THEORETICAL ASPECTS OF THE CONTINUOUSLY VARYING SCHEDULE PROCESS FOR TIMBER DRYING

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INNOVATION OF THESIS

The candidate to the best of his knowledge stipulates that the work presented in this thesis is an original research relating to the Continuously Varying Schedule (CVS) drying process of timber and the development of a circuit layout for air flow measurements. Any information used or derived from other sources has been acknowledged in the text.

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ABSTRACT

Drying of timber increases its durability and strength. Therefore, timber should be dried to a moisture content close to the equilibrium moisture content it will attain in service. The drying of timber from its natural green state to the required moisture content is thus an important part of the production cycle. Hardwood species, due to their macroscopic structures, are more difficult to dry as compared to softwood.

A great deal of research has centred in recent years on developing a fast drying process for softwood; on the other hand, there is a need for a process to dry hardwood rapidly. A new drying technique, called Continuously Varying Schedule (CVS) was recently developed by the author for the purpose of rapidly drying the medium to high density hardwood.

The investigation described herein was carried out to compare the CVS process with the conventional drying process. The factors compared were drying time, quality of timber produced and the energy consumed.

It was found that the CVS process reduced the drying time by 34.5% and saved 30.7% of the energy. It produced also, a competitive dried timber quality. The process achieved highly efficient drying, as the rate of drying (MC%/h x 100) was 80.3% higher than the conventional process and also, the amount of water evaporated per unit of drying time (g/h) was 67.1% higher. The CVS drying performance has achieved a 71.9% increase in the amount of moisture content reduced per unit of energy (MC%/kWh x 100) and a 57.8% increase in the amount of water

evaporated per unit of energy (g/kWh) as compared to the conventional process.

Much emphasis was placed on energy saving in the drying plant and it was suggested that a heat exchanger be used to recover waste energy from the exhausted air of the kiln. A dehumidifier coupled to a solar-powered system, backed up with an electric or wood waste booster, was recommended as a low-cost energy drying plant. An alternative source to the petroleum-based energy was also discussed.

The study of air flow through the timber stack in the kiln was a major part of this investigation as it is one of the principal features of the CVS process. A new technique was developed to measure the air velocity and the turbulence level %. The technique involves the integration of a hot wire anemometer, data logger, computer and computer peripherals. The air velocity profiles for twelve fan speeds, between 400 and 2200 rpm, were drawn by a computer graphical program, using data collected by the above circuit. It was obvious that the boundary layer which exists around the timber surface at the low air velocity protects the timber being processed against the high and continuously increasing temperature during the CVS drying process.

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INTRODUCTION

Wood, which has an organic, natural origin, is a renewable resource for structural material. Wood is a fascinating but complicated material, hence, it may be well to give a brief account of its nature and of those characteristics which affect the drying process.

Wood is classed as hardwood and softwood, the former derived from the broad-leaved trees and the latter from cone-bearing, needle-leaved trees. A mature tree of either the hardwood or the softwood class generally consists of a single stem which is covered with a layer of bark. This central trunk is the principal source of woody material which produces timber for structural purposes.

The growth and development of a living tree depend on the movement of water from roots to leaves, where food is manufactured by photosynthesis. The dissolved food produced is then moved to the areas where wood growth is taking place. As a result, the presence of large quantities of water in a tree is a natural and necessary condition for its life. When the tree is felled and sawn, it yields timber, which also contains water. This water is known as the timber's moisture content (MC) and is expressed as a percentage of the timber oven dry weight. The oven dry weight is used as a basis because it is a constant amount.

$$MC\% = \frac{\text{Initial weight of timber} - \text{Oven dry weight}}{\text{Oven dry weight of timber}} \times 100$$

In general, boards may be sawn from logs in two distinctly different ways. Back-sawn boards are also known as plain or flat sawn where the wide faces of the board are roughly tangential to the annual growth and at right angles to the rays. In practice, timber is regarded as back-sawn if the growth rings meet the wide faces of the board at an angle less than 45^{o}. Quarter-sawn boards are also known as rift, edge-grained and vertical-grained sawn where the wide faces of the board are parallel to the rays. Boards are called quarter-sawn when the growth rings show an angle between $45-90^{o}$ to the wide faces of the boards,(between 80 and 90^{o} they are called "fully quarter-sawn").

Freshly sawn timber is called "green" and the average moisture content of green timber varies due to differences in species and the location of the timber specimen in the tree. The water in timber is made up of two parts - the free water and the bound water. The former is the water which is present in the lumens or cell cavities and the latter is the water actually adsorbed in the cell walls. When timber starts to dry, it first loses the free water and then the bound water. When all the free water has been lost, the timber reaches a stage which is called the fibre saturation point (FSP). This stage marks the start of losing the bound water from the timber and also the start of its shrinkage. Shrinkage is entirely confined to the region below fibre saturation point, except for collapse . The amount of shrinkage of timber in the three co-ordinate directions is not the same, which could result in internal stresses. The severe drying conditions reveal internal stresses in different forms, such as checks, warp, casehardening, collapse and honeycomb, which are known as drying defects and greatly decrease the value of timber.

Timber is a hygroscopic material - it gives off or takes in moisture until it is in balance with the relative humidity of the air surrounding it. When timber has attained such a balance, it is said to have reached its equilibrium moisture content (EMC). Ideally, therefore, timber should be dried to a moisture content close to the EMC it will attain in service. In this way, neither shrinkage nor swelling will occur in finished structures or components. For example, for the Sydney area*, it is usual to select timber having a moisture content of between 12 and 15 percent for the manufacture of articles for use under normal weather conditions and a moisture content of 5 to 8 percent for articles which will be used under air-conditioned atmospheres.

