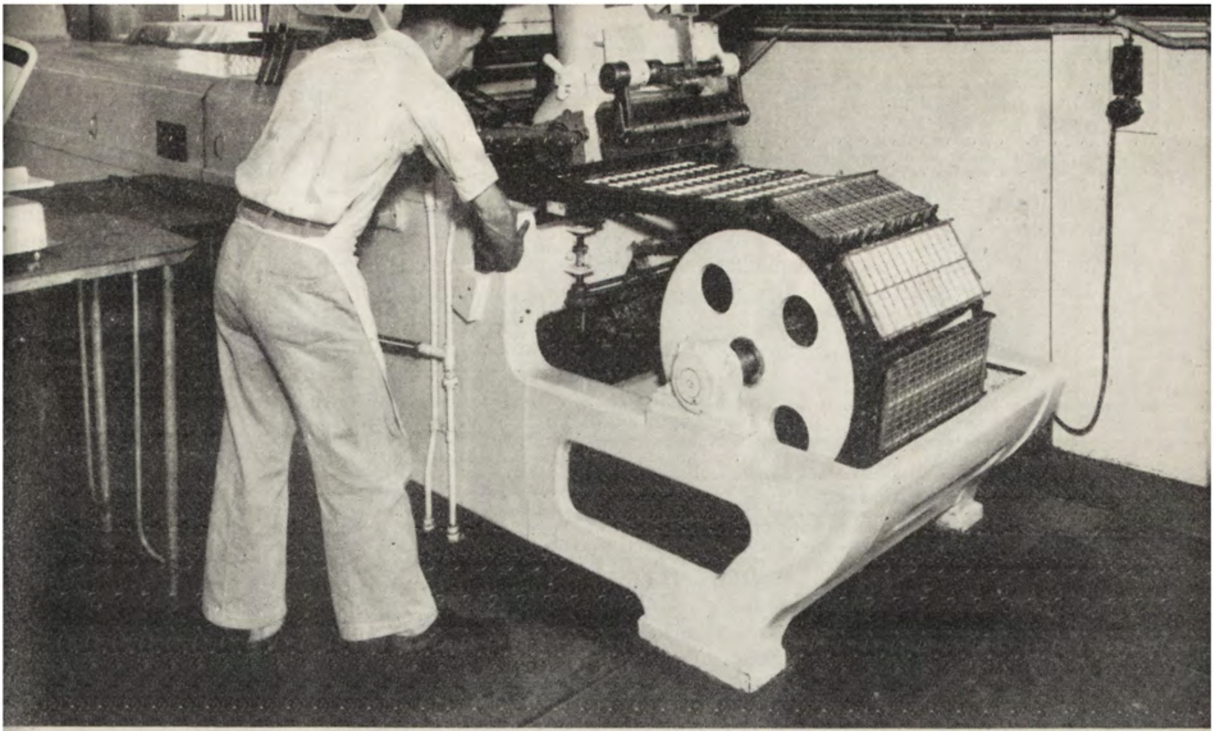


PLATE 1.—*Chocolate tablets being moulded at an Australian factory.*

CACAO PROCESSING—HISTORY AND PRINCIPLES

L. A. BRIDGLAND.

For many years, extensive research into the processes of cacao fermentation, with particular reference to New Guinea conditions, has been under way at Keravat, the Lowlands Agricultural Experiment Station of the Department of Agriculture, Stock and Fisheries. In this article, Mr. Bridgland, former Agronomist-in-Charge of the Station, discusses, in the form of an introduction to the history and principles of cacao processing, the conclusions reached during the research programme. The second article in this issue deals with the practical recommendations of the Department to New Guinea growers. Mr. Bridgland hopes at a later stage to publish in association with his co-worker, Mr. J. B. O'Donohue, the experimental methods and data embodied in these conclusions and recommendations.

HISTORICAL BACKGROUND

THE area covered by the various reaches of the Amazon and Orinoco Rivers, in which wild types of cacao can still be found, is believed to represent the main centre of origin of the crop. It is presumed that the cacao plant became distributed over other parts of tropical America by nomadic tribes, which suggests that these tribes made use of its fruit. In the historical record, it is evident that cocoa beans formed an integral part of the life and economy of the Aztecs, who had been settled in Mexico for nearly 200 years before the conquest of Mexico by Cortes in 1519.

As cocoa beans were used as a medium of exchange, the scale of cultivation must have been quite small. The modern planter no doubt looks back on these times with a feeling of nostalgia, since a slave could be purchased for 100 beans. Such as it was, a high proportion of the production found its way to court, where the crude but highly-prized beverage prepared from the beans was regarded as a luxury item. According to Jensen (1931), Montezuma was reputed to consume some 50 pitchers a day and he must have gone through life in a perpetual state of theobromine intoxication.

The Aztecs held that the plant was of divine origin and the name *Theobroma cacao* was accordingly conferred on it by Linnaeus.

It is an interesting pastime to speculate on how it first came to be discovered that cocoa beans could be utilized as a food or beverage. Certainly, the taste of unfermented, unroasted beans could scarcely have caused the primitive Indians to look twice at the plant. There is no doubt, however, that the Aztecs and Maya Indians were aware of the necessity for roasting. It is also a fairly safe assumption that some form of crude fermentation was practised. The series of accidental or deliberate treatments from which primitive processing techniques evolved will always remain unknown, but the modern grower owes a considerable debt of gratitude to a few primitive Indians who, having a capacity for observation and experiment, found that by appropriate treatment, cacao beans would yield chocolate flavour.

Chatt (1953) describes the Mexican process as a grinding of roasted nibs between a concave stone and a stone "roller", followed by mixing with corn and spices to form a cake. This could be eaten or beaten with water to the consistency of a thick sauce to which vanilla and other spices were added to form "*chocolatl*". At the time, sugar-cane was unknown in Mexico, and the brew was probably unsweetened. Urquhart (1955) refers to a preparation used by the Maya Indians made by pounding cocoa beans with corn and boiling the mixture with capsicum and water.

These established recipes understandably were not particularly to the liking of the Spanish conquerors who developed "chocolate" as a drink flavoured with sugar, vanilla and cinnamon. Jensen (1931) refers to the first manufacture of "chocolate" cakes by the Spanish physician, Maradon. The addition of sugar to the primitive formulae represents the first major turning point in the history of processing and established the basis of recipes as we know them to-day.

The first cocoa beans to reach Europe were taken back by Columbus, but these were received without much enthusiasm. When Cortes returned to Spain in 1528, he took with him samples of prepared products and from this humble beginning has arisen the highly-organized and complex modern trade in cocoa beans. As the popularity of the chocolate beverage spread through the Courts of Europe, the import of raw beans began and by the middle of the 17th Century, manufacture in Europe had its slow and uncertain beginnings. This represents another milestone in the history of the industry —a decided split in the processing between producing and manufacturing countries developed and this split has solidified with time.

It was not until early in the 19th Century that Van Houten evolved a technique for reducing the fat content of the cocoa bean. This made the beverage more palatable and digestible. Later still came the addition of milk to eating chocolate, the form in which by far the greater proportion of beans is consumed.

Over the centuries, the cacao plant became distributed through the West Indies, San Thome, West Africa and the East Indies to meet the increasing demand brought about by the manufacture of chocolate. The product "boomed" in the latter part of the 19th Century and the early part of the 20th Century. At this stage, manufacturers became discriminating about the quality of cocoa beans. The fundamental lessons learned were that on all counts the flavour of fermented beans was superior to unfermented beans and also that beans of varying genetic origin produced characteristic flavours. The art of blending the different types of beans and processing them to produce desired flavours became a highly-developed skill, about which manufacturers were secretive.

Depreciation of the price paid for unfermented beans led to the practice of "claying" in producing countries. This method was used to deceive manufacturers by reproducing the appearance (externally only) of fermented beans on unfermented beans (Shephard, 1932). "Claying" was widely practised in Trinidad and Venezuela. Beans were given a wash in a suspension of red clay. This imparted uniform and attractive external appearance. It was also believed that claying prevented mould development and preserved aroma. Abuses of the method, which leave little to the imagination, caused manufacturers to reject or severely down-grade beans which had been "clayed". The process has gradually died out.

The trend away from the use of unfermented beans has continued up to the present time and there is now almost no demand for such beans. Manufacturers soon began to realize that beans could be either well fermented or badly fermented and have become very discriminating on the question of goodness of fermentation. The same beans are capable of producing either good chocolate flavour or almost no chocolate flavour, depending on the grower's processing. Furthermore, objectionable flavours may be acquired during fermentation and drying. It is with this question of getting the best out of cocoa beans that this article is primarily concerned.

In the early days of the trade, the greatest demand was for the so-called "fine" cocoas of the Criollo type. Over the last fifty years, the demand has swung in favour of the "bulk" or Forastero type, although there is still a considerable demand for "fine" cocoas. It is evidently quite fortuitous that the huge plantings in West Africa are of the Forastero type. For the moment, there seems to be a fairly stable equilibrium between demand for the two types but on present indications the relative demand for "fine" cocoas will fall. The processing of the two types shows a good deal of variation but the same principles apply to both.

Over the last 50 years, manufacturers' processing methods have become highly mechanized and fully controlled. The modern chocolate factory is a model of industrial efficiency. Over the same period, the processing carried out by growers has shown no improvement. In fact, it appears to have deteriorated in many cocoa-producing countries. It is not surprising therefore to find that chocolate manufacturers are exerting pressure to hasten research work on the primary processing of the bean. They are themselves undertaking much of this research.

STEPS IN PROCESSING

The processing carried out by growers and manufacturers is complementary. Each should understand the problems facing the other and it will be of value to survey briefly the total processing.

PLATE 2.—*New Guinea cocoa beans are poured into factory hopper.*

Growers' Processing

Ripe pods are removed from the tree. The beans are extracted, fermented, cured/dried and winnowed. Details of these steps are described at a later stage in this article.

Manufacturers' Processing

The dry beans are winnowed to remove rubbish not removed by the grower. They are then roasted in either a "continuous" or "drum" roaster after which the beans are "kibbled".

This consists of shattering the roasted beans. The shell is winnowed off and although saleable for theobromine extraction, is regarded as a waste product by some manufacturers.

The shattered nibs are then ground between steel or stone rollers or in the more modern "liquor mill". This consists of two pairs of discs, one fixed and one rotating rapidly. The discs are of fluted steel and are water-cooled to prevent overheating and flavour destruction during operation. The "liquor mill" replaces the older "Melangeur" in which sugar and nib were ground together.

Grinding in the liquor mill takes place in two stages. The first stage gives a relatively coarse grind and the second stage a very fine grind. The nibs are reduced to a partially liquid state by the first stage and the second stage yields the so-called "chocolate mass" or "neatwork".

For the manufacture of cocoa powder, the chocolate mass is usually treated with alkali, this step being known as the "Dutch Process" or "Dutching". The alkalization neutralizes acidity, causes a darkening in colour and increases the solubility of the cocoa powder. The alkalized chocolate mass then enters "presses" which remove some 60 to 70 per cent. of the cocoa butter and yield "Press Cake", which forms the basis of all cocoa beverages. The expressed cocoa butter is used in the manufacture of chocolate.

In the manufacture of chocolate, the chocolate mass may or may not be slightly alkalized. Sugar and milk solids (the amount depending on whether the chocolate is to be "milk" or "dark"), some cocoa butter and lecithin are then added before the mixture goes to the "roller grinders". The lecithin is added to reduce viscosity. Roller grinding takes place in five or six stages. The machine consists of a battery of steel rollers. The whole battery may be vertical or inclined, each successive roller rotating slightly faster than the preceding one. This gives a tearing and rubbing action. Once again, considerable frictional heat is developed and the grinders are water-cooled to avoid overheating and damage to flavour but the mass is allowed to heat sufficiently to bring it to a fluid state.

The chocolate material is allowed to "flake" on the last roller, from which it is scraped. The flaking is achieved by controlling the cocoa butter content of the mixture. As particle size is reduced by grinding, correspondingly more cocoa butter is required to "wet" the particles and maintain the fluid state. Thus flaking at the correct stage is controlled by the amount of cocoa butter added before roller grinding and the fineness of grinding. In addition to reducing the particle size of the cocoa material, the main function of the roller grinders is to grind the sugar (added in the form of icing sugar) to an extremely small particle size.

The ground, sweetened chocolate mass is then "conched" after the addition of more cocoa butter and lecithin to reduce viscosity. The "conch" derives its name from the shell-like appearance of the early designs. There are now various improved versions of the machine. Fundamentally, they consist of a tank, containing the chocolate mixture in a fluid state, in which a relatively large roller runs slowly up and down. The chocolate mixture is "paddled", so to speak. The tank is, if necessary, heated by a hot-water jacket to maintain the material in the fluid state. The conch has a smoothing rather than a grinding action. There is some argument about what conching achieves. Cocoa butter becomes evenly distributed, oxidation of certain polyphenols may and probably does occur and there is also some volatilization of acetic acid from the chocolate mixture.

Following conching, more cocoa butter may be added to adjust viscosity and the mixture is then stored in large tanks from which it can be piped to any part of the factory.

Before final moulding, the mixture is "tempered". Cocoa butter may crystallize in any one of three forms usually denoted as "alpha", "beta" and "gamma". Of these, only the "beta" form is structurally stable. The crystal structure which develops depends largely on the rate of cooling to below the melting point of the fat. Thus, in tempering the chocolate mixture, the manufacturer controls the rate of cooling so that nuclei of the "beta" form are developed. The structure of the cocoa butter crystal following moulding is thereby predetermined.

Thus the main problems in the manufacture of chocolate are :—

(1) To bring out the best inherent flavour of the beans.

(2) To avoid destruction of flavour or the development of undesirable flavours.

(3) To remove or obscure any defective or unwanted flavours which exist in the dry beans. This is the problem which manufacturers find most objectionable and one which should not arise.

(4) To accomplish all the above at a cost which enables the manufacturers to market their products at a price which will maintain sales at a high and expanding level.

One of the major elements involved in this is economy in the use of the relatively expensive cocoa butter. Thus control of particle size is a major factor. Particle size must be reduced just to the point where the palate cannot detect coarseness. Further reduction unnecessarily increases the cocoa butter consumption.

Manufacturers' methods will not remain constant, but it is unlikely that the type of bean required (in respect of fermentation and drying) will change significantly. Various attempts have been made in manufacturing countries to apply "post-fermentation" or "reconditioning" techniques to beans which have been improperly prepared. Several methods have already been patented and these have been described by Roelofsen (1958). Whether the methods are effective or not seems to be beside the point. Such techniques would be of little use to manufacturers unless all the beans were of uniform defective fermentation. As this is never likely to be the case, it is unlikely that "fermentation" or any part of it will shift to the manufacturing countries.

A shift in the opposite direction is more likely. Producer countries may tend to carry processing to the manufacture of intermediates in chocolate manufacture before exporting. This is already being done in Brazil and to some extent in Ghana. The increasing number of small manufacturers who depend on the purchase of chocolate mass is making this trend possible. From the point of view of the producer countries, this development leads to substantial economies in shipping costs. More important still is the fact that the products of partial manufacture can be stored in the producing country whereas dry beans cannot. This can give the producing country more flexibility in marketing.

There is bound to be a more or less rigid upper limit to this trend, fixed firstly by the capacity of processing equipment in manufacturing countries and secondly by the highly-specialized requirements of many individual manufacturers. Therefore, while the trend to manufacturing in the producing countries may have some appeal for the major producing countries, it has no appeal whatsoever for the minor producers who could find themselves in the position of having nothing to offer but semi-manufactured products on a market where there was little demand for this type of product.

CACAO CURING AND FERMENTATION

The raw, unfermented cacao bean is extremely bitter and astringent, completely lacking in chocolate flavour and generally possesses a most obnoxious taste. By appropriate fermentation, curing and drying, the unpleasant flavours are removed and chocolate flavour is developed. Therefore, it cannot be repeated too often that the whole cocoa industry rests on efficient processing by the grower.

