains. The grass passes along the top of the upper conveyor belt, through an oscillating turnover guide and is returned by the bottom conveyor to a discharge cross-conveyor beneath the feed elevator. The discharge conveyor passes the dried material to a Christy & Norris "Briton" prebreaker and hammermill fitted with a bagging cyclone and dust filter.

The furnace is oil fired with a low-pressure-air burner and forge blower type fan. Gas oil is fed from the storage tank by a gear pump. Secondary air is admitted to the furnace by an opening round the burner



THE TEMPLEWOOD MARK 2 GRASS DRYER.

FIG. 18.

and diluent air is controlled by a damper at the rear of the furnace.

The main centrifugal fan draws the secondary and tertiary air through the furnace and blows this hot air into the brick duct beneath the two conveyors. This drying air passes upward through the partly dried grass on the lower conveyor and through the wetter feed on the top band. The exhaust air from one third of the conveyor nearest the feed end is discharged direct to the atmosphere, the remainder passing into the large leanto shed which houses the dryer and furnace. The shed thus acts as a recirculation duct and the fresh air for the furnace enters from an adjacent door.

The feed and drying conveyor speeds can be controlled by a hand--operated variable drive. The oil burner can be thermostatically or manually controlled and the drying conveyor speed can be automatically regulated to give a constant exhaust temperature at a point on the top band one-third along from the feed end. The furnace damper controls the volume of diluting air passing through the fan and hence the air velocity through the bed of material.

The horsepower of the electric motors in the installation is tabulated below :-

	H.P.
Main Fan	12.5
Furnace Blower	5
Feed & Drying Conveyor	1.5
Leveller & Elevator	1
Cross Conveyor	1
Prebreaker & Mill	50

5.3.3. Experimental Procedure

5.3.3.1. Air Temperature : These were measured from the dial thermometers provided on the dryer as standard equipment. A recording thermograph was installed as part of the automatic control instruments. A wet-bulb temperature measurement was made using the arrangement described in Section 5.2.4.2.

5.3.3.2. Air Flow: A rough estimate of the air flow through the dryer was made by taking a vertical 8-point pitot tube traverse of the inlet duct between the fan and the dryer. As there was only one opening in the duct a fuller traverse could not be made.

5.3.3.3. Material Measurement: A sack balance was available for weighing the dried product in the paper bags, but this method was impracticable for weighing the wet feed for every test. An estimate of the total amount of seaweed used in the tests was obtained by loading the chopped frond on to a lorry and having it weighed on a weighbridge. This gave a net weight of 28 cwt of seaweed.

5.3.3.4. Fuel Measurement: This figure was estimated by dip rod measure--ments at the start and finish of one day's testing. The average value of 19 gall/hr agrees well with the maker's figure of 18.5 gall/hr.

5.3.3.5. Raw Material: All the tests carried out on this dryer were made on L. cloustoni frond which had been harvested in the Firth of Forth, near Granton, from 16-22 November.

5.3.3.6. Drying Runs: The first test with whole fronds, showed that the existing elevating tines were unsuitable for seaweed, as the fronds slipped down the incline almost as fast as they were pulled up. When the fronds were eventually discharged from the dryer, some parts were crisp but where two adjacent parts had adhered, the surface was still wet. It was decided that precutting would be necessary and a "Papec" chaff cutter was used to reduce the fronds to pieces approximately $1\frac{1}{2}$-2 in square which were then manually loaded on to the conveyor belt. The drying conveyor belt speed could be altered from about 1.9 - 6.7 ft/min, (retention time 26 - 7.5 min) but at the lowest speed and with an air temperature of 300°F, the frond was not completely dry when discharged. It was apparent from this test that the dryer in its present form could not dry the chopped frond continuously. For the remainder of the tests, the plant was operated batchwise by loading up the top elevator, drying for about 15 minutes, running the conveyors till the upper load was transferred to the lower band and stopping for a further period of drying.

When the change over was taking place, the top conveyor was reloaded with wet weed.

Other useful information obtained from this set of runs was that air temperatures of 300 and 250°F caused perceptible scorching in the product and the maximum inlet air temperature which could safely be used was about 225°F. Frond dried at this temperature and milled gave a good quality seaweed meal based on appearance, odour and chemical analysis. The drying time at this temperature was 40-50 min per batch.

5.3.4. Results

One quantitative test was made, in which 472 lb frond was loaded evenly on to the top drying conveyor, dried for 20 minutes, turned over on to the lower one and dried for a further 15 minutes. During the turning and emptying operations, the hot air was still passing through the dryer. As these processes took 14 minutes each, the maximum possible drying time would be 63 minutes and the minimum 50 minutes, giving a mean time of about 56 minutes.

As the initial water content of the frond was unknown, an assumed figure of 5.5 lb/lb was taken, from which the theoretical product weight was calculated.

Other data for this run were as follows :-

Dry-bulb temperature	=	225°F.
Wet-bulb temperature	=	110°F.
Air mass flow	=	1,330 lb/min, i.e. G = 9.85 lb/(sq.ft.)(min).
Weight of feed	=	472 lb, i.e. L_W = 3.5 lb/sq.ft.
Water content (assumed)	=	84.5% (5.5 lb/lb).
Weight of product (measured)	=	49 lb.
Weight of product (calcd)	=	85 lb.
Water content of product	=	13.65% (0.16 lb/lb).
Specific Evaporation	=	7,400 B.Th.U/lb.

The weight of bone-dry solids entering and leaving the dryer in the final test did not agree (72.6 lb in, 42.3 lb out). This was believed to be due to the wetter material accumulating in the prebreaker and not passing to the mill as it was too dense to be carried by the pneumatic handling system. If there was no loss of product, the initial water content of the frond would require to be 11.2 lb water/lb bone-dry solid - a most improbable value.

5.3.5. Conclusions

This test has demonstrated the feasibility of drying frond on a full-scale through-circulation dryer, giving an excellent quality seaweed meal.

Two-stage drying is an advantage for frond as the turnover promotes more uniform drying. It was observed during the tests that the frond formed a rigid bed which broke into short fragments as it reached the end of the upper belt.

The Templewood Mk.2 grass dryer in its present form is unsuitable for drying chaff cut L. cloustoni frond economically, due to the drying time of the frond being too long to allow the dryer to be operated continuously.

At the second stage of drying, the exhaust air was only a few degrees cooler than the inlet air and this heat was largely wasted, whereas in normal operation it would pass through the wet material on the top conveyor belt. This accounts for the excessively high specific evaporation of 7,400 B.Th.U/lb water evaporated.

The existing feeding arrangement is unsatisfactory for loading chaff-cut frond on to the top conveyor belt. If the frond were shredded into long strips, say $\frac{1}{4}$ in wide, it is conceivable that the loading mechanism for grass might handle the seaweed satisfactorily.

The limiting air temperature for drying static beds of L. cloustoni frond is about 225°F, i.e. this is the maximum air temperature which the seaweed can withstand for prolonged periods without scorching.

5.4. GENERAL CONCLUSIONS AND FINAL SELECTION OF DRYER

5.4.1. Stipe

All three classes of dryers tested appeared to be technically capable of drying chopped or minced L. cloustoni stipe in the freshly harvested state. The Templewood dryer was not tested with stipe but numerous other tests on a smaller dryer have verified that stipe can be readily dried by through circulation of hot air.

The rotary-louvre dryer produced a good product and for a given output would probably be more compact than either a conveyor or pneumatic-tower dryer.

Pneumatic drying is capable of removing about half of the water initially in the stipe in a few seconds. Minced stipe could be used as a feed and the filtrate should be pumped into the tower to prevent loss of solubles. In this way advantage could be taken of the rapid drying rates of finely cut material.

5.4.2. Frond

The stickiness of the L. cloustoni frond caused uncertain retention time and irregular drying in the rotary-louvre dryer and would almost certainly give trouble with other designs of rotary dryer. Adhesion and bridging of the material could possibly be reduced by fitting loose chains inside the drum but this would increase wear and maintenance costs.

There are two alternative methods of drying thermally-sensitive vegetable material :-

(a) By drying at temperatures safely below scorching point.
(b) By flash drying in high-temperature gases for a few seconds.

Both systems have been used for grass and there is considerable controversy as to the relative merits of the two systems.

Method (a) is clearly applicable to seaweed but there is some dubiety about high-temperature drying of seaweed frond as the thickness of the algal particles is several times greater than that of grass. In the case of fronds, whilst chopping will reduce the area of the lamina it will rarely split it and reduce the thickness. If this is not done, the drying times will almost invariably be longer than the drying times for leaf grass under the same conditions.

Pneumatic drying of frond in the Pehrson dryer has the advantage that 60% of the water can be removed in a few seconds. Frond dis--charged from the tower had lost most of its stickiness and could be handled in the rotary dryers. Feeding difficulties, however, mean that the frond would have to be recycled through the tower as it did not always become airborne at the first attempt. Gordon (131) has stated that recirculation of the feed in flash-drying systems is undesirable if the material is heat sensitive.

As all the water content of seaweed is not present at the surface, pneumatic drying would have to be carried out in several stages. If the temperatures in successive stages were not considerably lower than the initial stage, the danger of overheating and combustion would increase rapidly. Bailey & Hamblin (93) reported that burning of the grass occurred in the majority of high-temperature pneumatic grass dryers tested by the National Institute of Agricultural Engineering. Seaweed frond would probably be more prone to scorching than leafy grass, since the thickness of the fronds may be ten times that of the grass. Contact time in the air would have to be extended to permit the internal water to escape.

If on the other hand, air temperatures are reduced substantially to prevent scorching, the efficiency of pneumatic drying is reduced markedly.

It would appear that pneumatic drying for frond has its main application as an initial drying stage, as typified in the Pehrson dryer, so that in effect two dryers would be required to dry the frond completely.

Mitchell (132) states that there is no evidence to support the contention that high-temperature pneumatic grass-dryers give greater thermal efficiencies and higher outputs per man-hour when compared with low temperature dryers of equal capacity. He found that the apparent loss of dry matter is usually in the range 5-10% for high-temperature grass dryers and about 3% for low-temperature dryers.

Through-circulation drying was the only system which handled the frond successfully and produced a high quality product (under the test conditions used). This process has been used for meat dehydration (113).

This method was not widely used for vegetable dehydration in the last war, but was coming into increasing use as the operating problems were overcome. The heavier belt loadings which were permissible in through-draught dryers reduced the dryer size appreciably when compared with over-draught dryers of the same capacity. The continuous belt dispensed with the car transfer tracks, tray washing plant and tray storage space which was required for tunnel dryers (133). Black (134) outlined the advantages of a continuous conveyor dehydrator for vegetable drying and Mitchell(135) has suggested the use of through-circulation drying for preserving natural products prior to extraction of fine chemicals.

Additional advantages of through-circulation conveyor dryers are that the drying times can be altered to meet variations of water content in the raw material and these times can be held within close limits.

As through-circulation drying was the only drying process tested by which both stipe and frond could be dried satisfactorily, this method was selected for further study to find the optimum working conditions and to study the drying characteristics of the seaweed.

6. THROUGH-CIRCULATION DRYING OF SEAWEED

6.1. PREVIOUS WORK ON THROUGH-CIRCULATION DRYING

Hop kilns or oasts are natural-draught through-circulation dryers. Burgess (136) has described work on hop drying from 1921 to 1938 on four small experimental kilns constructed by the Institute of Brewing. The hop cones are about 1 to 2 in. in length and $\frac{3}{4}$ to 1 in. in diameter, with initial moisture contents of approximately 80%. They are supported on a loosely-woven horsehair cloth which lies on an open slatted floor mounted several feet above an open fire, and are dried to a moisture content of about 6%. Burgess divides the drying time into two periods, the 'minimum time' required to dry a single layer of hops, and the 'extra time' necessary for the level of dryness to rise through the bed of hops. The time required to dry hops from 80 to 2% at a constant air temperature is given by the expression :-

$$\theta = \frac{1}{P - p} \left[\frac{716.5\ L}{V^{1.047}} + \frac{6250}{V^{0.39}} \right]$$

where P = vapour pressure of water at temperature of drying air, in of mercury,

p = vapour pressure due to humidity of atmosphere, in of mercury,

L = loss in weight during drying, oz/sq.ft. of kiln floor,

θ = drying time, min,

V = exit air velocity, ft/min.

Owen (137) describes a series of experiments on the desiccation of sugar-beet cossettes (2.2 in x 0.4 in x 0.2 in) on the laboratory scale and on the plant scale. The factors influencing drying which were studied included the porosity and depth of the bed of sugar beet, and the volume, pressure, and temperature of the air used. These tests were also concerned with the inversion of the sugar during drying, and it was found that the critical temperature of the material in the moist state was 220°F.

Scott (138) employed through-circulation of air to study the effect of temperature on grass drying. The limiting temperature for this material was 300-350°F, above which temperature, blowholes of scorched grass rapidly developed.

Marshall & Hougen (98) studied a wide variety of materials under similar conditions of through-circulation drying, and showed that the times required were much shorter than corresponding times for cross-circulation drying. These workers expressed the constant drying rate by the formula :-

$$dW/d\theta = kG^{0.81}(H_s - H_a)$$

where k = a constant,

H_s = saturation humidity at wet-bulb temperature of air,

H_a = humidity of air, lb/lb of air.

The value of k was about 3-6 for clays and pigments, 25-100 for granular solids, and 110-220 for fibres.

This exploratory study was continued by Gamson, Thodos & Hougen (54). From a study of the drying of wetted catalyst pellets, they derived an equation for the constant rate of evaporation of water from the surface of wet granular solids :-

$$\frac{dW}{d\theta} = \frac{0.42aG^{0.59}(\Delta H)m}{\rho\, D_p^{0.41}}$$

where a = drying area, sq.ft./cu.ft. of bed volume,

ρ = bulk density of dry granular bed, lb/cu.ft.,

D_p = average particle diameter, ft,

$(\Delta H)_m$ = log (mean of inlet and outlet humidity driving forces across the air film on the particle).

A more general form of the equation was also given, covering the vaporization of liquids other than water into gases other than air.

When the modified Reynolds number for gases passing through beds of solids is greater than 350, the flow is turbulent, whereas streamline flow occurs when the value is less than 40. Wilke & Hougen (55) gave equations for the constant-drying rate when the flow was in the stream--line region.

Mounfield (139) investigated the drying of wheat in a batch through-circulation dryer, consisting of a vertical cylinder and a conical base with provision for introducing hot air through a grating in the bottom. The wheat was continuously circulated by a vertical worm.

Brown & Van Arsdel (140) studied the through-circulation drying of white potato strips ($\frac{5}{32}$ in square) and presented their data in nomogra--phic form. The apparatus used was a cabinet dryer baffled to direct the air downward through the vegetable bed. Perforated metal sheet was used to create a substantial pressure-drop, thus ensuring a reasonably uniform air distribution at all parts of the bed.

Ede & Hales (80) described tests on vegetable and fruit dehydration with through-draught dryers. With vegetables, it was difficult to maintain steady drying conditions during a test owing to the contraction of the material, and little work was done. With fruit, however, the effect of tray loading, air speed, and specific surface on the rate of drying were investigated. Ede & Hales also investigated comprehensively the cross-circulation drying of scalded potato strips, and devised a unit wet-bulb depression evaporation-coefficient to correlate their experiments.

Allerton, Brownell & Katz (141) studied the mechanism of filter-cake drying by through-circulation of air, using glass balls (16-150 Tyler mesh) and crushed quartz (10-24 mesh) with water as the vaporizing liquid. Air flow was mainly in the streamline region. Because of the low air temperature used (85-95°F), and the large surface exposed, the air left the bed of material virtually saturated. Evaporation was considered to take place in a narrow zone ($\frac{1}{8}$-$\frac{1}{4}$ in) which passed through the bed. When this zone reached the end of the bed, the initial constant-rate period was succeeded by a falling-rate period. The drying rates were correlated on a vaporization-efficiency basis :-

$$r/R = E = (1 - e^{-YW}) \text{ and } Y = 2.72(Re)^{0.215}(d)^{-0.35}W^{0.36}$$

where r = rate of drying, and R = maximum rate of drying, lb/(sq.ft.)(min),
E = vaporization efficiency,
Y = drying factor, sq.ft./lb,
d = particle diameter, in,
Re = DG'/μ, where
D = particle diameter, ft.,
μ = viscosity, lb/(ft)(sec),
G' = mass velocity, lb/(sq.ft.)(hr).

Hendry & Scott (142) reviewed different methods of presenting experimental data on drying and showed how these could be applied to the design of full-scale dryers.

Drying tests on viscose staple fibre on the laboratory and plant scale were described by Coles (143). The following formula was derived for the down-draught through-circulation drying of viscose fibre :-

$$2.3\log_{10}W_o/W = 0.356G^{1.23}\theta dH$$

where W_o & W = the initial and final free moisture content, lb/lb of bone-dry product,

dH = difference between humidity of air saturated at wet-bulb and the actual humidity of the air, lb of water/lb of air.

Kraybill (113) described a process for dehydrating meat in a 2-stage continuous through-circulation dryer, 10 ft wide by 60 ft long. The fresh minced meat (55% water) was loaded to a depth of $1\frac{1}{2}$ in and dried to 34% moisture, when it was reloaded to a depth of $4\frac{1}{2}$-5 in on a second belt and dried to 10%. The output was 1,000-1,300 lb/hr. The use of a greater bed depth in the second stage was made possible by the increased porosity of the bed of partly dried material.

During the early part of the War, the Ministry of Food carried out several pilot-plant drying tests on vegetables. The first of these tests (144), on a Tomlinson's single-pass through-circulation dryer, was used to study the drying of potato and carrot strips and cabbage shreds. It was found that carrots and potatoes could be dried satisfactorily if due attention was paid to the air flow and strip size, but the cabbage shreds were blown off the belt very easily. If the thickness of the cabbage layer was over 2 in, the bed soon developed blowholes and scorched patches, but the vegetable strips rapidly formed a porous coherent bed which showed little shrinkage during drying. It was considered inadvisable to use multi-stage conveyors, as considerable fracturing of the strips was anticipated at the transfer point when the bed was being disintegrated and reformed.

A later test was carried out on a British Crop Dryer at Navenby (144). This dryer was a single-pass design, 94 ft long by 10 ft wide with three air temperature zones of 160, 180 and 210°F. The wet material passed through the high-temperature zone first, so that as drying proceeded the bed entered the cooler regions. The exhaust air from the coolest zone was mixed with hot gases from a coal-fired furnace to form the supply air to the middle zone and similarly this exhaust was recirculated through the high temperature zone.

On a test using potatoes cut into ridged cossettes (maximum thickness 1 m.m.) an output of 1,000 lb product per hour with a moisture content of 9% was obtained. The drying time was 3½ hours when the initial bed depth was 5 in. This installation gave an evenly-dried product free from scorched patches.

Ede (145) presented data on the effect of bed depth on the through-circulation drying of carrot, potato and meat.

6.1.1. Previous Work on Seaweed Drying

Mitchell (100) described some of the industrial uses of red and brown seaweeds and compared the methods of drying seaweed with those used for grass and vegetables.

Preliminary work on the natural air-drying of fresh *L. saccharina* and *L. digitata* was carried out in this laboratory by McLean & White (146) and Black & Duthie (147).

Other seaweed drying tests by Jackson (110), Anon. (111), and Clark et al (114) have been reviewed in Sections 5.1.1. and 5.1.2.

6.2 RAW MATERIAL

Seaweeds are arranged botanically in groups of descending magnitude as follows :- Class - Order - Genus - Species.

Fritsch (148) has defined eleven classes of which the brown seaweeds constitute the class Phaeophyceae. The three species studied in the present investigation belong to the genus Laminariaceae which, in turn, is a branch of the order Laminariales.

Structurally, the stipe of L. cloustoni consists of a surface meristoderm with its actively dividing cells covered by a mucilage layer acting as a cuticle (Plate 1). Internal to these small cells lies the outer cortex which is composed of wider and paler cells, while still nearer to the centre occurs the inner cortex with longer and squarer cells (Plate 2). In the centre of the stipe is the medulla which is a tangled mass of threads or hyphae. The tortuous paths pursued by these hyphae can be clearly seen from Plate 3 in which some of the cells have been cut transversely and others longitudinally by the microtome. All four regions just described merge into each other gradually so that no precise limits can be defined.

The frond (Plate 4) has the same basic structure as the stipe, but the medulla is more laminar. The transition zone between the stipe and frond is the area of active cell division in the plant.

Both the stipe and frond of L. cloustoni possess an interconnecting system of mucilage canals situated just below the meristem, but in L. digitata and L. saccharina the canals are confined to the fronds. L. digitata stipe is similar in structure to L. cloustoni, except that it is oval in cross-section.

The seaweed used in the laboratory tests was harvested from two areas (Kerrera Island, near Oban, and Inchcolm Island, Firth of Forth),

PHOTOMICROGRAPHS

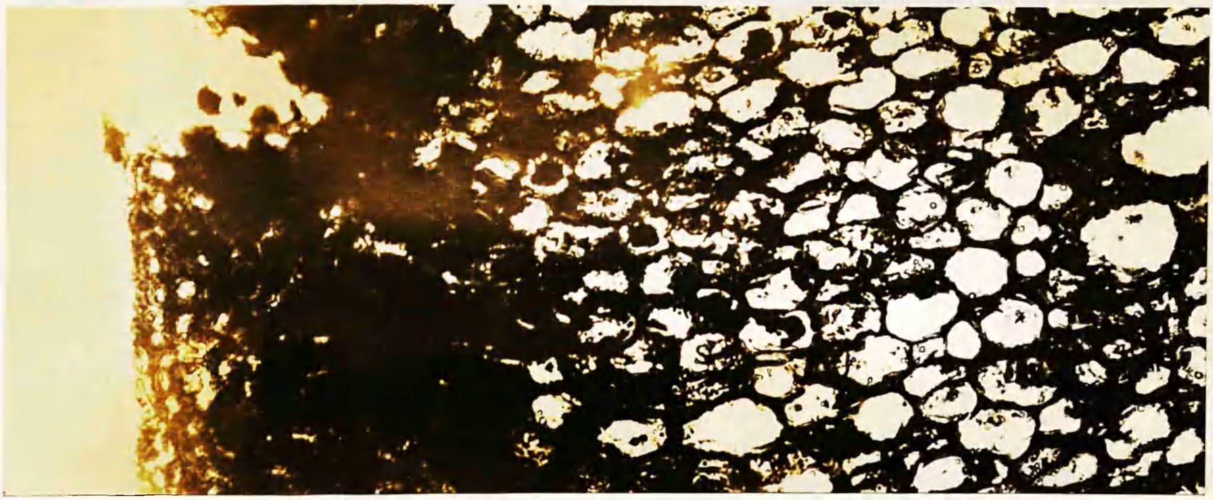


PLATE 1. Transverse section of L. cloustoni stipe showing the pigmented cells near the epidermis. The two large rings on the extreme right are mucilage canals. (X200).

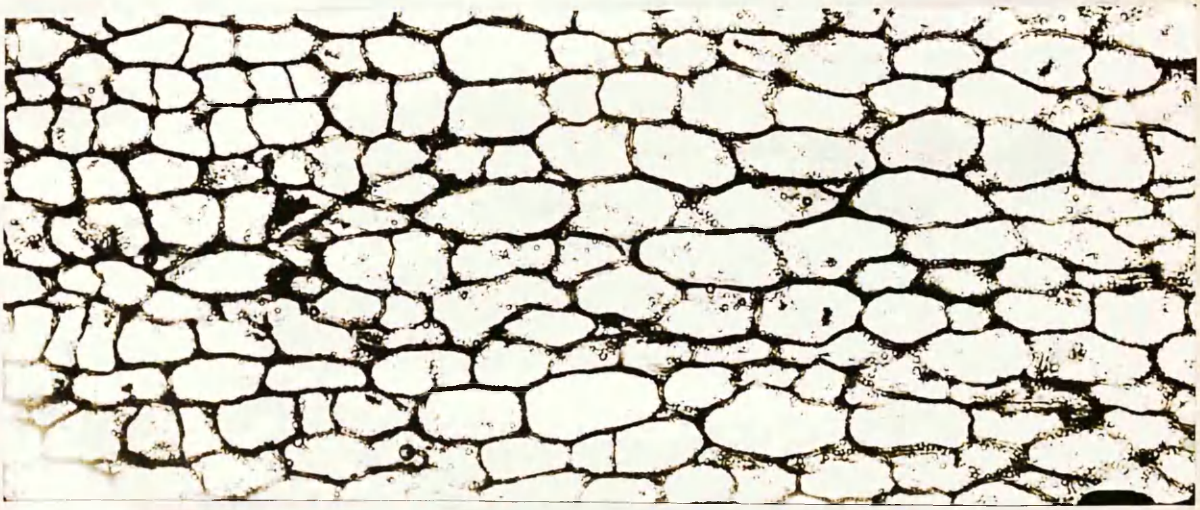


PLATE 2. Transverse section of L. cloustoni stipe showing the cells of the inner cortex. (X200).

<u>PLATE 3</u>. Transverse section of <u>L. cloustoni</u> stipe showing the hyphae in the medulla. (X200).

<u>PLATE 4</u>. Transverse section of <u>L. digitata</u> frond. (X200).

by a multi-pronged grapnel (Fig. 2) towed by a motor launch. The holdfasts were removed and the plants were dried, generally within 24 hours of harvesting.

As a set of drying tests required several weeks for completion, it was impossible to ensure that all the tests were strictly comparable, because of variations in the biological nature of the material. Whenever possible, tests on the effect of one variable were performed consecutively, to reduce this variation to a minimum.

6.3. APPARATUS

The laboratory dryer (Fig. 19) consists of a centrifugal fan, directly coupled to a d.c. motor, which blows the air over eight 1-kw. bar-elements into a plenum chamber at the base, and thence upwards through a vertical duct (12 in square) in which the basket of wet material rests on stout wire gauze. The lid for the drying chamber has an outlet (6 in. in diameter) fitted with a Perspex observation window surmounted by an aluminium cone, and is counter-poised for rapid opening. The outside of the dryer is lagged with $\frac{1}{4}$-in asbestos millboard. Wet-bulb and dry-bulb thermometers are fitted at the air inlet immediately below the dryer bed, and at the outlet in the Perspex cylinder. Wicks on the wet-bulb thermo--meters dip into small tubes connected to larger external reservoirs. The inlet dry-bulb temperature is regulated by a Sunvic thermostat and relay which controls one of the heaters. A 3-kw element fitted in a 5-in duct permits heating of the air entering the fan.

Air velocity is varied by a nine-position starter on the fan, with fine control by a separate rheostat. An ammeter on the motor allows easy duplication of any particular fan setting. Air velocities are measured by an anemometer which was a push-fit in the top of the aluminium cone. A steam injector in the entry duct enables the humidity of the inlet air to be increased (Fig. 19 insert). The injector is controlled manually by a steam valve, and once set for a given wet-bulb temperature requires only occasional adjustment.