The drying of timber from its natural green state to the required moisture content is an important part of the production cycle. There is an increasing awareness of the economic value of the timber drying process and recognition that the manner and care used in drying can significantly increase the final value of the timber.

The trend in the building and manufacturing industries towards automation will undoubtedly continue, causing the specifications of the raw materials used to become increasingly strict. In consequence, a greater volume of adequately seasoned timber is likely to be required by industry in the near future and the availability of efficient seasoning techniques is in great demand.

While much interest has centred in recent years on the development of high temperature kilns, primarily for the drying of softwoods, at the other end of the scale there is a need for a process to dry hardwood timber rapidly to a moisture content low enough to satisfy the requirements of end products.

* Marshall, P. (1965). The equilbrium moisture content of timber in Sydney. Architecural Science Review. Vol.8(2), (3) and (4): 46-53, 94-97 and 133-135.

Air drying is the traditional method of drying hardwood timber but often requires a heavy investment in stack and yard facilities, due to the high cost of land and the long drying times involved. These make the complete air drying practice uneconomical. Efforts were directed by different organizations to develop economical techniques to dry hardwood to satisfy a variety of end uses.

In 1974, a joint committee was formed from the Commonwealth Scientific and Industrial Research Organization (CSIRO), South Australian Woods and Forest Department, Wilkinsons Timber Industries Pty. Ltd. and Lee Barker and Associates as the design consultants. This collaboration led to the development of a progressive tunnel kiln. The concepts of this kiln were to be cheap to construct and to reduce drying time to a fraction of that required to air dry green hardwood. A constant heat input was used in this kiln to raise the temperature at the "dry" end of the kiln by some fixed amount above ambient, rather than controlling it at some predetermined level, as reported by Christensen et al (1978). The use of the progressive tunnel kiln was directed towards two areas - first, to dry softwood, and the second, to dry hardwood species*. Campbell (1978a) of the Division of Building Research, CSIRO, reported that the correct seasoning of eucalypts (hardwood species) is important to the well-being of the timber industry. However, the fact that no simple, practical solution to the surface checking problem has emerged, despite a continuing research effort over many years, shows just how the species concerned are refractory. Certainly, high temperature drying appears to be unsatisfactory for green ash-type eucalypts but the method could be used with success on material previously air dried to 30 percent or less moisture content. He concluded that the development of the progressive tunnel

* Christensen's work was not directed to the high temperature drying of green hardwood.

kiln is interesting as it provides means of reducing overall drying times.

Some of the medium dense hardwoods are kiln dried from the green condition using a very gentle drying schedule but the drying process is very lengthy. Kininmonth **et al.** (1974) reported that kiln drying of eight hardwood species from green condition was unsatisfactory but they dried adequately when air dried in commercial or small scale stacks down to 3Ø per cent moisture content and finished in a kiln.

Campbell **et al** (1978b) stated that, generally, the Australian practice of drying hardwood species is a combination of air and kiln drying or preliminary drying in a predrier, followed by kiln drying.

"Engineers Australia", dated June 29, 1984, reports that Mr. R.D. Schaffner, who heads a four-man team based at the University of Tasmania's Department of Civil and Mechanical Engineering, has been researching since 1979 to develop a drying method for backsawn hardwood. The $12Ø,ØØØ-a-year project is funded equally by the Tasmanian Timber Promotion Board and the State Government to enable Mr. Schaffner to develop a method of placing a plastic coating over green timber, the purpose of the coating being to act as a partial vapour barrier to the passage of moisture from the surface of the timber. This slows down the rate of evaporation and reduces the moisture gradient condition within the timber. As a result, the drying rate is controlled to prevent warping and splitting, but the drying time would inevitably be lengthy.

Australian hardwoods make up the bulk of the timber-producing forest. This is true in New South Wales where these species provide a very desirable high strength timber for construction*. It is widely recognised that the utility of these species would be considerably improved if an economical drying process can handle this timber from green to produce material of a final acceptable quality.

A new drying process called "Continuously Varying Schedule" (CVS) has been developed to dry green hardwood. Preliminary work in this field was reported [Nassif (1979)] to the 19th Forest Products Research Conference. It is this CVS process which forms the main subject of this work.

* Some statistical forecasts by the Foresty Commission of New South Wales foresee an increasing usage of radiata pine in the building industry which is expected to reach 50% of the total cut eithin 15 to 20 years.

Chapter 1

TIMBER DRYING IN PRACTICE

1.1 Introduction

Early in our century, traditional air-seasoning was the only widely-used method of bringing timber into a fit condition for use. Fresh sawn timber was stacked either in the open air or under cover of a shed and left for long periods of time. It was then commonly believed that the timber should remain stacked for one year per inch of its thickness. After being thoroughly air-seasoned, the timber, if required for more exacting purposes such as cabinet work and high class joinery, was roughly shaped and then allowed to remain for a further period in the warmer atmosphere of a workshop or factory before being assembled into the finished article.

There had been some earlier attempts to accelerate the seasoning process but few kilns were in use and those that did exist were simple heated chambers with little or no control over the air conditions in them. The results obtained were often far from satisfactory and, consequently, there was a widespread tendency to regard kiln drying as dangerously 'artificial' and a poor substitute for patient 'natural' air seasoning.
Research, stimulated by the shortage of seasoned stocks that arose during the First World War, soon showed that, while some other minor changes may occur when timber is held for air-seasoning, the most important change is loss of excessive moisture. It also exposed some limitations of the air-seasoning method. At the same time, improvements were made in kiln design and the need to provide a positive circulation of air inside the kiln and to control its temperature and humidity to suit each

particular load of timber was established. Gradually, it became recognised that the condition of timber which had been dried in a well-designed and properly operated kiln in days or weeks was at least as good, and often better, than similar material which had been air-seasoned for years. Further improvements in the design of kilns and in operating techniques have been made and the earlier prejudice against kiln-dried timber has almost entirely disappeared. From time to time, a number of novel methods of drying have been tried, such as radio-frequency heating, press-drying and vapour drying but have found limited application for specialised items. None have proved a real alternative to kiln drying for general use.