Fermentation may or may not achieve its objectives, depending on whether or not the necessary changes take place within the bean. Manufacturers have learned that beans which are light to chocolate-brown in colour, in which the cotyledons have taken on an open texture and in which the shell separates freely from the cotyledon, are more likely to possess good chocolate flavour and are much less bitter and astringent than beans which do not show these characteristics. Beans in which the required reactions have not gone far enough during fermentation and drying are characterized by varying degrees of white or purple colouration, have a tight cheesy texture and the shell remains firmly attached to the cotyledons or nibs. On the other hand, beans in which the necessary reactions have gone too far are usually very dark in colour of both skin and cotyledons and the colour is "dull" rather than bright. This "over-fermentation" is associated with a variety of foreign flavours of the "earthy-foetid-foul" type and there is a considerable weakening of chocolate flavour.

It is evident therefore that during successful fermentation major changes take place within the beans and it has become a matter of great importance to know what these changes are and what conditions are necessary for them to take place.

Early Studies of the Cocoa Bean

The first logical step was to conduct chemical analysis of both unfermented and well-fermented beans as it was thought that the comparison of the two analyses would throw light on the changes which take place. At the same time a chemical scrutiny was made of the pulp, since this was the fermenting medium. It was believed that part at least of the flavour of the fermented beans could be due to the production in the pulp of substances which entered the bean to produce the desired flavours.

This type of analysis was carried on for many years in the early part of this century and much useful information was obtained, but the investigations did not throw much light on what constituted the essential reactions. These early studies covered, *inter alia,* alteration which accompanied fermentation in the content of fats, carbohydrates, proteins, mineral constituents, theobromine and the broad group of pigments and tannins. It was found that almost every constituent showed some alteration during fermentation and it gradually emerged that it was the changes occurring in the polyphenolic fraction, which were somehow or other connected with the development of chocolate flavour.

The fresh cacao bean contains about a dozen different polyphenolic substances. Most of these have recently been identified with the help of chromatographic techniques—techniques which have given renewed impetus to research work on the chemistry of the cacao bean. There is a great number of names attached to these chemical investigations but without minimizing the value of the results obtained by the early investigations it is the recent work which is of greatest interest. In particular, the studies of Forsyth in Trinidad, Rohan in Ghana and Roelofsen and Giesberger in Java are highly relevant. It is only within the last few years that results capable of modifying field practice have been obtained.

Paralleling the chemical investigations, various experimenters have approached fermentation on the commercial scale on a "trial and error" basis. Conditions of fermentation have been varied in many ways and the effects judged by the altered pattern of fermentation and by the acceptability of the finished product. Until fairly recently, such work was largely unsupported by parallel chemical investigations, mainly because of lack of suitable techniques. Consequently the results obtained by different workers were contradictory in the extreme. However, much valuable information has been accumulated and as the chemistry of the processes becomes clearer the conflicting results obtained in the field will probably become reconciled. The effects of varying field conditions have been studied in recent years by Howat and Powell, Rohan, Roelofsen and Giesberger and in New Guinea.

Microbiological aspects of fermentation have generally been given insufficient attention in New Guinea and elsewhere. Knowledge of the subject up to 1937 was summarized by Knapp (1937). Since then, the major contributions on this subject have come from Rombouts and Forsyth working in Trinidad and further information has been obtained by Roelofsen and Giesberger working in Java.

The final test of theoretical knowledge is to reproduce the conditions thought to be necessary on a laboratory scale and compare results with those obtained using the best field methods. If the principles have been correctly understood and correctly applied, there seems to be no reason why equivalence cannot be obtained. If such laboratory techniques existed, then work on relating the fundamental principles to actual field methods would be greatly assisted. Over the last 50 years, various workers have attempted to evolve satisfactory small-scale methods, not so much for the reason just stated but mainly as a means of testing the flavour of individual clones. Until a few years ago, these attempts suffered from a lack of knowledge of the basic principles. None of the early methods produced beans with a normal chocolate flavour. For example, the method developed by the General Foods Corporation in 1948 produced chocolate which has been described as "distinctly unlike normal chocolate". This was followed by the methods of MacLean (1950) and de Witt (1951). In 1954, Wadsworth and Howat produced a method which is claimed to produce a normal chocolate flavour. This work is of noteworthy importance since an attempt was made to elucidate principles from variations in the method. Since then, the method of Quesnel (1957) has been published and this method is the only one which attempts to utilize knowledge of the chemical reactions known to take place during successful fermentation. It can perhaps be anticipated that completely satisfactory methods will be evolved within the next few years by refinement and perhaps synthesis of existing methods. It should then be possible to vary the different factors affecting fermentation under controlled conditions and this should lead to a stronger linkage between theory and practice.

Chemical Changes and Flavour Development

Research workers have long suspected that the chemical changes associated with the development of chocolate flavour are mainly concerned with the polyphenolic and "tannin" fraction. Workers who have taken part in recent chemical investigations (Rohan, 1951 ; Forsyth, 1957 and Roelofsen, 1958) classify these compounds into two major groupings :—

(*a*) Phenolic glycosides—in which the polyphenols exist in combinations with sugar molecules. The most important compounds here are the anthocyanins ; and

(*b*) Non-glycosidic polyphenols—some of which occur as such to begin with and some of which are produced as a result of hydrolysis of the glycosides during fermentation. The principal compounds here are catechins and leucocyanidins.

Forsyth (1957), whose work is a milestone in cacao research, has shown that the essential chemical changes associated with cacao fermentation take place in two distinct phases which he terms "The Anaerobic Hydrolytic Phase" and the "Oxidative Condensation Phase".

1. *Anaerobic Hydrolytic Phase.*

This involves the first series of chemical changes which takes place within the bean. In these reactions, the sugar molecules are split off the glycosides [Group (*a*)] by the action of a glycosidase enzyme. This process is anaerobic and Forsyth has produced evidence showing that the reaction is inhibited if preceded by oxidative changes. Chocolate flavour precursors are formed as a result of these reactions. If for any reason they fail to take place, chocolate flavour will not be developed.

Other complex chemical changes accompany the hydrolysis of the anthocyanins. Forsyth has shown that these are interactions between the phenols and the proteins and that these reactions have a marked influence on the solubility and flavour properties of the compounds concerned. The reactions are not well understood.

2. *The Oxidative Condensation Phase.*

According to Forsyth (1957), the oxidative reactions primarily concern the non-glycosidic polyphenols and polyphenol aglycones [Group (*b*)] liberated by hydrolysis of the anthocyanins. Oxidative changes take place through the agency of another enzyme—polyphenol oxidase. The reactions increase the insolubility of the polyphenols and this mitigates their bitter/astringent taste and also removes the nauseating taste of roasted fresh protein. In this way, the oxidative changes exert a considerable effect on the overall flavour of dried beans.

Additional Results Relating to the Development of Chocolate Flavour

The changes noted above and the order in which they take place now appear to be firmly established by the work of Forsyth and co-workers. There are, however, certain results which suggest that there are other important reactions which are not understood fully.

It is generally agreed that reactions associated with the anaerobic phase are of fundamental importance but there is some disagreement regarding the optimum conditions and the rates of the reactions. These questions are discussed later. As regards the oxidative phase, the chemists generally believe that the associated reactions play no part or only a relatively insignificant part in the development of chocolate flavour as such and that the influence of the oxidative reactions is, in a sense, negative. This is in direct conflict with the basis of quality assessment used by manufacturers. While buying beans primarily for their flavour, manufacturers base their method of assessment very largely on the degree of "browning", which is merely a rough measure of the level of oxidation. This basis gives no assurance of satisfactory completion of the anaerobic hydrolytic phase which results in the formation of the chocolate flavour precursors. If oxidative changes are not preceded by destruction of the anthocyanins by the glycosidase enzyme, it is possible to obtain brown, open-textured beans completely lacking chocolate flavour. This has been accomplished experimentally at Keravat and by Smith (1958) in Rabaul.

The results obtained at Keravat suggest that the oxidative reactions, when preceded by normal anthocyanin destruction, have a direct influence on chocolate flavour development. In a series of trials, beans were withdrawn from a fermenting mass at various intervals following bean death. Portion of these samples was pierced with a dissecting needle and the remainder was left unpierced. All were then sun-dried. The pierced beans all became plump and open-textured, while the unpierced beans remained flat and wrinkled and were cheesy-textured and purple or white in varying degree. Beans which were pierced eight hours after bean death developed strong chocolate flavour and the cotyledons had a distinct purple cast. Unpierced beans withdrawn at this stage developed no chocolate flavour. They were cheesy in texture and showed very little browning.

Beans which were pierced 24 hours after bean death developed very strong chocolate flavour and the cotyledons, although open-textured, had a slight purplish or whitish cast. Unpierced beans at this stage developed extremely weak chocolate flavour. Piercing at later stages of fermentation led to a reduction in chocolate flavour whereas the chocolate flavour of unpierced beans improved. Piercing at later stages also led to complete removal of purple pigmentation.

The chocolate flavour developed by beans pierced 24 hours after bean death was considerably stronger than is normally encountered in commercial beans in New Guinea. This indicates that the hydrolysis of anthocyanins was complete or virtually complete at this stage. Unpierced beans, taken at the same time, which developed extremely weak chocolate flavour, were also somewhat bitter and astringent, but the extent of anthocyanin hydrolysis must be presumed to have been the same or else oxidative changes did not inhibit the activity of the glycosidase enzyme.

There are only two ways of regarding the absence of chocolate flavour in the unpierced beans withdrawn 24 hours after bean death. Either the flavour is there but cannot be tasted owing to the masking effect of bitterness, or it is not developed in a form which gives the characteristic taste without the added changes brought about by oxidation.

Further investigation is required to determine which of these two explanations is correct. In a further series of trials at Keravat, beans were fermented under completely anaerobic conditions. The beans were then divided into three lots. the first lot was pierced and sun-dried. The second lot was unpierced and sun-dried. The third lot was dried in an atmosphere of CO_2. The beans which were pierced and sun-dried developed strong chocolate flavour. The beans which were not pierced and sun-dried developed mild chocolate flavour. The chocolate flavour could not be detected in beans dried in an atmosphere of CO_2. They tasted extremely bitter and astringent. This confirmed the results obtained by Wadsworth and Howat (1954).

The results of these trials, however, do not meet the anticipated objection that the chocolate flavour may be completely masked by bitter-

PLATE 3.—*Fermentation trials at Keravat. Note use of thermometers in fermenting mass.*

ness or astringency. This is a question which cannot be settled one way or the other until the compounds actually responsible for chocolate flavour have been isolated and identified. The "tasting test" is entirely subjective. The expert panel of tasters used in the above trials were of the opinion that if chocolate flavour were present in the beans dried in an atmosphere of CO_2, it could have been detected. This was also the writer's opinion. It seems unlikely that if the chocolate flavour were fully developed it could not be tasted at all. With beans fermented under anaerobic conditions and dried in CO_2, prolonged grinding was successful in reducing the level of bitterness, but chocolate flavour was still not revealed. It seems very probable, therefore, that the precursor formed on hydrolysis of the anthocyanins (P_1) requires oxidation to form precursor (P_2) which on roasting will yield chocolate flavour as such.

If a certain level of oxidation is essential, it is equally clear that too much oxidation is very harmful. It is a well-established fact that the longer the fermentation the browner the beans become when dry. Bridgland's (1959) results indicate that the extent to which beans become brown during drying is a linear function of the Time/Temperature product during fermentation. This does not necessarily imply continuous oxygen uptake during fermentation, but it certainly indicates that the susceptibility of the bean to oxidative changes (whether these occur during fermentation, drying or both) is a function of the Time/Temperature product. In a rough way, the piercing and drying of beans withdrawn at regular intervals during fermentation gives a regular increment in the extent of oxidative reactions. The piercing and drying of beans withdrawn more than 24 hours after bean death leads to an increasing overdosage of oxygen and to progressively weakened chocolate flavour. If such an overdose can destroy chocolate flavour, the susceptiblity to oxidative reactions of the compounds concerned with actual chocolate flavour must be accepted.

It is now worth recalling the finding of Wadsworth and Howat (1954) that beans maintained in an atmosphere of CO_2 during either fermentation or drying develop no chocolate flavour. This result is explicable in terms of an inhibition of essential oxidative changes if the oxidative reactions are restored to their rightful place in the scheme of things. Furthermore, the temperature optimum claimed by these workers can be viewed in a new light. This is discussed later.

At all events, even if the effect of the oxidative changes is to "unmask" chocolate flavour rather than to lead to its development, the above results indicate that these reactions are quite as important as those accompanying the anaerobic phase. It would give manufacturers no satisfaction to know that the flavour precursors are present if they cannot be tasted. If the oxidative changes do in fact make a positive and direct contribution to chocolate flavour, when preceded by the hydrolysis of the anthocyanins, then manufacturers' methods of visual assessment do not appear to be so inaccurately based.

Objects of the "Fermentation" Phase

(As distinct from the "Drying" phase.)

At this point, it has to be decided whether the reactions associated with the anaerobic hydrolytic phase constitute the only object of the fermentation phase; that is, the phase in the sweat boxes. Forsyth and Rombouts (1951) claim that this is substantially the case. At once a great discrepancy between the theoretical minimum duration of fermentation and the practical optimum becomes evident. It has been shown (Bridgland, 1959) that under reasonable to good conditions of temperature and acidity during fermentation fundamental precursor development (P_1) is complete, or very nearly complete, in beans which are dried 24 hours after bean death has occurred. This is fully supported by Rohan's (1957) chemical investigations in Ghana where it was shown that in beans withdrawn from the surface layers of fermenting heaps and dried the anthocyanin concentration had fallen to 10 per cent. of its original value after 48 hours' fermentation, i.e., 24 hours after bean death. Furthermore, Quesnel (1957), using his laboratory technique, found that chocolate flavour was well developed after 24 hours only. The standard plantation practice in Java is to ferment for two and a half to three days, giving less than 48 hours' fermentation following bean death.

Therefore, provided satisfactory conditions are obtained, if completion of the anthocyanin hydrolysis is the only object of the fermentation phase, then the duration of the whole process could be reduced to two and a half days. This can be, and in fact is, done in Java and Ceylon, but such fermentation must be balanced by very long and carefully controlled drying.

The interesting point is that most countries find it a distinct advantage not to follow this practice of short fermentation. Forsyth (1957) prefers a six-day fermentation for Trinidad. Although they have developed a method of fermentation which rapidly brings about anthocyanin hydrolysis, Rohan and Allison (1958) prefer a six-day fermentation with their method. Where optimum conditions for anthocyanin hydrolysis are quickly reached by methods evolved at Keravat, the results of six-day fermentation are far superior to the results of shorter fermentation. Roelofsen (1958) also states that fermentation for four and a half days, in Java, produces beans with stronger flavour than those fermented for three days or less.

The reason for this divergence between the theoretical minimum and the practical optimum has not been properly explained. Forsyth (1957) explains it on the basis of variable conditions in the mass of beans and the necessity for obtaining uniformity by mixing. This explanation is inadequate.

There is good reason to believe that prolongation of fermentation beyond three days is almost entirely for the benefit of the oxidative condensation phase. This involves the proposition that the objects of fermentation are to complete the reactions associated with the anaerobic phase and to initiate and partially complete reactions associated with the oxidative phase. The rationale of this is that it is cheaper to obtain necessary oxidative changes in the inexpensive sweat-boxes than in very costly drying equipment. The increased extent of oxygen uptake and the increased susceptibility of the bean to oxidative changes as the Time/Temperature product expands, greatly simplify the problem of "drying" and reduce its costs.

If partial completion of oxidative reactions should form a principal object of fermentation, then the conditions most favourable to these reactions is a matter which has been largely overlooked. That oxidative changes can take place to a considerable extent during fermentation is fully supported by observation. That they actually do so until the very end of fermentation is disputed by Forsyth and Rombouts (1951) who claim that it is necessary to maintain virtually anaerobic conditions within the bean for four or five days and that "browning" of the cotyledons does not occur during fermentation until the sixth day. Experience in New Guinea conflicts with this view and indicates that considerable oxygen uptake after the third day of fermentation is not only possible, but very desirable. The case for this proposition is expanded at later points in this article (Ref. p. 61.—"Conditions Required for the Oxidative Condensation Phase").