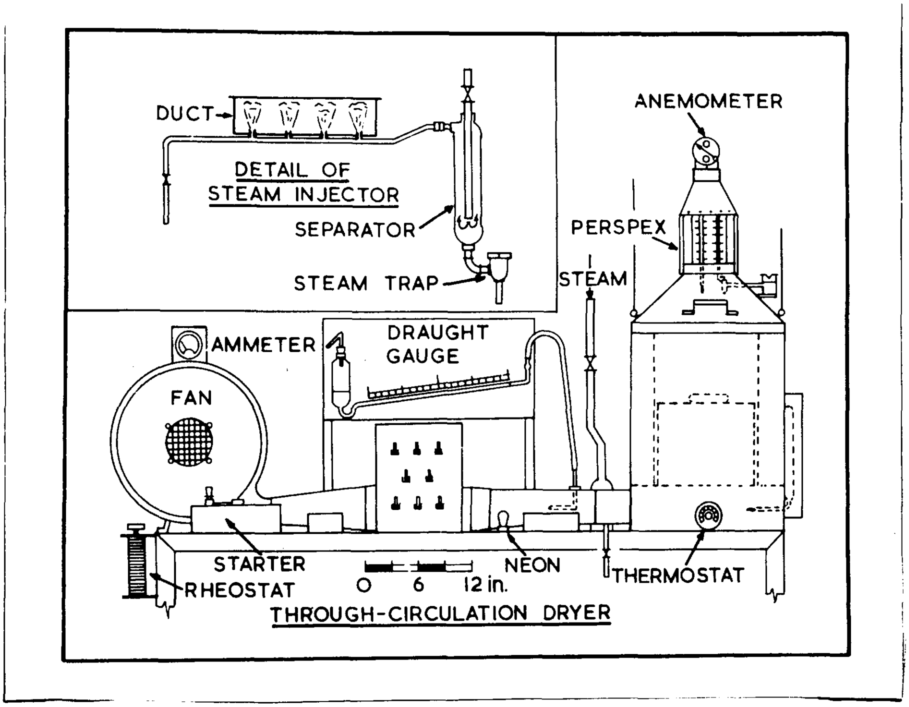

DUCT
DETAIL OF
STEAM INJECTOR
SEPARATOR
STEAM TRAP
ANEMOMETER
PERSPEX
STEAM
AMMETER
DRAUGHT
GAUGE
FAN
STARTER
RHEOSTAT
0 6 12 in.
NEON
THERMOSTAT
THROUGH-CIRCULATION DRYER

Fig. 19.

A static pressure-tube mounted in the inlet duct was connected by rubber tubing to a draught gauge reading to 2 in of water gauge by 0.01 in.

The removable container for the wet material (9 in deep, approx. 11 in square) was constructed of sheet aluminium with a floor of $\frac{1}{16}$-in copper gauze strengthened by a stouter $\frac{1}{4}$-in mesh gauze. Asbestos cord prevented air leakage between the edges of the basket and the sides of the duct.

6.4. DISCUSSION OF EXPERIMENTAL PROCEDURE

6.4.1. Bed Depth

In through-circulation drying, one of the principal variables is the bed thickness, which is best expressed as a linear depth. It is impracti--cable to measure this accurately if the individual pieces are large, and the bed loading is therefore usually expressed as lb of wet stock/sq.ft. of bed area. This is not entirely satisfactory, however, as two batches of material with the same wet loading but different water contents will have differing quantities of bone-dry material. This work has demonstrated that for seaweed within reasonably close limits of initial water content, the dry loading, L_d (lb of B.D.S/sq.ft.), rather than the wet weight governs the drying time (B.D.S. = bone-dry solid). This may be because the load with the higher water content will have a lower solids content, and therefore a smaller proportion of material to be dried in the diffusion period.

Although dry loading probably provides the more fundamental basis for expressing loadings, this system may be inconvenient for industrial use unless frequent values of water content are available.

6.4.2. Weighings.

The progress of each experiment was followed by weighing the sample periodically. Ideally, this should be done continuously without removing the sample from the dryer (138, 149), but this technique requires a correction for the upthrust of the air, any error in air-flow measurement being reflected in corresponding weight errors, and air flow is often the variable which is most difficult to measure accurately. The compensating advantages of the continuous method are that air conditions can be kept steady and there is no error due to cooling during weighing.

In the present work, the basket of seaweed was removed and weighed on a balance of 20-lb total capacity, calibrated by 0.005 lb. Weighings were estimated to 0.001 lb with a probable accuracy of ± 0.001 lb.

6.4.3. Moisture Content and Sampling

In the earliest tests of this series, the water content of the seaweed was determined by taking samples immediately before the drying run. This method proved inaccurate, the calculated weight of B.D.S. sometimes exceeding the weight of dried seaweed in the basket. This may be attributed to (a) sampling error, probably due to differences in water content from plant to plant and to variations in different parts of the same stipe, and (b) error in determining water content. This error may be considerable because of the large amount of water in the fresh seaweed. If the preparation of the material is slow, some pieces will dry out.

If, however, the water content of the dried product is determined, small differences do not affect the B.D.S. estimation seriously, and the water contents, in the second half of the test at least, can be calculated more accurately. Further, if the dried product is sampled at the end of a run, it will generally have a more uniform moisture content. The water content of the bed of seaweed is not uniform and must be expressed as an average value, which is best obtained by dividing the total weight of water by the bone-dry weight of the batch.

6.4.4. Particle Size

Owing to the large cross-section of the stipes, it is necessary to subdivide them to ensure reasonably short drying times. This involves an attempt to find an optimal particle size in relation to speed of drying and cost of pre-cutting. In up-draught through-circulation drying a lower limit to the piece size is reached when the particles are fluidized by the air stream.

An obvious method of reducing the stipe size is by slicing, and preliminary tests showed that $\frac{1}{8}$-in slices dried in a reasonable time. It was necessary to consider practical means of size reduction on the industrial scale, and it was later found that pieces of approximately this size could be produced on full-size equipment.

A hinged-knife arrangement used in the earlier tests was later replaced by a bacon slicer, which gave even slicing with much greater speed, keeping the factor of slice thickness constant throughout the tests. The diameter of the stipes increases from about 1 in at the end nearest the frond to $1\frac{1}{4}$ in at the holdfast end, but no attempt was made to classify the pieces, as this variation would be encountered in practice. The loss of water due to slicing was probably less than 1%.

Mincing was also attempted, but it was found that the crushing action in the machine expressed cell sap, which was separated by centrifuging, giving a loss in weight of 25-30%. The advantages of mincing combined with centrifuging before drying are that the minced seaweed has a more uniform water content, the smaller pieces dry more quickly, and the evaporation load is reduced. These advantages would probably be offset, as some of the chemicals are contained in the expressed liquid and they would still have to be recovered by evaporation.

6.4.5. Equilibrium Moisture Content

When a hygroscopic material reaches equilibrium with air at a definite humidity, the corresponding water content of the solid is designated the equilibrium moisture content. As seaweed is hygroscopic, the equilibrium moisture content must be considered when selecting a value for the commercial dry solid, i.e. the water content of the material when it is discharged from the dryer. If the seaweed is over-dried, it will regain water from the surroundings and so heat will have been needlessly used in the dryer. Another practical aspect to be considered is the case of grinding of the product. Stipe can be disintegrated in an impact mill when at a water content of about 50%, but frond must be crisp and free from wet patches, otherwise the mill becomes clogged.

Black (150) reported values of the equilibrium moisture content for L. cloustoni stipe and frond for various relative humidities at room temperature. Additional data at 77°F were obtained in the present investigation, using a static desiccator method with saturated salt solutions for humidity control (151).

From the combined plot in Fig. 20 it is evident that there is a sharp increase in moisture content at relative humidities of the order of 70%. The final moisture content selected for the drying tests was 0.15 lb/lb (approx. 13%) this being a reasonable compromise of the two opposing factors. As it was difficult to detect a water ratio of 0.15 by inspect--ion, the drying runs were continued to about 0.1 lb/lb and the times to 0.15 obtained by interpolation from the graphs.

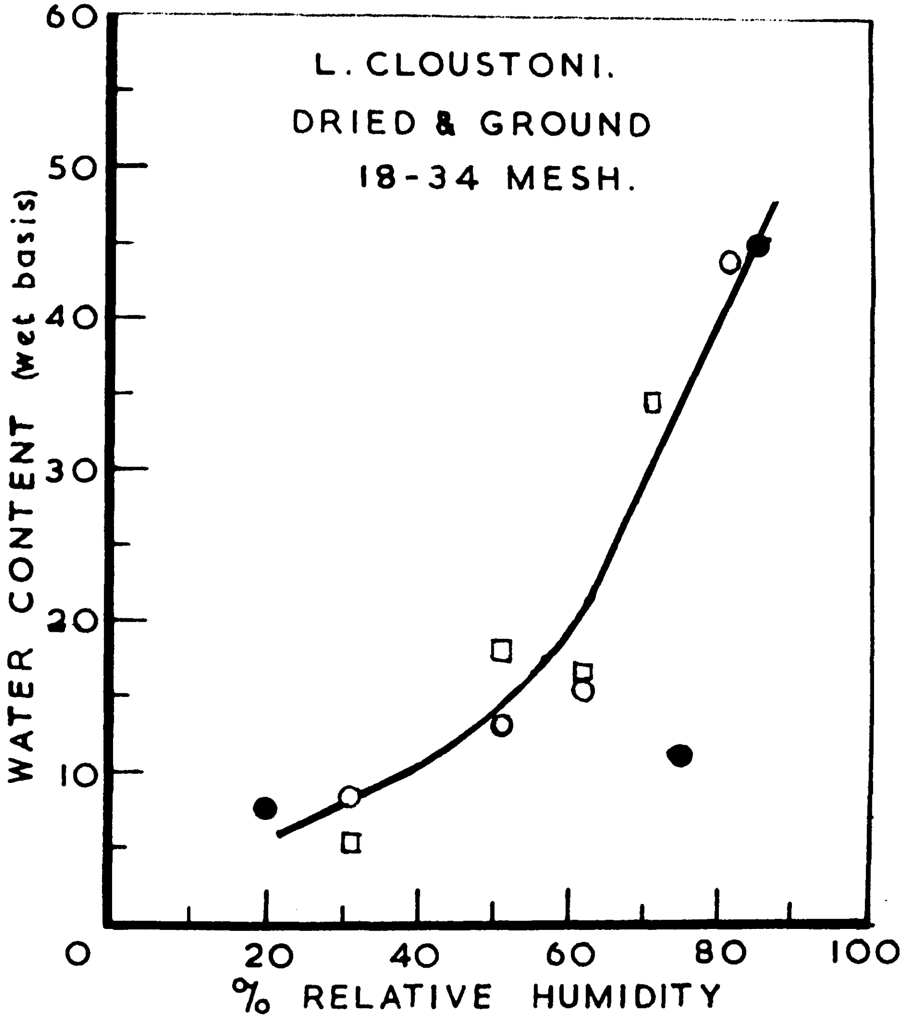
6.5. EXPERIMENTAL PROCEDURE

The fan was started, adjusted to the correct ammeter reading, the heaters switched on and conditions allowed to stabilize at the desired temperature (approx. 15 minutes).

Before slicing the seaweed, any barnacles or parasitic growths were scraped off the stipe, care being taken not to remove the outer skin. If not removed, these growths tended to crumble and to be blown out of the dryer towards the end of the test, causing loss of dry matter.

The empty basket was counterpoised on the balance and the desired amount of stipe slices weighed into it, with random packing. A 1-in layer of discs $\frac{1}{8}$ in thick corresponded to 2.5 lb, and bed loadings used were multiples of this figure. As the internal area of the basket floor was 0.896 sq.ft., the tray loadings were multiplied by 1.116 to express them as lb/sq.ft.

Immediately before a run, inlet and outlet temperatures were recorded



EQUILIBRIUM WATER CONTENT.

□ FROND AT 25°C
○ STIPE " "
● STIPE AT 13-15°C (W.A.P. BLACK)

FIG. 20.

and the atmospheric humidity measured with a whirling hygrometer. The static pressure was noted when the dryer was empty and closed.

The basket was then inserted in the dryer, the timer was started and the lid closed. The initial static pressure was noted and the exit temperatures were taken every minute. The basket was removed, weighed, and replaced in the dryer at regular intervals, five minutes for the first hour of drying, ten minutes for the second hour, and fifteen minutes thereafter. Before the lid was closed, the stopclock was reset to zero so that the measured time interval (5, 10 or 15 minutes) represented the actual time the material was in the dryer, and was not affected by any variation in the time occupied by a weighing (average, about 20 seconds).

Anemometer readings were taken about two minutes before each weighing to allow the exhaust temperature to steady after the interruption caused by the removal of the basket for weighing.

The experiment was generally concluded when the loss in weight was not greater than 0.005 lb over 10 minutes, but this figure depended to some extent on the original weight of material used.

After drying, the seaweed was allowed to cool, and samples were taken at the centre and corners of the bed. These individual samples were combined and ground in a Christy & Norris 8-in laboratory-mill to pass a 1-mm screen. This powder (5 g) was weighed into aluminium dishes ($2\frac{1}{2}$ in. in diameter x $\frac{7}{8}$ in deep) provided with tightly fitting lids, and dried in an electric oven for five hours at $104 \pm 2^{\circ}C$. The dishes were cooled and reweighed, the loss in weight being attributed to water. The mean of duplicate determinations was used as a basis for calculations.

6.5.1. Temperature and Humidity Measurements

Owing to errors arising from uneven air flow at the bend beneath the bed, and to radiation from the electric heaters, the inlet dry-bulb thermometer indicated a few degrees high. As the outlet thermometer gave a much more accurate value, the air temperature was measured here at the start of a run, and the inlet thermometer was used to measure any temperature fluctuations. This indicated that the thermostat could control the temperature to $\pm$ 1°F or better. The air-temperature variation at different parts of the empty bed was about $\pm$ 5°F, but it is probable that this scatter was reduced when the basket of seaweed was in position.

The outlet wet-bulb thermometer read a degree or two high when the dryer was empty just before a test. This was attributed to the comparatively low air velocity past the bulb and to the difficulty of keeping the wick wet at higher air temperatures. A correction was made by taking the atmospheric humidity and finding the wet-bulb temperature corresponding to the dry-bulb temperature from a psychrometric chart. The difference between calculated and experimental wet-bulb temperatures agreed reasonably well with the velocity correction chart drawn up by Carrier & Lindsay (152).

6.5.2. Air Velocity Measurement

The exit-air velocity was obtained by measuring the time for 1000 feet of air to be recorded on an anemometer in the outlet duct, and the value obtained corrected by the calibration factor for the instrument. The mass flow was calculated from the area of the outlet duct and the air density. The correction for the effect of density on the anemometer reading was neglected, as this is usually small for high air velocities (153). Because of frequent opening of the lid, it was difficult to keep the dryer airtight and some air leakage took place. An experimental factor determined from mass balances in 15 tests at different air velocities was used to correct for this air leakage.

6.5.3. Calculation of Results

The bone-dry weight of the seaweed was found from the final weight of product in the dryer and its water content. The weights of water associated with this weight of seaweed at each weighing were next calculated, and expressed as the water content (dry basis).

The curves of total water ratio versus time for each run were plotted, and the drying times between required moisture contents interpolated.

It was observed that the initial drying rates for beds of 2 in or over were approximately constant. To enable this constant rate to be calculated accurately, the appropriate part of the graph was redrawn on a larger scale so that the slope of the line was 45^{o}. The best straight line was drawn through the data and the two extreme experimental points which lay satisfactorily on this line were selected, and from the test data the drying rate between these two points was expressed as lb of water/(lb of B.D.S.)(hr). Instantaneous drying rates at other points on the curve were measured with a tangentimeter (Fig. 21) described by Simons (154).

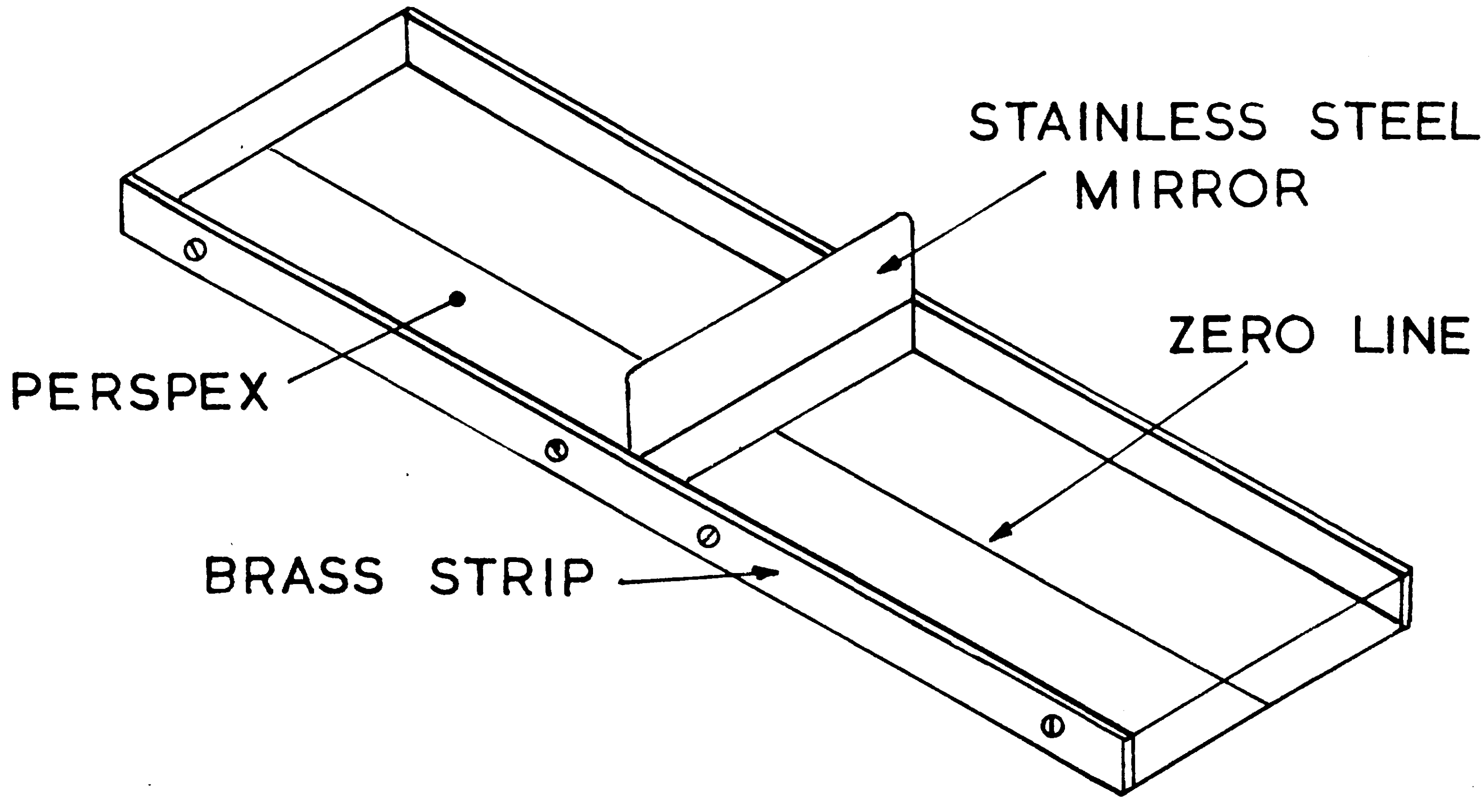
The curves of water content versus time were mostly plotted as obtained, showing the variation in initial moisture contents, but for clarity, others were plotted starting from a constant water content by subtracting a constant time from each time of weighing

6.5.4. Units

6.5.4.1. Temperature: Air temperatures are given in ^{o}F as this scale is still widely used in chemical engineering work.

6.5.4.2. Humidity: In this work, the psychrometric condition of the air is expressed as the wet-bulb depression (W.B.D.). This together with the wet-bulb temperature (W.B.T.) or the dry-bulb temperature (D.B.T.) is sufficient to define the condition of the air. If desired, the W.B.D. can readily be translated into the moisture content (lb water per lb dry air) or into percentage relative humidity by reference to a psychrometric chart or tables. The tables used were those by Macey (155) together with the nomograph published by the Institution of Heating & Ventilating Engineers and the Grosvenor psychrometric chart (156).

6.5.4.3. Air Velocity; This quantity is frequently expressed as a linear velocity, but this suffers from the disadvantage that a change of tempera--ture or humidity causes an alteration in the air velocity. The unit adopted in the present investigation is the air mass velocity G, lb dry air/(sq.ft. bed cross section)(min), as this function is constant throughout



TANGENTIMETER.

FIG. 21.

the dryer and is independent of temperature and humidity.

6.5.5. Nomenclature Used in Seaweed Drying Tests

Water contents are expressed on the dry basis as the ratio of the weight of water to the weight of bone-dry solids. This system has the advantages for drying calculations that the weight of the bone-dry material is constant throughout a run, and the water ratio is directly proportional to the evaporation load.

In this investigation, wet-basis moisture contents are expressed as percentages to differentiate them from the water ratio which is usually given as a number.

The term 'bone-dry solid' (B.D.S.) is in common use in drying literature and is justified by the fact that it implies the complete absence of water, whereas the simpler term 'dry solid' is defined by Marlow (157) as referring to material containing water in equilibrium with the atmosphere. The bone-dry seaweed is taken to be the material remaining in the dishes after oven drying under the conditions specified previously.

The phrase 'commercial dry solid' (C.D.S.) used in this work refers to seaweed having a water ratio of 0.15 (13.04% water on the wet basis). At this water content the seaweed can be readily ground and stored safely.

Symbols

T = total water content, lb of water/lb of B.D.S. = the water ratio.

G = mass air flow, lb of dry air/(min)(sq.ft. of cross-sectional area of bed)

L_d = dry loading, lb of B.D.S/sq.ft.

L_w = wet loading, lb of wet seaweed/sq.ft.

R = output rate, lb of C.D.S/(sq.ft.)(hr).

θ = drying time, min (usually for $T = 5$ to $T = 0.15$)

$dW/d\theta$ = constant drying rate, lb of water/(lb of B.D.S.)(hr)

S = slice thickness, in

t_d = D.B.T. = dry-bulb temperature, ^oF.

t_w = W.B.T. = wet-bulb temperature, ^oF.

$t_d - t_w$ = W.B.D. = wet-bulb depression, ^oF.

B.D.S. = bone-dry solid

C.D.S. = commercial dry solid

7. RESULTS: L. CLOUSTONI STIPE.

In the experimental work, when a suitable particle size had been determined, the following minor factors were investigated, namely interruption of drying, repeatability, initial water content and agitation. After thus ensuring a sound experimental technique, the major factors, bed depths, slice thickness, air velocity, temperature and humidity, and pressure drops, were studied.

In all the tests reported, random packing of the bed was used. The variation of the drying conditions (given on the graphs) is expressed as the standard deviation from the mean.

7.1. PARTICLE SIZE

Preliminary tests were carried out to find a suitable piece size of stipe to give reasonable drying times with the available air temperatures and velocities.

Fig. 22 shows the marked effect of the reduction of size on the drying time. The size selected for later tests was a $\frac{1}{8}$-in slice.

7.2. INTERRUPTION OF DRYING

Gamson et al. (54) found that the rate of drying of catalyst pellets was not greatly affected by the time lost when the sample was removed from the dryer for weighing. This was verified for seaweed by making two comparable tests on slices cut from the same batch of stipe and dried on the same day, using a 1-in bed and weighing at 3- and 15-minute intervals respectively. Fig. 23 shows that the points for the 15-minute test fall on the same curve as the 3-minute test, suggesting that the error caused by the weighing interval is small.

Two possible results of the interruptions were that the basket and seaweed cooled during the 20 seconds when they were outside the dryer, and that the seaweed was agitated slightly when the basket was replaced in the dryer. The first factor would tend to reduce the drying rate, whereas the second would increase it.

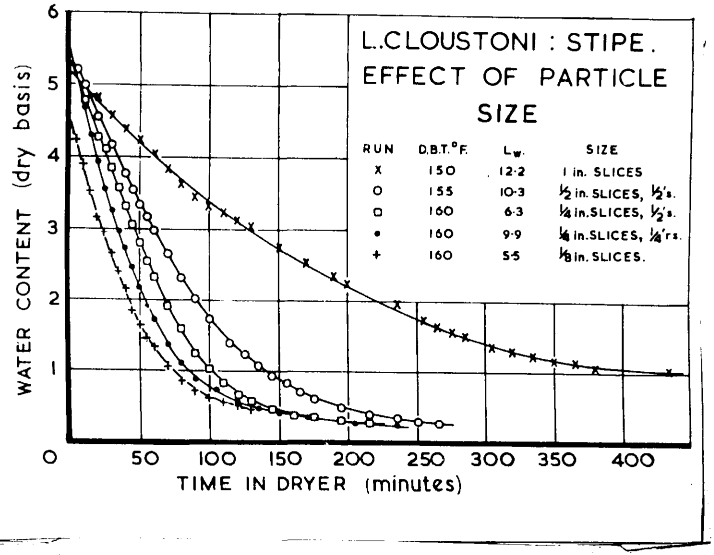

L.CLOUSTONI : STIPE.
EFFECT OF PARTICLE SIZE
RUN D.B.T.°F. Lw. SIZE
x 150 12·2 1 in. SLICES
o 155 10·3 ½ in. SLICES, ½'s.
□ 160 6·3 ¼ in. SLICES, ½'s.
• 160 9·9 ¼ in. SLICES, ¼'rs.
+ 160 5·5 ⅛ in. SLICES.
WATER CONTENT (dry basis)
TIME IN DRYER (minutes)
0
50
100
150
200
250
300
350
400
1
2
3
4
5
6

Fig. 22.

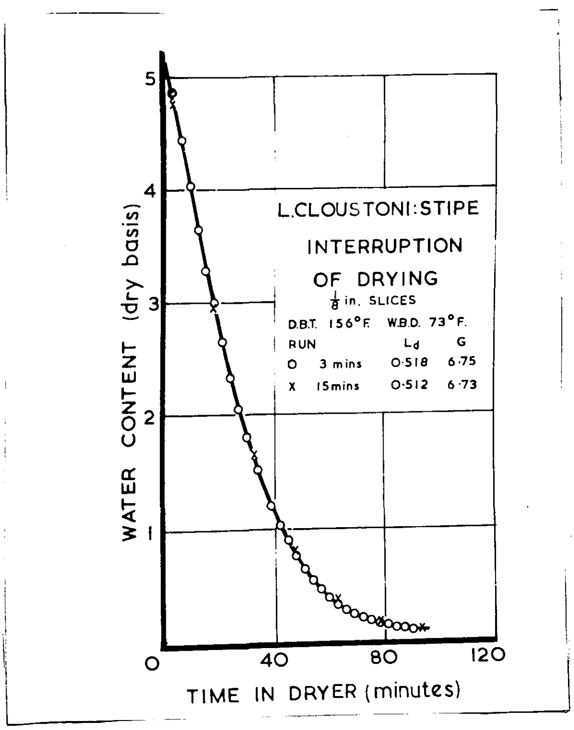

L.CLOUSTONI:STIPE
INTERRUPTION OF DRYING
⅛ in. SLICES
D.B.T. 156°F. W.B.D. 73°F.
RUN Ld G
o 3 mins 0·518 6·75
x 15mins 0·512 6·73
WATER CONTENT (dry basis)
TIME IN DRYER (minutes)
0
40
80
120
1
2
3
4
5

Fig. 23.

7.3. REPEATABILITY TEST

This test was designed to find how closely drying times of seaweed would agree when drying under conditions as nearly identical as possible. A batch of 5 lb of stipe was sliced and half of the material dried. Immediately after the first half had been dried, a second test was made using the remaining seaweed, which had been stored in a large bottle. Fig. 24 shows that the curves are very nearly coincident, the slight difference being probably due to small variations in dry loading and air velocity.