1.2 Principle of Timber Drying

The factors affecting the timber drying process, either natural or artificial, are the air flow, temperature and humidity. Evaporation of water from the timber surface depends on the temperature difference between the air and the surface, relative humidity of the air surrounding the timber and the velocity of that air. On the other hand, moisture movement inside the timber relates to the specific gravity, diffusion coefficient, which is a function of the temperature and the moisture gradient inside the timber. It is obvious also that the thickness of the timber is a major factor affecting the drying process. A number of drying processes have been developed and used as a result of different applications of these factors. The drying processes which are more applicable for softwood are discussed separately from those principally used for hardwood, as reported by Fricke **et al.** (1974).

1.3 Processes Mainly Applicable to Softwood Drying

1.3.1 Constant Condition Process

The kilns used for this process consist of a number of parallel drying lines of timber with re-heat coils between each, while the fans, vents and a primary heating system are housed in an overhead air duct. The air, heated by the primary heater, is blown to dry and wet bulb sensors on the side wall adjacent to the first line of timber. Evaporation of water from timber causes a reduction of air temperature but a thermostat ensures that the re-heat coils heat the air to a level sufficiently above its initial temperature to allow for its increased humidity. This process is repeated after each line until the moisture laden air leaves the last line, whence vents are used to adjust its humidity before heating it again for re-circulation. Mostly, steam coils are used as a source of heating energy.

1.3.2 High Temperature Drying Process

High temperature drying is referred to in the literature as those processes which dry timber at a temperature above 100°C. These temperatures can be obtained by using steam, air-steam mixtures or air as the heating medium. A recent development for high temperature drying of timber using air-steam mixtures has been patented in the United States by Koch (1972b). Koch's patent is based on a series of publications [Koch (1969); (1971a); (1971b); (1972a) and (1973)] in which he describes procedures for drying southern pine studs from the green condition to a final moisture content of 10% in twenty-four hours. A mechanical fixture is used to rigidly restrain the timber against distortion before entering the kiln. The timber is then held under restraint throughout drying, steaming and cooling phases of the process. Studs (51 x 102 mm) are dried for twenty-one hours at a dry bulb temperature of 116°C with a wet bulb depression of 35°C, which is followed by steaming at a dry bulb temperature of 90°C with a wet bulb depression of 9°C for three hours to relieve case hardening. Throughout the entire process air is cross-circulated at five metres per second, the direction of air flow being reversed every seventy-five minutes. After drying, the timber is cooled for forty-eight hours in an atmosphere having a relative humidity ranging from 40% to 60% and a temperature range from 21°C to 27°C.

Koch claims that under the above drying conditions, drying time is directly dependent on timber thickness and that both drying time and energy cosumption are reduced to one quarter and one half, respectively, as compared with conventional drying. Further, if timber is held under restraint during drying, steaming and cooling, the collapse is less than that occurring during low temperature drying. The results of the work by CSIRO on high temperature drying of softwood has been widely applied in industry.

1.4 Processes Mainly Applicable to Hardwood Drying

1.4.1 Under Cover Air Drying Process

Air drying followed by kiln drying is by far the most common procedure for seasoning hardwood species in Australia. Frequently, the hot, dry climatic conditions that can occur during the summer months cause surface checking during air drying, particularly in boards of the top layer of the stack and it has now been fairly well established that this checking occurs during the initial period of drying, while the timber is still at high moisture content.

A number of sawmillers are now successfully overcoming this problem by air seasoning under cover, either in open-sided sheds or under individual stack roofs. In a few cases, where climatic conditions are severe and the timber is check-susceptible, stacks have been wrapped in vapour resistant material during the first few weeks of air drying.

1.4.2 Predrying Process

Brennan **et al.** (1968)introduced large, low cost timber driers, known in Australia as predriers, which have been used increasingly to replace the air drying of hardwoods in those regions of southern Australia where climatic conditions are unfavourable for air drying.

Predriers usually contain from three to twelve drying lines and are neither progressive nor compartment types. Progressive drying results are achieved by replacing the dry line with a green one so that at any time the predrier contains a random pattern of green to almost dry lines. Most predriers have reheat coils which restore the drying air to entry conditions after every few lines. Conditions within the drier are constant and controlled to suit the thickness, species and initial moisture content of the product, while the air flow is fixed and non-reversible. Drying temperatures are usually below 5Ø^{o}C and humidities above 5Ø%.

Although the operating costs for air drying hardwoods are sometimes lower than for predrying, the overall cost usually favours predrying if the establishment costs, including the cost of timber held in stock are taken into account.

1.4.3 Progressive Tunnel Kiln Process

The kiln used in this process is constructed as a tunnel through which the timber stacks are moved longitudinally and progressively. Heated air is admitted at one side of the "dry" end and deflected from side to side across the kiln by hinged baffles, until the cold and nearly saturated air is exhausted through a fan at the green end. The rise in temperature of the incoming air should be such that the EMC lies within the range 3-8% MC. For most localities, this rise is about 15^{o}C and can be provided by a constant burning rate oil furnace. Campbell (1976) claimed that hardwood can withstand relatively severe drying conditions when almost dry. This enabled the use of an oil burner with constant heat output at the dry end. The effect of this would allow the dry bulb temperature to be raised to a variable level which is dependent on the temperature of the surrounding air at that particular time, rather than to a predetermined level.