Normal Fermentation of Pulp

The chemical changes taking place within the bean are entirely dependent on changes occurring in the pulp as a direct or indirect result of the activity of micro-organisms. Changes in the pulp usually follow a sequence which appears to be similar under all conditions. There are, however, exceptions to this and the intensity and duration of different actions taking place within the pulp evidently vary a great deal. What is "normal" in Trinidad or Ghana is not "normal" in New Guinea.

Fresh beans become inoculated with many organisms during "breaking" and transport but after a few hours of fermentation the yeasts predominate (Rombouts, 1952). The pulp sugars are metabolized by the yeasts with the production of carbon dioxide and alcohol. At the same time the yeasts macerate the pulp cells which collapse and conditions become more anaerobic. These conditions favour the action of the lactic acid bacteria, the role of which appears to vary from place to place. They are relatively unimportant in Trinidad but seem to be more important in Java. Roelofsen and Giesberger (1958) state that the main product of their activity under sweat-box conditions is acetic acid.

Under New Guinea conditions (Bridgland, 1959), extractions of titrable acid from the pulp show that there is a sharp fall in the overall acidity for the first 36 hours of fermentation. This is attributed to breakdown of citric acid, occurring naturally within fresh pulp. There is a corresponding rise in pH of the pulp over this period but the pH of the cotyledon shows very little change.

With greater maceration of the pulp, conditions become more aerobic favouring the growth of the acetic acid bacteria which convert the alcohol produced by the yeasts into acetic acid. There is some rise in the temperature of the mass of beans during the period of maximum yeast activity but striking rises in temperature accompany the acetic phase. The rate of temperature rise varies a great deal from place to place. It is a good deal slower in New Guinea than in West Africa. Even on the same estate there are considerable seasonal fluctuations, but normally the temperature rises to about 45 degrees C. within three days and may rise to 50 to 51 degrees C. a day or so later.

In Trinidad, micro-organisms reach their greatest concentration after two days of fermentation (Rombouts, 1952) after which there is a spectacular fall. After the third day, the number of organisms present is relatively very small but temperatures of 45 to 50 degrees C. are maintained until fermentation ends after six to eight days.

following the addition of dextrose on the third day of fermentation.

After the first 36 hours, there is a considerable production of acetic acid. The effects and significance of this are discussed below. Under New Guinea conditions the level of titrable acid normally shows a fairly steady rise to the end of fermentation (Bridgland and Friend, 1957). The pulp, however, usually buffers out at about 4.5. Cotyledon pH falls from about 6.2 initially to about 4.0 or 4.5 by the fourth day and remains fairly constant for the remainder of fermentation. Should the level of acidity be low, the cotyledon pH may show a considerable rise towards the end of fermentation, but this occurs only when special steps are taken during fermentation.

At the beginning of fermentation, the beans when cut show a bright purple or violet pig-

PLATE 4.—*Trial lots of beans are dried at Keravat.*

The more anaerobic yeasts die out quickly during a normal fermentation, but Roelofsen and Giesberger (1958) have shown that certain aerophilic yeasts are present in small concentration side by side with the acetic acid bacteria, following the lactic acid bacteria. A significant rise is acidity has been obtained at Keravat

mentation in Forastero or hybrid beans, but no pigmentation in Criollo beans. There is no visible free moisture within the beans and the cotyledons are tightly bound together. After 30 to 40 hours' fermentation (i.e., after bean death) the cotyledons show some slight separation and all interstices within the bean are filled with a fluid which is inky in pigmented beans and clear in non-pigmented beans. With further fermentation the beans take on a bleached look and the cotyledons show additional slight separation fragmenting easily between the fingers and separating easily from the testa.

The free liquid within the bean becomes quite "muddy" by the fourth day of fermentation and a "brown ring" appears in the cotyledon tissue adjacent to the testa on the fourth or fifth day. This browning gradually moves inward, but is usually variable in extent at the end of fermentation, depending on the level of aeration.

The visible internal changes noted above are accompanied by striking changes in the external appearance of the beans. The pulp and the testa are both white initially. The pulp collapses during the period of yeast dominance and becomes off-white in colour. With the onset of the acetic phase following improved aeration, the pulp becomes light fawn and this changes to light brown and then to dark brown by the end of fermentation. The more acid the conditions, the lighter the colour. The progressive browning of the pulp is generally attributed to the extrusion from the cotyledons of tannins which are oxidized to become brown.

CONDITIONS REQUIRED FOR ANAEROBIC HYDROLYTIC PHASE

1. *Bean Death*

The pigmented polyphenolic compounds are not uniformly distributed throughout cotyledon tissue in fresh, unfermented beans. They are localized within special groups of storage cells. The glycosidase enzyme is located in cells other than the pigment cells (Forsyth, 1957). It is only when the beans are killed that the polyphenols become evenly distributed throughout cotyledon tissue. Only then can the enzyme attack the anthocyanins.

The progress of fermentation can be uniform only if there is a clearly-defined starting point for the essential reactions taking place within the bean. This point is established when the beans die. It is for this reason that the question of the cause of bean death becomes important. This is considered later.

2. *Absence of Oxygen*

As noted above, Forsyth has shown that the activity of the glycosidase enzyme is inhibited by the intermediates of oxidase activity. Therefore conditions within the bean must remain anaerobic until the anthocyanin hydrolysis is completed. It is evident from the foregoing that such anaerobic conditions should be maintained for the first three days of fermentation. This period coincides with the period of maximum microbial activity (Rombouts, 1952) and it has already been pointed out by various workers that even under conditions of good aeration in the mass, the extent of oxygen penetration to the cotyledons is likely to be negligible during this phase. It is interesting to note that the first visible signs of appreciable oxygen uptake occur on the fourth day even under conditions of good aeration. This occurs after the dramatic decline in the numbers of active micro-organisms during the third day as demonstrated by Rombouts (1952).

It may be concluded, therefore, that, as a general rule, no special steps are required to maintain anaerobic conditions within the bean over the vital period.

3. *pH*

It has been shown by Forsyth and Quesnel (1957) that the glycosidase enzyme is most active in destroying the pigments of cacao cotyledon tissue at a pH between 3.8 and 4.5. The difference in rate of activity within this range is slight. At pH below 3.5 the rate of activity falls off very rapidly. Above pH 4.5, the rate of activity falls off more gently but at pH 6.0 the rate is about two-thirds that at pH 4.0.

4. *Temperature*

Forsyth (1953) has shown that in unfermented, dehydrated bean powder there is considerable non-enzymic destruction of the anthocyanins above 55 degrees C. but at the temperatures normally encountered in commercial fermentations (45 to 50 degrees C.) the destruction which occurs is caused by the activity of the glycosidase enzyme to the extent of 75 per cent. Further, the optimum temperature for the enzymic hydrolysis is sharply defined at 44.5 degrees C. The rate of conversion is very much less at a temperature of 40 degrees C. With live beans, it was concluded that "provided the temperature exceeds 44 degrees C. for about three days, practically complete destruction of the pigment should occur".

Temperature/pH interactions are probably deserving of further study. It seems likely that where optimum pH and temperature are obtained together, the reaction will be completed in considerably less than three days. Experience at Keravat suggests that temperature is the more important determinant. This agrees with results obtained by Rohan (1957) where it was shown that beans withdrawn from the surface of fermenting heaps before there was any significant reduction in pH, but which had reached a temperature of 45 degrees C., had lost some 90 per cent. of their original anthocyanin content by the time the beans were dry.

To return to a consideration of the optimum temperature pattern during fermentation, there is some disagreement between the results of Wadsworth and Howat (1954) and Forsyth (1953). Wadsworth and Howat state that a temperature of 50 degrees C. is essential to the full development of chocolate flavour. It is suggested that the two conflicting temperature optima, 45 degrees C. on the one hand and 50 degrees C. on the other, may actually refer to the temperature optima for two different phases. Perhaps the temperature should reach 45 degrees C. for the anaerobic phase and 50 degrees C. for the initiation and partial completion of the oxidative phase. Results obtained at Keravat on a commercial scale over the past five years indicate that chocolate flavour is appreciably stronger from fermentations at 50 degrees C. than at 45 degrees C. In further support of Wadsworth and Howat, fermentation temperatures of 40 to 45 degrees C. have usually been associated with strong side-flavours such as liquorice, raisin or caramel.

The results of piercing trials (Bridgland, 1959) at Keravat which indicated very rapid completion of the anaerobic phase, suggest that beans need to be held near the optimum of 45 degrees C. for this reaction for only about one day. Further experience indicates that for the remainder of fermentation the temperature optimum is about 50 degrees C.

CONDITIONS REQUIRED FOR OXIDATIVE CONDENSATION PHASE

Oxidative changes depend on the activity of the enzyme polyphenol oxidase. The factors which are capable of modifying the rate of oxidase activity are the concentration of the enzyme and the conditions under which it has to operate. There is no evidence to suggest that enzyme concentration ever becomes a limiting factor. Provided other requirements are fulfilled, beans can invariably be made to go brown.

Two sets of conditions are required for oxidase activity, namely those occurring in the sweat-box and those occurring during drying. The latter are more conveniently dealt with under the heading "Curing/Drying". As far as the fermentation phase is concerned, the factors which immediately suggest themselves as being of potential importance are the availability of oxygen to the enzyme and the temperature, moisture, pH/acidity complex.

At the end of the anaerobic hydrolytic phase, cotyledon pH should ideally be somewhere between 4.5 and 5.0. Findings on the optimum pH for polyphenol oxidase are contradictory. De Witt (1951) claims that it is strongly defined at 5.0, but Roelofsen (1958) states that it is about 7.0 ; further, that as pH falls, so does the rate of enzyme action ; that activity is still present, but at a very reduced rate at pH 4 ; and that there is no activity at pH 3. In practice a cotyledon pH above 5.0 by the end of fermentation will almost invariably be associated with putrefaction.

Very little information is available on the temperature optimum for the action of polyphenol oxidase. Quesnel (1957) has stated that there is no marked temperature optimum within the range 30 to 40 degrees C., but has informed the writer in private correspondence subsequently that above 40 degrees C. the activity is about 25 per cent. higher than 30 degrees C. Certain results regarding the heat stability of the enzyme are available but do not appear to be relevant to the optimum. The question of temperature in relation to oxidase activity is still open and further work is necessary.

Moisture content of the cotyledon tissue cannot become limiting during the fermentation phase and is considered in the section on drying.

The weight of evidence indicates that the rate and extent of oxidative changes occurring during fermentation are limited by the rate of oxygen penetration of the testa. Roelofsen (1958) suggests that the rate of oxygen uptake becomes greater as fermentation is prolonged due to increased permeability of the testa. He claims to have demonstrated this by pressing air into beans while they were steeped in water and suggests that the increased permeability is due to the action of pectinase produced by yeasts, spore-forming bacteria and other bacteria such as *Aerobacter*. There is no doubt that the testa is an imposing barrier. Forsyth (1952) found that when cotyledons were ground all polyphenols were oxidized so rapidly and extensively that they became insoluble within an hour.

Under the saturated conditions prevailing in the sweat-box, any oxygen penetration of the bean must occur in the dissolved state. Oxygen penetration is therefore a function of aeration of the mass in the first instance. The only oxygen available for penetration of the bean is that which is not immediately metabolized by micro-organisms. As noted above, the activity of micro-organisms shows a dramatic decline from the second to the third day of fermentation. Oxygen penetration of the bean may be aided by moisture uptake by the bean during fermentation. Beans do show an increase in moisture content during fermentation (Howat, 1957), but it is not known whether this is caused by the direct uptake of moisture. As pointed out by Forsyth and Rombouts (1951), all interstices within the bean are filled with juice containing polyphenols, particularly L—epicatechin, in solution. As oxygen enters the bean, this is precipitated. Completion of this precipitation is therefore an essential condition for oxidation of polyphenols occurring within the cotyledons. Because of these barriers, Forsyth concluded that browning of the cotyledons cannot occur to any significant extent during fermentation and that what is commonly regarded as "browning" is in fact a "bleaching" only. This is not necessarily so.

Browning can and does occur during fermentation. In trials conducted at Keravat, fresh beans were taken and excess pulp rubbed off (Bridgland and O'Donohue, unpublished). Several groups of 10 beans were then placed in small, airtight, thin plastic bags and just covered with one per cent. acetic acid. These were then sealed and buried in a normal fermenting mass as soon as the mass reached a temperature of 45 degrees C. and were maintained at this temperature for four days. At the end of this period, the cotyledons were certainly bleached but showed no evidence of browning whatsoever. Beans from the mass at the same time showed a high degree of browning. In fact some beans were completely brown. The mass was fermented in a way which ensured adequate air penetration.

Quite apart from the optimum conditions required for the oxidase, conditions of temperature and acidity should be considered in relation to possible effects on oxygen penetration of the bean. In trials covering only the normal range of temperatures occurring during fermentation (i.e., not exceeding 50 degrees C.) Bridgland (1959) has shown that the extent of browning in dry beans is a linear function of the Time/Temperature product. This immediately indicates that temperature is a major factor and, in view of the foregoing, this effect is more likely to be caused by increased oxygen uptake at higher temperatures than by an effect on the rate of activity of polyphenol oxidase. Beans fermented at 50 degrees C. showed a much higher degree of browning than beans fermented at 45 degrees C. Above the normal temperature limits, results were not the same, but as very much higher temperatures are associated with lower acidity and perhaps abnormal moisture relations between pulp and cotyledon it is impossible to separate out the effects (Bridgland 1959—see 1,138 series). However, it did appear that the level of acidity had no effect on oxygen penetration of the testa.

Although the effect of time—generally the longer the fermentation the greater the oxygen uptake and the browner the dry beans—is well known, the maximum duration of fermentation is fixed by the onset of putrefactive changes. Fermentation must be stopped before this occurs and duration of fermentation is not a factor which can be varied independently of other factors.

There is one other important condition for the oxidative condensation phase. This is the satisfactory completion of the anaerobic hydrolytic phase. Whereas the degree of browning is a linear function of the Time/Temperature product when the testa is unbroken, if beans are pierced and dried at regular intervals during fermentation the degree of browning no longer shows this linear relationship. The rate of browning shows a sharp increase after the 700th-900th "degree hour". This roughly coincides with the period at which chocolate flavour precursors are fully developed—that is, with completion of the anaerobic hydrolytic phase of fermentation.

This suggests that the bean is rendered more susceptible to oxidative changes as the anthocyanins are destroyed and, further, that the presence of unhydrolysed anthocyanin in a bean imparts a resistance to the essential oxidative changes. Rohan (1957) has shown that "pale-purple" beans (i.e., beans which have failed to become open-textured and brown) frequently contain only 10 per cent. of the initial anthocyanin concentration. Nevertheless, they have failed to become brown and open-textured because of insufficient oxygen uptake. This, together with the results of piercing trials, is the basis of the statement (Bridgland, 1959) that the "under-fermented bean" (as distinct from the unfermented bean) is basically an "under-oxidized" bean.

In trials at Keravat (Bridgland and O'Donohue, unpublished), beans pre-killed by freezing were placed in small polythene envelopes containing one per cent. acetic acid and buried in a normal fermenting mass for varying periods. This was done in such a way that all samples were withdrawn from drying at the same time. Results on cutting showed that the appearance of purple pigment and under-fermented beans decreased markedly as the duration of fermentation increased. Fermentation was quite anaerobic, but all beans were equally exposed to oxidative changes during drying. Forsyth (1957) has shown that the purple anthocyanins are capable of being attacked by polyphenol oxidase, but this reaction does not result in the formation of chocolate flavour precursors. It is reasonable, therefore, to conclude that anthocyanin hydrolysis is associated with a loss of resistance to oxygen uptake by the bean. If this were not so, all beans should have become equally brown. In practice, incomplete destruction of the anthocyanins could be caused by a prolonged deferment of bean death or unsatisfactory conditions for the activity of the glycosidase enzyme involving temperature pH or premature oxygen uptake.