It therefore seems possible, under ideal conditions, to obtain close agreement with a biological material such as seaweed, from the same batch of material.

7.4. EFFECT OF INITIAL WATER CONTENT

A feature of the drying of biological material is the variation of initial water content which makes direct comparison of tests difficult. Brown & Kilpatrick (158) encountered this factor when drying riced potatoes, and overcame it by making small time corrections so as to base each test on a common moisture content.

Three 2.5-lb portions of fresh stipe slices were prepared from one batch of seaweed and the first portion dried immediately. The two remaining parts were spread on trays in the laboratory and allowed to air-dry for 1 and 5 days before being dried under identical conditions.

In this way three tests were made with seaweed of different initial water content, but with the same bone-dry loading per unit of basket area. Fig. 25 shows that the three curves of water content versus time are coincident, a time correction being added to the last two to allow for their lower water content.

This shows that samples of seaweed with the same bone-dry loading will require the same time to dry (through the same water-content range) under the same drying conditions, irrespective of their original water content.

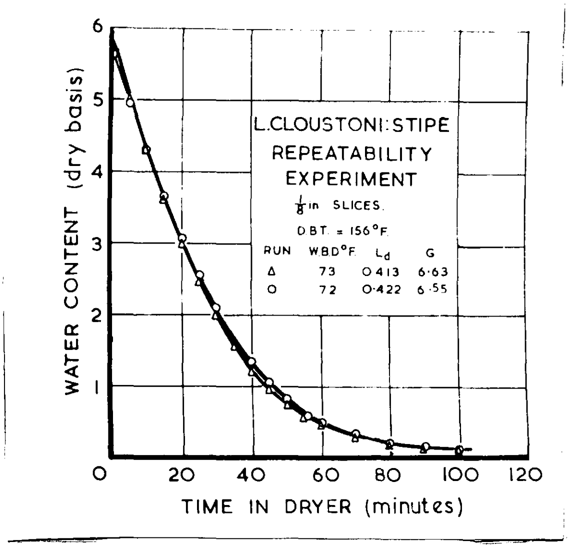

L.CLOUSTONI: STIPE
REPEATABILITY
EXPERIMENT
1/8 in SLICES.
D.B.T. = 156°F.
RUN WBD°F. Ld G
Δ 73 0.413 6.63
O 72 0.422 6.55
WATER CONTENT (dry basis)
TIME IN DRYER (minutes)
0 20 40 60 80 100 120
1 2 3 4 5 6

Fig. 24.

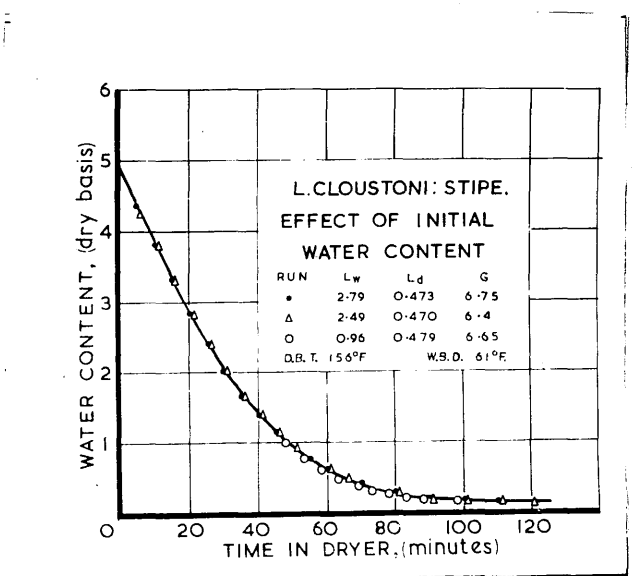

L.CLOUSTONI: STIPE.
EFFECT OF INITIAL
WATER CONTENT
RUN Lw Ld G
• 2.79 0.473 6.75
Δ 2.49 0.470 6.4
O 0.96 0.479 6.65
D.B.T. 156°F W.B.D. 61°F.
WATER CONTENT, (dry basis)
TIME IN DRYER, (minutes)
0 20 40 60 80 100 120
1 2 3 4 5 6

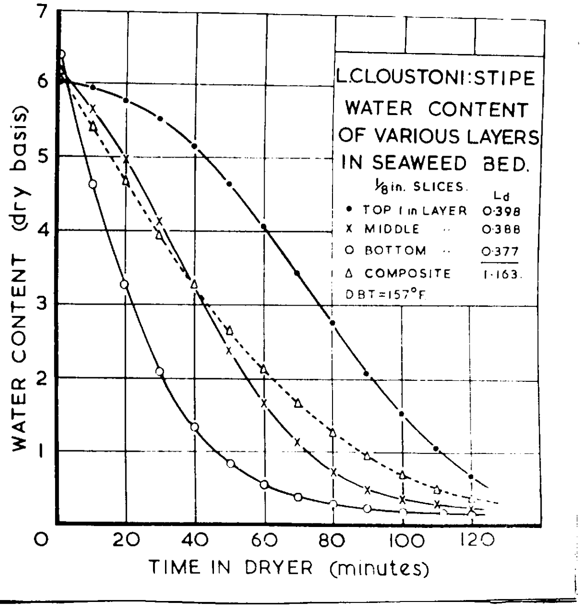
Fig. 25.

It follows that the amount of previous air drying does not affect the drying rates in later stages.

7.5 AGITATION

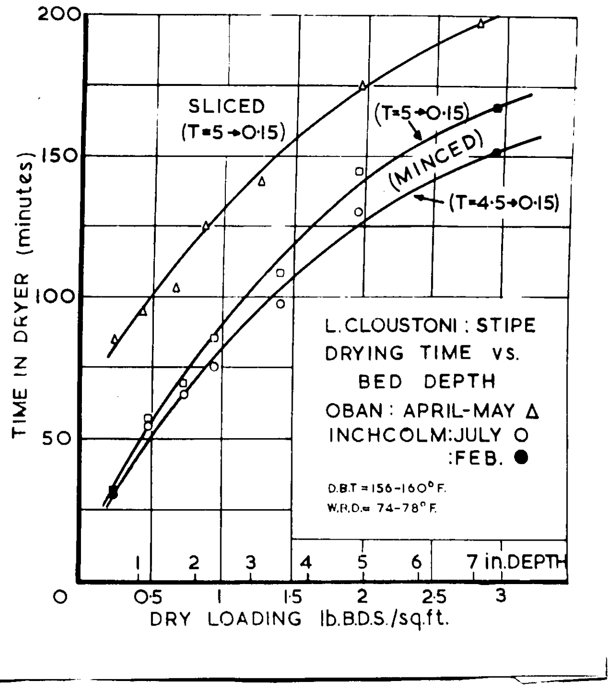
The drying rates of different layers of a bed of seaweed were studied using three baskets which fitted inside each other. Each was loaded with 2.5 lb of seaweed, giving a composite 3-in bed when the containers were assembled. The baskets were weighed separately so that the average water contents of each layer could be calculated (Fig. 26). This graph shows that the water contents of the three layers vary widely during drying, and maximum deviation occurs at an average value of about 3.25. At the start of the drying there is apparently no condensation of water on the upper layer, as the uppermost curve shows a small but significant loss in weight. It is also demonstrated that the constant drying rates of the composite bed are a combination of the falling drying rate of the bottom section and increasing drying rates of the upper layers.

A disadvantage of static through-draught drying is disclosed, namely, that the bottom layer is subjected to the full inlet-air temperature after it has been dried until the remainder of the bed is dry. This defect is less serious in through-circulation drying than in cross-circulation drying, owing to the shorter times involved, and is often overcome in practice by inverting the bed at intervals or by reversing the air flow. Agitation has the added advantage that agglomerates are broken up and surfaces of pieces which have adhered to each other are exposed. Fig. 26 also shows that although the drying operation is nearly complete in the lower layers, the run as a whole must be prolonged until the top layer is dry. If mixing is employed, less time should be required to dry the whole bed to an average water content. Other tests on seaweed stipe with rotary dryers showed that higher air temperatures than were possible with static through-circulation dryers could be used before scorching resulted. This may be explained by the dual effects of increased evaporation by exposure of new surfaces and uniformity of heating and drying. If a dryer is operated



L.CLOUSTONI:STIPE
WATER CONTENT
OF VARIOUS LAYERS
IN SEAWEED BED.
1/8 in. SLICES.
Ld
• TOP 1 in LAYER 0·398
X MIDDLE .. 0·388
O BOTTOM .. 0·377
Δ COMPOSITE 1·163.
D.B.T=157°F
WATER CONTENT (dry basis)
TIME IN DRYER (minutes)
0
1
2
3
4
5
6
7
20
40
60
80
100
120

Fig. 26.



SLICED
(T=5→0·15)
(T=5→0·15)
(MINCED)
(T=4·5→0·15)
L.CLOUSTONI : STIPE
DRYING TIME VS.
BED DEPTH
OBAN : APRIL-MAY Δ
INCHCOLM:JULY O
:FEB. ●
D.B.T = 156-160° F.
W.B.D.= 74-78° F.
TIME IN DRYER (minutes)
DRY LOADING lb.B.D.S./sq.ft.
1
2
3
4
5
6
7 in.DEPTH
0
0·5
1
1·5
2
2·5
3
50
100
150
200

Fig. 27.

correctly, the material should be discharged when at an optimum water content and before overheating becomes serious.

An estimate of the expected time-reduction on agitation of the material was obtained from a test in which the stipe slices were turned over by hand every 10 minutes. A static experiment was carried out for comparison. The stirred sample dried in about 86% of the time taken by the control test, and the constant drying rate was 4.07 lb/(lb of B.D.S.) (hr) for agitation compared with 3.65 for a static bed.

7.6. BED DEPTH

In cross-circulation drying, light loading of the wet material is generally necessary, since the air cannot penetrate readily to the lower regions of the bed and drying is thus prolonged. With through-circulation drying the air comes into contact with all parts of the bed and much heav--ier loadings may be practised.

Stipe slices, $\frac{1}{8}$ in thick, were dried at an average air temperature of 157°F with an average air flow of 5.8 lb/(sq.ft.)(min). When these runs were made, fine speed control of the fan was not possible, so that the average air flow for a run decreased as the bed thickness was increased. The time required to dry the stipe slices from 5.0 to 0.15 water ratio was plotted against the dry loading, L_d. This curve (Fig. 27), has the empirical equation :-

$$\theta = 245\left[\log_{10}(L_d + 0.944) + 0.232\right]$$

The constant-drying rate plotted against the dry loading gives a curve (Fig. 28) which may be expressed by the equation :-

$$dW/d\theta = 1.48 + 10^{1.03-0.536L_d}$$

The output of commercial dry seaweed (0.15 lb/lb of B.D.S.), starting at an initial water ratio of 5, is given by :-

$$R = (L_d \times 69)/\theta$$

When this output is plotted against the dry loading (Fig. 29), it is seen

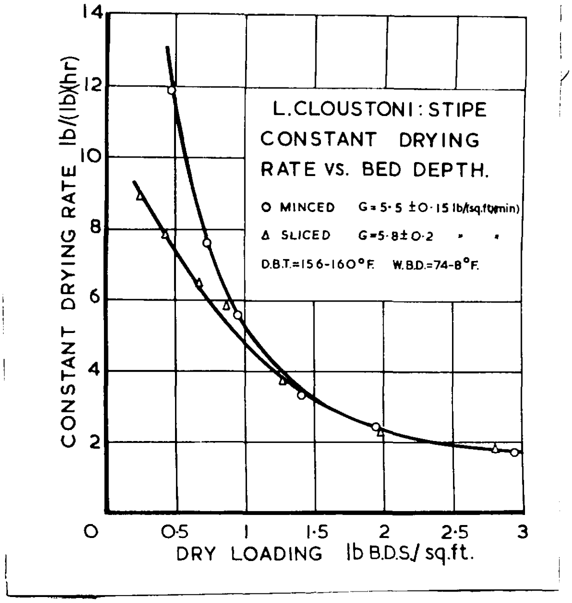

L.CLOUSTONI : STIPE
CONSTANT DRYING
RATE VS. BED DEPTH.
O MINCED G = 5·5 ±0·15 lb/(sq.ft)(min)
Δ SLICED G = 5·8±0·2 " "
D.B.T.=156-160°F. W.B.D.=74-8°F.
CONSTANT DRYING RATE lb/(lb)(hr)
DRY LOADING lb B.D.S./ sq.ft.

Fig. 28.

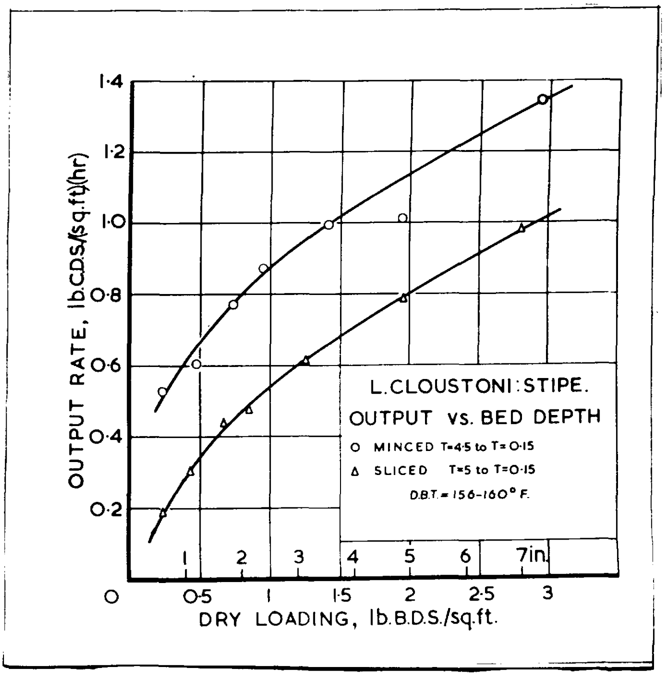

L.CLOUSTONI : STIPE.
OUTPUT VS. BED DEPTH
O MINCED T=4·5 to T=0·15
Δ SLICED T=5 to T=0·15
D.B.T.= 156-160° F.
OUTPUT RATE, lb.C.D.S./(sq.ft)(hr)
7in.
DRY LOADING, lb.B.D.S./sq.ft.

Fig. 29.

that the highest output is obtained with the deepest bed. The increase in output is most marked up to bed depths of about 3 in ($L_d = 1.2$), and this bed thickness was used for the remaining tests as it gave what was considered a convenient drying time. This quantity of seaweed was found just sufficient to cover the basket floor when drying was complete.

A complementary series was produced on the variation of output and drying time at different bed depths using minced and centrifuged stipe in place of the sliced material. When centrifuged for two minutes (centri--fugal effect = 820), the initial water content was reduced to about 4.5 lb/lb of B.D.S. A screen analysis of this material is given in Table 10.

The curve of drying time for 4.5 to 0.15 water ratio (Fig. 27) has an equation similar to that for the slices :-

$$\theta = 239\left[\log_{10}(L_d + 0.93) + 0.0568\right]$$

TABLE 10.

SCREEN ANALYSIS OF MINCED AND CENTRIFUGED STIPE (MEDIUM CUTTER)

		Differential, %	Cumulative, %
Retained on ½-in mesh	.....	0.00	0.00
" ¼-in "	.....	47.10	47.10
" ⅛-in "	.....	31.40	78.50
" 3/32-in "	.....	4.96	83.46
" 1/16-in "	.....	11.45	94.91
Passing 1/16-in "	.....	5.09	100.00
		100.00	

The constant drying rate decreases as the bed loading is increased (Fig. 28), and the value of the drying rate is related to the dry loading by the expression :-

$$\frac{dW}{d\theta} = \frac{0.525}{L_d^{1.12}}$$

The curve of drying time ($T = 5$ to $T = 0.15$) versus L_d for minced stipe was obtained from the time versus water content curves by slight extrapolation, i.e. assuming the constant drying rate to have the same value at higher water contents. From this curve (Fig. 27) the drying time for $L_d = 1.2$ lb/sq.ft. was found, and the equivalent slice-thickness corresponding to this time interpolated from Fig. 31. This gave a thickness of 0.0675 in ($^1/16$ in approx.).

7.7. SLICE THICKNESS

Fig. 30 shows the effect of slice thickness on the time of drying. The thickness has very little effect on the constant drying rate, but reduces the times in the later stages considerably. These drying tests have been correlated by the time required to dry the seaweed from a water ratio of 5 to 0.15, and Fig. 31 shows the drying time for different thick--nesses. The data are represented by a smooth curve which has the equation:-

$$\theta = 411S^{0.523}$$

When the constant drying rate is plotted against the slice thickness (Fig. 32) the points are fairly widely scattered, but lie on a smooth curve when corrected for the effect of bed depth. The specific surface (sq.ft./lb of wet seaweed) of the slices was calculated assuming an average slice diameter of $1\frac{1}{8}$ in and the constant-rate period when plotted against the specific surface gave a straight line. It is unlikely that the total surface of the material was exposed to the drying air, but the fractional amount exposed was possibly similar in each case.

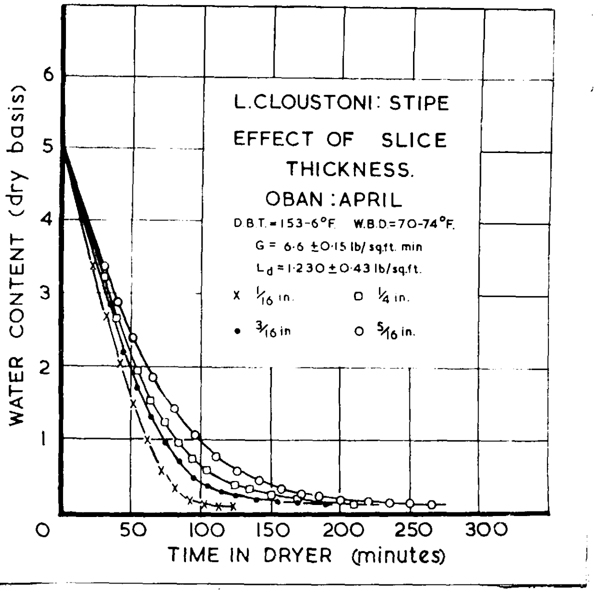

L.CLOUSTONI: STIPE
EFFECT OF SLICE THICKNESS.
OBAN : APRIL
D.B.T. = 153-6°F. W.B.D.=70-74°F.
G = 6·6 ±0·15 lb/sq.ft. min
Ld = 1·230 ± 0·43 lb/sq.ft.
x 1/16 in.
□ 1/4 in.
• 3/16 in
○ 5/16 in.
WATER CONTENT (dry basis)
TIME IN DRYER (minutes)
0
50
100
150
200
250
300
1
2
3
4
5
6

Fig. 30.

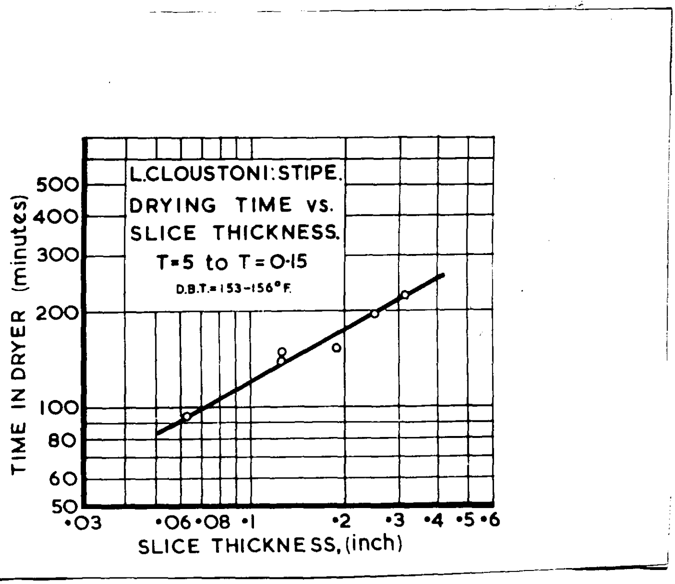

L.CLOUSTONI: STIPE.
DRYING TIME vs. SLICE THICKNESS.
T=5 to T=0·15
D.B.T.=153-156°F.
TIME IN DRYER (minutes)
SLICE THICKNESS, (inch)
50
60
80
100
200
300
400
500
·03
·06
·08
·1
·2
·3
·4
·5
·6

Fig. 31.

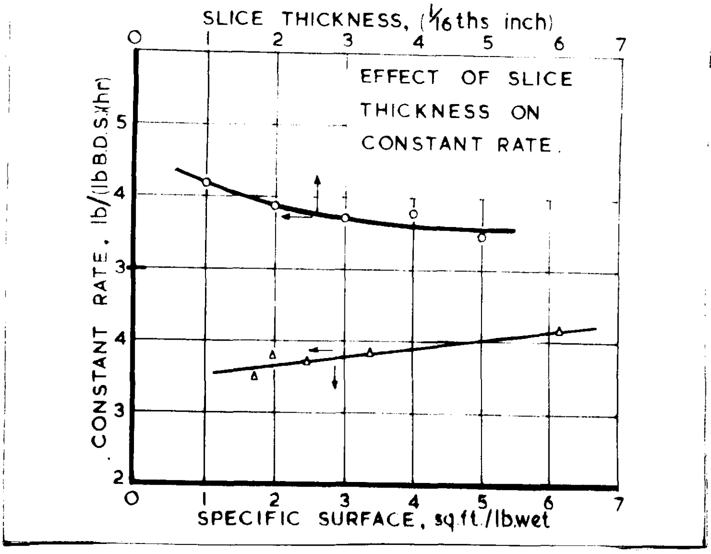

SLICE THICKNESS, (1/16ths inch)
EFFECT OF SLICE THICKNESS ON CONSTANT RATE.
CONSTANT RATE, lb/(lb B.D.S.)(hr)
SPECIFIC SURFACE, sq.ft./lb.wet

Fig. 32.

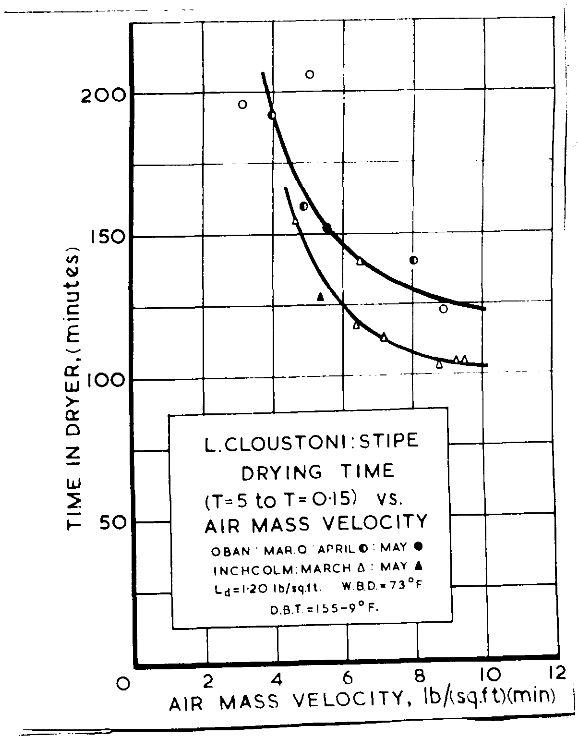

L.CLOUSTONI: STIPE
DRYING TIME
(T=5 to T=0·15) VS.
AIR MASS VELOCITY
OBAN : MAR.O APRIL ◐ : MAY ●
INCHCOLM: MARCH Δ : MAY ▲
Ld=1·20 lb/sq.ft. W.B.D.=73°F.
D.B.T.=155-9°F.
TIME IN DRYER, (minutes)
AIR MASS VELOCITY, lb/(sq.ft)(min)

Fig. 33.

7.8. AIR VELOCITY

The air-flow rates used in this series ranged from about 3 to 10 lb/(sq.ft.)(min). The fan speed was adjusted to a prearranged ammeter reading which was kept constant during a test. As drying progressed, the seaweed bed contracted, its resistance decreased, and the air flow consequently increased until approximately midway through a test, when no further shrinkage occurred (Fig. 44). The average mass air flow was taken for a run. No pronounced 'edge effect' was apparent for the stipe slices, since the slight vibration resulting from the weighing operation caused the pieces to settle down evenly.

The plots of drying time versus air flow for 15 tests are shown in Fig. 33. These runs had to be classified into two groups, depending on the plant habitat, before correlation could be attempted. Plants from Oban require about 20% longer time for drying at higher air velocities than plants taken from the Firth of Forth. The data can be represented by two equilateral hyperbolae with equations :-

$$\theta = G/(0.0103G - 0.02) \quad \text{... Oban}$$
$$\theta = G/(0.013G - 0.03) \quad \text{... Inchcolm}$$

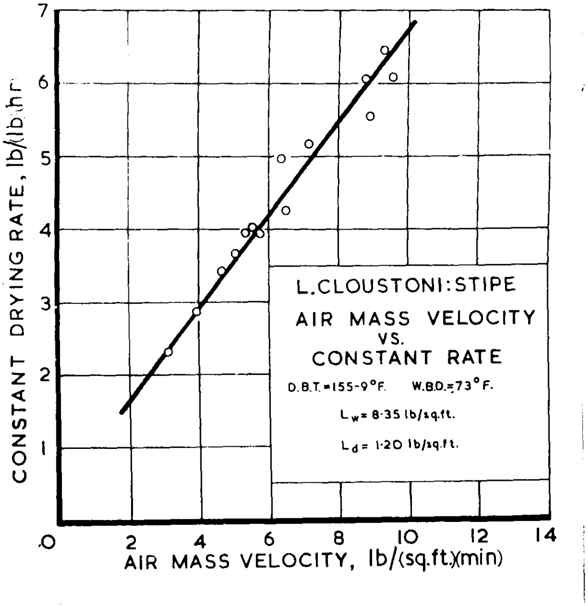
The scattering of the data at low air velocities may be due to the Reynolds number approaching the transition value between turbulent and streamline flow. As the air flow increases the scatter is reduced, and if the same equations hold beyond G = 10 the drying time will approach a limit, so that any increase in air flow will have a negligible effect.

The plot of constant drying rates versus air flow (Fig. 34) is a straight line having the equation :-

$$dW/d\theta = 0.64G + 0.34$$

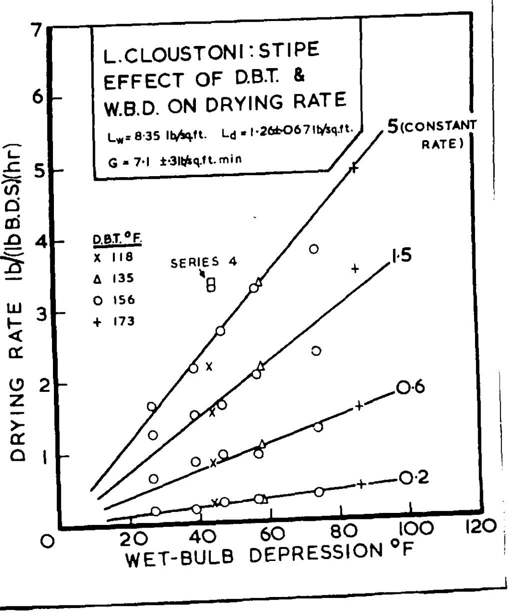
By extrapolation this gives a value of 0.34 lb/(lb of B.D.S.)(hr) for the drying rate when $G = \theta$ (i.e. static air conditions).