Although the system is considered to be five to six times faster than air drying, it is still dependent on the weather.

1.4.4 Dehumidification Drying Process

Dehumidification has been developed in the UK and Europe for humidity control in industry and for drying a number of materials, including timber. In conventional timber drying kilns, venting is employed to replace the hot moist air in the kiln with ambient air to achieve the required humidity. Thus the penalty for removing the excess moisture is to heat the inlet air. In the system developed for drying with dehumidifiers, venting is unnecessary. The dehumidifier has a refrigeration circuit comprising a compressor arranged to pump refrigerant around the circuit, a condenser coil, a pressure reducing valve and an evaporator coil. Evaporator and condenser coils are arranged in series in an air duct. A fan is positioned to draw air from the drying chamber over both coils after which it is returned to the drying chamber. As the air passes over the evaporator coil, it is cooled to a temperature below dew point with the consequent deposition of moisture which is collected and drained off. The air is then reheated by the condenser coil to a temperature slightly above its original entering temperature. The air leaving the dehumidifier is, therefore, reduced in relative and absolute humidity. The dehumidifier thus utilizes electric power to produce dried air for the purpose of timber drying. The timber charge is placed in well sealed chambers equipped with a fan to circulate air through the timber stacks and through booster heaters to raise it to the operating temperature. Dehumidification of the drying air is achieved by the fan of the dehumidifier unit drawing off air from the main circulating air stream. Although the operating temperatures are comparatively low, usually ranging from 20°C to 50°C, the drying potential is considerable because of the low relative humidity attained.

Cech **et al.** (1978) reported that total energy consumption for dehumidification drying to 7.5% MC exceeded that of conventional kiln drying by 11 to 36%, depending on schedule. They expected also that, on a commercial scale, dehumidification drying would show some saving in energy but not necessarily a saving in total drying costs. Their conclusion was that a combination process of a dehumidification drying down to FSP followed by conventional drying would probably minimise time, energy and degrade. Boone (1978) compiled the papers presented in the proceedings of the 21st Annual Joint

Meeting of the Midwest Wood Seasoning Association and the Wisconsin-Michigan Wood Seasoning Association and he stated that drying of timber by the dehumidification process had been used in Europe for ten to fifteen years. In more recent years, he added that it has spread to other parts of the world and in North America has been used increasingly for the last three to four years.

1.4.5 Solar Drying Process

Research during the past two decades led to the development of two major solar kiln types. The first is the "greenhouse" type, consisting of a framed structure with a transparent roof and walls to transmit the largest amount of solar energy into the dryer. Surfaces inside the dryer are painted dull or flat black so that as much of the transmitted energy as possible is then absorbed [Bois (1977); Casin **et al.** (1969); Chudnoff **et al.** (1966); Gough (1977); Johnson (1961); Maldonado **et al.** (1962); Peck (1962); Sharma **et al.** (1973); Singh (1976); Troxell **et al.** (1968)]. The second kiln type consists of an enclosed heavily insulated drying chamber and some form of external collector [Little (1979); Lumley **et al.** (1979); McCormick **et al.** (1977); Read **et al.** (1974); Simpson **et al.** (1977); Tschernitz; **et al.** (1979)]. All solar kilns rely on solar heated air as the drying medium, while two different systems are employed to transfer the heat energy from where it was collected to where it was used. The hot air or water was used as the heat transfer fluid. Hot air transfer systems were used in the 'greenhouse' type of kiln where the collector formed an integral part of the kiln, as well as in certain dryers with external collectors. They are relatively cheap to install and perform acceptably but it is difficult to store heat for use during cloudy periods and at night.

Liquid transfer systems were sometimes used with external collector kilns. They are more complex and expensive to install than air transfer systems but can store heat for use during periods when the sun is not supplying any energy. Liquid transfer systems, however, require corrosion and possibly freeze protection and additional heat exchanges to heat the drying medium (air).

A thermal storage unit consisting of a rockpile was used in some kilns to store excess heat during the day, to be used at night to reduce the effect of the diurnal temperature difference and provide better drying conditions.

Steinmann **et al.** (1981) stated that four factors determine the performance of the solar kiln. They are the kiln design, wood species, weather conditions and kiln control. Control instrumentation used in the solar experimental kiln consisted of a temperature probe and a temperature compensated equilibrium moisture content sensor inside the kiln, as well as a load cell. Another temperature probe and EMC sensor were used to measure the EMC and temperature of the outside air. The microprocessor control system used could be divided into the data acquisition subsystem, the control unit and the data logger. The data acquisition subsystem contained all the required analogue interfacing circuits needed for measurement and recording of the following parameters on magnetic cassette:-

1. Mass of the solar kiln load
2. Air temperature inside the kiln
3. Air temperature outside the kiln
4. EMC of the air inside the kiln
5. EMC of the air outside the kiln
6. Status of valve: OPEN/CLOSED
7. Solar radiation at the test-site

8. Time of the day
9. The calculated moisture content of the wood.

The analogue signals from the sensors were multiplexed, digitised and converted into current loops for transmission via multicore cable to the control unit.

1.5 Auxiliary Processes

There are some practices used prior to or after drying processes to overcome phenomena, such as slow drying rate and excessive collapse occurring during drying. Some of these are described below.