A direct chemical inhibition of oxidative changes by anthocyanin appears to be unlikely but there are physical changes associated with anthocyanin hydrolysis which could affect the uptake of oxygen. In contradiction to Quesnel (1957) who states that there is a slight unfolding of the cotyledons prior to bean death, observation under local conditions indicates that there is no change in the texture of the cotyledons until after bean death has occurred. As the anthocyanin hydrolysis proceeds, the cotyledons show quite definite signs of progressive shrinkage. This shrinkage is accompanied by a filling up of all interstices with liquid. Whether there is ingress of moisture from outside the bean is for the moment beside the point. Skinned fresh beans, containing no visible free moisture when buried in a normal fermenting mass in small polythene bags, show considerable extrusion of free moisture within 24 hours of bean death (Bridgland, 1959). This can have derived only as a result of extrusion from cotyledon tissue and is accompanied by corresponding shrinkage. It may be that, if destruction of the anthocyanin is limited, shrinkage is also limited and this may interfere with oxygen uptake later on. It is also possible that moisture uptake by the bean is affected by the extent of anthocyanin destruction. Howat's (1957) figures certainly show that the greatest apparent increase in moisture content occurs between 24 and 48 hours of fermentation, coinciding with the period of maximum anthocyanin destruction.

To summarize, experience at Keravat indicates that the conditions required for the oxidative phase consist of satisfactory completion of the anaerobic hydrolytic phase, adequate aeration of the mass and a temperature of 50 degrees C. Other factors not yet understood may also be important.

EXAMINATION OF VITAL FACTORS DURING FERMENTATION PHASE

Although there may be some haziness about some of the precise conditions required for successful curing of cacao, we at least now have a series of definite objectives. The pattern of fermentation of the pulp shows a good deal of variation and is bound to have a profound influence on the conditions to which the contents of the bean are subjected. Thus the interplay of factors governing the conditions of known or supposed importance to the full development of chocolate flavour deserves full consideration.

1. *Viable Period of Beans*

In all methods of fermentation there is a period at the beginning during which the beans are fully viable. Loss of viability is not uniform throughout the mass in ordinary box fermentation. As practised in New Guinea, there is a high loss of viability in the surface layer after 24 hours, but not in the centre of the mass. Most beans, however, are dead after 36 hours and no viability whatever remains after 48 hours. Rohan (1958) has obtained similar results in heap fermentations in Ghana.

Attention has been drawn to the possible importance of the preliminary period of viability by Wadsworth and Howat (1954). These workers claim that a viable period of 84 hours is necessary to the full development of chocolate flavour and that no chocolate flavour is produced if this phase in eliminated. Dr. Howat has informed the writer in private correspondence, however, that there is very little flavour lost by reducing the period of viability to 48 hours. The interpretation of these results is difficult but it is presumed that the initiation of the germination process results in a mobilization of essential enzymes.

This claim has been the subject of a great deal of contention and some evidence to the contrary has been produced by Quesnel (1957). Early results obtained at Keravat fully supported the view that a viable period of 48 hours does much to assist the development of chocolate flavour and that chocolate flavour is extremely weak if the viable period is eliminated (Bridgland, 1959). In practice, it has so far been impossible to maintain viability for 84 hours without actually initiating germination and this of course is most undesirable.

In further trials at Keravat (Bridgland and O'Donohue, unpublished), results have been irregular and impossible to interpret. Methods of fermentation which allow a period of viability of only 30 hours have yielded beans with a very strong chocolate flavour. Much more work is required before the importance of the period of viability can be properly assessed.

Assuming that a period of viability is necessary, it is not known whether it affects the actual flavour potential of the bean or merely the rate of reactions leading to the development of chocolate flavour. If it should be the latter, it is possible that the same effects could be produced by altering the duration of fermentation or some other factor. Further work is required to clarify the position, but in the meantime, in attempting to evolve an improved technique for New Guinea, it has been found easier to obtain other essential conditions if the period of viability is of about 30 hours' duration. Given optimum conditions, this results in the development of strong chocolate flavour.

Control of the period of viability at Keravat has been achieved through the use of what we have termed a "resting phase" prior to bean death. Beans are placed in a draining box for 14 to 16 hours after "breaking" and sweatings are allowed to drain away. The beans are then spread out on a shaded, wooden floor at the rate of one cubic foot of beans to 10 square feet of floor-space. With periodic stirring, full viability can be maintained until the beans do in fact begin to germinate. While the holding of beans in a viable state presents no particular problem, there are other important auxiliary effects which exert a powerful influence on the progress of fermentation. The condition of the pulp unfortunately does not remain static when the period of viability is prolonged. These effects are discussed later.

2. *Time and Manner of Bean Death*

Argument on the cause of bean death has been going on for the last 50 years and still continues. Bean death has been variously attributed to the simple thermal effect of high temperature and to poisoning by alcohol, acetic acid and carbon dioxide.

From the weight of evidence accumulated overseas and from experiments conducted on this station (Bridgland, 1959), there appears to be little doubt that the primary cause of bean death is acetic acid. Increased temperature must increase the lethal effect of acetic acid, but there is little evidence available on this point.

In trials at Keravat, beans have been subjected to the normal sweat-box temperature pattern over the critical period both in the presence and absence of normal acetic acid development. Loss of viability was deferred by approximately 10 hours in the absence of acetic acid. Furthermore, when more or less acetic acid was produced by varying the pattern of fermentation, there was a direct relationship between the extent of acid development and the rate of loss of viability.

No one has ever questioned the fact that beans can be killed thermally. But because sufficiently high temperature in a mass of fermenting beans cannot be obtained without the prior production of acetic acid, there is not a great deal of room for doubt that acetic acid is the primary cause of death, particularly as acetic acid formation begins almost as soon as that of alcohol. Forsyth (1957) has found that acetic acid is much more toxic to the cocoa bean than ethanol.

Consideration of the cause of bean death is important in relation to the question of prolonging the period of viability. The pulp undergoes considerable alteration during this phase and it may be necessary under such circumstances to take steps to restore the conditions responsible for bean death and subsequent changes.

3. *Alcohol/Acetic Acid/pH/Temperature Complex*

These factors, which form an interdependent complex, must be considered in relation to the conditions required for the anaerobic hydrolytic phase and also for the oxidative phase.

The two factors of direct importance are cotyledon pH, which is controlled by the level of acetic acid development, and temperature, which is raised somewhat by the initial yeast activity but more significantly by the action of the acetic acid bacteria. This latter action is dependent on the prior production of alcohol by the yeasts. Thus it is difficult or impossible to vary one of the above factors without causing significant alteration to the others.

The level of alcohol production depends on the period of yeast dominance and the intensity of yeast activity. These are functions of aeration and the concentration of pulp sugars. Measures which maintain low pulp pH also have the effect of prolonging the period of yeast dominance. This has been achieved by Roelofsen and Giesberger (1958) by the addition of sulphuric acid near the beginning of fermentation.

The rate and level of acetic acid development is related to the concentration of ethanol and aeration. It is mainly produced by the acetic acid bacteria but Roelofsen (1958) has indicated that it is also produced by the lactic acid bacteria. However, as the period of activity of these bacteria appears to be quite short, it is probably a very minor source of acetic acid under normal circumstances. The immediate effects of acetic acid, which rapidly passes through the testa into the cotyledons, are to kill the bean and lower the cotyledon pH. Trials conducted at Keravat (Bridgland, 1959) showed conclusively that there was a consistent inverse relationship between the level of titrable acid and cotyledon pH from the 36th hour to about the 115th hour of fermentation. After this time, cotyledon pH appeared to stabilize and did not follow movements in pulp acid unless conditions of fermentation were altered radically.

In normal fermentations the cotyledon pH at about 115 hours does not alter a great deal for the remainder of fermentation. Thus cotyledon pH is determined by the production of acetic acid during this period. It will be fixed at a higher or lower level according to conditions of fermentation. As a cotyledon pH of 4.5 is said to be optimum for the activity of the glycosidase enzyme (Forsyth, 1957) this is a point of considerable importance.

Theoretically, once it has been determined just when bean death should take place, it would be an advantage to have control over the onset of the acetic phase. It has already been stated that it is possible to prolong the period of yeast dominance which means deferring the acetic phase. Similarly, up to a point, increased aeration in the early stages of fermentation leads to a more rapid onset of the acetic phase. This is in fact the explanation of the observations (Bridgland and Friend, 1957 ; Rohan, 1957 ; Howat, 1957) that the top layer of beans in a fermenting box heats up much more rapidly than beans at the centre or bottom of the mass.

The presence of acetic acid in the pulp is also important in maintaining conditions which restrict the growth of putrefying organisms. Titrable acid normally falls rapidly from the beginning of fermentation for 39 or 40 hours and then rises again. The rising trend may continue until the end of fermentation or may level out from about 50 hours depending on conditions (Bridgland, 1959). With appropriate treatment it can be made to show a consistent fall to the end of fermentation (Bridgland and Friend, 1957). The curve produced in all probability represents two intersecting curves —the initial fall in extractable acid representing the breakdown of citric acid and subsequent movements reflecting the level of acetic acid production. As it appears that citric and acetic acids are the only two organic acids of any importance which occur in normal fermentations (Roelofsen, 1958), this explanation would appear to be sound. That citric acid is broken down by yeast activity has been proved by Roelofsen (1958) by growing yeasts in synthetic media under aerobic conditions where sodium citrate was the sole source of carbon.

It is not surprising, therefore, that the fall in extractable acid at the beginning of fermentation is reflected in sharply rising pH, but as citric acid does not enter the bean (Forsyth, 1957) there is no significant alteration in cotyledon pH. As acetic acid production begins, the rate of rise in pulp pH falls off and after 42 hours cotyledon pH begins to show a sharp drop from its initial level of about 6.2 and falls to about 4.5 after 115 hours' fermentation. Howat (1957) considers that the fall in cotyledon pH cannot be attributed entirely to the uptake of acetic acid by the bean. In a trial conducted at Keravat (Bridgland and O'Donohue, unpublished), fresh beans were depulped, given a quick dip in one per cent. mercuric chloride, well rinsed and buried in a normal mass of fermenting beans in very small plastic bags. These beans were therefore subjected to very nearly normal temperature treatment since the mass developed and maintained a temperature of 48 to 50 degrees C. The beans, however, would not have come into contact with acetic acid. Determinations of cotyledon pH were carried out on beans both from the small bags and from the main mass over a period of five days. The results are given in Table I.

TABLE I

Changes in Cotyledon pH in Absence of Acetic Acid

—	pH Cotyledon		Temperature (Main Mass Degrees C.)
	Plastic Bags	Main Mass	
1st day	6.08	6.11	42
2nd day	5.91	4.55	50
3rd day ...	5.96	4.74	50
4th day	5.87	4.83	48
5th day	5.80	4.77	47

It is clear that there was no significant reduction in cotyledon pH in the absence of acetic acid. The very small drop shown was probably due to incomplete removal of the pulp and incomplete sterilization.

In most overseas cacao-producing countries, pulp pH shows a steady rise to the end of fermentation. Under New Guinea conditions it usually becomes buffered at about 4.5 after 70 to 90 hours' fermentation (Bridgland, 1959; Bridgland and Friend, 1957). This applies to the standard method of box-fermentation. Where steps are taken to reduce acidity, pulp pH continues to rise towards the end of fermentation. In extreme cases, it has been raised to 7.0 after six days' fermentation (Bridgland and Friend, 1957). Rising pulp pH is almost invariably associated with the more rapid onset of putrefactive changes. It has been found consistently that the higher the level of extractable acid the safer it is to prolong fermentation. Conditions of high acidity are usually associated with poor aeration and, correspondingly, increased aeration, while causing rapid increase in the level of acidity initially, causes a steady loss of acid subsequently. This loss is attributed partly to volatilization at turnings and partly to the oxidation of acetic acid by such organisms as *Acetobacter rancens* (Roelofsen, 1958).

It might be expected that, as the conversion of alcohol to acetic acid is a highly exothermic reaction, a higher level of acidity would always be accompanied by a higher temperature. This does not always conform with the observed facts under New Guinea conditions. The problem here is frequently one of excessive acidity and this is accompanied by depressed temperatures.

The production of a high level of acidity in association with lower temperatures is perhaps explicable in terms of the rate of energy release. If conditions in the sweat-box greatly slowed down the growth of the acetic acid bacteria and at the same time favoured the activity of another organism capable of producing acetic acid at a slower rate, a high level of acidity could ultimately be developed. This however would be associated with lower temperatures due to consistent radiation losses over a longer period. As high acidity and low temperatures are associated with poor aeration, it is possible that such conditions favour the growth of lactic acid bacteria. The conversion of sugars to acetic acid by these organisms through several intermediates (Jorgensen, 1948) suggests a more gradual energy release than would occur with the oxidation of alcohol to acetic acid by the acetic acid bacteria. In fact, poorly aerated ferments do show a slow but consistent rise in acidity to an abnormally high level as compared with well-aerated batches where the initial rate of rise is very rapid but falls rapidly after about three days' fermentation. In the latter case temperature rise is rapid while in the former instance it is much slower and reaches a lower level.

Excluding abnormal ferments of the type mentioned above, temperature rise in fermenting beans appears to take place in two distinct phases. In the "acetic" phase, temperatures usually rise to 45 to 50 degrees C. within three days and are maintained at this level throughout fermentation. Within certain limits, reduced moisture and excessive aeration will tend to elevate temperatures by a few degrees.

The next phase which does not normally occur in commercial fermentations may be described as non-acetic. There appears to be a fairly sharply defined concentration of acetic acid above which the fermentation will remain "acetic". Temperatures rarely go as high as 52 degrees C. Conditions of alcohol deficiency, reduced moisture and excessive aeration will cause a drop in the level of acetic acid to below the critical level. Temperatures will then rise above 52 degrees C. and may go on rising until a temperature of 65 degrees C. is reached. This was achieved experimentally on a commercial scale at Keravat within six days of the beginning of fermentation. Undue prolongation of any fermentation will lead into this phase when acidity falls to a sufficiently low level. This is the explanation of the temperature curve obtained by Howat (1957) in his 16-day fermentation trial in Ghana.

The non-acetic phase is almost invariably accompanied by putrefaction and should be avoided at all costs.

The temperature pattern during fermentation was studied at Keravat using continuously-recording thermographs. It is interesting to note that the heat losses during "turnings" were much lower than would be expected. Within a few minutes of turning, the sum of top and bottom temperatures was only a few degrees lower than the total just before turning. Following turning, when the position of the beans in the box was reversed, the temperature at the top usually showed a steady rise. Temperature at the bottom remained at its initial level for about one hour, frequently showed a steady fall for six to nine hours and then began to rise. The loss of heat was attributed to an increased rate of convection, due to the improved aeration in the mass of beans, so that the bottom showed a loss and the top showed a gain until settling in the mass restricted air intake.

The responsibility of convection for the drop in temperature at the bottom of the mass was also supported by trials using the method of Rohan and Allison (1958), namely, fermenting in a tier of trays, one on top of the other. The bottom tray was usually some 10 degrees colder than the top tray. If the position of the trays was reversed, the initial temperature gradient from top to bottom was quickly restored. With this technique the effect could be observed in the absence of a corresponding pressure gradient.

4. *The CO_2/Aeration/Moisture Complex*

The CO_2/aeration/moisture factors form an interdependent complex and this complex stands in a direct causal relationship to the alcohol/acetic acid/temperature complex. It is therefore vital to any consideration of the time and manner of bean death. Furthermore, since oxygen uptake by beans during fermentation depends on the availability of oxygen, the CO_2/aeration/moisture complex is of paramount importance to the oxidative as well as the anaerobic phase.

As noted above, the period of yeast dominance, the duration of the lactic phase and the timing and intensity of the acetic phase are greatly affected by conditions of aeration. Therefore, in commercial fermentation, aeration must be controlled. Then, if a period of viability is important, bean death will occur at the appropriate time and temperature and cotyledon pH will then quickly reach their respective optima of 45 degrees C. and pH 4.5.

The problem in New Guinea is usually one of inadequate aeration. For reasons already stated, improved aeration does not lead to a breakdown in the anaerobic conditions prevailing within the bean until necessary reactions within the bean have been completed—this is with the proviso that conditions for these reactions are at or near optimal. Control of conditions during the anaerobic phase presupposes control of the various groups of micro-organisms and in this aeration is a critical factor. Conditions of good aeration at the beginning of fermentation favour yeast activity and if a breakdown of aerobic conditions is avoided, the lactic phase is probably eliminated altogether.