Drying rates are frequently expressed as a power function of air



L.CLOUSTONI:STIPE
AIR MASS VELOCITY
VS.
CONSTANT RATE
D.B.T.=155·9°F. W.B.D.=73°F.
Lw= 8·35 lb/sq.ft.
Ld= 1·20 lb/sq.ft.
CONSTANT DRYING RATE, lb/(lb)(hr)
AIR MASS VELOCITY, lb/(sq.ft.)(min)

Fig. 34.



L.CLOUSTONI:STIPE
EFFECT OF D.B.T. &
W.B.D. ON DRYING RATE
Lw= 8·35 lb/sq.ft. Ld = 1·26±0·67 lb/sq.ft.
G = 7·1 ±·3 lb/sq.ft. min
D.B.T. °F.
x 118
Δ 135
O 156
+ 173
SERIES 4
5 (CONSTANT RATE)
1·5
0·6
0·2
DRYING RATE lb/(lb B.D.S.)(hr)
WET-BULB DEPRESSION °F

Fig. 35.

velocity. A distinction should be drawn between the index of a rate (often the constant rate) and the index for the drying time. The time index may be regarded as the inverse of an 'average rate' index between specified water contents. The velocity index often changes as drying proceeds, so that the index for the 'average rate' will depend to some extent on the limits of water content chosen.

Marshall & Hougen (98) showed that the constant drying rate of char--coal was proportional to the 0.81-power of the air flow, whereas Gamson et al., (54) with wetted catalyst pellets, obtained a value of 0.59. Working with viscose rayon fibre, Coles (143) obtained a velocity index of -1.25 for the time of drying.

Burgess (136) found that the 'minimum time' for hops was related to the - 0.39-power of the air speed, and Ede & Hales (80) found that drying rates for fruit ($T = 6$ to $T = 2$) varied as the 0.4-power of the air velocity for through-circulation drying. The plot of air velocity correction factors given by Brown & Van Arsdel for potato strips is broadly similar to Fig. 33. The index for the time of drying was - 0.4 in the range 5.7 - 10.3 lb/(sq.ft.)(min).

The drying times in the region $G = 6$-9.5 lb/(sq.ft.)(min) for Inchcolm seaweed are approximately proportional to the - 0.4-power of the air flow.

Burgess (136) pointed out that the higher velocity indices obtained by other workers on evaporation were obtained from free water surfaces or inert wetted solids and not from initially living plant material. He further suggested that the lower velocity indices for hops and plant material may be related to the time required to kill the material in the dryer.

The velocity index (= 1) for the constant drying rate of sliced seaweed stipe is higher than that for inert solids, possibly because the air approaches the limit of its water-carrying capacity, owing to the use of a deeper bed.

7.9. TEMPERATURE AND HUMIDITY

For tests on temperature and humidity, a 3-in bed of $\frac{1}{8}$-in thick slices was used throughout. The humidity of the air is expressed as the wet-bulb depression (W.B.D.), in agreement with the reasons put forward by Ede & Hales (80).

The tests were formed into five series (Table 11).

TABLE 11.

Series	D.B.T., ^{o}F	W.B.D., ^{o}F	G, lb/(sq.ft.)(min) average
1	120-212	44-116	7.2, Oban, Apr.
2	148-205	66-111	4.5, Inchcolm, July and Sept.
3	157	27-57	7.0, Oban, June
4	120-180	44	8.3, Inchcolm, Oct.
5	200-340	108-228	10 (smaller dryer), Inchcolm, Jun

In Series 1, only the dry-bulb temperature (D.B.T.) was controlled so that the absolute humidity of the drying air (lb of water/lb of air) was that of the atmosphere. Series 2 was produced at a lower air velocity to enable higher temperatures to be attained. The humidity series (Series 3) utilized steam-injection to give higher wet-bulb temperatures (W.B.T.) at a constant dry-bulb value. The plot of constant drying rate versus W.B.D. for Series 1 and 3 (Fig. 35) and for Series 2 (Fig. 36) is a straight line passing through the origin, as follows :-

$$dW/d\theta = 0.057(t_d - t_w) \quad .. \text{ Series 1 and 3}$$

$$dW/d\theta = 0.0374(t_d - t_w) \quad .. \text{ Series 2}$$

The corresponding points for Series 4 are in close agreement with each other, but the cluster lies above the straight line for the constant rate (Fig. 35). This is probably due to the different source of the plants used and to the higher air velocity.

The drying time gives a smooth curve when plotted against W.B.D. (Fig. 37).

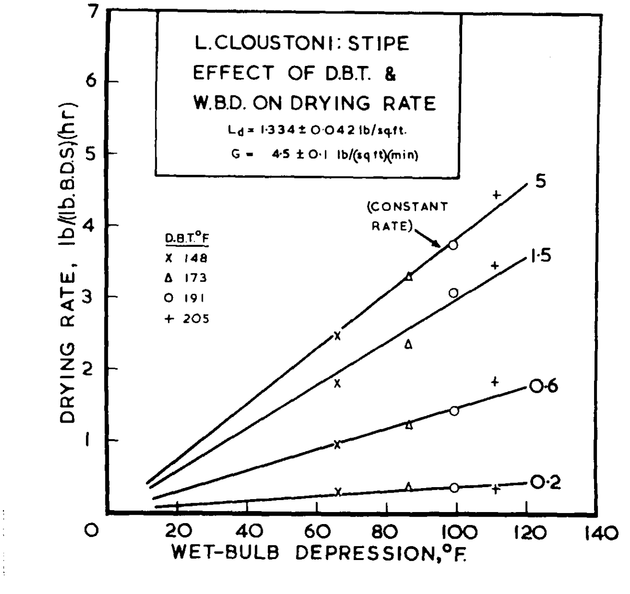
The curve for mass flow 7.1 was extended by results obtained at higher temperatures in a smaller similar dryer which had a basket 6 in square (Series 5).

It is often stated that when a material is nearly dry the W.B.D. of the air has little effect on the drying rate and that this rate depends mainly on the D.B.T. of the air. This effect is illustrated by Series 4, where the W.B.D. was constant but the D.B.T. was increased. With D.B.T. of 120, 140 and 180°F, the drying times were 187, 177 and 167 minutes respectively.

The plot of drying rates at different water contents versus the W.B.D. (Fig. 35) shows that although there is some scattering of the points, there is no significant deviation from a straight-line relation--ship. The drying rates are therefore proportional to the W.B.D. even at water contents as low as 0.2 lb/lb of B.D.S. These points include runs at different D.B.T. and runs at constant D.B.T. using humidified air (Series 1 and 3). It was observed that the higher W.B.D. are usually associated with higher D.B.T. and that, within limits, the W.B.D. of a sample of air with a constant absolute humidity increases in direct proport--ion to the D.B.T. The drying rates for Series 2 show a similar relation--ship to the W.B.D. (Fig. 36).

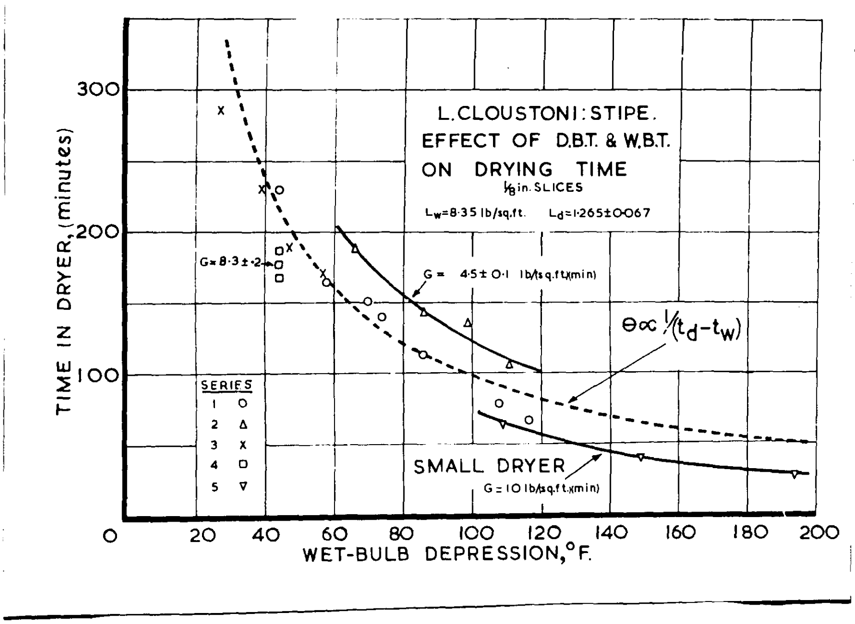
The proportionality of the drying rates to the W.B.D. at low water contents may perhaps depend on the layer drying effect (Fig. 26), which results in comparatively wet samples of seaweed being present in upper strata of the bed until near the end of a run. For a given W.B.D. these wetter pieces would dry more rapidly than the average, and would tend to increase the proportionality of the bed-drying rate as a whole.

Ede & Hales (80) dried $^3/_{16}$-in x $^5/_{16}$-in potato strips individually and also in a layer by cross flow of air at a D.B.T. of 158°F. They found that the drying rates, except at the beginning of a run, showed a clear departure from proportionality to the W.B.D. This departure was more pronounced in the experiments with individual strips. A further series



L. CLOUSTONI: STIPE
EFFECT OF D.B.T. & W.B.D. ON DRYING RATE
Ld = 1·334 ± 0·042 lb/sq.ft.
G = 4·5 ± 0·1 lb/(sq ft)(min)
D.B.T.°F
x 148
Δ 173
o 191
+ 205
(CONSTANT RATE)
5
1·5
0·6
0·2
DRYING RATE, lb/(lb.B.D.S.)(hr)
WET-BULB DEPRESSION, °F.

Fig. 36.



L. CLOUSTONI: STIPE.
EFFECT OF D.B.T. & W.B.T. ON DRYING TIME
1/8 in. SLICES
Lw=8·35 lb/sq.ft. Ld=1·265±0·067
G = 4·5 ± 0·1 lb/(sq.ft.)(min)
G = 8·3 ± ·2
θ ∝ 1/(td-tw)
SMALL DRYER
G = 10 lb/(sq.ft.)(min)
SERIES
1 o
2 Δ
3 x
4 □
5 ▽
TIME IN DRYER, (minutes)
WET-BULB DEPRESSION, °F.

Fig. 37.

by Ede & Hales, with $^3/16$-in x $^1/4$-in potato strips on trays with a lower bed loading and different D.B.T., indicated that the drying rates were directly proportional to the W.B.D. at water contents ranging from 5 to 0.2 lb/lb of B.D.S. Ede & Hales attributed this difference partly to the effect of the smaller strip-dimension and the different D.B.T. The effect of the non-uniform drying on the relationship to the W.B.D. suggested for through-circulation drying may also apply to the tray-drying experiments on potatoes. Ede & Hales showed graphically the variation in water content of potato strips on a single tray during drying, and the points obtained agree fairly well with Fig. 26. The thickness of the stipe slices used in the present work ($\frac{1}{8}$ in) is less than the smaller dimension of the potato strips, which may account for the absence of any serious departure from the proportionality to the W.B.D.

Brown & Van Arsdel (140) gave drying-time nomographs for the through-circulation drying of $^5/32$-in square potato strips. The first period (water contents 4 to 0.2 lb/lb of B.D.S.) appears to be almost entirely dependent on the W.B.D. and only slightly dependent upon the D.B.T. In the range of 0.2 to 0.06 the reverse is true.

It would appear that the proportionality of the drying rate to W.B.D. may be used without serious error for seaweed with average water contents down to about 0.2 lb/lb of B.D.S., below which the D.B.T. is increasingly important.

If the drying rates at all water contents are directly proportional to the W.B.D., the time of drying should be inversely proportional to the W.B.D. The curve for this relationship (Fig. 37, dotted line) shows that the agreement with other experimental points is good except at the extremes. This curve was based on a reference run of 164 minutes at 58^{o}F W.B.D., 135^{o}F D.B.T. and it was selected because it gave the best agreement with Fig. 35.

Ede & Hales suggested the use of the wet-bulb depression evaporation-coefficient, i.e. lb of water/(lb of B.D.S.)(hr)(W.B.D. in ^{o}F), since the drying rates were proportional to the W.B.D. As this has been shown to

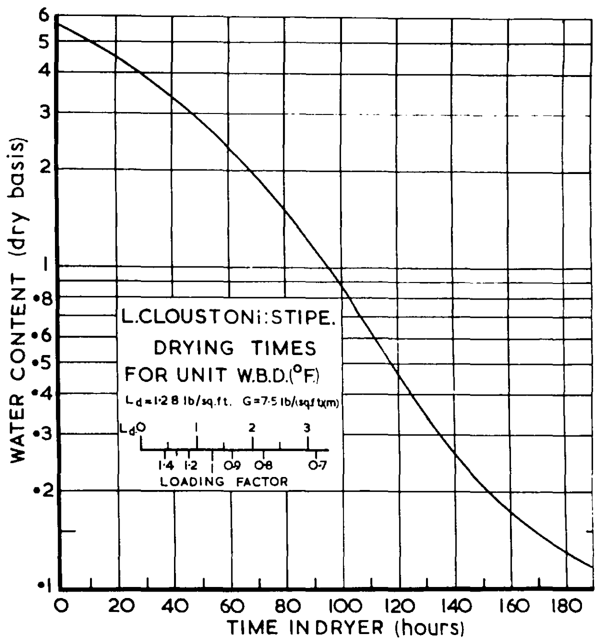

L.CLOUSTONi:STIPE.
DRYING TIMES
FOR UNIT W.B.D.(°F)
Ld=1·28 lb/sq.ft. G=7·5 lb/(sq.ft)(m)
Ld 0 1 2 3
1·4 1·2 0·9 0·8 0·7
LOADING FACTOR
WATER CONTENT (dry basis)
6 5 4 3 2 1 •8 •6 •5 •4 •3 •2 •1
0 20 40 60 80 100 120 140 160 180
TIME IN DRYER (hours)

Fig. 38.

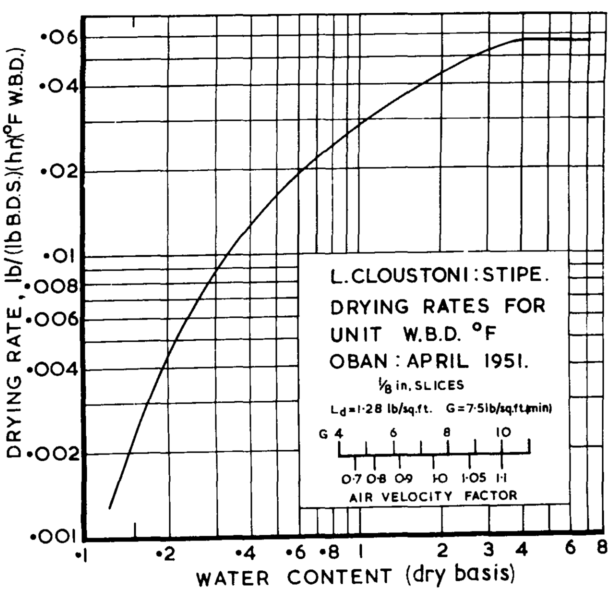

L.CLOUSTONI:STIPE.
DRYING RATES FOR
UNIT W.B.D. °F
OBAN: APRIL 1951.
1/8 in. SLICES
Ld=1·28 lb/sq.ft. G=7·5lb/sq.ft.(min)
G 4 6 8 10
0·7 0·8 0·9 1·0 1·05 1·1
AIR VELOCITY FACTOR
DRYING RATE, lb/(lb B.D.S.)(hr)(°F W.B.D.)
•06 •04 •02 •01 •008 •006 •004 •002 •001
•1 •2 •4 •6 •8 1 2 3 4 6 8
WATER CONTENT (dry basis)

Fig. 39.

hold approximately for through-circulation drying of seaweed, the basic curves for drying time and rates per unit W.B.D. (^{o}F) are plotted for the reference experiment at a W.B.D. of 58^{o}F referred to previously (Figs. 38 and 39). These curves refer to $\frac{1}{8}$-in stipe slices at a bed loading of 1.28 lb of B.D.S./sq.ft. and an air flow of 7.5 lb/(sq.ft.)(min). Drying times should be divided and rates multiplied by the W.B.D. in ^{o}F. For other loadings and air speeds, times should be divided and rates multiplied by the factors given, which are taken from Figs. 27 and 33. This basis of dryer design is stated by Hendry & Scott (142) to be at least as accurate as other methods, with the additional merit of simplicity.

7.10. TEMPERATURE OF SEAWEED DURING DRYING

The internal temperature of a $\frac{1}{8}$-in slice of L. cloustoni stipe was measured during drying by a copper-eureka thermocouple. A small radial hole was drilled through the outer skin of the slice and the couple pushed home so that the junction was embedded in the centre and did not break through the cut surface of the slice. A single layer of similar stipe slices (lying flat) was placed in the basket so that samples could be abstracted periodically for water-content determination as the customary procedure of weighing the basket and contents was impracticable.

The plot of material-temperature versus time (Fig. 40) shows that the seaweed temperature rose continuously during drying and did not remain at the W.B.T. for any appreciable length of time. At a water content of 0.25 the seaweed was 5^{o}F below the D.B.T. and it reached the D.B.T. when at a water content of approximately 0.15. Ede & Hales (80) obtained substantially similar results for the internal temperature of a potato strip during drying.

Shrinkage of the individual slices is illustrated in Fig. 41, which was prepared from full-size photographs of the slices. The samples shown were selected as being reasonably typical of the batch. During the first ten minutes of drying, the slices contracted slightly in diameter and the surface water dried off. Slight curling became noticeable at a water ratio of 2-3, and buckling became severe below 1, the material finally assuming the shape of a twisted saddle when dry. (Numbers on Fig. 40 correspond to the section numbers on Fig. 41). This agrees with the observation (Fig. 44) that the static pressure drop of a 3-in bed of stipe slices becomes constant at an average water ratio of 1-1.5, when the bulk of the shrinkage will have occurred.

The initial drying period, when little shrinkage occurs, may correspond to the loss of water from the cell cavities, whereas severe shrinkage might ensue when the cell walls dry and change their shape. This water content, which would correspond to the fibre saturation point of wood, appears to be of the order of 2.0.

7.11. CONSTANT DRYING RATE

The initial drying rates of seaweed-stipe beds of three-inch depth or more are linear. Marshall (159) illustrated a water-content versus time curve for potato in which he suggested that the initial stages be approximated to by a straight line to simplify calculations for design purposes. For the seaweed tests the rates are linear (within small experimental error) and are not approximations. It was also observed that the exhaust air from the dryer was unsaturated and further investiga--tion revealed that in most cases the output air from the deepest beds was about 90% absolute humidity. It appears therefore that as the drying air approaches this value, its capacity for evaporating much more water falls away rapidly. This is in line with theory in that the air would require an infinitely deep bed to reach saturation under adiabatic conditions. It appears, then, that mass transfer for deeper seaweed-beds is of the order of a '90% equilibrium stage' for the air conditions specified.

Brown (160) did not observe constant-rate drying in tests with through-circulation drying of $^5/32$-in square potato strips when using inlet air conditions of 140°F D.B.T., 120°F W.B.T. and 5.6 lb/(sq.ft.)(min) at a bed loading of 3 lb of wet material/sq.ft. This may reasonably be attributed to the comparatively light loading used, since the constant drying rates

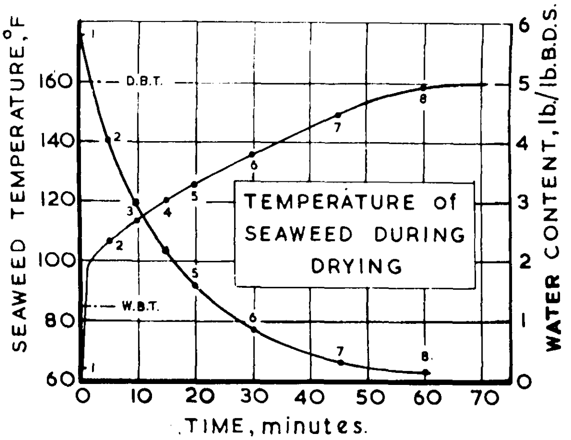

SEAWEED TEMPERATURE, °F
WATER CONTENT, lb./lb. B.D.S.
TIME, minutes.
TEMPERATURE of SEAWEED DURING DRYING
D.B.T.
W.B.T.
160
140
120
100
80
60
0
10
20
30
40
50
60
70
6
5
4
3
2
1
0

Fig. 40.

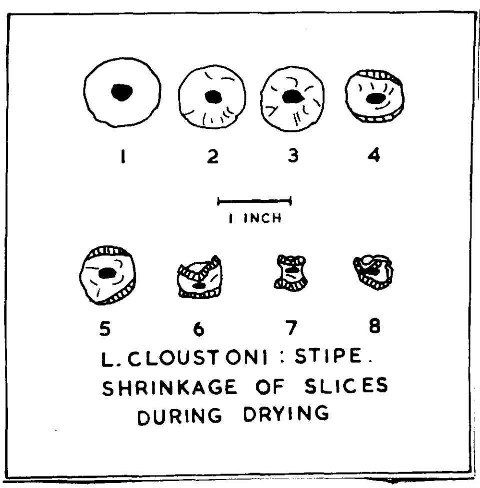

1
2
3
4
1 INCH
5
6
7
8
L. CLOUSTONI : STIPE.
SHRINKAGE OF SLICES
DURING DRYING

Fig. 41.

for seaweed beds below 8.35 lb of wet seaweed/sq.ft. had only a transient existence and, as shown in Fig. 40, a unit layer of stipe slices has no constant rate whatever. Constant drying rates have also been observed by the authors for through-circulation drying of three-inch beds of cloves, brewer's grain, sugar-beet and peat with air conditions approxi--mating to those for stipe in Table 18.

Another factor that would tend to prolong the constant drying rate for vegetable material is shrinkage. As the bed contracts its resistance decreases and for a constant fan setting the air velocity should increase, so that the increased air flow would counteract the reduced water pick-up caused by the material becoming drier.

7.12. STATIC PRESSURE DROPS

Static pressure drops were measured by taking the draught-gauge reading when the bed of seaweed was in position with the dryer closed, and deducting the resistance of the dryer and basket at the same air-flow rate. Plots of static pressure drop versus mass air flow are given in Figs. 42 and 43 for beds of fresh and dried stipe slices, using air at room temperature.

When the pressure drops are expressed as in of water gauge/ft of bed depth, the values for the 1-in layers are $1\frac{1}{2}$ to $2\frac{1}{2}$ times the value for the deepest beds. This is the reverse of what would be expected if compression was taking place, and may be the result of errors being magnified when the pressure drops are very small and bed thicknesses are difficult to measure accurately. This error was negligible for depths greater than 3 in.

Using freshly sliced sugar-beet cossettes, Owen (137) found that the static pressure drop at constant air velocity was directly proportional to the bed depth, and he derived the following equation for the pressure drop:-

$$X = (0.0015V - 0.09)Z$$

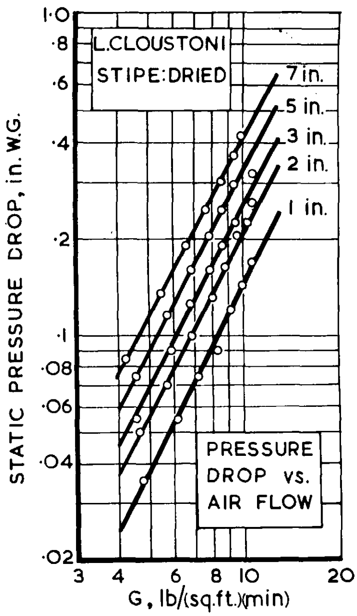

L.CLOUSTONI
STIPE:DRIED
7 in.
5 in.
3 in.
2 in.
1 in.
PRESSURE
DROP VS.
AIR FLOW
STATIC PRESSURE DROP, in. W.G.
G, lb/(sq.ft.)(min)

Fig. 42.

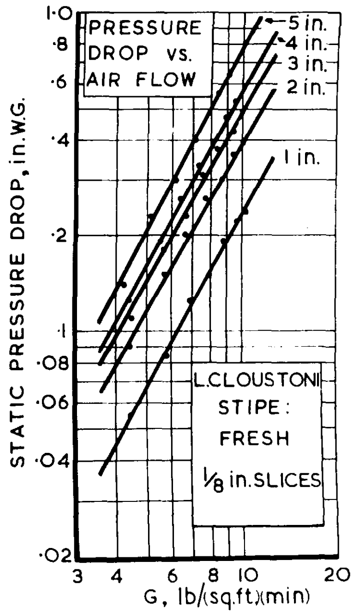

PRESSURE
DROP VS.
AIR FLOW
5 in.
4 in.
3 in.
2 in.
1 in.
L.CLOUSTONI
STIPE:
FRESH
1/8 in.SLICES
STATIC PRESSURE DROP, in.W.G.
G, lb/(sq.ft)(min)

Fig. 43.

where X = static pressure drop, in of water gauge,

Z = bed thickness, in.

Spaugh (161) studied the resistance of beds of dehydrated vegetables to the through-flow of air, using bed depths up to 36 in and air velocities of 37-170 ft/min. Spaugh found that the values of the pressure drop per unit bed depths at different heights in the bed were fairly widely scattered, and showed no definite correlation. He concluded from this that the packing effect was negligible for dehydrated vegetables up to 36-in beds.

A general equation for dehydrated vegetables given by Spaugh is :-

$$Q = (C_1V/C_2 - b)^n,$$

where Q = static pressure drop in of water gauge/ft of bed,

C_1, C_2 = experimental constants,

b = ft of perimeter/sq.ft. of bin cross-section,

n = experimental exponent.

Spaugh suggested that when b is greater than unity the simpler equation $Q = CwV^n$ may be used, where C is again an experimentally determined constant, and w = air density, lb/cu.ft. (For the present dryer, b = 4.23). He also showed that the effect of the air viscosity could be neglected for the range of temperatures studied (room temperature to 200°F).

The straight lines on Figs. 42 and 43 may be represented by the equation:-

$$Q = CG^n$$

The exponent n varies from 1.76 to 1.88 for dried stipe and from 1.75 to 1.92 for wet stipe slices. Spaugh obtained values ranging from 1.60 for flaked onions to 1.82 for strip potatoes, and Coles gave a value of 1.5 for a bed of viscose fibre.