1.5.1 Presteaming

It has been well known that steaming of timber, especially the refractory species, for two to four hours at 100°C prior to the commencement of drying, will considerably reduce moisture gradients during the subsequent drying. Overall, presteaming reduced the drying time of the refractory species by about 20 to 30 percent of that required for unsteamed timber as reported by Campbell (1961). However, Mackay (1971) reached a different conclusion where he reported that presteaming of Eucalyptus has very little effect in increasing the diffusion coefficient at lower moisture content. Such a result is not totally unexpected since a particular situation exists here between the presteaming treatment and timber collapse. He quoted Greenhill (1936a) who reported that specimens exposed to initial high temperatures in the green condition showed great increase in collapse intensity upon subsequent drying. Mackay added that one would, therefore, expect to find contradictory effects working in the drying of presteamed samples; on the one hand, a direct effect of high temperature steam acting on the wood is to increase the permeability and, on the other hand, the collapsing effect of individual cell walls resulting in an effective increase of specific gravity and rendering of the material less permeable. That is, in this species, any beneficial effect of presteaming is largely offset by an intensification of collapse.

1.5.2 Pre-freezing

Freezing of timber in the green condition prior to the drying processes is one of the most effective methods found to date for reducing collapse [Erickson **et al.** (1966); Erickson (1967); Wright (1967); Erickson (1968); Erickson **et al.** (1971); Choong **et al.** (1973); Chen (1974)].

Results indicate that pre-freezing at a temperature of minus 20°C reduces collapse by 40%. However, freezing of 71,200 kg of green ash eucalypt at 100% moisture content from 21°C to minus 26°C would require 4,500 kcal of refrigeration. The high cost of the process is a big disadvantage which limits the industry from using it.

1.5.3 Reconditioning

Extensive investigation in Australia by Greenhill (1938; 1940) has led to the development of a method for reconditioning collapsed Eucalyptus timber. It was found that the cells can be restored to their original shape if the walls have not broken down completely, by remoistening the collapsed timber in saturated steam at 100°C after which the timber is redried. In this procedure, the timber is first dried to about 10 or 15% MC; it is then subjected to a high humidity treatment at 100°C for several hours to permit it to reabsorb 2 to 6% MC and to return to its original shape. The timber is then redried to its original MC, this time without developing the collapse again, since the redrying process was started below the FSP.

Research into the process variables that govern the reconditioning treatment for recovery of collapse in seasoned timber has yielded few reports over the last four decades which in any way expand or clarify the hypothesis suggested by Greenhill.

Mackay (1972) reported that reconditioning of **Eucalyptus delegatensis** using steam and ammonia play a similar role in collapse recovery in a number of respects. Although it has been demonstrated that shrinkage following ammonia treatment is greatest in the radial direction, contrary to normal or collapse shrinkage, the results suggest that recovery in ammonia as in steam reconditioning may be greatest in the tangential direction. In both systems, 12% was shown to be the optimum moisture, although timber at a slightly lower level could still be expected to recover during steaming because of moisture pickup.

Marshall (1975) claimed that reconditioning of hardwood after drying it to 6-8% MC has the following advantages:-

1. It recovers any collapse present in the timber and results in a 2-5% increase in width.

2. It equalises the moisture gradient through the flitch to an even 10-12% MC.

3. It assists in straightening out warped timbers since the steam slightly softens the timber and

the weight of the stack tends to straighten out any warping.

4. It relieves any drying stresses present in the flitch.

Nassif (1984) reported that the results of reconditioning of **Eucalyptus laevopinea** at two different stages of the timber drying process, were not significantly different. The first stage, when the timber was considered to be dried to below FSP and the second at the end of drying at below 15% MC.

Chapter 2

DRYING PROCESSES

2.1 Introduction

The timber drying process takes place as a result of the evaporation of moisture from the exposed surface of the timber. This moisture is then carried away as vapour by the air passing over the timber. The rate of evaporation depends on the difference between the vapour pressure at the timber surface and the partial pressure of the water vapour in the air. Moisture will continue to evaporate as long as the former is greater than the latter. If the rate of evaporation from the timber surface is faster than the rate at which the moisture can move up from the inner layers of timber to the outer layers of the surface, the outer layers tend to dry and shrink in advance of the inner layers. This tendency of the outer layers to shrink is resisted by the wetter layers beneath them, which create a pattern of stress within the timber with the outer layers in tension and the inner in compression. This can lead to splitting and checking of the surfaces.

During the drying process, some difference in moisture content is unavoidable. Indeed, it is this difference which promotes the outward movement of moisture and skill in timber drying lies in allowing a moisture gradient to develop but in preventing it from becoming so steep as to damage the timber.

The elevation of temperature is beneficial in three ways. First, and perhaps most important, the rate of outward movement of moisture, under a given moisture gradient condition, increases rapidly as the temperature is raised, so that the rate of surface drying can be accelerated. Secondly, it makes it possible to evaporate at a faster rate than can be achieved at a low temperature. Thirdly, the capacity of the air for holding and carrying away the evaporated moisture increases greatly at elevated temperatures.

However, there are limits for the temperatures to which the various timbers can be subjected without developing excessive drying defects. Bramhall **et al.** (1976) pointed out that, to increase the temperature without increasing drying defects, a high humidity should be maintained at the timber surface. This is not going to slow down the rate of drying. He stated, also, that when the surface of timber contains its free water, the temperature of the timber is the same as that of the wet bulb temperature (WBT) and will stay at that temperature as long as there is sufficient moisture moving from the inner layers to keep the surface moist. When the free water at the surface is evaporated, the MC of the surface approaches the EMC and concurrently, the temperature of the timber surface increases and approaches the dry bulb temperature (DBT).