These same conditions, however, favour the acetic acid bacteria and both temperature and acidity rise sharply. This results in rapid bean death. If, during the initial period, aeration is so excessive that alcohol may evaporate rapidly, then viability can be maintained. This leads to the lowering of the level of acidity but temperature development is equally or more rapid when the conditions of excessive aeration and radiation are removed. Manipulation of aeration can in this way prolong the period of viability and then rapidly bring beans to the optimum temperature for glycosidase activity. Cotyledon pH will remain above the optimum unless the period of viability is reduced and more acid produced.

Following the anaerobic phase, aeration continues to exert a controlling influence on temperature and provides a source of oxygen which can at this stage penetrate the bean. Uptake of oxygen by beans can be followed by observing the precipitation of tannins held in solution in the free moisture within the bean. The liquid becomes "muddy" when the tannins are precipitated by oxidation. This is apparent to a limited extent in good fermentations after 72 hours and is very pronounced after 96 hours. From this point onwards, oxygen uptake can be followed by observing the brown ring of cotyledon tissue immediately inside the testa. As more oxygen is taken up, so the thickness of this ring increases. Quesnel (1957) has suggested that the thickness of the brown ring could be used to determine the end-point in fermentation.

In a normal box fermentation, there is usually a very thin brown ring after 96 hours and almost all the beans show some browning after 120 hours. At 170 hours, the degree of browning is usually pronounced. However, at this stage it should be emphasized that in cold, wet ferments the degree of browning at 170 hours may be only very slight and irregular. The results of such batches are invariably poor. Oxidative changes do not necessarily occur during fermentation. Whether they do or not is a function of aeration and temperature. Given a variable extent of oxidative changes during fermentation, the degree of browning could be used as an index of the end-point only under certain specified conditions of temperature and aeration. Otherwise, the limits imposed by the tendency to putrefy will set the end-point.

In box fermentation on the commercial scale, factors which affect the level of aeration of fermenting beans are the dimensions of the mass, external barriers such as box walls, the temperature of the mass and condition of the pulp.

As the volume of beans in a fermenting mass is reduced, particularly in respect of depth, aeration is correspondingly improved. The poor aeration of deep boxes is due simply to the elimination of air spaces between beans, because of pressure. Even in more shallow layers, however, there is an important interaction between aeration and temperature. Evidence given above suggests that the rate of air movement through a mass of beans is dependent on convection. Thus, the higher the temperature the more rapid the air movement. Adequate ventilation of sweat boxes is an obvious necessity.

A significantly higher rate of aeration cannot be obtained in large, deep fermenting boxes except as a result of reduced moisture content of the pulp. The consequent shrinkage of the pulp leads to better aeration. The specific effects of reduced moisture are obscured by the fact that this condition cannot be achieved without at the same time causing other drastic changes in the pulp. It seems likely that moisture balance is important in fermentation. Howat (1957) has shown that there is an apparent increase in moisture content of the cotyledons from 33 per cent. to 39 per cent. during a six-day fermentation and that if fermentation is prolonged for 16 days the apparent increase continues throughout. It is not yet known whether this increase is real. There is no doubt that moisture is extruded by cotyledon tissue during fermentation. If the increase is real, water uptake from the pulp could greatly influence oxygen uptake by the beans. In trials at Keravat, where pulp was subject to great moisture loss as a result of a 36-hour "resting phase", the production of free moisture within the bean during subsequent fermentation appeared to be unaffected; but since the treatment led to temperatures of 60 degrees C. and greatly increased aeration, the beans were comparatively dry and contained very little free moisture by the end of fermentation. The cotyledons were quite brown.

The role of CO_2 during fermentation is a contentious topic. CO_2 is produced in abundance in the first stages of fermentation by respiration of the bean, as a by-product of sugar metabolism by yeasts and as a result of citric acid breakdown. The proportions of CO_2 production from the various sources is not known. Wadsworth and Howat (1954) have shown that a single bean fermented under aseptic conditions may produce up to 10 ml. CO_2, but this ceases when the bean dies. The pulp was not removed in these experiments.

In commercial fermentations, Howat (1957) and his co-worker, Powell, have shown that the atmosphere about fermenting beans is frequently above 90 per cent. CO_2. No details are given regarding the points in fermentation when these observations were made. It appears that citric acid breakdown is completed within 48 hours and that respiration by the bean will also have ceased within this period. Having regard to the period of yeast activity and the dramatic decline in the number of micro-organisms in fermenting pulp between the second and third day of fermentation, as discussed by Rombouts (1952), it seems most unlikely that such concentration of CO_2 will continue beyond the third day of fermentation, provided the beans are turned at normal intervals. However, high concentrations of CO_2 appear to be unavoidable in the early stages of fermentation and the proposition that this is harmful to the development of chocolate flavour is untenable. When the beans are turned, it is probably more important to emphasize the positive effect of recharging the atmosphere with oxygen rather than the more negative effect of removing CO_2 which is no more than a dependent component of the CO_2/aeration/moisture complex.

At this stage attention is drawn to the fairly frequent occurrence in the Gazelle Peninsula of New Britain of what have been termed "dead ferments". The extent to which this phenomenon may occur in other parts of New Guinea is not known. It has been impossible so far to relate the occurrence of dead ferments to seasonal conditions. This is made difficult by the fact that seasonal conditions vary tremendously from year to year. The dead ferments sometimes occur during the dry, and sometimes during the wet, season.

In "dead ferments" (and some are not as dead as others), the normal sequence of changes in a sweat box fails to occur. In extreme cases, the temperature has failed to rise significantly after four days and the beans have much the same appearance as when first placed in the sweat box. Following this, temperature rise is slow and irregular and the odour of acetic acid is very strong. Fermentation is necessarily prolonged for up to 10 days but when putrefactive changes make it essential to remove the beans from the box, the beans frequently turn out to be over 80 per cent. underfermented after drying.

"Dead ferments" take place even where the planter is fermenting beans from the same area, using the same harvesting frequency of pods at the same stage of ripeness and using precisely the same fermenting technique in the same sweat boxes as he does with normal ferments.

"Dead ferments" have been produced artificially at Keravat by adding water to the beans at the beginning of fermentation (Bridgland and Friend, 1957). Similar results were obtained by insulating the sweat boxes against air penetration with polythene sheeting. These trials have been reported fully elsewhere (Bridgland, 1959).

It seems highly likely, therefore, that the explanation of dead ferments lies within the CO_2/aeration/moisture complex. It seems certain that the amount and wetness of the pulp about the beans may vary considerably. For two years we have recorded the weight per cubic foot of beans as they reach the fermentary from the field and have found that the weight may vary from 53 to 62 lb. If the difference is mainly due to water, it is equivalent to nearly a gallon of water for every cubic foot of beans. Consequently it is not surprising that beans behave differently at various times of the year. Apart from its effect on aeration, the increased quantity of water will have a very significant effect on maximum temperatures developed. Attention was drawn to this in a previous article (Bridgland and Friend, 1957).

The pulp has been fairly well studied qualitatively. Quantitative studies obviously deserve greater attention. On a recent visit to West Africa, the writer was most forcibly struck by the apparent differences in the pulp between Africa and New Guinea. The squeezing of a few beans taken directly from the pod in New Guinea wrings out a flow of water and soft pulp. Admittedly, observations in Africa were made after the end of the main crop, but both in Ghana and at Mokaria Plantation in the Belgian Congo, the pulp appeared to be much firmer than in New Guinea. Only a small amount of water and soft pulp could be wrung from a handful of beans. After nine days' fermentation at Mokaria, the beans were dry-ish and did not soil the hand to any great degree. In New Guinea, the hand is left covered by wet broken-down pulp.

The observation that the occurrence of dead ferments is most probably caused by impeded aeration is supported by the fact that they tend to occur more frequently in the very wet areas than in the drier areas. Furthermore, more or less normal fermentation can be restored by reducing moisture and improving aeration. In fact, the occurrence of dead ferments provides an object lesson on the importance of aeration.

The trials in which sweat boxes were lined with polythene sheeting at the beginning of fermentation were most illuminating (Bridgland, 1959). In spite of the fact that the beans were "mixed" or "turned" at 24-hourly intervals, the temperature pattern was drastically depressed and the beans behaved abnormally in every way. It has been proved beyond all doubt that a regular and slow air penetration into the mass of beans is absolutely essential to successful fermentation. It is thought that some of the odd results obtained by fermentation in stainless steel vessels (Howat, 1957) are explainable on the basis of abnormal aeration. Unless the necessary continuous air-flow at the optimum rate were provided, results could be expected to to be poor. The experimental value of such vessels in determining the results given by varied air-flow, is considerable. Similarly, artificial aeration with nitrogen should give a clear answer to the question of whether the presence of CO_2 or the absence of oxygen is the more important factor during fermentation.

Forsyth (1957) has already suggested that one of the main problems in cacao fermentation is the question of balanced aeration. With this, the writer heartily agrees.

FIELD FACTORS AND METHODS AFFECTING FERMENTATION

1. *Stage of Pod Ripeness*

Precise information on the question of the effects of ripeness of pods is not available. Trials conducted by Bridgland and Baseden (Bridgland, 1959) indicated that the harvesting of pods, the skins of which were still partly to half green, resulted in slightly lower temperature development, lower acid development and slightly higher cotyledon pH during fermentation. The trials did not include pods which were so green that the pulp was still firm.

The pulp from under-ripe pods appears to have a higher citric acid content than that from fully-ripe pods, but this effect apparently disappears after 36 hours of fermentation. The slightly lowered acidity throughout the remainder of fermentation is not understood. It could possibly be caused by reduced sugar content of the pulp or by different conditions of aeration due to slightly different pulp texture.

Although the ripe pods gave a more normal pattern of fermentation there was no significant difference in the chocolate flavour development. For a standardized method of fermentation pods should be harvested when fully ripe. There is no possibility of obtaining desirable variation in the pattern of fermentation by departing from this standard.

2. *Harvesting-Breaking Interval*

Information on the effects of the period between harvesting and breaking is scant. The effect is primarily on the ripening process and it would be expected that a comparison of a long interval compared with no interval would be similar to the comparison between fully-ripe and under-ripe pods. This is so. Work done at Keravat (Bridgland, 1959) shows that pods broken on the same day as harvesting show a slightly depressed temperature curve, slightly lower acid development and slightly higher cotyledon pH when compared with other pods with a three-day harvesting-breaking interval. The citric acid content of the pulp seems to be slightly diminished by the three-day interval. It will be noted that in terms of ml. N/10 NaOH per bean the fresh bean from an under-ripe pod required 1.77 ml. for neutralization. A bean from a freshly harvested ripe pod required 1.5 ml. and a bean from a pod harvested three days previously required 1.0 ml. for neutralization. This supports the proposition that citric acid is enzymatically destroyed during the ripening process.

An interval between harvesting and breaking leads to a more normal pattern of fermentation. The limit of this interval is set by the tendency of the pod-rotting organisms to proliferate rapidly in bruise marks and insect-damaged tissue after four days. Invasion of the pulp by these organisms causes the pulp to dry out and become sugar-deficient. Thus the minimum interval should be three days and the maximum four days. Nothing can be gained by departing from this procedure.

3. *Varying Duration of Fermentation*

Variation in duration of fermentation may vary the extent of essential processes, but not their rate or nature. The factor which is most affected by varied duration is oxygen uptake. It is desirable to achieve the maximum possible oxygen uptake during fermentation within the limits set by the initiation of putrefactive changes. With a given volume of beans and certain specified drying conditions, once the maximum duration is defined there is little room for variation.

When conditions of low temperature and higher than normal acidity are obtained, fermentation can be safely extended with apparent advantage. The grower, however, wishes to operate to a routine and this possibility is not a source of great satisfaction. Experience at Keravat indicates that the prolongation of fermentation is not an effective substitute for the optimum conditions for normal fermentation.

There is an important interaction between duration of fermentation and the volume of beans being fermented. This is discussed below.

4. *Variation in Volume and Dimensions of Fermenting Mass*

These factors exert a powerful influence and are capable of producing radical changes in the mode of fermentation. The effects are obtained primarily through alteration of the rate of air penetration into the mass but also by changing the heat balance sheet.

Experience both in New Guinea and overseas indicates that a major factor in aeration is the depth of beans—not so much the length and breadth of the mass. Beginning for example with a mass of beans three feet deep, aeration improves as depth is reduced. The effect of this is to shorten the period of yeast dominance and to cause an earlier initiation of the acetic phase. This results in a more rapid and more uniform rise of temperature and, since the amount of alcohol produced is reduced, shallow ferments tend to be less acid than deep ferments. Nevertheless, bean death occurs somewhat earlier in shallow ferments. Fermentation is usually faster and more complete. A parallel effect of reduction in depth is the increase of the surface area of the mass in relation to its volume. Consequently heat loss by radiation tends to be greater and this becomes important when heat input by micro-organism activity falls off. Under New Guinea conditions, below a depth of 15 inches the loss of heat by radiation is excessive after three or four days of fermentation. In conjunction with the higher rate of aeration this quickly leads to putrefaction.

Shallow layers therefore have an advantage in the early stages of fermentation but have serious disadvantages in the later stages. The logical step of course is to begin fermentation in shallow layers and complete it in deep layers. This forms the basis of a proposed modification of the standard method of box fermentation presently being used in New Guinea. Details of this method (Method A) and the existing standard method are given in the succeeding article. The effects on acidity, temperature and pH of pulp and cotyledons are given in Figures I, II, III and IV.

If, at the same time as depth is reduced, the total volume is also greatly reduced, the problem of the onset of putrefaction becomes more marked. But, for the first three days, the effects of causing a rapid rise in temperature and reduced acidity are also more pronounced. The tendency to putrefaction can again be overcome by increasing volume as fermentation proceeds. Another method (Method B) has used this principle successfully. In this method, beans are fermented for three days in baskets each containing only 4 cubic feet of beans. These baskets are placed for three days in a "hot box" of black-painted corrugated iron in the sun. The beans are turned each day, one basket in the "hot box" remaining empty to facilitate this. While the method does not depend on it, solar heat aids the rise in temperature. After three days, the contents of 12 to 15 baskets are placed in a standard fermenting box and with daily turning fermentation proceeds for a further four days. The pattern of fermentation is more reliable than with "Method A". The process is again brought within a weekly cycle and this is important to the routine established by the grower.

The effects of this method on temperature, acidity and pH of pulp and cotyledon are shown in Figures I, II, III and IV.

Rohan and Allison (1958) have utilized the principle of fermenting in shallow layers to the limits of its capability with their method of tray fermentation. In this method, beans are placed in trays with slatted bottoms and measuring four feet by three feet by four inches deep. The trays are stacked one on top of the other in batteries of about twelve. The beans are not turned at all during fermentation, which continues for six days. Throughout fermentation, the stack of trays is covered by a tarpaulin bag or sacking to reduce radiation losses. This method overcomes the problem of excessive radiation losses from shallow ferments, but at the same time gives very much improved aeration. The method apparently works well in Ghana. It has been tried at Keravat and the results under these conditions have so far not been encouraging. The different performances of the method under Ghana and New Guinea conditions is probably due to the difference in pulp character mentioned earlier.

In trials with tray fermentation at Keravat, tiers of 12 to 13 trays were used and all specifications were followed in detail. Temperature development was irregular, not particularly rapid, and compared unfavourably with temperatures obtained by other methods developed at Keravat. A temperature of 45 degrees C. was obtained only after three days and then only in the top few trays. At this stage the bottom trays were still at 37 to 38 degrees C. This order of temperature in the lower trays was maintained throughout. The highest temperature recorded (48.5 degrees C.) occurred in the centre of the top tray on the sixth day of fermentation. The temperature gradient of 10 to 13 degrees C. from top to bottom trays is most undesirable. This gradient was quickly restored if the position of the trays was reversed.

In addition to the vertical temperature gradient, there was a less significant horizontal temperature gradient. Six inches in from the walls of the trays, the temperature was usually two to three degrees C. below that of the centre. The effect was more marked closer to the tray walls. This was reflected in altered conditions of pH and acidity. Putrefaction around the edges was evident on the fifth day and a four-inch band of beans was badly putrefied by the sixth day.