Equations for pressure drops of seaweed beds (random packing) have been derived from the average value of the exponents and the pressure drop from the deepest beds. These equations are :-

$$Q = 0.011G^{1.83} \quad \text{for dried stipe slices,}$$

$$Q = 0.027G^{1.8} \quad \text{for fresh stipe slices.}$$

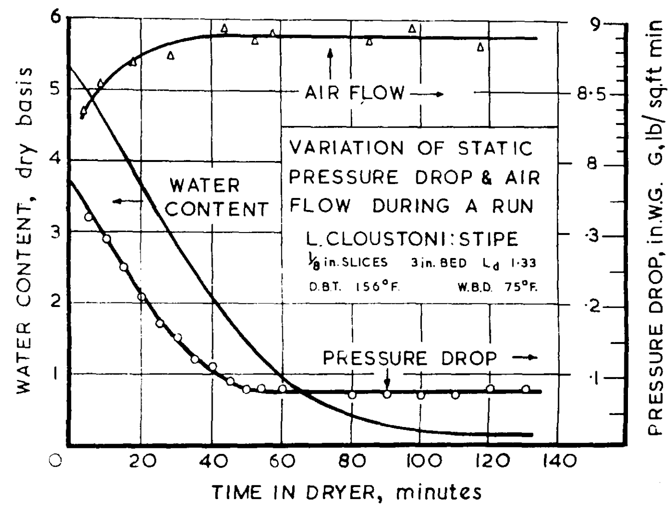

VARIATION OF STATIC PRESSURE DROP & AIR FLOW DURING A RUN
L. CLOUSTONI : STIPE
1/8 in. SLICES 3 in. BED Ld 1·33
D.B.T. 156°F. W.B.D. 75°F.
AIR FLOW
WATER CONTENT
PRESSURE DROP
WATER CONTENT, dry basis
PRESSURE DROP, in.W.G. G, lb/ sq.ft min
TIME IN DRYER, minutes
0
20
40
60
80
100
120
140
1
2
3
4
5
6
·1
·2
·3
8
8·5
9

Fig. 44.

From Fig. 44, which shows the variation of pressure drop during a drying run, shrinkage appears to be negligible after a water content of 1-1.5 lb/lb of B.D.S. is reached.

8. RESULTS: L. CLOUSTONI FROND

The fronds of the sublittoral seaweed species L. cloustoni used in this investigation formed flat brown strips 18-24 in long by 3-6 in wide and about 1/16 in thick.

The fronds received 24 hours after harvesting were covered with a mucilage containing sodium alginate, which caused the blades to adhere to each other. They decomposed within about 48 hours of harvesting if stored wet, and decomposition was often most marked at points where two pieces had adhered.

Differences in chemical constitution between frond and stipe which arise from their different functions are shown in Table 12 compiled from a paper by Black (10).

TABLE 12.

L. CLOUSTONI, HARVESTED OBAN, 1947

		Frond	Stipe
Water content (lb water/lb of B.D.S.)	...	2.7-6.6	4.6-6.1
Total ash (dry basis) %	...	13-37	30-38
Alginic acid (dry basis) %	...	8-19	19-23
Laminarin (dry basis) %	...	1-32	Nil
Mannitol (dry basis) %	...	6-23	5-9
Average weight (450 samples), lb	...	1.5	2.6
Specific Gravity (wet)	...	1.041	1.072

These figures are the minimum and maximum values obtained for 1947.

Extraction of the various constituents has been hindered in the past by the difficulty of harvesting and drying fresh seaweed. Cast seaweed is not so suitable, as some of the soluble constituents may be leached out by the sea or by rain water. If the frond is not dried promptly, many of the organic compounds are degraded by bacterial action.

The experimental procedure used for frond was similar to that described in Section 6.5. with the following slight modifications.

The prepared frond was weighed into the basket and the bed levelled off without any pressure being applied. No method of arranging the pieces was possible, so the bed was packed at random. During drying, the dark-brown frond changed to a dark-green colour. When steam injection was used to humidify the inlet air, the colour changed initially to a bright-green shade which ultimately became dark green. As the mucilage dried, the various particles were cemented together until, at the end of the test, the entire bed could be lifted out as a mat.

In most of the tests reported, the seaweed frond was minced before drying. The factors studied were: bed depth, particle size, air velocity, air temperature and wet-bulb depression, and the seasonal variation of the drying times.

Physical differences between the frond and stipe have a profound effect on their drying characteristics.

Frond particles are sticky and flexible in contrast with the uniformly-sized, rigid, non-sticky stipe slices. This causes the frond bed to show a marked edge-effect, produced by the shrinkage of the materials from the edges of the basket; hence there is short-circuiting of the air through the resulting spaces, leading to uneven drying. In the bed of stipe, on the other hand, the slices are sufficiently mobile to fill up any gaps formed during drying.

The stipes have a reasonably uniform water content throughout the year, but the frond water content can vary up to three times its minimum value. In addition to the increased drying time caused by the greater evaporation load, the frond also offers more resistance to drying at the time of year when the water content is highest. With the stipe, no marked seasonal change of drying time was observed.

8.1. BED DEPTH

The effect of increase of bed depth was studied for minced and shredded frond at an inlet air temperature of 156°F. The curves of drying-time versus dry-loading are given in Fig. 45. Both curves are concave upwards,

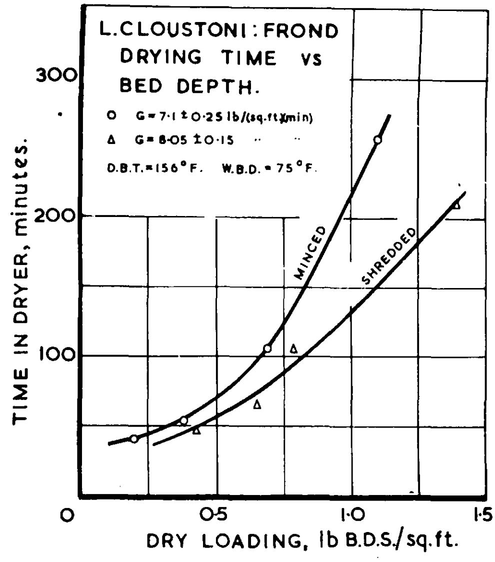

L.CLOUSTONI: FROND
DRYING TIME VS
BED DEPTH.
O G = 7·1 ± 0·25 lb/(sq.ft)(min)
Δ G = 8·05 ± 0·15
D.B.T. = 156°F. W.B.D. = 75°F.
MINCED
SHREDDED
300
200
100
0
0·5
1·0
1·5
TIME IN DRYER, minutes.
DRY LOADING, lb B.D.S./sq.ft.

Fig. 45.

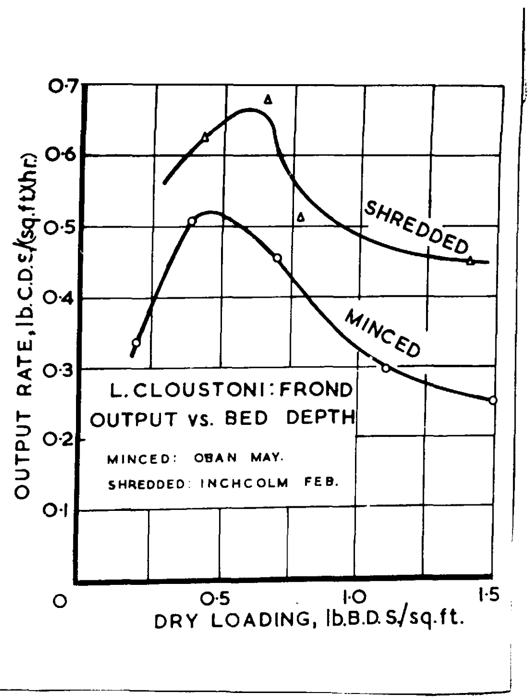

0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
0·5
1·0
1·5
SHREDDED
MINCED
L.CLOUSTONI: FROND
OUTPUT VS. BED DEPTH
MINCED: OBAN MAY.
SHREDDED: INCHCOLM FEB.
OUTPUT RATE, lb.C.D.S./(sq.ft.)(hr.)
DRY LOADING, lb.B.D.S./sq.ft.

Fig. 46.

showing that the drying time increases rapidly for small increments of depth. When the output versus bed-loading curve is plotted (Fig. 46) for minced frond, it may be seen that there is a marked optimum loading, at 0.45 lb of B.D.S./sq.ft. or 1-1½ in deep. (Intermediate points on the output curve were interpolated from the curve in Fig. 45).

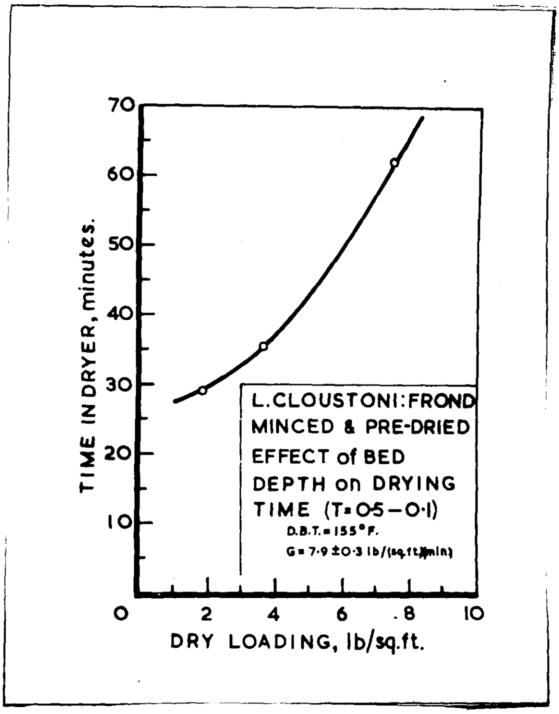
The points for the shredded seaweed are more scattered but it is probable that the output curve is of a similar form to that for minced frond, with a slightly higher optimum point at 0.6 lb/sq.ft. (4-4½ in deep). It would at first appear from these curves that shredding was superior to mincing in giving speedier drying, but these tests are not comparable as the place and time of harvesting were different. The comparison test between the two forms of pre-cutting showed that mincing was faster.

It is suggested that the disproportionate increase of drying time with increasing bed depth and the low optimum loading are the result of two factors: (a) the stickiness of the frond, (b) the lack of rigidity of the material.

The mucilage tends to fill the interstices between the individual particles, preventing the ready access of air, and the lack rigidity of the fresh frond allows the lower strata to be compressed into a compact mass. This is partly confirmed by three tests with minced L. cloustoni frond which had been pre-dried in a rotary dryer at 300°F. The particles, at a water ratio of 0.5 lb/lb had lost all stickiness, but were still flexible. Beds of this material 1¼, 2½ and 5 in thick were successfully dried, showing that heavy loadings may be practised when the effect of the mucilage is minimized. The drying-time versus loading curve (Fig. 47) still shows a slight upward curvature, probably caused by compression of the lower layers with heavier loadings.

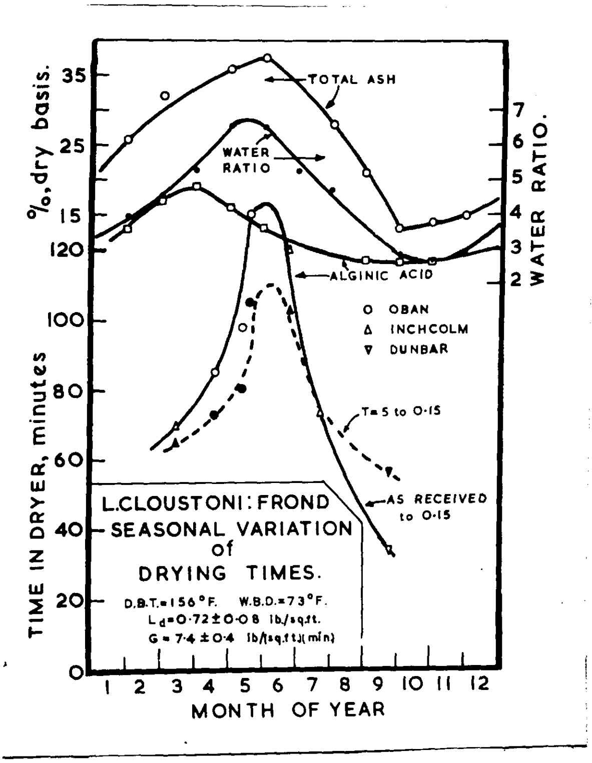
8.2. PARTICLE SIZE

Earlier experiments showed that 6-in lengths of frond could not be dried satisfactorily as a bed, as the outside of the layer was often crisp



TIME IN DRYER, minutes.
DRY LOADING, lb/sq.ft.
L.CLOUSTONI: FROND
MINCED & PRE-DRIED
EFFECT of BED
DEPTH on DRYING
TIME (T=0·5—0·1)
D.B.T.=155°F.
70
60
50
40
30
20
10
0
2
4
6
8
10

Fig. 47.



%, dry basis.
WATER RATIO.
TIME IN DRYER, minutes
MONTH OF YEAR
TOTAL ASH
WATER
RATIO
ALGINIC ACID
O OBAN
Δ INCHCOLM
∇ DUNBAR
T=5 to 0·15
AS RECEIVED
to 0·15
L.CLOUSTONI: FROND
SEASONAL VARIATION
of
DRYING TIMES.
D.B.T.=156°F. W.B.D.=73°F.
Ld=0·72±0·08 lb/sq.ft.
G=7·4±0·4 lb/(sq.ft.)(min)

Fig. 49.

while the inner parts were wet and sticky. Where two strips had stuck together, the air could not penetrate and the drying time became excessive. It was apparent that some form of subdivision of the frond was required, not only to increase the specific surface, but also to allow the drying air to reach all the particles forming the bed. If the pieces are too finely cut or are crushed, more mucilage tends to exude from the fragments and some of the advantages of size reduction are lost.

Mincing is effective for disintegration of the frond, but the design of the mincer has a noticeable effect. Where the material is extruded through small holes, considerable amounts of mucilage are produced and the seaweed becomes like a sticky paste. The domestic mincer used in the present work has an external cutting ring which gives more of a shearing action. In all the tests on minced frond, the largest cutter was used giving pieces about $\frac{3}{8}$ in x $\frac{1}{2}$ in x $^1/16$ in.

Tests were also carried out on frond which had been shredded in a rotary bean-cutter. This machine (Fig. 48) produced frond strips $^3/16$ in wide by about 6 in long. This method of pre-cutting seemed to cause less exudation of mucilage than mincing. A direct comparison between shredded and minced frond was made from tests on the same batch of seaweed (Table 13).

TABLE 13.

L. CLOUSTONI FROND HARVESTED AT INCHCOLM ON 14 MARCH, 1952

D.B.T. = 156°F Wet loading = 4.375 lb/sq.ft.

	Shredded	Minced
Bed depth, in	5	2
Dry loading, lb of B.D.S/sq.ft. ..	0.65	0.68
Wet-bulb depression, °F	76	74
Mass air flow, lb/(sq.ft.)(min) ..	8.1	7.9
Drying time (T = 5 to T = 0.15), * min	76.5	62.5
Static pressure-drop, in (water) ..	0.17	0.36

* T = total water content, lb water/lb of B.D.S. (i.e. water ratio)

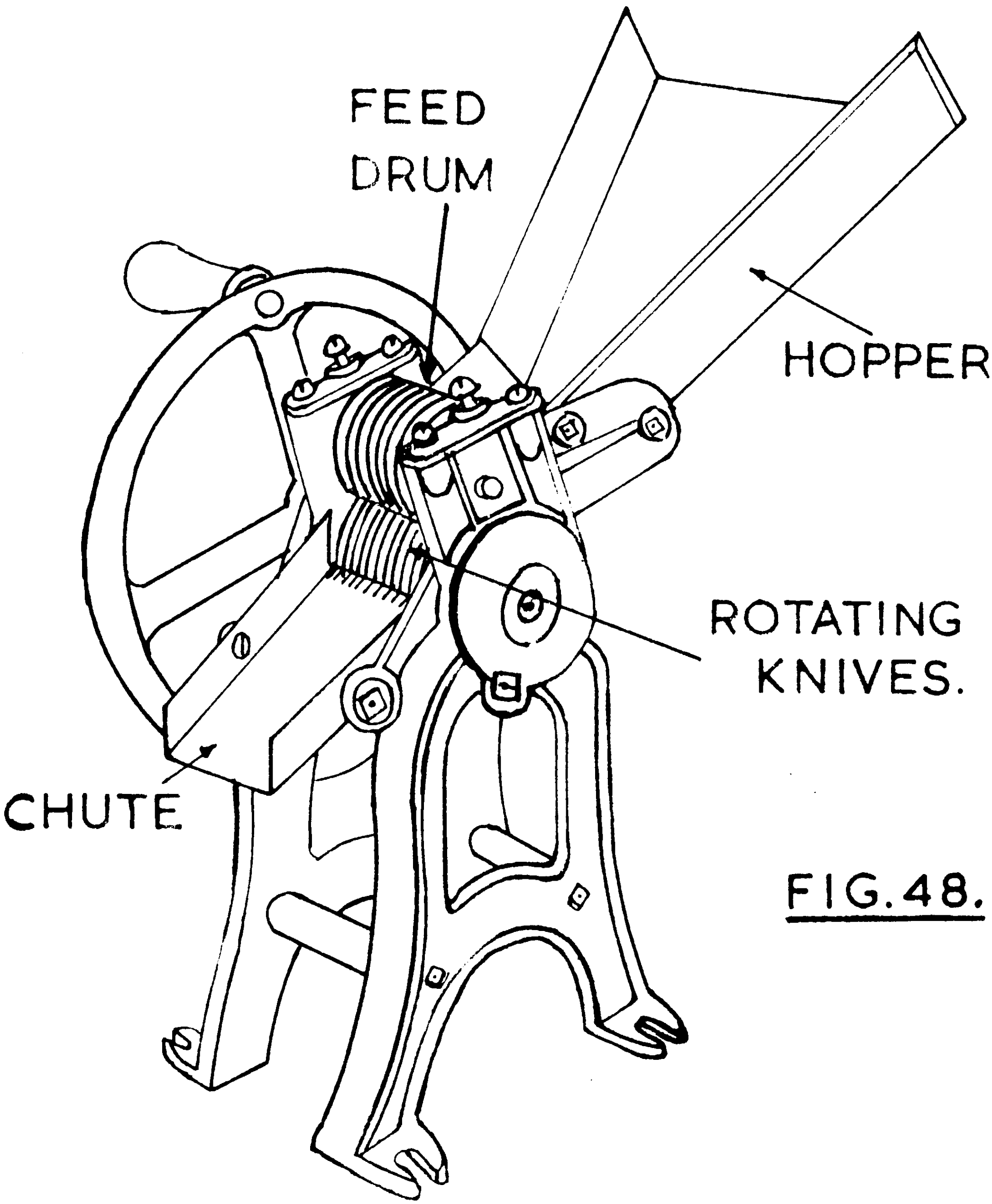


FIG. 48.

ROTARY SHREDDING MACHINE

This shows that minced frond dries more rapidly than the strips for plants harvested in March (when the alginic acid content is highest). Comparable drying times for L. cloustoni stipe are 68 minutes for minced stipe and 110 minutes for stipe slices, $\frac{1}{8}$ in thick. It should be noted that the bulk density and static pressure drop of the shredded frond bed are much lower than the values for the minced frond.

Trouble was experienced with the fronds slipping on the feed drum of the rotary shredder, and in the remaining tests (except bed-depth runs) minced frond was used to reduce the preparation time. It is thought that this difficulty could be overcome on industrial shredding machinery, possibly by the use of spiked feed-drums. It may here be observed that, unlike the stipe, no water can be separated from the minced frond by centri--fuging.

8.3. SEASONAL VARIATION

The seasonal change in water content, which is of especial interest as regards drying, is plotted as the water ratio in Fig. 49. It can readily be seen that the water content is highest in the spring (April-May) and lowest in the autumn (September-October). The mineral matter content, expressed as total ash, exhibits similar maxima and minima (Fig. 49) as also does alginic acid (March). On the other hand, laminarin and mannitol are at a maximum in the autumn, the laminarin curve being the inverse of the total ash graph.

Seven drying tests under similar conditions were made at different times between March and September. When the drying times for the water-content range 5-0.15 are plotted (Fig. 49, broken line) it can be seen that the drying time reaches a maximum in the spring and appears to be at a minimum in the autumn. (The time for September was obtained by extrapolation, as the initial water content was only 2.05). This curve follows the total-ash line, and the increased drying time is probably related to the reduced vapour pressures caused by the higher salt concentrations.

The total ash of the fronds consists of soluble and insoluble salts. Black (7) found that the principal seasonal variation occurred in the water-soluble constituents which were presumably in solution in the cell sap, and they will naturally influence the vapour pressure. The insoluble mineral matter does not vary widely throughout the year and is comparatively low (the average value for the seven drying tests being 5% of the weight of the bone-dry frond). This means that the soluble ash content will follow the total-ash curve, but the actual values will be about 5% less. The total-ash content has been retained, as little information is available on the soluble ash content of seaweed.

The maximum drying time may be related also to the alginic acid content. The alginic acid would be expected to reduce the drying rate of a seaweed bed in two ways, externally by the production of mucilage on the surface of the frond pieces, and internally by its affinity for water. The latter effect would probably be more noticeable in the later stages of drying. It appears, however, that the salt concentration is the overriding factor controlling drying time, since the peak value of alginic acid occurred two months before the maximum drying time was reached, whereas the total ash maximum coincided with this maximum drying time.

The comparison of frond-drying times for a given water content range (i.e. 5-0.15 water ratio) gives some indication of the resistance to drying, provided of course that all other conditions are similar. In view of the wide variation of the initial water content of the frond, it is more realistic to compare the times required to dry from the initial condition to a standard final moisture content. This curve is shown in Fig. 49 (full line) and indicates that the minimum drying time may be about one-quarter of the peak value (i.e. 130 minutes in May-June to 33 minutes in September).

If the frond was being harvested and dried for the eventual extraction of any one particular compound, the seaweed would naturally be collected in the month when the constituent was at its maximum. None of the major constituents appear to have their peak value at the time of the lowest drying rate, but if the harvesting of frond for alginic acid is continued after March, the seaweed will become progressively more difficult to dry. Alginic acid is at present the principal commercial algal chemical, but it is almost invariably extracted from the stipe.

The curves for water content, total ash and alginic acid (Fig. 49) are taken from results reported by Black (10) for frond harvested at Oban in 1947. Determinations made on the material from the drying tests reported agree in general with Black's results.

This seasonal change in the drying rate of frond precludes any rigorous comparison, but the general effect of any one variable will probably be the same at any time of the year, although the actual value of the drying rates will have altered.

Owing to harvesting difficulties caused by bad weather, it was necessary to collect plants from different areas, so that the seasonal variation tests are not strictly comparable, but they give some indication of the fluctuations to be expected. It is apparent that any dryer for seaweed must be sufficiently flexible in operation to cope with these variations.

8.4. AIR VELOCITY

This series of tests was done on 2-in beds of minced frond, which, although greater than the optimum bed-loading, are nevertheless sufficiently close to be of value. At the time of testing, the maximum air flow of the dryer was about 7 lb/(sq.ft.)(min), so that only four runs were attempted.

The effect of mass air flow on the drying time (Fig. 50) has a similarity to the corresponding curve for stipe, and it is probable that this frond curve will also level off at higher air flows. It may be concluded that the minimum air flow should be 7 lb/(sq.ft.)(min).

The plot of constant drying rate against air flow shown in Fig. 51

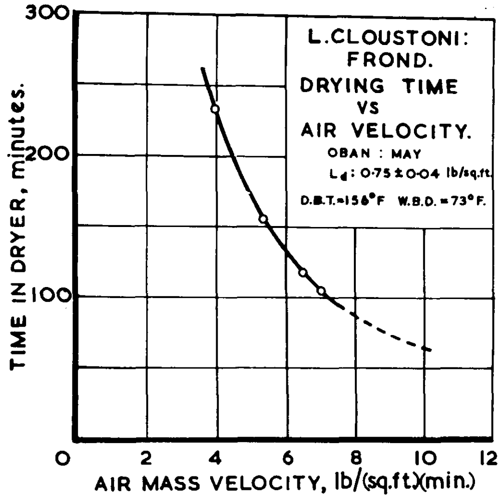

L.CLOUSTONI:
FROND.
DRYING TIME
VS
AIR VELOCITY.
OBAN : MAY
Ld: 0·75±0·04 lb/sq.ft
D.B.T.=156°F W.B.D.=73°F.
TIME IN DRYER, minutes.
300
200
100
0
2
4
6
8
10
12
AIR MASS VELOCITY, lb/(sq.ft)(min.)

Fig. 50.

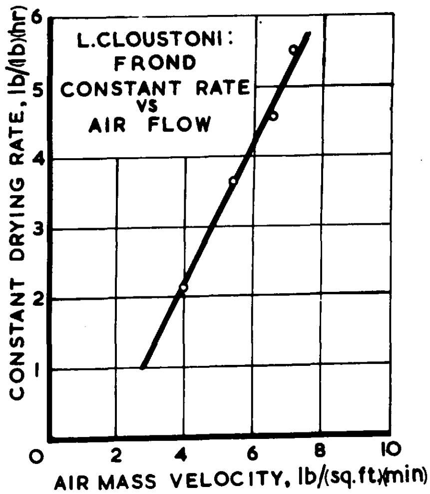

L.CLOUSTONI:
FROND
CONSTANT RATE
VS
AIR FLOW
CONSTANT DRYING RATE, lb/(lb)(hr)
6
5
4
3
2
1
0
2
4
6
8
10
AIR MASS VELOCITY, lb/(sq.ft)(min)

Fig. 51.

appears to be linear, but differs from that of stipe in that the straight line would intercept the x-axis if produced.

8.5. TEMPERATURE AND HUMIDITY

Seven tests were carried out at an average dry-loading of 1.10 lb/sq.ft. ($1\frac{1}{2}$ in approx.).

As the seaweed was harvested in August and September, the water ratio was only 2.4-3.0. The curves of water content versus time were drawn and the instantaneous drying rates at water ratios of 2.5, 0.6 and 0.2 were determined.

These drying rates (Fig. 52) show a linear relationship to the wet-bulb depression (W.B.D.) similar to that for stipe. It is most likely that the drying rates at higher water contents will obey the same rule. A test using humidified air (170°F B.D.T.) agrees reasonably well with the other points obtained from tests using heated air of normal room humidity.

As the drying time of the frond varies so widely with the season, it was considered unwise to construct a curve for unit W.B.D. on which to base a dryer design. If, however, the drying time for a given W.B.D. is known then the drying time for any other W.B.D. may be estimated by proportion with reasonable accuracy.

8.6. STATIC PRESSURE DROPS

The static pressure drops of beds of dried minced L. cloustoni frond were measured by noting the draught-gauge reading when the bed was in position with the dryer closed, and deducting the resistance of the dryer and basket at the same air-flow rate. Plots of static pressure drop against air flow are given in Fig. 53 with air at room temperature. These results could be directly applied to the design of finishing bins which are used to condition nearly dry material to a standard moisture content. The main features of these bins are that deep beds and low air

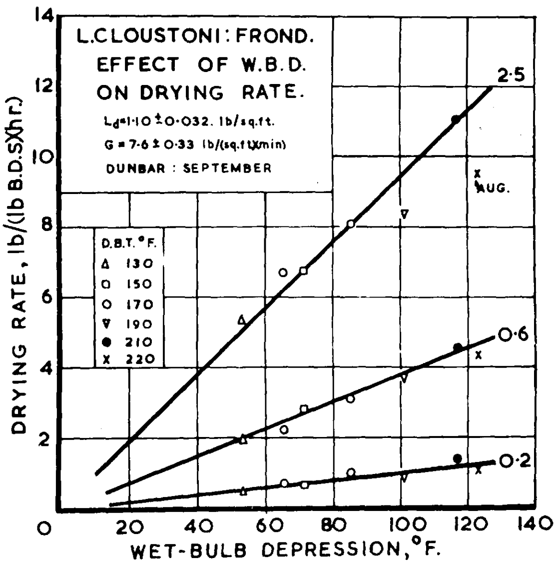

L.CLOUSTONI: FROND.
EFFECT OF W.B.D. ON DRYING RATE.
L_d=1·10 ± 0·032. lb/sq.ft.
G = 7·6 ± 0·33 lb/(sq.ft)(min)
DUNBAR : SEPTEMBER
D.B.T. °F.
Δ 130
□ 150
○ 170
▽ 190
● 210
x 220
x AUG.
2·5
0·6
0·2
DRYING RATE, lb/(lb B.D.S)(hr.)
WET-BULB DEPRESSION, °F.