Bramhall has summarised the drying process by saying that, at the beginning of drying, a considerable amount of water is being evaporated and, as a result, the drop in air temperature across a stack is very high and the humidity of the air increases almost to the saturation point. Under these conditions for rapid drying, the air velocity should be high. On the other hand, when the surface of the timber has been dried below the FSP, the rate of evaporation is reduced. Under these conditions, a much reduced air velocity is acceptable. From the point of view of energy savings, Bramhall recommended the use of variable speed fans.

Efforts were directed towards every possibility to save energy during the drying process. It also became a matter of concern in Australia to develop new drying techniques, instead of the conventional lengthy schedules, to optimize energy use. It is obvious that the basic principles of drying processes are the same, however, the application of heat, humidity and air circulation is different. It is therefore not so much a question as to how these are applied but, rather how a certain process ranks in terms of economic output and energy consumption.

2.2 Conventional Schedules

The schedules of conventional processes consist of a series of steps of progressively increasing temperatures and decreasing relative humidity. The choice of any particular schedule depends on the drying characteristics of the different species. The progress from step to step is governed by the average moisture content of the timber inside the kiln. Accordingly, as the timber dries it is subjected to more and more severe drying conditions by means of higher temperature and lower relative humidities. Schedules based on the results of trials and other information have been published by Campbell (1980) for a great number of species. This process utilises close control over the DBT and WBT of the air inside the kiln. Conventional schedules for drying hardwood start with DBT's ranging from 45°C to 80°C and wet bulb depression (WBD) of 3°C to 20°C. The first change is when the mean MC drops from the green condition to 60% then changes are made at MC's of 40, 35, 30, 25, 20 and 15%. Conventional drying also uses high air velocity (3-5m/sec) to create a turbulent air flow across the timber stack; the faster the air can be blown across the stack, the more thoroughly the moist layers around the boards will be removed and replaced by fairly dry air.

2.3 Conventional Kilns

The conventional drying process is conducted in kilns which are a chamber to accommodate the timber in the form of stacks. The timber is sawn to boards and placed in layers separated by wooden stickers. Kilns vary in a number of respects, including the materials with which they are built, the method by which the timber is loaded and positioned in the kiln, the fan arrangement which is used to circulate the air, the heating method used to supply the heat energy to evaporate moisture and the venting system.

2.3.1 Materials for Kiln Construction

The most common construction materials presently used for kilns are aluminium and concrete products. Aluminium kilns usually consist of prefabricated panels having aluminium inner and outer skins with insulation between them. Concrete-block kilns have a tendency to crack due to thermal expansion and contraction, therefore, the vapour barrier which is applied on the inside of the walls must be capable of withstanding some movement.

2.3.2 Kiln Loading Arrangements

Timber can be loaded into kilns either on special kiln trucks, which run on rails installed through the kilns and the loading and unloading areas, or by placing it on blocks in the kiln by means of forklift trucks.

Timber in the kiln remains stationary for the duration of the drying process, after which it is unloaded by the same means as it was loaded. This type of kiln is referred to as a compartment kiln to distinguish it from a progressive kiln, where the timber moves progressively through a drying tunnel. Whereas in a compartment kiln, the temperature and humidity of the air are changed throughout the drying process, in a progressive kiln, a constant air quality is usually applied at the dry end and this becomes cooler and more humid in moving to the green end. Thus, the driest timber is exposed to the most severe drying conditions.

2.3.3 Kiln Fans

Two main types of fan arrangement can be found in kilns, namely line-shaft and cross-shaft fans. In the line-shaft system, a series of fans are mounted on a shaft running along the length of the kiln. Thus the air leaving the timber stack has to be turned through 90 degrees to pass through the fans and then returned to its former direction to enter the timber stack. In the cross-shaft system, fans are mounted on individual shafts at right angles to the length of the kiln so that air is guided directly to the timber stack.

2.3.4 Kiln Heating and Humidifying

The circulating air can be heated either directly or indirectly. In direct-fired kilns, hot furnace gases, which are the combustion products of gas, oil or wood residues, are diluted with some of the kiln air and then fed into the kiln. In indirect-heated kilns, steam or hot water is passed through radiator coils suitably located in the kiln and air is heated as it passes over them. A distinct advantage of a steam-heated kiln is that some of the steam can be used for maintaining a desired humidity in the kiln. The direct-fired kilns are humidified by means of a disc-type humidifier or other water atomising device.

2.3.5 Kiln Vents

Excess kiln moisture is normally discharged by vents. These vents are placed in the roof on the intake and exhaust sides of the fan so that, when they are opened, fresh air is drawn in on the suction side and moist air forced out on the compression side of the fan. Vents are arranged in line along the length of the kiln, hinged and connected by means of a continuous control rod, so that each line can be opened and closed as a unit either manually or automatically.

2.3.6 Automatic Control for Kilns

In some kilns, the air conditions are controlled by manual adjustment for the sources of heat energy and humidity, but many are now equipped with instruments for automatic control. Control instruments, usually electrically operated, are regarded as essential on new kilns. Time switches for the frequent reversal of the air-flow, which improves the uniformity of drying, are also fitted on most modern kilns. Process programmers and micro-computers are now available to make kiln-drying a fully automatic process but, so far, this level of automation has not been much used. It makes a continuous estimate of the moisture content of the load by measuring the electrical resistance of timber samples and the air conditions are changed as the estimated moisture content falls [Arganbright (1974), (1979); Carlson (1977); Resch **et al.** (1977); Johnston (1973)].

2.4 Continuously Varying Schedule (CVS)

One of the common goals of drying research on hardwood is to reduce the long drying times involved in wood processing. This has been attempted over the years by a number of research workers without obtaining an optimum solution to the problem.