Beans withdrawn and dried before the sixth day became hard and flinty and showed a very high degree of purple or white pigmentation. Under New Guinea conditions, the necessity for turning or mixing obviously cannot be escaped. If this must apply to tray fermentation, the one big advantage of the method is lost.

5. *Frequency of "Turning" or "Mixing"*

This factor has been varied greatly in trials at Keravat. Very frequent turning in the early stages of fermentation (two or three times a day) has an advantage in causing more rapid temperature rise. The increased aeration favours the activity of the acetic acid bacteria. Frequent turning towards the end of fermentation depresses temperature and encourages putrefaction. In any case a variation requiring more frequent turning is largely impracticable owing to the greatly increased box capacity required.

In every method of fermentation used at Keravat, daily turning has resulted in a better temperature pattern and lower acidity than alternate daily turning (Bridgland and Friend, 1957). In boxes five feet by four feet by three feet deep, the loss of heat is surprisingly small. Temperature in the top half of the box invariably shows a steady rise immediately after turning and frequently shows a slight fall about 16 hours after turning. Temperature in the bottom half of the box frequently shows a drop soon after turning, followed by a steady rise up to the next turn 24 hours later.

6. *"Resting" Phase*

The term "resting phase" is used for want of a better one but it is not really satisfactory because the beans are in anything but a state of rest. Relatively little variation can be introduced by varying the factors noted above, with the exception of changes in the dimensions of the fermenting mass. By contrast, the use of a "resting phase" can produce radical variation in the behaviour of fermenting beans.

After breaking, the beans are allowed to drain overnight in a box and the resting phase begins at 6 o'clock the next morning. The beans are spread out thinly on a wooden floor in shade, the building being arranged to give

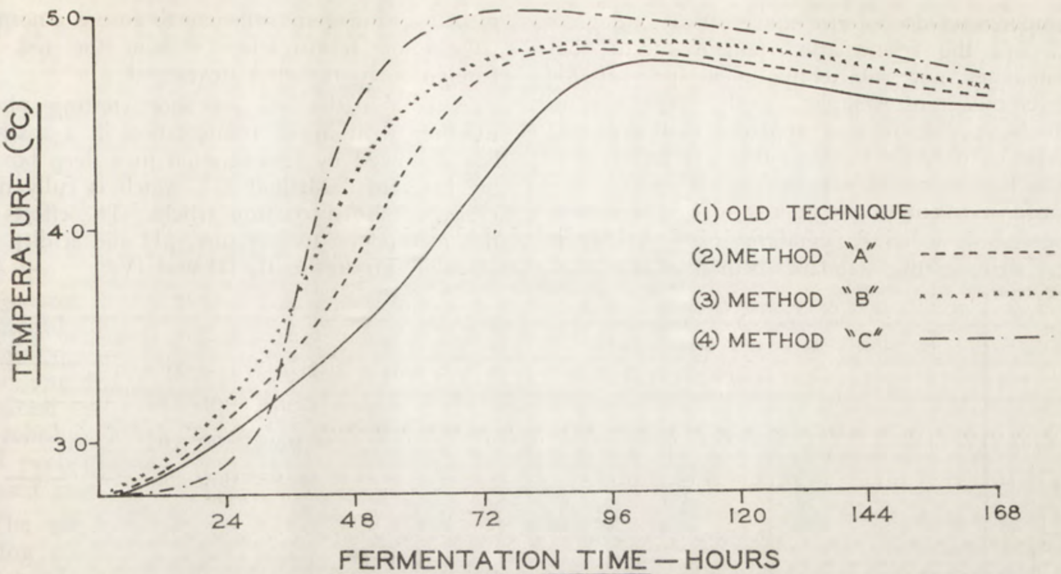


FIG. I.—Methods of fermentation—effects on temperature development.

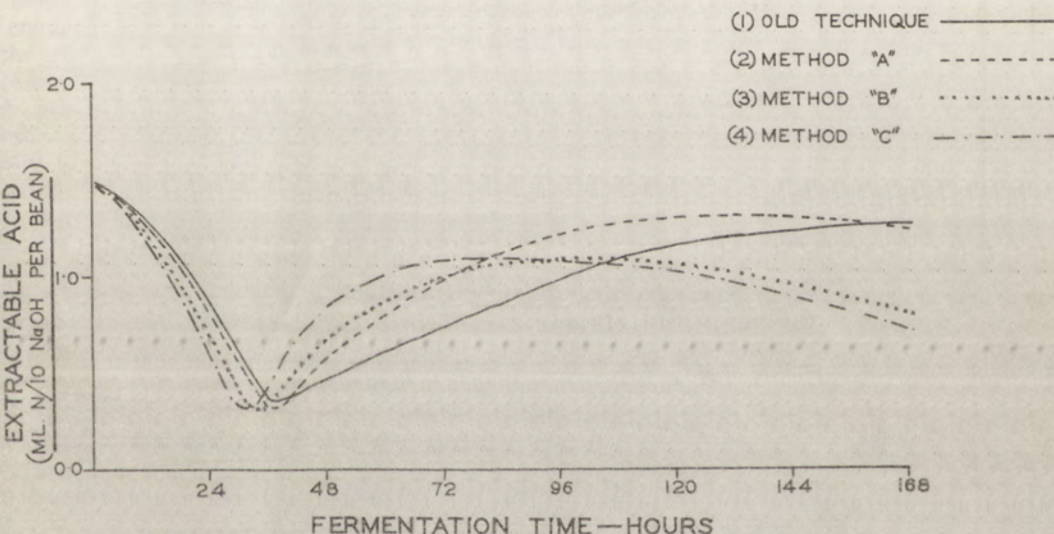


FIG. II.—Methods of fermentation—effects on acid development.

the maximum air-movement across the beans. From time to time, the beans are stirred by "walking".

The resting phase causes rapid maceration and shrinkage of pulp and removal of excessive moisture (Bridgland and Friend, 1957). This leads to greatly improved aeration during subsequent fermentation and a high temperature is developed rapidly. The fact that the level of acidity is depressed considerably indicates the removal of alcohol during the resting phase. The more prolonged the resting phase, the hotter and drier the atmospheric conditions and the thinner the layer of beans, the more pronounced become the effects noted above. With a 24-hour resting phase, temperatures may rise as high as 65 degrees C. by the end of fermentation and acetic acid is virtually eliminated. Foreign flavours are extremely common in this type of fermentation. With a 12-hour resting phase, temperatures do not rise above 50 to 52 degrees C. and the fermentation remains acetic, but sometimes not sufficiently so to prevent the development of a slight "earthy" character in the beans. It is now apparent that a resting phase of only six to seven hours is sufficient to give the improved aeration which ensures successful fermentation. Following this treatment there is a sharp temperature rise. Acidity is less than in the standard method of box fermentation but quite sufficient to ensure a normal pattern of fermentation without the risk of foreign flavours being developed.

A combination of a short resting phase together with initial fermentation in a shallow box followed by fermentation in a deep box is the basis of "Method C" which is fully described in the succeeding article. The effects of this method on temperature, pH and acidity are given in Figures I, II, III and IV.

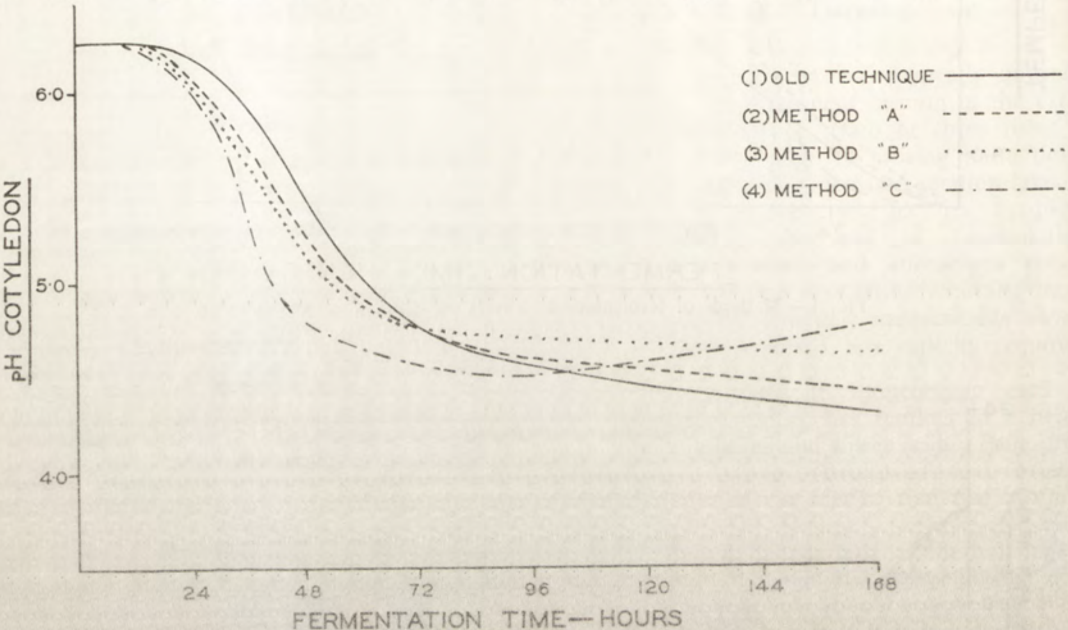


FIG. III.—Methods of fermentation—effects on cotyledon pH.

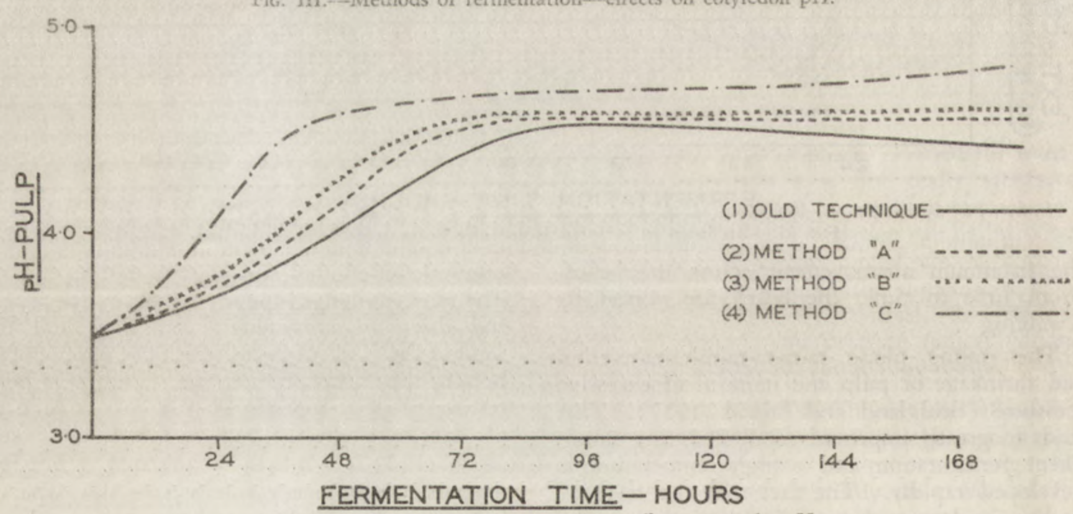


FIG. IV.—Methods of fermentation—effects on pulp pH.

It is apparent that after a long resting phase the pulp is sugar-deficient. It has been demonstrated (Bridgland, 1959, Bridgland and O'Donohue, unpublished), that it is possible to restore a considerably higher level of acidity by adding dextrose or sucrose to the beans at the end of a 24-hour resting phase, or later during fermentation. It would appear, therefore, to be possible to gain control of acidity, temperature and the period of viability by using sugar in conjunction with a resting phase. By this means it should be possible to control all the essential conditions required during fermentation. Encouraging results along these lines have been obtained recently at Keravat (Bridgland and O'Donohue, unpublished) but this approach will probably be ruled out because of the increased costs involved.

The effects of variation of duration of the resting place on temperature, acidity and pulp and cotyledon pH are given in Figures V, VI, VII and VIII.

Very little work has been carried out directly on the effect of a resting phase on microflora. A 24-hour resting phase probably favours the more aerophilic types of yeasts during this period. On return to the sweat boxes there appears to be normal but restricted activity of the acetic acid bacteria. With breakdown of acetic acid and rising pulp pH, fermentation enters the non-acetic phase and temperatures rise to 60 degrees C. or higher. Cultures on yeast-mannitol agar at this stage produced profuse and rapidly growing colonies consisting of large rods, provided culturing was carried out at a temperature of at least 55 degrees C.

As the duration of the resting phase is reduced, the microflora approach "normality". However, when the resting phase is only six to seven hours it is probable that the phase normally dominated by lactic acid bacteria is eliminated.

7. *Ventilation and Insulation*

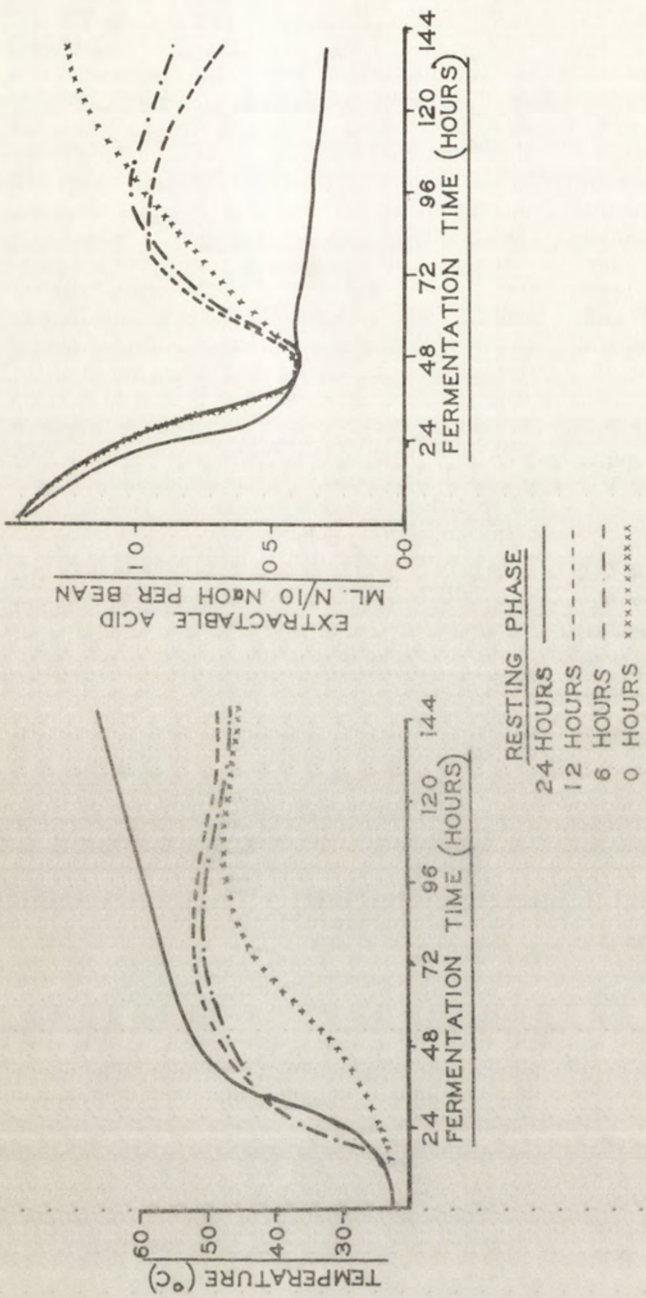
Early trials involving the lining of sweat-boxes with polythene sheeting have been described elsewhere in this article. In these trials, the boxes were lined from the beginning of fermentation and "dead ferments" were produced. The results were disastrous.

In subsequent trials (Bridgland and O'Donohue, unpublished) sweat-boxes were lined with polythene sheeting after the temperature of the mass had risen to 50 degrees C. When the treatment was sustained for 48 hours with a "turn" after 24 hours, there was a steady fall in temperature (10 degrees C. over 48 hours) and a substantial increase in the level of titrable acid. When the treatment was applied for periods of 24 hours on alternate days, the temperature pattern (in time) was not significantly affected, but the tendency for beans in the bottom of the box to show a sharp fall in temperature after a "turn" was eliminated. Two periods of 24 hours in polythene on alternate days maintained a steady and even temperature pattern and caused a noticeable rise in acidity. The technique may be of significance to the inhibition of putrefactive tendencies where fermentation is prolonged or when the level of acidity is low. However, beans tend to develop an odd "carbolic" odour when boxes are lined with polythene. It is by no means certain that the acid developed is acetic acid and the use of polythene sheeting must be viewed with suspicion.