Fig. 52.

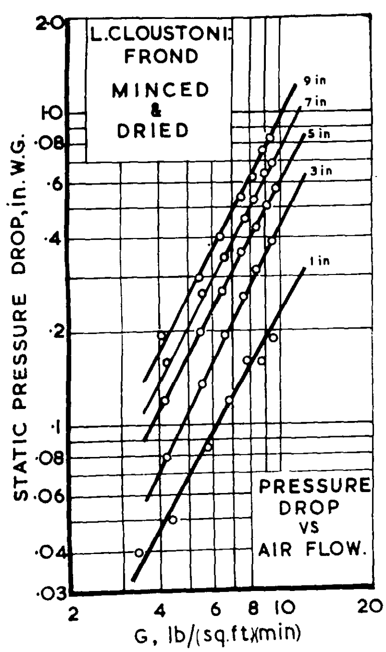

L.CLOUSTONI: FROND
MINCED & DRIED
9 in
7 in
5 in
3 in
1 in
PRESSURE DROP VS AIR FLOW.
STATIC PRESSURE DROP, in. W.G.
G, lb/(sq.ft)(min)

Fig. 53.

velocities are used.

The deepest bed (9 in) was prepared first and weighed so that the remaining layers could be measured by weight, as this was more accurate than direct linear measurement. Static pressure drops for wet frond are shown in Table 13. It can be seen from Table 14 that the static pressure drop per unit of bed depth decreases to a constant value as the bed loading is increased. This characteristic was observed with beds of L. cloustoni stipe slices (Section 7.12.).

The velocity index also tends to a constant value with increasing depths, and the average value (1.85) is close to the indices for stipe (1.83 and 1.80 for dried and fresh slices respectively). A formula relating the pressure drop to air flow for dried frond beds (random packing) has been derived from the pressure drop of the 9-in bed and the average exponent :-

$$P = 0.0183G^{1.85}$$

where P = static pressure drop, in water/ft of bed,

G = air mass velocity, lb/(sq.ft.)(min).

TABLE 14.

STATIC PRESSURE DROPS OF BEDS OF L. CLOUSTONI FROND (MINCED AND DRIED)

G = 9 lb/(sq.ft.)(min)

Bed depth, in	1	3	5	7	9
Pressure drop, in (water)/ft bed	2.28	1.40	1.20	1.08	1.07
Velocity index	1.70	1.98	1.85	1.85	1.87

9. RESULTS: L. DIGITATA FROND AND STIPE; L. SACCHARINA FROND

In the previous section the physical and chemical differences between the two parts of the plant - stipe and frond - were compared and contrasted. Physical differences between the three common sublittoral seaweeds used in the drying tests are described below (162).

L. cloustoni has a sturdy stipe with a circular cross-section. The epidermis, or outer skin, of the stipe is rough and often has adherent parasitic growths (Fig. 1). The stipe is surmounted by a flat palmate frond. The plant anchors itself firmly to rocks and is normally found in strong tideways, the buffeting of the water being apparently beneficial to its growth.

L. digitata has a smooth oval stipe which rarely has any parasitic growths. The frond is divided into 'fingers' from which the plant derives its name. This species prefers medium tideways.

L. saccharina consists of a soft flexible stipe and a single crinkled frond. It usually attaches itself to shells or small stones and thus offers little resistance to dislodgment; it is consequently found only on sandy sea-beds in sheltered waters.

Black (10) measured the seasonal variation of the fresh weight of samples of these three species over a two-year period. Table 15, taken from his paper, summarizes the average weight of the plants.

It would appear from Table 15 that the heaviest plant is L. cloustoni followed by L. digitata. The fronds of L. digitata and L. saccharina are here heavier than the corresponding stipes, whereas the reverse is true for L. cloustoni. Although these generalizations are not rigid and will vary with the habitat of the plant, they hold for the seaweed samples received for the drying tests.

TABLE 15.

COMPARISON OF THE WEIGHTS OF THREE COMMON SUBLITTORAL SEAWEEDS

		Maximum wt.,lb	Minimum wt.,lb	Average (450 plants) wt.,lb
L. cloustoni (Luing Island)	Frond	2.06	1.12	1.50
	Stipe	3.94	1.50	2.63
L. digitata (Atlantic Bridge)	Frond	4.18	0.75	2.13
	Stipe	0.94	0.31	0.56
L. saccharina (Shuna Island)	Frond	2.25	0.44	1.31
	Stipe	0.50	0.19	0.44

In all the tests on L. digitata frond, the raw material was minced before drying. Factors studied were: agitation of the frond bed, the effect of storage between harvesting and drying of the frond, and the effect of air velocity and bed depth on L. digitata frond and stipe. Seasonal variation of drying time was also observed for L. digitata frond, but there were insufficient data to allow this effect to be evaluated.

9.1. AGITATION EXPERIMENTS

During drying, a bed of minced seaweed frond shrinks away from the basket sides allowing part of the air to short-circuit the bed. An experiment on stipe slices (Fig. 26) verified that the upper layer of the bed did not dry appreciably until the later stages of the run. It follows that the upper central part of the bed will be the last to dry as it is remote from conduction from the walls, and this will prolong the drying operation as a whole.

One possible remedy for this condition is to reverse the air flow about half way through the drying operation. This would be suitable for materials like stipe, which are non-adherent, but with frond the shortening of the drying time would not be so marked since the gaps in the bed would reduce the effectiveness of contact with the air. Agitation, on the other hand, if properly applied, is equivalent to inverting the bed and, in addition, larger masses containing wet knots are broken up and the spaces caused by edge shrinkage are closed. The following agitation tests were carried out to find if there was an optimum number of 'agitations' for a bed of seaweed frond.

A common basis of comparison for these tests is difficult to estab--lish since the drying times (between the same limits of water content) for different degrees of agitation are not known until the end of the run. Consequently the agitation cannot be spaced out at equal time-intervals between the initial and final water-content limits. If a run is carried out with, say, three agitations at twenty-minute intervals, and the final water content is reached five minutes after the last agitation, then the operation is strictly a four-stage process but the number of 'effective' stages would probably be nearer 3.25. Although this concept of an effective stage is not wholly satisfactory in that it gives rise to fractional stages, it has been adopted in an attempt to proportion out the relative effect of mixings and to enable comparisons to be drawn. An effective stage is obtained by dividing the 'agitated' drying time (between specified limits) by the time interval between stirrings.

The drying times with different degrees of mixing cannot be directly compared because of variations in the dry loadings. This has been over--come by interpolating the corresponding time for a static bed at the same dry loading from Fig. 58, and expressing the effect of agitation as a percentage of the static-bed drying time. In this way, the series of tests were rendered independent of dry loading.

Agitation of minced L. digitata frond was carried out at regular time-intervals from the start of the run immediately after the basket had been weighed. Mixing was done by hand and required 80-100 seconds at the start (when the frond was sticky) and 40-50 seconds for the partly dried material. Intermediate weighings were also taken to enable the

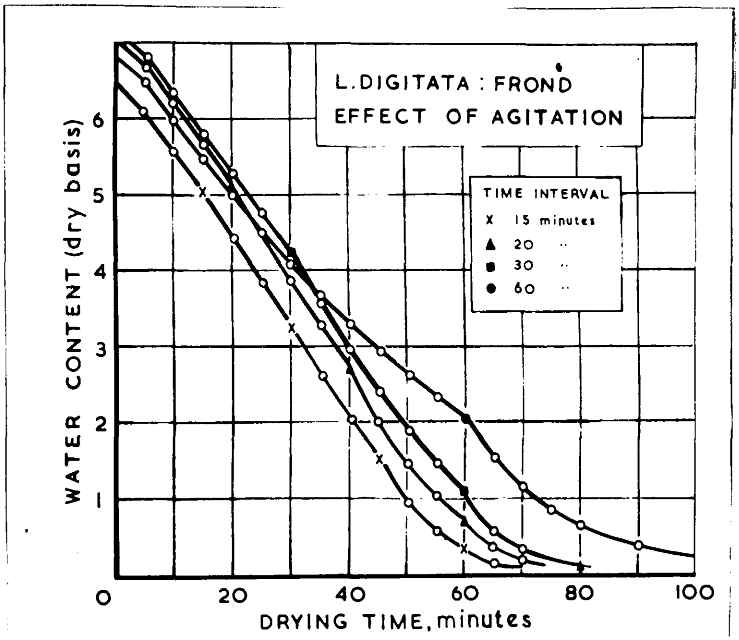


Fig. 54.

D.B.T. = 158°F, W.B.D. = 75°F,

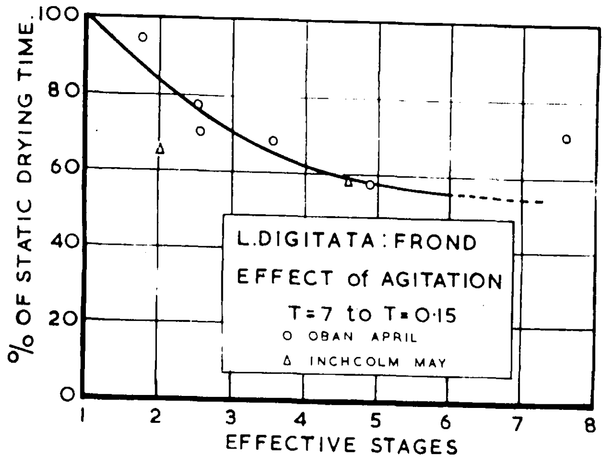
L_d = 0.92 lb B.D.S/sq.ft.

G = 7.6 lb/(sq.ft.)(min).

curves to be plotted accurately. Fig. 54 illustrates some typical runs with agitation, and shows clearly the kinks in the curves caused by the sudden increase of drying rate after the bed had been disturbed. As the initial water ratio of the runs in this series straddled 7.0, this value was selected as the upper limit of water content in preference to the value of 5.0 used in other tests.

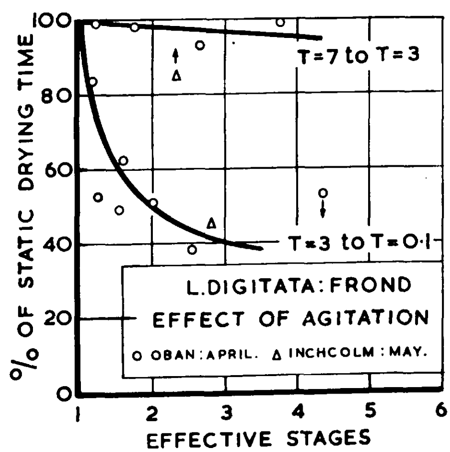
A plot of the percentage reduction of drying time (T = 7.0 to T = 0.15) for various effective stages is given in Fig. 55. The points are some--what scattered, as would be expected for such variable material, but it appears that the effect of agitation falls off after three or four stages (i.e. two or three agitations). Inspection of Fig. 54 suggests that stirring is more effective in the later stages of drying, and this is borne out by Fig. 56 which shows the effect of agitation on the first and second parts of the drying runs. It is apparent that stirring brings about only a small time-reduction (5%) in the range T = 7 to T = 3 (which corresponds approximately to the constant drying-rate period), whereas the drying time in the latter part of the run (T = 3 to T = 0.1) may be reduced to 40% of the time for a static bed. This may possibly be explained by the fact that at the start of the run the exhaust air is almost saturated and cannot pick up much more water even from freshly exposed surfaces. Towards the end of a run this condition does not hold, and the air can then dry the wet surfaces more readily. After stirring of the bed has been sufficient to expose all the wet fragments, and the air can penetrate easily, the controlling factor becomes the rate of release of water from the cells.

Tests on rotary-louvre and through-circulation dryers have shown that agitation is ineffective in the earlier stages of drying frond. This may be explained by the observation that the fronds initially had only isolated patches of mucilage, so that mixing in the wet state probably coated all of the surface with mucilage making conditions worse. If instead, the frond is allowed to dry undisturbed until the mucilage coagulates the individual particles can then be separated and dried to completion.



% OF STATIC DRYING TIME.
100
80
60
40
20
0
1
2
3
4
5
6
7
8
EFFECTIVE STAGES
L.DIGITATA : FROND
EFFECT of AGITATION
T=7 to T=0·15
O OBAN APRIL
Δ INCHCOLM MAY

Fig. 55.



% OF STATIC DRYING TIME
100
80
60
40
20
0
1
2
3
4
5
6
EFFECTIVE STAGES
T=7 to T=3
T=3 to T=0·1
L.DIGITATA: FROND
EFFECT OF AGITATION
O OBAN : APRIL. Δ INCHCOLM : MAY.

Fig. 56.

Figs. 55 & 56 show multistage drying with equal residence times in each stage, but it appears from Fig. 56 that better results would be obtained with unequal drying stages. This would mean that if a three-stage drying process were planned for frond, it would probably be better to agitate the bed at one-half and three-quarters of the drying time, rather than at one-third and two-thirds of the time.

If a continuous conveyor-belt through-circulation dryer is used for seaweed, and the bed depth is progressively increased by reducing the speed of the lower belts, then the interval between agitations will increase towards the end of the run (assuming belts of equal length).

Tests on pre-dried minced frond (Fig. 47) showed that much heavier loadings could be used in the later stages of drying (when the stickiness of the particles was reduced) with a resultant increase in output. This would indicate that the effect of increasing output by using deeper beds and by frequency of stirring are in opposition, and their relative importance will have to be assessed.

It should be noted, however, that the above agitation experiments were carried out with an average bed loading (L_d) of 0,92 lb of B.D.S/sq.ft. Agitation will probably allow the optimum bed loading for frond to be substantially increased.

9.2. TIME INTERVAL BETWEEN HARVESTING AND DRYING

As it was impossible to ensure that all drying tests were carried out at exactly the same time after harvesting, three tests were made in which wet L. digitata frond was kept in a loosely closed sack in the laboratory for varying periods before drying to find if this affected the drying time. The seaweed was harvested at Inchcolm Island, Firth of Forth, on 2 April, 1952. Results of the tests are set out in Table 16.

TABLE 16.

EFFECT OF TIME INTERVAL BETWEEN HARVESTING AND DRYING L. DIGITATA FROND

Time between harvesting and drying, days		1	2	3
D.B.T., ^{o}F	...	160	159	157
W.B.T., ^{o}F	...	82	81	81
G, lb/(sq.ft.)(min)	...	7.75	7.8	7.75
L_d, lb of B.D.S/sq.ft.	...	0.644	0.640	0.668
Drying time (T = 5.0 to T = 0.15), min		57	64.5	79.5

A previous test on L. cloustoni stipe (Fig. 25) did not reveal any marked alteration of drying time on standing, and it is possible that the behaviour of L. digitata frond may be related to the exudation of mucilage on the surface of the plants. By the third day the frond showed considerable evidence of decomposition. Comparatively little water appears to have been lost since the initial water content decreased only from 7.7 to 7.35 lb/lb of B.D.S. over the three days.

9.3. AIR VELOCITY

9.3.1. L. digitata Frond

The curve of drying time (T = 5 to T = 0.15) versus air mass velocity for L. digitata frond is shown in Fig. 57 and Table 17 lists the drying conditions used.

The curve of drying time versus air mass velocity for L. cloustoni frond is drawn on the same graph for comparison. It is apparent that the curves are similar in shape and that the L. digitata frond dries in about 60% of the time required for L. cloustoni. It should be noted from Table 17 that the dry loading of the L. digitata was lower than that of L. cloustoni frond. The reduction in drying time with increasing air flow falls off after a rate of about 8 lb/(sq.ft.)(min) is reached, although if air recirculation is utilized, the air flow will probably have to be increased to compensate for the increased humidity.

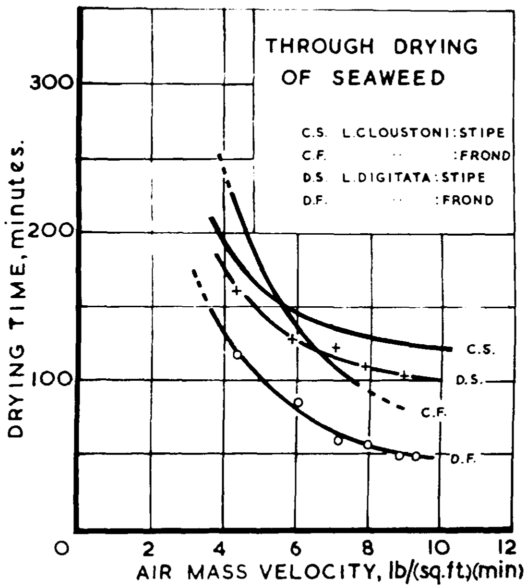


Fig. 57.

Effect of air mass velocity on drying time (T = 5 to T = 0.15). Data in Table 17.

The curve of drying time for L. digitata frond may be represented by the equation :-

$$\theta = 634G^{-1.17}$$

The smooth curve for L. cloustoni frond is given by an equation of the same form :-

$$\theta = 1620G^{-1.4}$$

TABLE 17.

EFFECT OF AIR MASS VELOCITY ON SEAWEED DRYING

	Habitat	Month	D.B.T., °F	W.B.T., °F	L_d, lb B.D.S/sq.ft.
L. cloustoni frond	Oban	May	156	83	0.75
L. digitata frond	Oban	May	159	83	0.71
L. cloustoni stipe	Oban	Mar.-May	157	84	1.20
L. digitata stipe	Oban and Inchcolm	May	159	83	0.97

9.3.2. L. digitata Stipe

Fig. 57 illustrates the curve of drying time versus air-flow rate for L. digitata stipe at an average D.B.T. of 157°F. The corresponding curve for L. cloustoni stipe is included for comparison (Table 17). The marked similarity in appearance between the curves for stipe is further confirmed by their empirical equations which are both rectangular hyperbolae :-

$$\theta = G/(0.013G - 0.03) \quad .. \quad \text{L. digitata stipe}$$

$$\theta = G/(0.0103G - 0.02) \quad .. \quad \text{L. cloustoni stipe}$$

All the curves shown in Fig. 57 are for samples harvested at Oban, but the curve for Inchcolm L. cloustoni stipe is superimposable on the graph for L. digitata and the equations are therefore identical.

9.4. BED DEPTH

9.4.1. L. digitata Frond

The effect of bed depth on the drying time of minced L. digitata frond was investigated with an inlet-air temperature of 159°F. Drying conditions are listed in Table 18. This curve (Fig. 58) is concave upward and the output for T = 5 to T = 0.15 reaches an optimum value at a dry loading of 0.53 lb of B.D.S/sq.ft. or 1½-in initial bed-depth.

The L. digitata frond particles forming the bed were sticky and flexible and the fresh L. digitata and L. cloustoni fronds were almost indistinguishable in appearance when minced. Curves for bed depth versus time for these two species of fronds are given on the composite graph (Fig. 58). The two curves should be reasonably comparable since the L. digitata was harvested at Oban in April, 1952, and the L. cloustoni at Oban in May, 1951. Black (10) found that the ash contents of fronds taken from the same locality in different years were reproducible to within a month.

Comparison of the two species suggests that slightly heavier bed-loadings may be practised with L. digitata (0.53 lb/sq.ft. as against 0.45 lb/sq.ft. for L. cloustoni). These optimum bed-loadings are applicable only if the bed is undisturbed during the drying run and if the frond is loaded when wet and sticky. If partly dried frond is loaded, the optimum loading can be increased as discussed previously. It is clear that the close similarity of the physical nature of the fronds results in the similarity of the effects of bed depth on the drying time of the two species.

9.4.2. L. saccharina Frond

Owing to difficulties of obtaining supplies of this species, only six tests were carried out. The fronds received were much thinner and more flexible than those of either L. cloustoni or L. digitata. As a result, the beds of L. saccharina were very compressible, and slight variations in packing appeared to cause wide fluctuations in drying time.

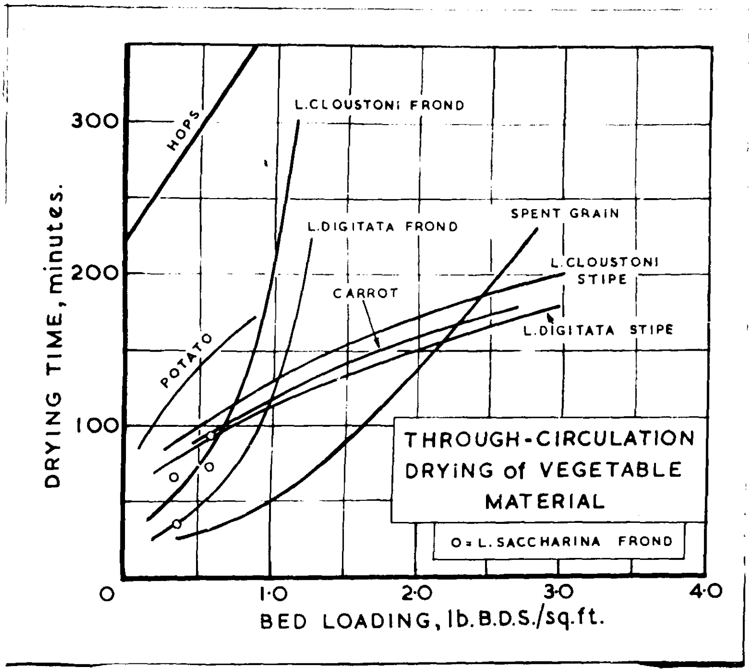


Fig. 58.

Effect of bed depth on drying time.

Data in Table 18.

The four points shown as circles in Fig. 58 represent the four bed-depth experiments and it can be seen that the drying times correspond roughly to those for L. cloustoni frond. Two pairs of tests, in which samples of L. saccharina and L. cloustoni fronds were harvested at the same time and place and dried under comparable conditions, indicated that L. saccharina required two to four times the drying time for L. cloustoni. This was attributed to a compression effect, which may have been exaggerated by the use of young fronds. L. saccharina stipes were not studied since they represented a very small fraction of the plant (Table 15). It would be uneconomical to separate these stipes from the fronds, and in any case they would probably increase the porosity of the bed if they were minced with the fronds.

9.4.3. L. digitata Stipe

The drying-time versus bed-depth curve for L. digitata stipe is plotted on Fig. 58. The equation for this curve is :-

$$\theta = 296\left[\log_{10}(L_d + 2.02) - 0.102\right]$$

and it is of the same type as the curve for sliced L. cloustoni stipe also included in Fig. 58.

It is obvious that the L. digitata stipe dries in about 90% of the time required for L. cloustoni species. It should be stated, however, that the majority of the L. digitata stipes used were apparently from younger plants and the cross-section of the stipe was smaller than that of L. cloustoni. The largest L. digitata stipe section encountered in these tests was an ellipse about $1\frac{1}{4}$ in x $\frac{5}{8}$ in but most were nearer $\frac{3}{4}$ in x $\frac{3}{8}$ in with some even smaller. This smaller size may increase the drying rate to some extent but it is possible that the thickness rather than the diameter of the stipe slices is the controlling factor. The epidermis or outer skin of plants is often intended to prevent the loss of water. If the slice-thickness is kept constant then the skin will represent a higher percentage of the total surface area of the slice as the diameter is reduced. The skin will probably not lose water so readily as a cut surface, especially as the normal movement of water in the stipe will possibly be longitudinal rather than radial.

The striking similarities of drying characteristics existing between the stipes and fronds respectively of the two species suggests that the physical differences between the two parts of the same plant have a far greater effect than the differences between the two species. It should be noted, however, that the three plants belong to the same genus. The chemical and biological differences appear to govern the difference in time of drying between the three species.

If the physical differences of stipe and frond control the relation--ship of drying time to bed depth, and to a lesser extent air velocity, then these differences should be general and apply to vegetable material other than seaweed.

It has been suggested in Section 8.1. that the optimum bed-loading value for through-circulation drying of frond was caused by compression of the lower layers of the bed preventing the ready access of air. As the bed depth is increased the lower strata are progressively compressed and consequently the drying time increases sharply. In addition, the frond particles are sticky and flat and they would be particularly susceptible to this effect. However, the test with shredded frond, which formed a much more porous bed, still gave the characteristic upward curvature. The stipe, on the other hand, was in the form of flat discs, but was more rigid and apparently was not markedly compressed even when minced.

The physical characteristics of material in the two classes may be summarized :-

Class 1. - Rigid or granular, forming a porous bed.
Only slight compression of lower layers.
Examples: Stipe or stalks.

Class 11.- Particles are soft, flexible, easily compressed. Bulk density increases markedly with increasing bed-depth.
Examples: Frond or leaves.

9.5. EFFECT OF BED DEPTH ON OTHER VEGETABLE MATERIAL

This theory has been tested for the through-circulation drying of other vegetable material. Through-circulation drying tests for potato, hops and carrot have been published (140, 163, 145) and tests on brewers' spent grain have been carried out on the present dryer. The physical appearance of these materials is listed below and the drying conditions used are given in Table 18.

TABLE 18.

THROUGH-CIRCULATION DRYING OF VEGETABLE MATERIAL

Material	D.B.T. °F	W.B.T. °F	G, lb/(sq.ft.)(min) Average	Water Content lb/lb of B.D.S. Initial	Final
L. cloustoni frond (minced)	156	81	7.1	5.0	0.15
L. digitata frond (minced)	159	83	7.8	5.0	0.15
L. cloustoni stipe (⅛-in slices)	157	82	5.8	5.0	0.15
L. digitata stipe (⅛-in slices)	157	82	7.8	5.0	0.15
Potato (5/32- x 5/32-in strips)	150	90	6.0	4.15	0.2
Brewers' spent grain	180	90	4.6	3.25	0.15
Hops	149	80	2.4	4.0	0.02
Carrot (3/16- x 5/16-in strips)	158	126	27.0	6.0	0.15

Potato - This vegetable was cut into 5/32-in square strips which were then steam-scalded at atmospheric pressure for four minutes (160). The curve was plotted from the bed-loading factors given in a U.S. Department of Agriculture publication (140).

Hops - The hop cones used were approximately ¾ in diameter and 1 in long. They consist of a central axis or 'strig' surrounded by leafy bracts. The bulk density of beds of hops varies with the hop variety, the ripeness of the cones, and the moisture content. Burgess found (164) that the bulk density of the hop beds increases with greater bed-depths (Table 19) indicating that slight compression of the lower layers was taking place. The cones did not pack very tightly together, however, and offered only slight resistance to air flow.

TABLE 19.

BULK DENSITY OF HOP BEDS OF DIFFERENT DEPTHS (164).

Bed depth, in		Bulk density, lb/cu.ft.
$1\frac{1}{4}$	...	4.20
$8\frac{1}{4}$	...	5.04
$11\frac{3}{4}$	...	5.40
$18\frac{1}{2}$	...	5.64
$1\frac{3}{4}$	...	3.0
$5\frac{1}{4}$	...	3.96
$10\frac{1}{2}$	...	4.20
$13\frac{1}{2}$	...	4.44

Carrot - The carrots were cleaned, peeled, and cut into strips $^{3}/16$ in x $^{5}/16$ in cross-section, which were scalded before being dried. The air-flow rate used for the carrot tests was very much higher than that for the other vegetables.