In establishing the CVS process, two experimental projects were carried out to optimize the kiln drying process of hardwood from green:-

1. Drying 17 mm brush box **(Tristania conferta)** from green to 9% MC in less than one week.

2. Drying 50 mm back- and quarter-sawn silvertop stringybark and blue-leaved stringybark (**Eucalyptus laevopinea** and **E. agglomerata**) from green to below 15% MC [Nassif (1979)].

This work was guided by the results reported by Dedrick (1968, 1973a, 1973b, 1974) and Quemere (1976), on drying some softwood species in USA and France. Dedrick's reports had created some confusion between research workers in Australia, which was clarified by Nassif (1980).

As a result of these studies, the new drying process was developed and called Continuously Varying Schedule (CVS). Nassif (1981) reported that this process is based on two features. The first is to increase the temperature continuously for both dry and wet bulb temperatures from initial mild conditions at a suitable rate per hour. The second is to use a low air velocity across the timber stack. In this process, the temperature increase is characterised by two stages. The first is from green to approximately fibre saturation point at a relatively low rate of temperature increase, followed by a second stage using a higher rate. The process was designed as two stages to reduce the risk of developing drying defects during the first stage from green to FSP.

The reason for using a low air velocity is to achieve as close as possible a state of laminar air flow. Laminar flow is characterised by an immobile layer of air around the timber surface, through which all the moisture evaporating from the timber must pass and then diffuse into the main air stream. Thus, the immobile layer becomes more saturated than subsequent layers. It is, therefore, possible to use air having a low relative humidity, due to its elevated temperature, while maintaining a relatively high humidity condition at the timber surface.

CVS can be applied using a process programmer to drive the kiln controllers according to a pre-programmed schedule to vary the DBT and WBT continuously.

2.5 Differences Between Processes

The differences between the CVS and conventional timber drying processes can be summarised as follows:-

1. Laminar air flow is used across the timber stack in the CVS process, while turbulent flow is used in the conventional processes.

2. The CVS start with a low temperature as near as practical to ambient.

3. The basis of controlling the DBT and WBT are different in the two processes. During CVS, kiln conditions change continuously, where in a conventional schedule, it is according to the change in MC of the timber.

4. In the CVS process, the temperature gradient between air and timber surface is maintained, thus keeping the rate of drying uniformly high,

while the timber is protected by the laminar boundary layer of the low velocity of air stream.

5. CVS uses two drying stages as an added safeguard to the timber quality.

Continuously Rising Temperature (CRT) is an accelerated drying process for softwood species. A DBT rise ranging from 0.5 to 5.5°C per hour is recommended. It should be remembered that these "rise" ranges were used for drying U.S.A. softwood species. When using the CRT process, there is no need for close humidity control in the sense that moisture is added to the air. However, there is a need for a control device which can open the vents to discharge moisture if the humidity in the kiln builds up. Dedrick emphasised that low air flow should be used through the timber stack.

Differences between CVS and CRT:

1. CVS uses a very small rate of temperature increase as compared to the CRT.
2. CVS is different from CRT in that it uses control over the WBT.
3. CVS uses two drying stages while CRT is one stage process.

2.6 <u>Energy Saving Measures</u>

The increasing cost of fossil fuel as compared to other energy sources has caused the industrialized nations of the world to look for new sources of energy, as well as the use of more efficient processes. The increasing use of the world's timber also will require innovative drying technology to efficiently produce timber products.

Without question, the drying of timber is the largest single user of energy in all primary manufacturing of forest products. Heat consumed in drying accounts for 6∅-7∅% of the energy used in timber manufacturing (Comstock (1975)). Thus, savings during drying could have considerable impact on the overall energy usage of the timber industry. Reduction in drying time is, therefore, not only desirable, but essential, towards energy conservation.

Fortunately, some steps can be taken to reduce the petroleum-based energy consumed in kiln-drying of timber. Suggestions in this thesis towards this end are divided into:-

(a) The efficient use of energy in the drying system.

(b) Recovery of the waste energy from the drying system.

(c) Exploring other energy sources.

2.6.1 The Efficient Use of Energy in the Drying System

A conventional drying schedule proceeds under controlled constant conditions of DBT and WBT between the change points. As a consequence, a part of the energy added to the system is used to increase the timber temperature. As the timber becomes hotter, the temperature gradient between the stable temperature of the air flow inside the kiln and timber surfaces decreases and, as a result, the rate of drying also decreases.

As a result of keeping the DBT and WBT constant during each step of the conventional schedule, the moisture evaporated from the timber increases the relative humidity inside the kiln during the duration of that step. Humidity is controlled in these kilns by venting the excess humid air directly to the atmosphere. This vented air contains a considerable amount of energy, which represents one of the major sources of energy loss and deserves some particular attention.

Conventional kilns will continue to play a large role in timber drying but new kilns should be constructed with greater emphasis on energy savings and reduction in drying time. Tighter construction to eliminate leaks near doors and vents and more insulation will reduce energy consumption. Schedule modifications to reduce energy requirements and increase product quality also will be very important in the future.

Rosen (1981) reported that softwood species can be dried by the continuously rising temperature which is a kiln schedule modification whereby water is removed from the timber at a substantially constant rate [Dedrick (1974)], which reduces drying time and achieves a higher recovery over other kiln drying schedules. CVS is another modification along that line, which keeps a temperature gradient between the air flow inside the kiln and the timber surfaces, thus accelerating the drying process of hardwood.

Recent advances in integrated circuits and micro-processor technology have reduced the cost of the electronic components necessary to automate kilns. The saving in product quality , drying time, energy consumed (as a result of close control over the drying process) and reduced manpower to operate computer-controlled kilns, will make these kilns more attractive in the future.