These trials give yet another indication of the controlling influence of aeration and suggest means of preventing ill-effects produced late in fermentation by greatly increased aeration early in fermentation.

The results of Roelofsen and Giesberger (1958) indicate that air ascends through the mass of beans. Work at Keravat fully supports this conclusion. Cool air is taken in through the bottom of the box. During the first three days of fermentation, when micro-organism activity is at its peak, this results in a rise in temperature of the beans at the bottom of the box and a more marked temperature rise in beans at the top of the box. Subsequently, air intake at the bottom of the box has a cooling effect on these beans, while beans at the top are maintained at high temperature. The insertion of a plywood baffle, with no holes, to cover completely the bottom of the sweat box after the third day of fermentation greatly reduced the vertical temperature gradient in the beans. The level of ventilation in the bottom of the sweat boxes was evidently of considerable importance.

Experience at Keravat indicated that there was also air intake through the sides of the box. It is not a point which has been established


TEMPERATURE (°C)
60 50 40 30
FERMENTATION TIME (HOURS)
24 48 72 96 120 144
EXTRACTABLE ACID
ML. N/10 NaOH PER BEAN
1·0 0·5 0·0
RESTING PHASE
24 HOURS
12 HOURS
6 HOURS
0 HOURS
pH COTYLEDON
6·0 5·0 4·0
pH PULP
5·0 4·0 3·0

but it would appear that air intake through the sides can lead only to inequalities in aeration in the mass. The point will be checked.

On certain estates in Trinidad, the sweat-boxes are double walled and the intervening space is packed with insulating material. The order of advantage obtained by this procedure is not known.

Trials conducted at Keravat involving the insertion of perforated bamboo tubes into the mass both horizontally and vertically appeared to produce no significant variation in the course of fermentation. They appeared to act as flues through which heat could more readily escape.

8. *Added Chemicals and Water*

The idea of adding chemicals to fermenting beans to produce desired changes is one which has always had great appeal to research workers. It has been approached mainly on the basis of the false assumption that the presence of acetic acid is detrimental. With the object of prolonging the alcoholic phase and eliminating the acetic phase, efforts have been made to prolong the period of yeast dominance and eliminate the acetic phase. Success in achieving this has been reported from several sources, but the results have been such that they can be dismissed as irrelevant.

Work at Keravat is in accord with the view that acidity can be, and frequently is, excessive. Our object is to reduce acidity but not eliminate it. The use of sugar in conjunction with a resting phase as a means of manipulating acidity has been described above.

References are occasionally seen to the addition of water to fermenting beans. Dr. Quesnel has informed the writer that it is a common practice in Trinidad, where about four gallons of water are added after each turning to each 1,000 lb. of wet beans. The object of this treatment is to reduce acidity. The theory is that, as acetic acid is derived from the heat-producing oxidation of alcohol, reduced aeration due to swelling of the pulp will necessarily cause a reduction in both temperature and acidity.

Under standard conditions of fermentation in New Guinea, the reduction in acidity following the addition of water is only temporary. The final effect is to increase the level of acidity and depress the temperature curve. The treatment accentuates rather than solves the problem (Bridgland and Friend, 1957). It seems that under New Guinea conditions any measure which leads to more anaerobic conditions causes a rise in acidity.

Where a resting phase of 24 hours is used, aeration during subsequent fermentation is greatly increased. Moisture in the pulp is also very greatly reduced and it appears possible that this radical alteration in the moisture balance may be unfavourable to the growth of acetic acid bacteria. Trials carried out by Bridgland and O'Donohue (unpublished) showed that under these circumstances the addition of about ten gallons of water at 55 degrees C. per 4,000 lb. wet beans on the fourth day of fermentation did lead to a significant increase in acidity, but did not cause significant alteration in temperature.

9. *Artificial Inoculation*

It is not worth reviewing the work on this subject. Results of work both overseas and at Keravat have produced nothing significant. The general conclusion is that control of micro-organisms can be effected only by controlling conditions. Given the right conditions, the micro-organisms will look after themselves.

CURING/DRYING PROCESS

The handling of cocoa involves a sharp break in technique between so-called "fermentation" and so-called "drying". There should not, however, be a corresponding break in the processes taking place within the bean. That "drying" involves more than dehydration has often been repeated and it is a truism which cannot be repeated enough.

Rohan (1957) has shown that if beans are removed from fermenting heaps to the drying trays at the moment of, or soon after, bean death the breakdown of anthocyanins (strictly part of the "Anaerobic Hydrolytic Phase") continues for some time. Presumably this reaction could proceed only until inhibited by intermediates of the oxidase reactions. This anthocyanin conversion during drying is scarcely a matter of practical importance to the New Guinea grower. For reasons which have already been given, the anthocyanin conversion will be completed during fermentation proper, long before drying commences. Under field conditions, methods of drying need not be considered in relation to this reaction.

Of far greater importance is the fact that the "Oxidative Condensation Phase", which begins during fermentation, can and must continue during the drying process. Apart from removal of moisture, this is the most significant factor to be considered—hence the term "Curing/Drying" is preferred to "Drying". Besides the direct influence of the oxidative changes on final quality, there are other effects tied up with the rate of dehydration. It has been shown by Powell and Wood (1957) that rapid drying results in a higher content of volatile acid. The effect implied is that there is a greater loss of acetic acid by volatilization with slow drying than with fast drying. The tendency of the broken-down pulp to putrefy is bound up with its moisture content. Extremely slow drying can thereby result in the development of earthy and foul flavours in the bean. It is usually a matter of good judgment to dry at a rate which will permit the necessary oxidative changes to take place and yet inhibit the growth of putrefying organisms.

The loss of moisture and progress of oxidative changes are accompanied by obvious physical changes in the bean. Before any significant amount of oxidation has occurred during fermentation, the beans have a "crisp-wet" cut. There is considerable softening by the end of fermentation. After one day's sun-drying the beans have a much softer cut and after two days they have a soft, rubbery consistency. With further drying the texture becomes "leathery" and finally the cut is "crisp-dry". These changes of texture follow oxidative changes and variations in moisture content. The "under-fermented" or under-oxidized bean becomes cheesy instead of rubbery and after drying the cut remains "hard-cheesy".

These changes are necessarily related to "browning" and the development of the characteristic open texture of a well-fermented bean. Beans at the end of fermentation show varying degrees of browning and the cotyledons should show significant separation. At the end of fermentation, cotyledons can be fragmented between the fingers much more readily than in fresh beans. At the soft rubbery stage, the cotyledons show considerable opening-up and browning. By the leathery stage, the texture is almost that of a fully-dried bean and the cotyledons are, or should be, almost completely brown with perhaps a slight residual purple or whitish cast. From this point onwards, "drying" becomes a simple matter of dehydration.

As moisture is lost from the bean, there is a marked reduction in volume. Not only do the cotyledons shrink but the testa also shrinks about the cotyledon. Measurements by Bridgland and O'Donohue (unpublished) show that there is a 38 to 45 per cent. total reduction in the volume of a mass of beans during drying (see Table II). This reduction is largely accounted for by bean shrinkage but comparison of volume determinations by count per cubic foot against actual displacement shows that of the 38 to 45 per cent. total reduction in volume about three per cent. is caused by reduction in "pore-space" between beans and 35 to 42 per cent. by reduction in individual bean volume. The variation in loss of volume is due to variation in fermentation. With good fermentation beans remain "plumper" and the loss of volume is reduced.

TABLE II.

Reduction in Volume during Fermentation and Drying

Stage	No. Beans/Cu. Ft.	Reduction in Volume
	(approx.)	(per cent.)
Ex-pod	7,000	....
End fermentation	7,650	5 (approx.) (1)
End drying	13-14,000 (2)	43-50

(1) Probably entirely due to maceration of the pulp.
(2) After rotary drying.

1. *The Problem in New Guinea*

Under New Guinea conditions, the problem is usually one of insufficient oxygen uptake. However, abnormally long fermentation and very slow drying do result in over-oxidation and loss of flavour. This effect is accentuated as batch size is reduced. Of more importance to the manufacturer than the loss of chocolate flavour, however, is the fact that such methods invariably result in foetid or foul flavours, which are intolerable.

De Witt (1952) has drawn attention to the fact that in cacao-producing countries generally there is an inverse relationship between fermentation time and drying time. The shorter the fermentation, the more prolonged the drying and vice versa. This can be explained simply in terms of oxidation. The greater the extent of oxidation by the end of fermentation proper and the more susceptible the bean to oxidative changes, the shorter the drying time can become without detriment to quality. Under the best conditions of fermentation yet devised to suit local conditions, a drying time of not less than four days is required to give the necessary level of oxidation.

The economic implications of this are considerable. Evidently the output from a given fermentary set-up could be quadrupled if drying could be accomplished in one day, assuming that the drying equipment available had a capacity equal to the daily discharge capacity from the fermenting boxes. As the amount of capital invested in fermenting boxes, etc., in relation to their potential output is considerably less than the amount involved in hot-air driers, there would be a considerable saving if fermentation were such that rapid drying would not be detrimental to quality. Work along these lines is proceeding.

Further work with the object of accelerating the rate of oxidative changes during drying is continuing. No very significant results have yet been obtained and no alternative to four-day drying has been found. This is at variance with results obtained by Wood (1957) and with techniques used by Mokaria Plantation in the Belgian Congo and by the United Fruit Company in Costa Rica. In trials conducted by Wood in Ghana, using a modified "Chula" drier, drying was completed in 15 to 24 hours. Sun-dried controls were kept. The conclusion reached was that there was little to choose between sun-dried and machine-dried beans. "The artificially-dried beans had a rather brighter coloured testa", Wood reported. " . . . the nib was dark chocolate brown, there was no sign of brittleness nor were the beans any more wrinkled than normal West African Beans". The writer has observed similar results at Mokaria Plantation in the Belgian Congo where drying is completed in 18 to 22 hours using the "Buttner" dryer. The trials in Ghana followed fermentation in 1,200 lb. lots of wet beans for six days. At Mokaria, much larger boxes were used and fermentation proceeded for nine days.

It is re-emphasized that such rapid drying in New Guinea has given disastrous results. Most of the beans failed to become sufficiently brown and remained cheesy in texture. The different results are probably due to the fact that oxidative changes by the end of fermentation have normally gone further under West African conditions and, more important still, oxygen uptake during the early stages of drying probably proceeds much more rapidly with the thinner-shelled Amelonado beans than with the New Guinea Trinitario (the shell percentage of which is some four to five per cent. higher). Finally, the writer is not at all satisfied that such drying methods do not interfere with flavour development. When trials are conducted over a full cropping season and the results evaluated by a representative panel of manufacturers, the results claimed can be accepted, but in any case great caution is necessary in dealing with Trinitario beans where rapid drying results in a marked weakening of chocolate flavour.

2. *Interrupted Drying/"Post-Fermentation"*

Consideration of the question of increasing the output of artificial driers and thereby reducing costs, raises the question of "post-fermentation". This term is not a good one. It sometimes refers to a "special oxidation period" or "interruption" before or during the normal course of drying. Alternatively, it is used to cover the re-processing of dried beans with a view to causing further oxidation.

As far back as 1908, Schulte-im-Hofe developed a method by which, in the course of drying, partially-dry beans were placed in a box overnight. In this overnight period, moisture loss was prevented and heat was said to have developed and this aided the oxidation process. It was claimed that more browning and better flavour resulted from this procedure. Since then, the method has been elaborated in Venezuela (Vyle, 1949), and in Samoa (Eden, 1953), but the principle remains the same. These techniques are very good and very useful. An interruption of drying is not necessarily costly because the drier can be used for other batches for the period of the interruption and a bottleneck in production can be avoided. Interrupted drying is recommended in the succeeding article as a means of increasing the potential output of hot-air driers. Total drying time, including an interrupted period of two days, extends over a minimum of four days. Thus, actual drying facilities need be occupied by a given batch for only two days. In this way, a compromise is reached between the necessity for slow drying and the high cost of using a given drier continuously on the same batch over a long period.

Methods of "reconditioning" dry beans, implying retreatment to promote further oxidation have been suggested and tried ever since 1818. Presumably, if the enzymes are not destroyed during drying, itself a very doubtful point, there may be some possibility of doing this, but it is not a question which need concern us here. The only object worth pursuing is to process the bean properly in the first instance and this obviates any necessity for re-processing. "Reconditioning" can only result in reduced returns to the grower. The possibility of reducing skin percentage and improving the external appearance of beans by appropriate methods of "reconditioning" is not questioned, but real gain in quality is unlikely to occur.

"Post-fermentation" or a "special oxidation period" used before drying is completed circumvents the problem of oxidation without actually increasing its rate. However, since these methods involve more handling and more supervision, they are not entirely satisfactory.

3. *Rate of Oxidative Changes*

Limitations on the extent of oxidative changes occurring during fermentation have been discussed above. It was noted that information on the optimum pH for activity of polyphenol oxidase is lacking but experience indicates that browning is more rapid as pH rises from four to above five. Conditions of low pH at the end of fermentation are common in New Guinea where the old standard method of box fermentation is used. Very little can be done about this until beans are removed from the sweat boxes. Roelofsen and Giesberger (1958) have found that fermented beans steeped in water containing calcium carbonate brown more completely than beans steeped in plain water. Such trials are to be repeated at Keravat.

Observations noted above regarding the temperature optimum for the activity of the enzyme polyphenol oxidase are not very helpful, but apply as much during drying as during fermentation.

Moisture content of the beans is a controlling factor during drying. Knapp (1937) states that activity of the cacao oxidase falls off rapidly below a moisture content of 20 per cent. Under New Guinea conditions, rapid removal of moisture greatly increases the percentage of underfermented beans. This means that rapid drying must either interfere with oxygen uptake by the bean in the early stages of drying or the enzyme must be inactivated by dehydration before sufficient oxidation has taken place or the explanation could be in a combination of these factors.

4. *Oxygen Penetration of Testa*

It has already been noted that oxygen uptake during fermentation is likely to be limited mainly by the barrier imposed by the testa. This applies with even greater emphasis during drying. The greater proportion of oxygen uptake apparently occurs during drying, although the mechanism of this is not understood.

Superficially, it appears that oxygen has to enter the bean against an outward moisture flow during drying. Whether it enters in solution or the gaseous phase or both is not known. Roelofsen (1958) claims that, in the early stages of drying, loss of moisture is balanced by shrinkage of the testa and cotyledon tissue and concludes that there is no tendency for air to be drawn into the bean until the final stages of drying are reached. By this time, the enzyme would be inactivated by dehydration. He further concludes, therefore, that the oxygen effective in causing browning must enter the bean in solution in the early stages of drying, and that the gas phase plays no part in the "browning" reactions occurring during drying. This interpretation of events may be partly true—it would probably be quite true under conditions of short fermentation or very rapid drying. It is certainly not argued that oxygen cannot and does not enter the bean in solution during the early stages of drying, but the writer believes that Roelofsen's theory does not cover all observations. It should be understood, however, that these arguments are theoretical and there is little relevant evidence available.

Using an analogy, Roelofsen states that if the cotyledon tissue were rigid like wood any water evaporated from it would immediately be replaced by air. He showed convincingly that the central parts of the bean contained more water than the outer parts and claimed that these central parts showed correspondingly higher shrinkage during drying. It was concluded that, as drying proceeds, the bean, unlike a rigid ece of wood, would show overall shrinkage ıd as dehydration proceeded further the central ırts would shrink more than the outer parts. loisture lost would not be replaced by air to ıe same extent as in the piece of wood. The ifferential shrinkage would result in a suction orce developed at the centre of the bean. This ould be resisted by a plump bean owing to its ıore spherical configuration, but not by a bean hich was originally flat. Such a bean would ınd to "cave-in" during drying and no central ıvity would be formed. On the other hand, bean which was originally plump and which ould resist the suction force would develop a ıntral cavity on drying. Air would necessarily e drawn into the bean but at this stage the xidase enzyme would be inactive because of ehydration.