Brewers' Spent Grain - This is a waste product from the brewing industry and the samples used had a water content of 76-80%. In this condition the grains were sodden and tended to pack down in a mushy mass. Towards the end of the drying run the smaller husks became fluffy and were liable to become airborne, and consequently a lower air velocity had to be used.

The time versus bed-loading curves for the above vegetable materials and for seaweed are plotted on a composite graph (Fig. 58) with the experimental points omitted for clarity. Fig. 58 is intended to illus--trate the shape of the curves for each material and is not a direct comparison of drying times. It shows that potato and carrot strips behave in a similar manner to stipe slices, whereas spent grain resembles the frond curves although the increase in curvature is not so sharp. Hops appear in a mid-way position as the effect of bed depth is linear. Possibly the larger material size produces a bed with a greater percentage of voids. Spheres are the ideal particle shape for through-circulation drying and hops approximate to this shape. From a study of the time versus bed-depth curves, it is seen that none of them, on producing the smooth curve, would pass through the origin but would intercept the ordinate. This fact was observed for hops by Burgess (163) who called this time intercept the 'minimum time', i.e. the time required for a single layer of the material to dry under the same air conditions used for drying the bed.

It is now possible to postulate three types of time versus bed-depth curves for through-circulation drying of vegetables: Type I, curve concave upward; Type II, curve concave downward; Type III, linear.

9.5.1. Type I, Curve Concave Upward

Examination of the curves for frond in Fig. 58 suggests that they may be parabolic. The condition for this type of curve to reach a turning point is best considered by an example.

Let L = bed loading (lb of B.D.S/sq.ft.)

θ = drying time (min)

Let $\theta = aL^2 + b$

where b = minimum time, min, a = a constant

Now the output rate $R = L/\theta$, therefore $R = L/(aL^2 + b)$

The condition for R to have a turning value (in this connection it is a maximum) is that $dR/dL = 0$.

i.e. $$\frac{dR}{dL} = \frac{(aL^2 + b) - L(2aL)}{(aL^2 + b)^2} = \frac{b - aL^2}{(aL^2 + b)^2}$$

For dR/dL to be o, aL^2 must equal b.

The value of θ to give the optimum output is therefore $\theta = 2b$, and the value of L when θ equals twice the minimum time gives the optimum bed-loading.

This result has been verified by an examination of the experimental curves for frond (dried, fresh and shredded) and for brewers' grain, In these instances the minimum time was obtained by extrapolation of the curve. This finding enables an estimate of the optimum drying time for this class of material under any conditions of temperature, humidity and air velocity to be calculated from one experiment - a test using a single layer under the same conditions. The actual value of L_d would still have to be determined by experiment but this should require only two or three further runs, e.g. pre-dried frond. The preceding mathematical treatment applies strictly only to a parabolic function, but it is possible that most curves of a similar shape can be closely approximated to by a parabola.

The curves for the other vegetable materials of this type in Fig. 58 can be represented quite well by a parabola in the region near the optimum time, so that the factor of 2 appears to be sufficiently accurate for practical use.

9.5.2. Type II, Curve Concave Downward

This type of curve cannot be so readily treated mathematically as there is some uncertainty as to the shape of the curve for values beyond the deepest beds used. The effect of bed depth on the output can, however, be predicted from consideration of the evaporation rates of beds of differing loadings. Fig. 59 is a plot of total evaporation rate in lb of water/(sq.ft.)(hr) versus drying time between water ratios of $T = 5.5$ and $T = 0.15$ for L. cloustoni stipe slices. To enable the runs to be more easily compared, times are expressed as a percentage of the drying time between $T = 5.5$ and 0.15 for each individual run.

A study of Fig. 59 reveals that for higher bed-loadings the initial

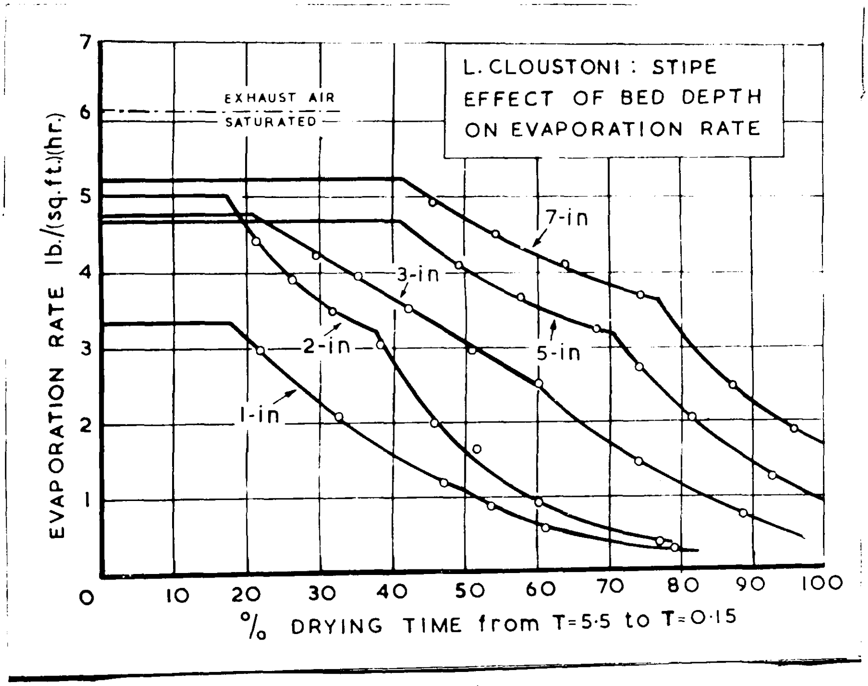


Fig. 59.

Data in Table 18.

constant evaporation rates are approximately equal, due to the exhaust air approaching the limit of its water uptake. Evaporation is more efficient for the deepest beds because the constant rate extends over a larger time fraction of the drying run and also the evaporation rate is still at a reasonably high value when the material reaches the discharge water content.

The maximum evaporation that could take place for the conditions of the test would occur if the exhaust air was saturated throughout the run. It can be seen that the deepest bed approaches most closely to this state of affairs, and it may be postulated that as the depth is increased the area in the upper right side of the graph will become a smaller and smaller fraction of the whole. Clearly then the evaporation, and hence the output, will approach a limiting value, so that, within limits, the deeper the bed the higher the output becomes.

The areas under the curves in Fig. 59 give the quantity of water evaporated (in the run time) for each bed-depth. This average evapora--tion rate for a run is proportional to the output, and will have the same relation to bed loading as the curve of output versus bed depth given for L. cloustoni stipe. This type of curve appears to be of the same general class as the linear type (e.g. hops) and the curves for stipe may in fact become linear in the region of higher bed-loadings.

These considerations are based on the assumption that the laws will hold for the greater depths, but it is obvious that compression must eventually occur even with comparatively rigid vegetable material, and the curves will then behave as Type I. As a result of air-pressure-drop measurements with beds of sugar-beet cossettes, Owen (137) concluded that compression was negligible for beds of this material up to 12 in deep. It is probable that the physical characteristics of sugar-beet cossettes would not be widely different from those of stipe slices.

9.5.3. Type III, Linear (Upward)

Let $\Theta = b + KL$,

where b = minimum time, and K = constant.

Then $$R = \frac{L}{\Theta} = \frac{L}{b + KL} = \frac{I}{b/L + K}$$

As $L \rightarrow \infty$, $b/L \rightarrow o$; therefore $R \rightarrow I/K$ = a constant.

Therefore so long as the time versus bed-depth relationship remains linear, the output will approach a limiting value asymptotically. The output will not have an optimum value and so the bed depth will be determined by practical considerations, e.g. dryer size and fan power. If the effect of bed depth on the output rate is adopted as a criterion, it appears that the Type III curve is a special case of Type II. The physical characteristics of both types are defined in Class I.

10. THE DESIGN OF A CONTINUOUS THROUGH-CIRCULATION DRYER FOR SEAWEED.

As has already been emphasised, drying of seaweed must be accomplished at a minimum cost since the product may be required solely as a raw material for chemical processing.

Drying costs may be grouped under three main headings :-

(a) Fuel and power costs
(b) Capital and maintenance charges
(c) Labour costs.

In the case of seaweed with its high water content the first item is critical since the evaporation rate is high in relation to the production rate and fuel costs can easily become the largest single item of expenditure.

The capital cost should be considered in relation to the frequency of operation of the dryer. An installation in continuous use could probably justify a much higher capital cost than a plant which is only in seasonal use. Generally speaking, for a given evaporation rating, the more expensive the dryer the higher the thermal efficiency becomes and the manpower requirements are lower.

Similarly if the throughput of a dryer is increased the manpower costs usually account for a smaller fraction of the costs, since approximately the same number of men are required to operate a dryer regardless of its size.

Ramage & Rasmussen (133) found that in commercial vegetable dehydration practice the total running charges for one month were often equivalent to the first cost of the dryer, although the example they quoted was for a tunnel-truck dryer which requires more personnel both for drying and material preparation.

It would appear that there will be an optimum capacity for a seaweed drying station, governed by factors such as size, density and proximity of the seaweed beds. Obviously the transport costs of the wet material to the dryer will increase with distance until they reach a point where it would be more economical to install a second drying station nearer to the weed bed.

Bearing in mind that most of the dryers would possibly be situated in remote localities where the seaweed growth is most prolific, it will probably be most economical to construct dryers of moderately high capacity. Extra capital expenditure on the dryer would probably be regained in the reduction of fuel freight charges occasioned by the higher thermal efficiency obtained.

Recent work on the drying of seaweed beds consisting of a mixture of minced L. cloustoni frond and sliced stipe showed (165) that the output curve had a maximum value of 0.4 lb C.D.S/(sq.ft)(hr) at a loading of approximately 1.25 lb B.D.S/sq.ft. (Fig. 60). This is lower than the frond optimum output of 0.52 lb/(sq.ft.)(hr) at $L_d = 0.45$ and the corresponding stipe output of 0.6 lb/(sq.ft.)(hr), suggesting that the frond controls the drying characteristics of the mixed bed.

In the following pages, design methods are presented for dryers using stipe or frond as the feed. It may not be possible or economical to separate these two components of the seaweed plants, but it is desirable from the aspect of efficient drying and possibly for subsequent extraction of any particular constituent. This separation need not be 100% effici--ent, however, since small amounts of contamination would not seriously affect the drying properties of either of the beds.

10.1. PREVIOUS WORK

While the designing of truck-and-tray tunnel dehydrators for vegetables has been given full attention in the literature, very few design methods have been published for through-circulation dryers.

Brown & Van Arsdel (140) presented nomographs for the through-draught drying of potato strips and demonstrated how this data could be

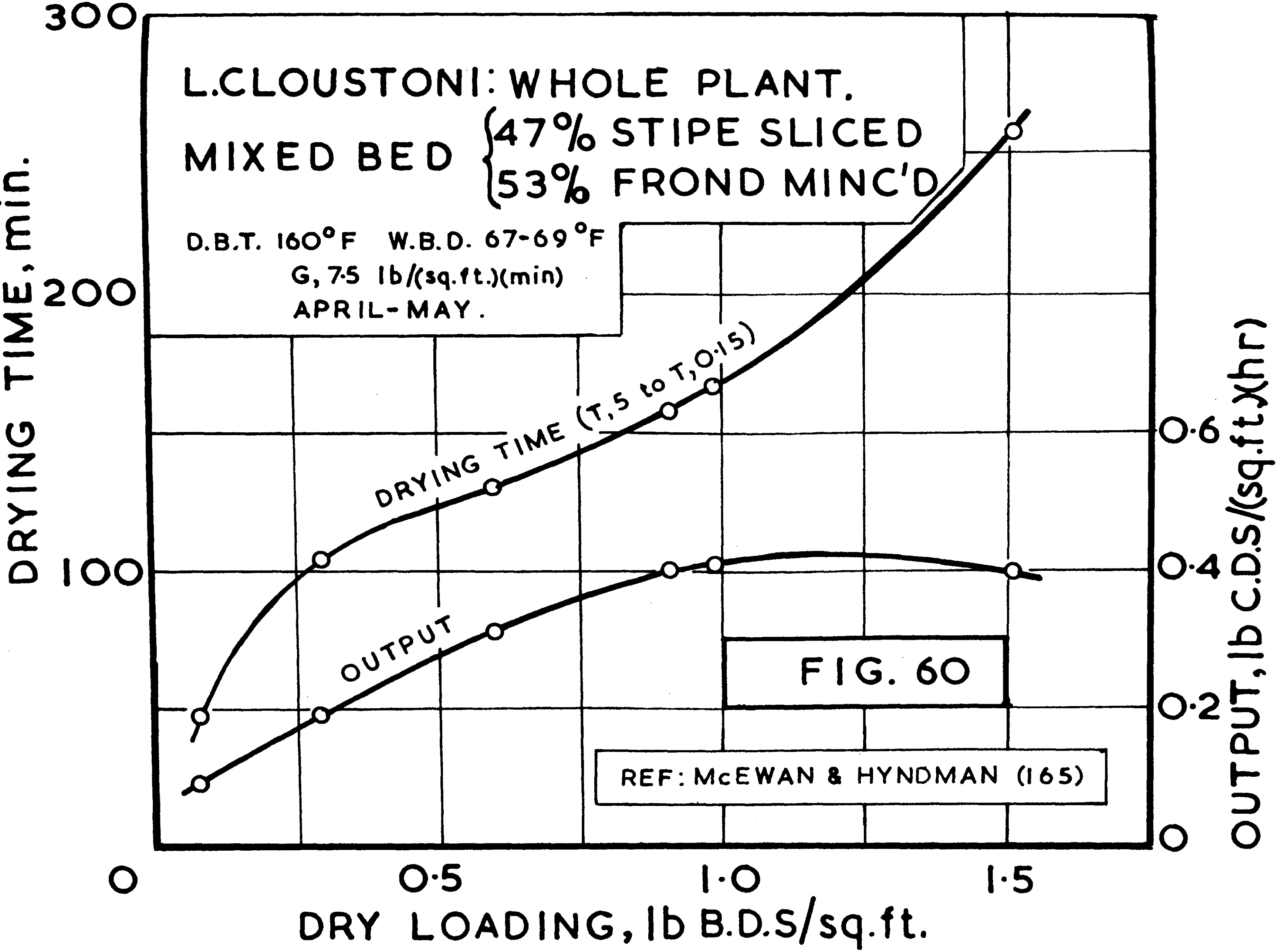

L.CLOUSTONI: WHOLE PLANT.
MIXED BED {47% STIPE SLICED
{53% FROND MINC'D
D.B.T. 160°F W.B.D. 67-69°F
G, 7·5 lb/(sq.ft.)(min)
APRIL-MAY.
DRYING TIME (T,5 to T,0·15)
OUTPUT
REF: McEWAN & HYNDMAN (165)
300
200
100
0
0·5
1·0
1·5
0·6
0·4
0·2
DRYING TIME, min.
DRY LOADING, lb B.D.S/sq.ft.
OUTPUT, lb C.D.S/(sq.ft.)(hr)

FIG. 60

used to calculate the water content/time relationship for heavily loaded beds by subdividing the bed into a number of thinner layers.

Marshall (166) provided data for the through-circulation drying of foodstuffs, in which he demonstrated the advantages to be gained by mixing and reloading vegetable beds during drying. In one instance, the constant-drying rate of a bed of diced beet was nearly doubled by mixing the bed when about 40% of the water had been removed.

Burton (167) recommended the use of multistage dryers for vegetable dehydration, as this enabled the heating load at various stages of drying to be proportioned more accurately. He advocated the use of finishing bins where vegetables are to be dried to low final water contents.

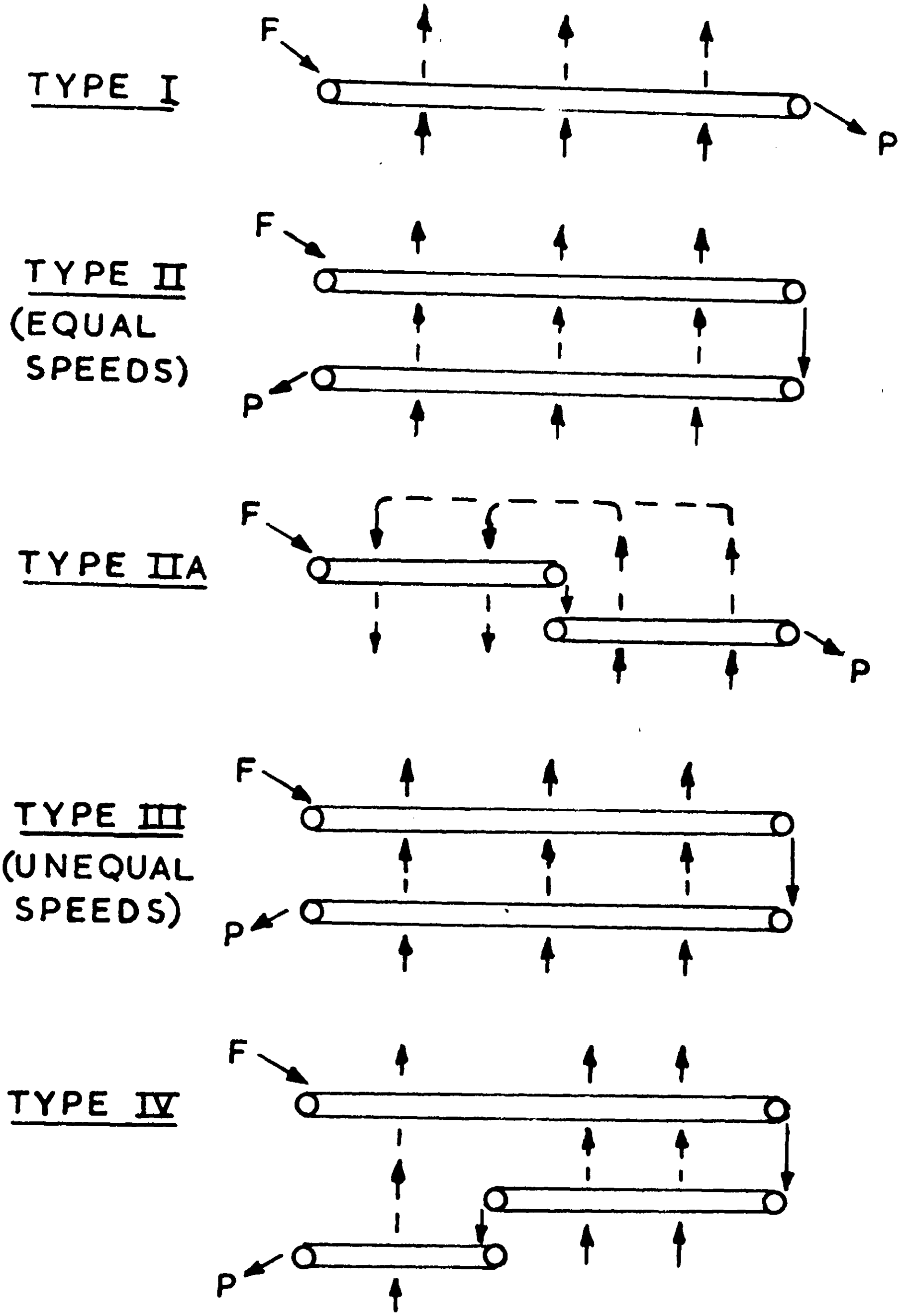
10.2. DESIGN OF A DRYER FOR L. CLOUSTONI STIPE

Several factors to be considered in a dryer design are apparent from the laboratory tests.

(a) The maximum D.B.T. of the air should not exceed 225°F for static beds of L. cloustoni stipe as scorching takes place at temperatures above this value.

(b) There is evidently little advantage to be gained by using air flows greater than 8-9 lb/(sq.ft.)(min) for stipe beds, since the overall drying time is not greatly shortened at higher air velocities, although it would probably be advantageous to use higher air velocities in the initial stages when the constant drying rate increases linearly with air velocity (Fig. 34).

(c) The minimum bed depth should be 3 in (L_d = 1.28 lb B.D.S/sq.ft.) as the output decreases rapidly below this value. The shrinkage of the bed appears to be virtually complete at a water ratio of 1 - 1.5, so that this may be a convenient point to deepen the bed to make more effective use of the drying air.



FLOW SHEETS FOR CONTINUOUS THROUGH-CIRCULATION DRYERS

F=FEED ; P=PRODUCT ; - - → AIR ; → SOLID

FIG. 61.

10.2.1. Type I Single-Stage Conveyor Dryer.

Example 1.

A continuous through-circulation dryer 60 ft long x 6 ft wide is to be used to dry L. cloustoni stipe slices ($\frac{1}{8}$ in thick) from a water ratio of 5.5 to 0.15. The air flow rate is to be 7.5 lb/(sq.ft.)(min) at 220°F D.B.T. and 95°F W.B.T. which is heated from air at 50°F D.B.T. 49°F W.B.T. If the seaweed loading on the belt is 3 lb B.D.S/sq.ft., determine (a) the drying time (b) the output of C.D.S. per hr, (c) the evaporation rate and (d) the specific evaporation.

(Total heat of air at 49°F W.B.T. = 12 B.Th.U/lb at 95°F W.B.T. = 54.9 B.Th.U/lb).

(a) From the basic drying time curve for L. cloustoni stipe (Fig. 38), Θ = 170 hr/1°F W.B.D. Loading factor for L_d = 3.0 is 0.72. For G = 7.5, factor = 1.

Hence for 125°F W.B.D. and L_d = 3.0,

$$\text{Drying time} = \frac{170 \times 60}{0.72 \times 125} = 1.89 \text{ hr} = 114 \text{ min.}$$

$$\text{(b) Output of C.D.S.} = \frac{360 \times 3 \times 1.15}{1.89} = 656 \text{ lb C.D.S/hr.}$$

$$\text{(c) Evaporation} = \frac{656 \times 5.35}{1.15} = 3{,}060 \text{ lb/hr.}$$

(d) Heating Load = 7.5 x 60 x (54.9 - 12) x 60 x 6

= 6,950,000 B.Th.U/hr.

$$\text{Specific Evaporation} = \frac{6{,}950{,}000}{3{,}060} = \underline{2{,}270} \text{ B.Th.U/lb.}$$

This example represents the simplest design of through-circulation dryer and it can be solved by the direct application of the basic drying curve (Fig. 61) for stipe given in Section 7.9. It is assumed for the present that there is no "scale up" factor involved in the calculations for the full sized dryer.

This layout of dryer has a high output because the seaweed is supplied with hot dry air at all stages of drying, but has the disadvantage that the heat economy is correspondingly low.

10.2.2. Type II. Double-Stage Conveyor Dryer

In this design, the 60 ft belt is replaced by two superimposed belts 30 ft long, the upper one discharging on to the lower (Fig. 61). The hot air leaving the dried seaweed at the discharge end of the dryer passes through the fresh seaweed on the upper belt, thereby improving the thermal efficiency at the cost of a lower output.

Example 2.

A two-stage through-circulation dryer with belts 30 ft x 6 ft is to be used to dry L. cloustoni stipe slices $\frac{1}{8}$ in thick from 5.5 to 0.15 water ratio using air conditions similar to those in Example 1. Both belts are to be operated at the same speed and the loading is to be 3 lb B.D.S/sq.ft. Calculate (a) the drying time (b) the water ratio at the changeover (c) product rate (d) the evaporation rate and (e) the specific evaporation.

The problem in this instance is to determine the total drying time such that the times in each stage are equal. This is complicated by the fact that the supply air to the upper belt is not constant as its humidity varies along the length of the dryer.

A trial and error method can be used in which an assumed value for the water ratio at the turnover (T_c) is taken. From the basic curve, the time for the seaweed to dry from T_c to 0.15 on the lower belt can be computed. From the average evaporation rate the average exhaust temp--erature can be evaluated using a mass balance. Using the average W.B.D. from the bottom belt, the drying time for 5.5 to T_c can then be found. This process is repeated until the two drying times are equal. To obviate the possibly tedious calculations, the following graphical design method has been devised which is more positive in action.

10.2.3. Graphical Design Method for Double-Stage Dryer

(1) From the basic drying curve calculate the water-content/time curve for the lower belt and plot it on a reverse time scale, i.e. with zero time at 0.15 water ratio.

(2) Select suitable time increments and interpolate the terminal water ratios for each increment from the curves.

(3) Calculate the average evaporation rate per increment and hence the outlet D.B.T. and W.B.D.

(4) From the basic curve and the appropriate W.B.D., compute the water content at the end of each successive time increment.

(5) Plot the water-ratio/time curve for the upper belt until it intersects the corresponding curve for the lower belt. This inter--section gives the water content at the turnover and the drying times on each belt (which are equal in this case).

This graphical method is shown in Fig. 62.

The water pick up in lb water per lb dry air is given by :-

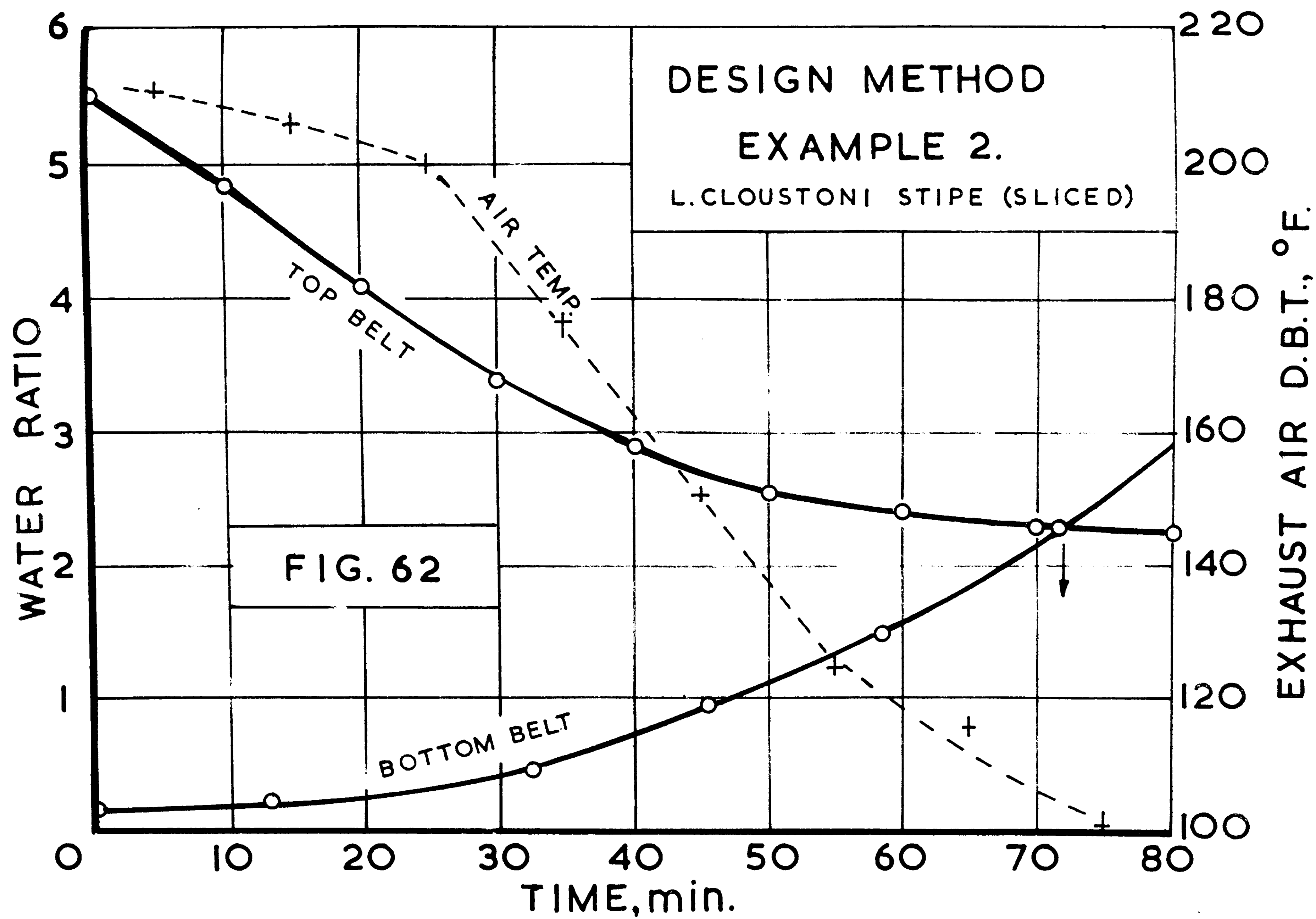
$$\frac{L_d\,(T_o - T_1)}{G\theta}$$

where T_o and T_1 = the terminal water contents for each increment,
θ = the incremental time (min).