This hypothesis does not explain why dried nfermented beans, while showing considerable verall shrinkage, fail to develop anything like normal cavity whether they are flat or plump o begin with. Nor does the theory explain why all "flat" beans are not "caved-in" nor why such beans frequently do develop an interıal cavity. On the other hand, the theory gives good explanation of why it is easier to 'brown" plump beans than flat beans.

Roelofsen's conclusions are based on a moisure gradient from the outer cotyledon tissue to he central tissue noted after two days' fermenation. For this short fermentation his concluion that browning during drying is largely due o the penetration of oxygen in the dissolved tate is probably valid.

As fermentation is prolonged to six days or more, cotyledon tissue shows progressive shrinkıge. This shrinkage is largely away from the entre of the bean. After two days' fermentaion the cotyledons show some slight and irregular separation. After six days the cotyledons may have separated by as much as a millimetre. This suggests a steady extrusion of moisture from cotyledon tissue during fermentation, and this is supported by observation. After six or seven days' fermentation the moisture gradient may have almost equalized. At all events, the central cavity, or at least large central interstices, are usually formed before drying commences and in reality loss of moisture must be considered in relation to two separate halves rather than from a single cotyledon unit.

The removal of moisture from the bean during drying should be considered in two phases, firstly, the removal of free moisture held within all interstices and, secondly, the removal of moisture from cotyledon tissue. The moisture content of cotyledon tissue will scarcely be affected until all free moisture is removed. Removal of free moisture may be reflected by shrinkage of the testa but not the cotyledon tissue. Shrinkage of the testa will be resisted to some extent by cotyledon structure, regardless of its shape, and there will be a tendency for air to be pulled into the central interstices of the bean as moisture is evaporated and before the moisture content of cotyledon tissue shows a significant fall. The more pronounced the interstices and the greater the content of free liquid, the greater the tendency to pull air into the bean.

Under these circumstances, oxygen in the gas phase would be of paramount importance in promoting browning quite apart from the effects of penetration of dissolved oxygen. It is a matter of common observation, at least under New Guinea conditions, that when beans are placed on the drying floor there is usually a brown ring of outer cotyledon tissue due to oxygen penetration in the dissolved state during fermentation. After a six-day fermentation, the browning which occurs during drying does not represent a continuation of this effect. A significant increase in browning first becomes evident about the radicle channel and then extends to the centre of the bean and outwards along folds in the cotyledon tissue. The soft-celled radicle shows the greatest apparent differential shrinkage subsequent to the evaporation of free moisture. Observation on the course of browning suggests that air is drawn into the bean along the radicle channel, the tip of which coincides with the thin, spongy testa tissue at and around the hilum.

This will occur only if there has been adequate shrinkage of cotyledon tissue during fermentation. Otherwise Roelofen's theory will operate, a suction force will be developed, flattish beans will cave in and air intake and browning will be inhibited unless drying is so slow as to permit sufficient uptake of dissolved oxygen.

In the normal course of drying, provided that large liquid-filled central interstices have developed by the end of fermentation, air will be drawn into the bean to replace moisture loss and browning will be rapid and complete. This generally seems to be a more acceptable explanation than postulating the penetration of oxygen in the dissolved state in the opposite direction to the flow of moisture.

As drying proceeds, cotyledon shrinkage would be expected to take place more or less uniformly and the internal cavity would become "fixed" whether the bean was plump or flattish to begin with. Shrinkage would take place both towards and away from the imaginary central point in the bean. A suction force about the imaginary central point would not be developed.

As a theory, this explanation closely fits the observed facts and explains the reason for the widespread inverse relationship between fermentation time and drying time. The important divergence from Roelofsen's theory is the rationalization of the uptake of oxygen in the gas phase before the enzyme polyphenol oxidase is inactivated by dehydration.

The theory assists in explaining the divergent results obtained from rapid drying under varying conditions. If there has been sufficient preliminary shrinkage, rapid drying will not be expected to cause "caving-in" or to interfere unduly with browning. But if this is not the case, rapid drying will cause "caving-in", prevent further air intake, inhibit browning and shrunken "under-fermented" (or "under-oxidized") beans will result. This has usually been the result of rapid drying in New Guinea.

The theory has considerable significance in explaining the presence of purple beans. If the normal shrinkage of cotyledon tissue during fermentation runs parallel with anthocyanin destruction, then incomplete destruction can be expected to lead to the occurrence of purple beans even though the anthocyanins themselves are susceptible to oxidation. Their presence would be a symptom of inadequate shrinkage by cotyledon tissue. Both Roelofsen and the author have noted that this effect can be overcome by piercing. This removes the possibility of a suction force developing even if there has been little cotyledon shrinkage at the time of piercing. In terms of air penetration, piercing at an early stage of fermentation achieves much the same result as prolongation of fermentation, but more rapidly.

The theory is also relevant to the question of accelerating oxidation. Work on this question would be assisted if the mechanism of oxygen penetration of the bean were understood.

Whether the above theory is tenable or not, other factors which may influence the rate of oxygen penetration are the permeability of the testa and temperature. Efforts to increase the rate of browning by varying drying temperature have so far led to no significant results. In these trials a rotary drier is being used with provision for the recirculation of moist hot air; in this way, the effects of higher temperature are not obliterated by the faster drying time. This work is still in its early stages and is continuing.

Efforts to vary the permeability of the testa have given more promising results but there are serious disadvantages in methods which have so far been tried. In one series of trials at Keravat (Bridgland and O'Donohue, unpublished), fermented beans were steeped in water at 25 degrees and 55 degrees C. for five and 60 minutes. Some were thoroughly washed and all were then rapidly sun-dried in four days.

It was found that steeping in water at 55 degrees C. for 60 minutes and thorough washing resulted in what to the trade would be a significantly higher proportion of brown beans (improvement of 44 units on our method of scoring or a difference of 11 per cent.). The beans which were steeped in water increased in volume (plumpness) by seven per cent. whereas the washed beans, although quite plump, decreased in volume by eight per cent. The loss in volume in washed beans is thought to be due to the removal of all pulp, plus the outer layers of the testa, and perhaps to greater total shrinkage but without "caving-in". With both treatments there was a reduction in shell percentage amounting to approximately 4.5 per cent. with the washed beans and 2.5 per cent. with the beans steeped in water for an hour at 55 degrees C. The beans steeped in water were more brittle than the controls, but not to the extent where this would be of practical importance. On the other hand, the beans which had been washed were extremely brittle.

Steeping for one hour at 55 degrees C. caused a lowering of cotyledon acidity (pH 4.94) compared with steeping for five minutes at 25 degrees C. (pH 4.75). The pH of washed beans remained unaltered (pH 4.76). As the washed beans dried out much faster than the others, this may simply be a rate of drying effect.

Taken overall, steeping at 55 degrees C. made considerably more difference than steeping at 25 degrees C. and steeping for one hour had a greater effect than steeping for five minutes. The effects of the various treatments on flavour have yet to be determined.

The above results are in substantial agreement with those of Roelofsen (1958) who found that steeping beans in water for two hours before drying yielded plumper and browner beans. The effect was attributed to an increase in shell permeability as a result of loss of soluble matter.

Steeping involves more equipment, more handling and more supervision. Washed beans also have the serious disadvantage of being very brittle and will not ship without considerable shattering. This is not regarded seriously by those manufacturers using continuous roasters, but is regarded as a major defect by the majority who are still using drum roasters. "Steeped" beans are not so brittle as washed beans. More work is required before the value of these techniques can be properly assessed.

Mechanical factors may play a part in limiting oxygen uptake by the bean. Where beans are dried entirely in a rotary drier, experience at Keravat suggests (but this is not certain) that the smearing action by which pulp becomes uniformly distributed over the bean tends to seal the bean against oxygen penetration and leads to a slightly higher proportion of under-fermented beans. This effect was accentuated by adding a small quantity of odourless oil to the fermented beans. This was done with the object of preventing clogging and in this it was successful, but the practice cannot be recommended in any form.

In the course of work described above, it has unfortunately not been possible to carry out detailed micro-biological and chemical investigations. It is hoped that this will be rectified at some future date.

It must, however, at least be evident that the processing of cocoa beans, while involving only simple principles, is quite complex in the interplay of controlling factors. "Hit or miss" methods have been used in the past and at best these methods give only partial development of the flavour potential of cacao beans. We require methods that will develop this potential fully. The best methods recommended in the succeeding article are not perfect but they go a long way towards achieving this object. This paper will have served its purpose if the grower is convinced that the fermentation and drying of cacao are matters worthy of infinite care and attention.

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Plates 1 and 2 were kindly provided by Cadbury-Fry-Pascall Pty. Ltd.

GLOSSARY OF TERMS

It has been impossible to avoid the use of technical terms in this article and the brief notes given below may assist growers who have a more detailed interest in the process of curing.

Anaerobic.—Indicates absence of oxygen in any set of conditions, as distinct from "aerobic" where oxygen is present.

Anthocyanins.—A general term covering a large group of glycosides occurring in nature as plant pigments.

Chocolate Flavour Score.—In trials at Keravat, skilled "tasters" employed by manufacturers are asked to award a score on the strength of chocolate flavour according to the following scheme :—

No chocolate flavour	1
Weak chocolate flavour	2
Fair chocolate flavour	3
Good chocolate flavour	4
Very good chocolate flavour	5

Condensation.—The reverse process to a hydrolysis, i.e., the linking of two or more molecules with the elimination of water. Such reactions are frequently catalysed by enzymes.

Cotyledon.—The intricately folded and interlocked, fleshy primary leaves which account for the greatest part of the bean. This tissue, which is referred to as "nibs" in dry cocoa, contains the substances which are responsible for the development of chocolate flavour. They are white in the case of Criollo beans and purple in the case of Forastero beans. The embryo tissue is not pigmented.

Criollo/Forastero.—Two terms covering the two main types of cacao. Since the proportion of the various polyphenolic substances are different in the two types, they yield different flavours on processing.

CO_2.—The gas, carbon dioxide.

Chromatography.—A fairly recently developed and very useful analytical technique by which complex mixtures or organic substances can be separated.

Ethanol.—Ethyl Alcohol.

Enzyme.—Complex organic compounds which catalyse a great number of chemical reactions occurring in organic tissues.

Fermentation Score.—After drying, beans are cut and divided into five categories which are weighted according to the extent of purple or white pigmentation as follows :—

Per 100 beans—

(1) No. Wholly purple or white beans—X4

(2) No. beans 75 per cent. purple or white ....—X3

(3) No. beans 50 per cent. purple or white ....—X2

(4) No. beans 25 per cent. purple or white ....—X1

(5) No. wholly brown beans .... —

TOTAL—Fermentation Score

A completely unfermented sample would thus score 400 and a completely brown sample would score 0. Experience shows that the strongest chocolate flavour is associated with a score of 40 to 80.

Glycoside.—Compounds formed by the combination of one or more sugar molecules with other substances, frequently polyphenols and tannins. An anthocyanin is one such example.

Hydrolysis.—A type of chemical reaction catalysed by a large group of enzymes and involving the addition of the elements of water to a molecule with consequent separation of the latter into two or more simpler molecules.

Polyphenols.—A broad term used in this article to cover a complex group of substances with a similar basic structure, including the pigments (anthocyanins), tannins, etc. Non-glycosidic polyphenols are those to which no sugar molecules are attached. When the glycosides are hydrolysed and the sugar molecules split off the parent molecule, polyphenol aglycones are formed.

Precursor.—" Precursors " of chocolate flavour do not give chocolate flavour as such. The " precursor " is the building block from which the compounds with actual chocolate flavour will be developed.

Radicle.—The primary root. This lies between the cotyledons towards one end of the bean.

Testa.—The skin of the bean.

Titrable Acid/pH.—" Titrable Acid " refers to the total amount of acid present. " pH " is a measure of the degree or intensity of the acidity or alkalinity of a solution. Low pH means high acidity. At pH 7.0 a solution is neutral. High pH means high alkalinity.

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Figure 1: Yields of Palms in New Ireland Field Trials.

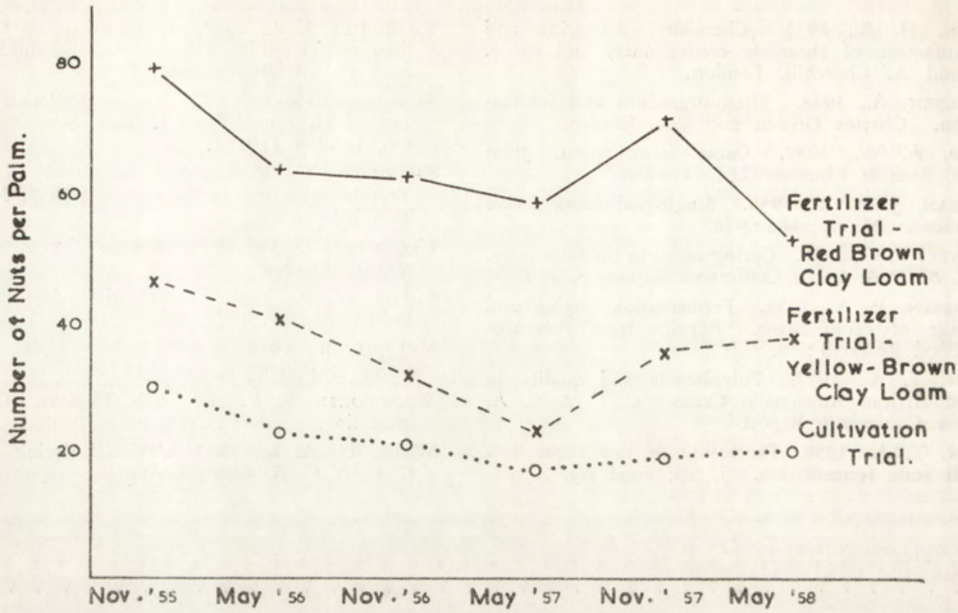
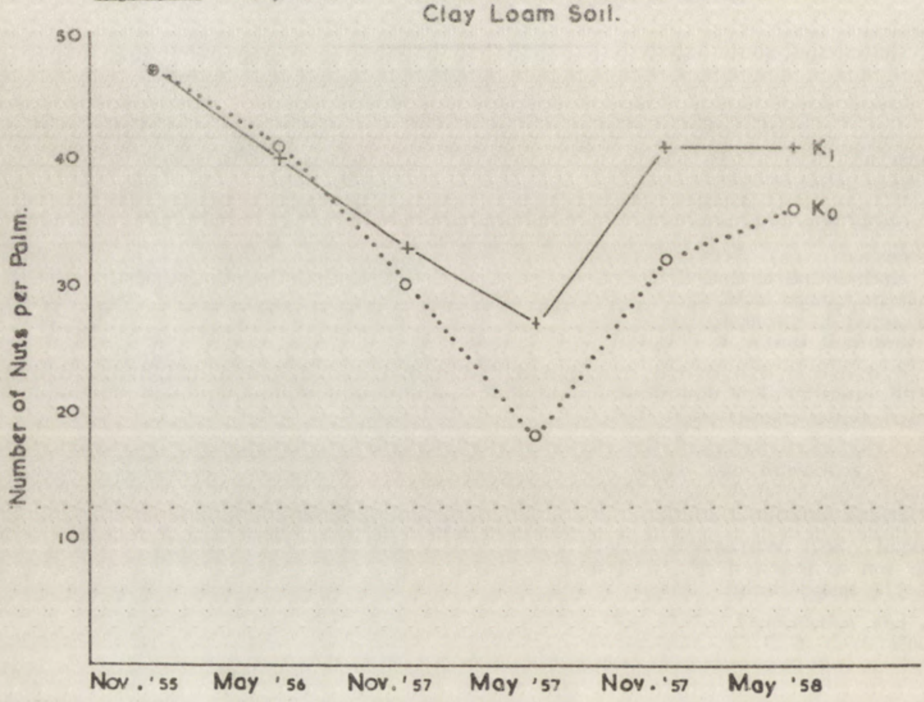


Figure 2: Response to Potassium of Coconut on Yellow-Brown Clay Loam Soil.



Coconut yield figures in New Ireland trials [see "Coconut Experiment Work in New Ireland, Part II"—"Progress report on field trials" (Vol. II, No. 4)].