The calculations are conveniently set out in tabular form using a 10-minute time interval (Table 20).

TABLE 20.

Terminal Water Ratios	Δ T	Water Pick up lb/lb	Exhaust Air from lower belt Humidity lb/lb	D.B.T. °F	W.B.D. °F
0.15 - 0.20	0.05	0.0020	0.0092	211	116
0.20 - 0.28	0.08	0.0032	0.0104	206	111
0.28 - 0.40	0.12	0.0048	0.0120	200	105
2.40 - 0.65	0.25	0.0100	0.0172	177	82
0.65 - 1.05	0.40	0.0160	0.0232	151	56
1.05 - 1.60	0.55	0.0220	0.0292	125	30
1.60 - 2.20	0.60	0.0240	0.0312	116	21
2.20 - 2.90	0.70	0.0280	0.0352	99	4


DESIGN METHOD
EXAMPLE 2.
L.CLOUSTONI STIPE (SLICED)
FIG. 62
AIR TEMP.
TOP BELT
BOTTOM BELT
WATER RATIO
EXHAUST AIR D.B.T., °F.
TIME, min.
0
1
2
3
4
5
6
10
20
30
40
50
60
70
80
100
120
140
160
180
200
220

As drying is assumed to take place at a constant W.B.T. (95°F) the D.B.T. can be obtained from the exhaust humidity using a psychrometric chart. The time scale of the basic chart for stipe (Fig. 38) is graduated in 10-hour divisions for unit W.B.D., so that from a knowledge of the W.B.D. and the relevant loading factor, the number of these divisions corresponding to the 10-minute interval can be calculated, and the water ratio at the end of the increment can then be read off from the curve.

(a)(b) By interpolation the drying time on each belt is 72 min and the water ratio at the turnover is 2.3.

(c) Product rate $= \dfrac{180 \times 3 \times 1.15 \times 60}{72} = 518$ lb C.D.S/hr.

(d) Evaporation rate $= \dfrac{180 \times 3 \times 5.35 \times 60}{72} = 2{,}410$ lb/hr.

(e) Heating Load $= 450(54.9 - 12)\ 180$ B.Th.U/hr.

$= 3{,}480{,}000$ B.Th.U/hr.

Specific evaporation $= \dfrac{3{,}480{,}000}{2{,}410} = 1{,}440$ B.Th.U/lb.

It can thus be seen that the heating load is halved by superimposing the belts, and that the air is much more effectively used than in a single-pass dryer. The two-stage dryer is operating with an equivalent bed loading of 6 lb B.D.S/sq.ft.

An alternative way of achieving the same result is by having the two belts arranged in series, so that the exhaust air from the second half of the drying cycle is blown through the wet, fresh material (Fig. 61). The same graphical method could be adopted for the design of this type of dryer, although this tandem dryer arrangement would be less compact.

Example 3.

For comparison, the design for a dryer identical to that of Ex.2 has been calculated, except that the bed loading on each belt was reduced to half the value of the previous example (i.e. $L_d = 1.28$ lb/sq.ft.).

The corresponding data for Ex.3. are :-

Drying time (total)	-	92 min.
Product rate	-	345 lb/hr
Evaporation rate	-	1,600 lb/hr
Specific evaporation	-	2,180 B.Th.U/lb.

This shows clearly the advantage of using the deepest convenient bed for stipe. A dryer with intermediate characteristics can be obtained if the lower belt is operated at half the speed of the top belt thus doubling the bed loading on the lower band.

10.2.4. Type III. Double-Stage Conveyor Dryer (Unequal belt speeds)

Example 4.

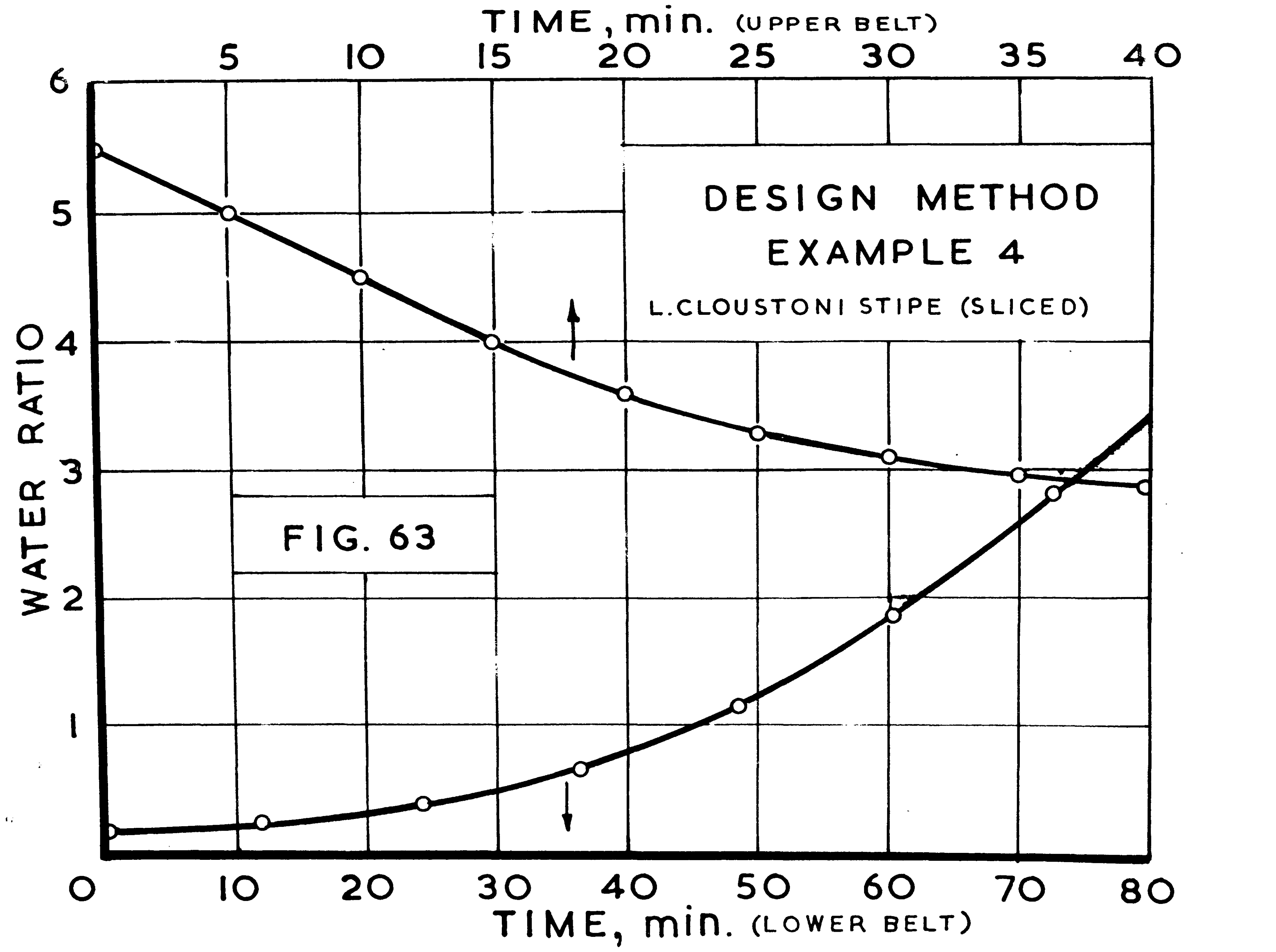
If the dryer of Ex.2. is run so that the top belt loading is 1.28 lb B.D.S/sq.ft. and the lower is 2.56, calculate the output and evapora--tion rates and the specific evaporation.

The problem is approached in a similar manner to Ex.2. for the calculation of the times on the bottom belt.

The time axis for the upper belt is now plotted on a scale twice that of the lower belt (Fig. 63), since for a given length increment of the dryer, the seaweed on the upper belt will only be exposed to the air for half the time of the material on the lower belt. The curve for the top belt is plotted in the usual way until it intersects the curve for the lower belt. The output can be calculated from the B.D.S. flow/hr on either belt using the appropriate bed loading and residence time, since the flow of B.D.S. through the dryer must be constant.

The output and evaporation rates for this arrangement are respect--ively 408 and 1,900 lb/hr and the specific evaporation is 1,830 B.Th.U/lb.

The substitution of minced stipe for sliced stipe would increase the output when a single-stage dryer is used, but for multistage dryers the drying time has a diminishing influence on the output. As the


TIME, min. (UPPER BELT)
5 10 15 20 25 30 35 40
6 5 4 3 2 1
WATER RATIO
DESIGN METHOD
EXAMPLE 4
L.CLOUSTONI STIPE (SLICED)
FIG. 63
0 10 20 30 40 50 60 70 80
TIME, min. (LOWER BELT)

efficiency of evaporation is increased, the output will eventually depend on the water uptake capacity of the drying air.

10.3. DESIGN OF A DRYER FOR L. CLOUSTONI FROND

Some of the drying characteristics of L. cloustoni and L. digitata frond are summarized below.

(a) To prevent scorching of the frond, the air D.B.T. should not exceed 225°F.

(b) Air velocities above approximately 8 lb/(sq.ft.)(min) result in a comparatively small reduction in drying time.

(c) There is an optimum bed loading for frond which appears to vary with the particle size and the time of year when the plant was harvested.

(d) Agitation of the frond bed during drying brings about a marked reduction in drying time, particularly if the bed is broken up in the later stages of drying.

(e) The drying times for frond show a substantial seasonal variation.

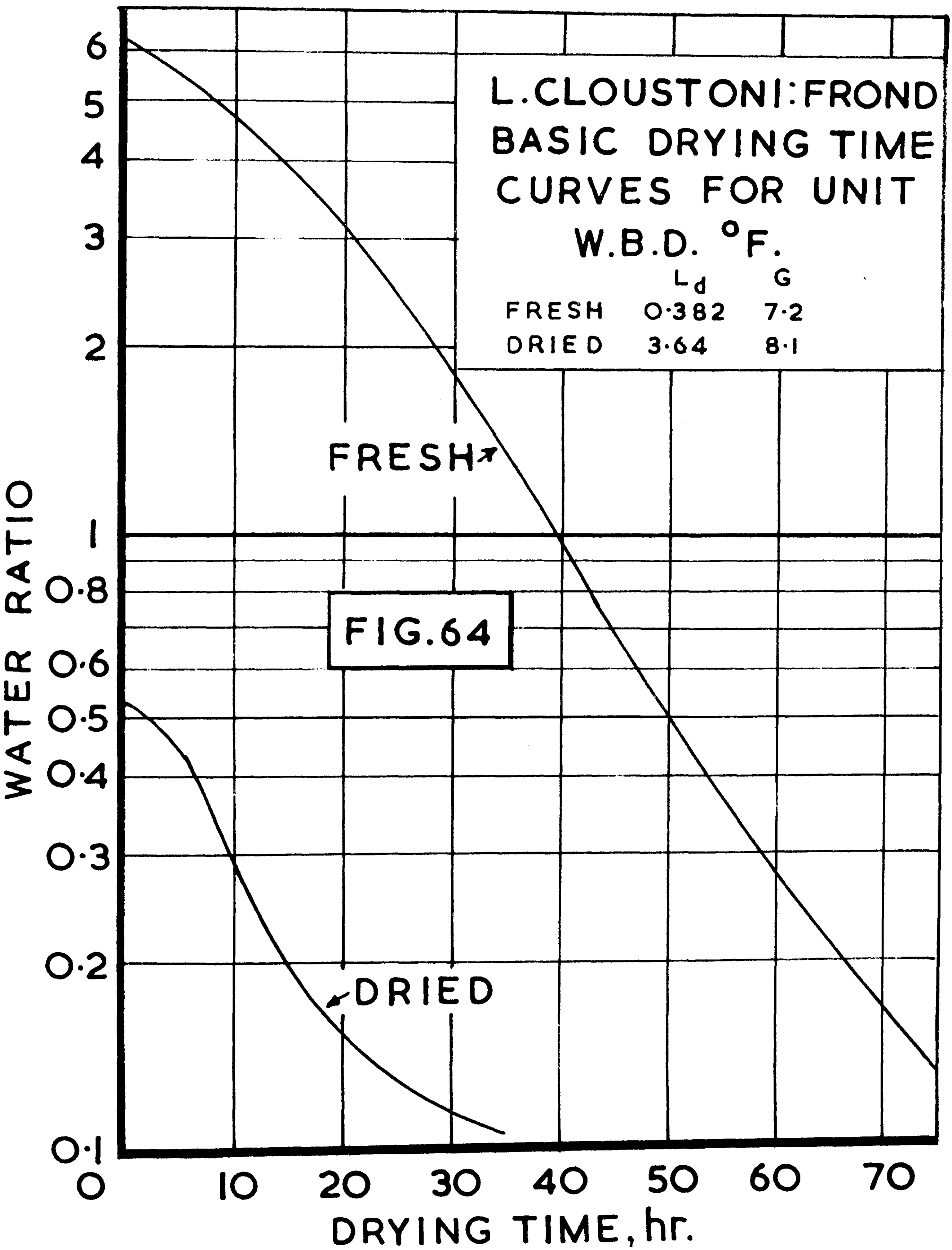
10.3.1. Type I. Single-Stage Conveyor Dryer

Example 5.

If the dryer described in Ex.1. is loaded with minced L. cloustoni frond, using similar air conditions, determine (a) drying time, (b) production rate, (c) evaporation rate, and (d) specific evaporation.

In Section 8.1. it was shown that there was an optimum bed loading for frond which gave the maximum output. The experimental run which was closest to the peak in Fig. 46 was selected to form the basic drying curve for L. cloustoni frond, and it is plotted on a semilog graph in Fig. 64. This curve strictly applies only to Oban seaweed harvested in May.

The bed loading in this test was 0.382 lb B.D.S/sq.ft. at 156°F D.B.T., but it will be assumed that the optimum bed loading for this material will be the same if air at 220°F D.B.T. is used.


L. CLOUSTONI: FROND
BASIC DRYING TIME
CURVES FOR UNIT
W.B.D. °F.
Ld G
FRESH 0·382 7·2
DRIED 3·64 8·1
FRESH
DRIED
FIG. 64
WATER RATIO
6
5
4
3
2
1
0·8
0·6
0·5
0·4
0·3
0·2
0·1
0
10
20
30
40
50
60
70
DRYING TIME, hr.

(a) L_d = 0.382 lb B.D.S/sq.ft.

G = 7.2 lb/(sq.ft.)(min)

W.B.D. = 125°F

Drying time (75°F W.B.D.) = 53.5 min

Thus drying time at 125°F = $\frac{53.5 \times 75}{125}$ = <u>32.1 min</u>

(b) Output = $\frac{360 \times 0.382 \times 1.15 \times 60}{32.1}$ = <u>301 lb/hr</u>

(c) Evaporation rate = $\frac{301 \times 5.5}{1.15}$ = <u>1,140 lb/hr</u>

(d) Heat Input = 7.2 x 360 x 60 x 42.9

= <u>6,680,000 B.Th.U/hr</u>

Specific evaporation = $\frac{6,680,000}{1,140}$ = <u>5,860 B.Th.U/lb</u>

It is evident that the efficiency of drying frond is much lower than that of stipe, largely due to the comparatively shallow bed that must be used. The position can be improved by using a two-stage dryer.

<u>10.3.2. Double-Stage Conveyor Dryer (Type II)</u>

<u>Example 6.</u>

If the dryer in Ex.5 is replaced by a double-belt dryer (30 ft x 6 ft) determine the corresponding drying data. The belt speeds are to be equal.

The design method described in 10.2. can be applied to this problem, from which the total drying time of 34 min was obtained. The output was only slightly smaller (279 lb/hr) but the specific evaporation was markedly reduced to 2,510 B.Th.U/lb.

Fig. 47 for pre-dried frond shows that much heavier bed loadings may be employed when the frond is dried to less than 0.5 water ratio. No figures are available for material at intermediate water ratios e.g. starting from 1.5 - 2.0, but it seems probable that the bed loading could be progressively increased with improved efficiency of drying. Moreover the transfer points at the end of the belts will give some degree of agitation to the bed and will promote more rapid drying as illustrated by Figs. 55 & 56.

A three-stage dryer can, however, be designed in which the drying from T, 0.5 to T, 0.15 is carried out at the heavy bed loading, so that the last belt is in effect a finishing bin.

10.3.3. Type IV Triple-Stage Conveyor Dryer

Example 7.

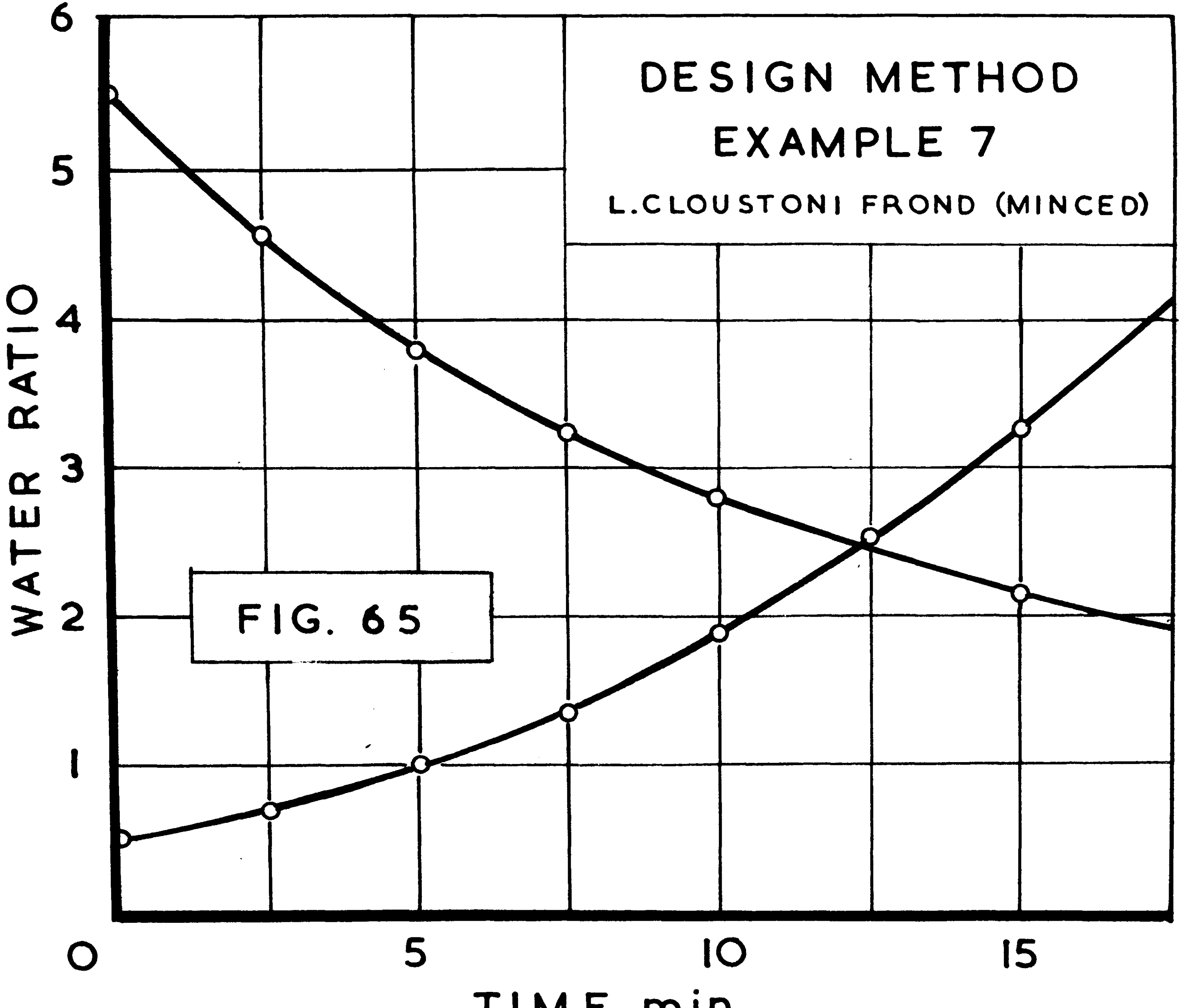
A three-stage dryer for minced L. cloustoni frond is to be designed as shown in Fig. 61, such that the loading on the final belt is to be increased tenfold. The bed loading for the first two stages is 0.382 lb B.D.S/sq.ft., and the air conditions are identical to those in Ex.5. If the dryer is 30 ft long by 6 ft wide, evaluate (a) drying time in each stage, (b) the length of the last belt (c) product and evaporation rates and (d) specific evaporation.

The example can be solved by first computing the D.B.T. of the exhaust air from the deepest bed (Belt 3) and hence calculating the moisture content of the frond on the top belt as it leaves the zone above the third stage. The remainder of the problem now becomes similar to that of Ex.6, except that the terminal water content is different.

(a) From the basic curve for frond at L_d = 3.82 (Fig. 64) the drying time for T, 0.5 to T, 0.15 = 11.5 min for 125°F W.B.D. The slight variations of the bed depth and air velocity may be neglected in this low water content region.

The average water pick up in this time is 0.0762 lb/lb of air corresponding to an exhaust D.B.T. of 150°F. As the top belt is only in contact with this air for 1.15 min the loss of water will be small and has been neglected.

The graphical solution for the range 5.5 to 0.5 water ratio is given in Fig. 65 from which it can be seen that the drying time is 12.5 min.


DESIGN METHOD
EXAMPLE 7
L.CLOUSTONI FROND (MINCED)
WATER RATIO
6
5
4
3
2
1
0
5
10
15
TIME, min.
FIG. 65

Hence the time on the top belt is 12.5 + 1.15 = 13.65 min, and on the lower belts 12.5 and 11.5 min respectively.

(b) Let the length of the third belt = X ft and the speed of the second belt = Y ft/min.

Hence X = 11.5 x 0.1Y and also X = 30-12.5Y.

Thus 1.15Y = 30-12.5Y whence Y = 2.2 ft/min and X = 2.53 ft

(c) Product rate (calculated from top belt)

$$= \frac{180 \times 0.382 \times 69}{13.65} = \underline{349 \text{ lb C.D.S/hr}}$$

Evaporation rate = 1,625 lb/hr.

(d) Heat input = 3,340,000 B.Th.U/hr.

Hence, specific evaporation = 2,060 B.Th.U/hr

It may be possible to reduce this specific evaporation figure still further by recirculation of the air.

As has been shown in Section 8.3. the drying time of frond varies with the season, so that the output of dried product will likewise fluctuate. The belt speeds of the dryer should be capable of control within wide limits to enable the dryer to be adapted to the prevailing conditions.

Dryers of larger capacity than those in the examples can be designed by increasing the length and breadth of the conveyors. The largest belt width used in normal practice is about 10 ft.

It is recommended that pairs of spiked rollers be installed at the end of the belts to ensure that the frond particles in the partly dried bed are separated and do not form wet knots on the following belt. It is also suggested that shredding, if practicable on the large scale, should be used as it gives a bed with greater porosity resulting in lower fan power requirements

10.4. DISCUSSION OF SCALE FACTORS

The preceding calculations have neglected one factor - the elusive "scale up" factor which is required to allow for differences between laboratory and commercial operating conditions. This factor consists of a number of components which are summarized below.

Uneven air distribution is probably the major inherent cause of error in through-circulation drying. Ede (145) found that beds of vegetable material had a tendency to develop weak spots through which the air passed more readily than the remainder. The resultant increased drying and shrinkage made the blowhole worse and preserved the condition which Ede described as "autocatalytic drying".

The condition was not serious in the case of the laboratory tests on stipe since the slight movement of the basket when it was removed for weighing tended to fill up any large voids. The relatively deep beds used for stipe should lessen the chances of any channel persisting from the bottom to the top of the layer.

Edge effect - the shrinkage of the bed away from the basket walls - was noticeable in the case of frond but the maladjustment of the air was possibly minimised by the relatively high resistance of the gauze on the basket floor. In full size practice the edge effect would be very much smaller due to the bed perimeter per unit area being lower. The drying rate for a given velocity on the small dryer will therefore be conserva--tive if the large dryer is supplied with air uniformly distributed. If the air flow is uneven, the predicted drying times can be in serious error.

Conduction from the basket walls will tend to increase the drying rates for the laboratory runs but this is mainly confined to the initial stages of drying. Radiation errors should be negligible, since the surface exposed to radiation is a small fraction of the total surface available for mass transfer, especially where deep beds are involved.

It appears, therefore, that the dual effects of edge effect - the increase of drying rate by conduction and the decreased rate by the air short circuiting the bed - are in opposition. It is probable that the air leakage will be the predominant factor but their relative magnitudes can only be evaluated by tests on different sizes of dryers.

The use of the proportionality of the drying rate to W.B.D. for calculating drying rates at higher temperatures may involve an error as the basic curve was based on a run at a moderate temperature. This error should also be conservative since higher temperatures will tend to shorten the drying times at the tail end of the drying run. The bed loading and air velocity factors should be used cautiously since they are average values for the total drying time and may not hold for drying rates at intermediate water contents.

10.5. HEAT SUPPLY

In order to obtain maximum fuel efficiency, a direct fired furnace should be used in which the combustion products are diluted with air and passed through the seaweed bed. If complete combustion is secured and the dryer is adequately lagged, the proportion of the calorific value of the fuel which is transferred to the drying gases should be high.

Suitable fuels may be solid liquid or gaseous. Gas is very conveni--ent in use as it is readily controlled and is clean, but would not be available in remote localities. Oil fuel has the advantage of simple control, comparative ease of storage, and uniform quality, but there must be no danger of unburnt liquid contaminating the seaweed in the event of flame failure.

Coal-fired heaters can also be used, but the furnace requires careful design to give clean smokeless combustion when using high volatile coals.

The method recommended for a seaweed dryer is a semi-producer furnace, fired with gasworks coke. The price of this coke is about 2/3rd that of oil when the fuels are compared on the cost per therm; also the cost of the solid fuel furnace is less due to its simpler construction.

Storage of the coke presents no problem, as it can be stacked in the open if necessary.

A typical design for such a furnace has been described (168) where it is seen that the method of controlling the air temperature is by adjusting the secondary air damper. In a seaweed dryer an increase in the air velocity would be preferable to a rise in the air temperature.

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