The dehumidification drying process mentioned in 1.4.4 also has the potential for considerable energy savings especially when the dehumidifier is coupled to solar-powered refrigeration and heating with possible electric or wood-waste fired back-up and boosting. The potential savings are considerable, especially since dehumidification drying involves no energy loss to the atmosphere. In a high solar radiation exposure country like Australia, such a combination should be particularly attractive.

2.6.2 Recovery of the Waste Energy from the Drying System

The energy conservation in timber drying is an important factor to be observed in designing new kilns. Heat exchangers can be used to recover energy from vent exhausts of kilns to preheat incoming air to the kiln, to supply supplementary heat for another kiln or to provide heat energy to another process in the timber processing plant. Rosen (1980) showed a saving of 12 to 15% over conventional methods when the vent air from a jet dryer was directed through a recovery heat exchanger located in a conventional kiln. Corder (1980) showed that up to 60%

additional water removal can be achieved with a hot water storage recovery system, which couples a conventional and a low-temperature kiln (or predryer), as compared to a conventional kiln alone. A suitable air-to-air heat exchanger to preheat incoming kiln air is commercially available from several companies in Germany and Holland, no doubt, also in Australia.

2.6.3 Exploring Other Energy Sources

Wood waste is potentially our largest renewable energy resource which is fairly readily available around timber industry plants. One ton of dry bark has the heat energy equivalent of about 2.2. barrels of oil [Youngquist (1977)]. Modern technology can take care of the air pollution problem normally associated with the use of wood waste.

Coal based synthetic fuel is another important resource in Australia to be considered as replacement to petroleum-based energy. Two major direct coal liquefaction technologies, Exxon's Donro Solvent process and Dynalecton's H-Coal process are now considered by their developers to be ready for commercial application, should economic circumstances become favourable [Energy Authority of New South Wales (1983)].

Nuclear power is the largest single source of new power which Australia can put its hands on but the problems of nuclear safety and waste disposal should be investigated. Oil shale, wind, tides, waves, ocean temperature differentials, garbage and animal wastes are different sources of energy which can contribute to our energy supplies.

Chapter 3

CVS AND CONVENTIONAL PROCESSES

3.1 Drying Experiments

A drying investigation was undertaken to compare the CVS and the conventional schedule processes. The timber species dried was silvertop stringybark (**Eucalyptus laevopinea**). Factors compared were drying time, drying rate, amount of water evaporated during the drying process, volumetric shrinkage, recovery of collapse, quality of timber and the electric energy consumed during drying.

The drying time was counted as the time needed to reduce the mean MC of samples from green condition to below 15% MC, reconditioning time was not included. The drying rate is an indication of the speed of the drying process which is expressed by equation (1) below, while the amount of water evaporated is calculated using equation (2) below. The volumetric shrinkage was calculated as a percentage, using the shrinkage data of thickness and width measured for each sample at marked positions. Vernier calipers and a micrometer were used to measure the widths and thicknesses of the samples respectively. Equation (3) [Greenhill (1936a); Kelsey **et al.** (1953)] was used to calculate the volumetric shrinkage. Recovery of collapse is the difference between the value of mean volumetric shrinkage at the end of the drying process and the value of mean volumetric shrinkage after reconditioning treatment as shown by equation (4). After drying, all samples were reconditioned, dressed all round, then graded for structural purposes according to AS 2082 - 1979 (Standards Association of Australia, 1979) by a competent timber inspector. Electrical energy used by the heating coils and the fan's motor during the drying process was measured using a kilowatt-hours meter. It was beyond our financial capacity to facilitate an instrument needed to measure the amount and quality of steam used during the drying processes.

A portable hand-held velocity meter manufactured by Thermo-Systems Inc., Model 1650-1, was used to measure air velocity at the outlet side of the timber stack. Photos 1 and 2 in Appendix A show the instrument and the probe. An air velocity of approximately 1.3 m/s at a fan speed of 490 rpm and approximately 3.3 m/s at 1200 rpm were used during CVS and conventional processes respectively. The air velocity through the timber stack is the subject of discussion of the next chapter.

$$\text{Drying Rate (MC\%/h)} = \frac{\text{Initial MC\%} - \text{MC\% after Drying}}{\text{Drying Time in Hours}} \qquad (1)$$

$$\begin{array}{c}\text{Amount of Water}\\ \text{Evaporated (g)}\end{array} = \begin{array}{c}\text{Initial Mass}\\ \text{of Samples (g)}\end{array} - \begin{array}{c}\text{Mass of Samples}\\ \text{After Drying (g)}\end{array} \qquad (2)$$

$$Sv = St + Sw - \frac{(St \times Sw)}{100} \qquad (3)$$

where Sv = volumetric shrinkage %.

St = shrinkage in thickness %.

Sw = shrinkage in width %.

$$\begin{array}{c}\text{Recovery}\\ \text{of}\\ \text{Collapse}\end{array} = \begin{array}{c}\text{Volumetric}\\ \text{Shrinkage After}\\ \text{Drying \%}\end{array} - \begin{array}{c}\text{Volumetric}\\ \text{Shrinkage After}\\ \text{Reconditioning \%}\end{array} \qquad (4)$$

3.2 Experimental Kiln

The kiln used in the drying investigation is a compartment type made of Aluminium panels, insulated with 75 mm of fibreglass to minimise heat losses. The kiln's dimensions are 2.22 m (long) x 2.14 m (wide) x 0.72 m (high), where the drying compartment is 1.31 m (long) x 0.81 m (wide) x 0.70 m (high). This area is covered at the top with a readily removable lid. The timber is stacked and can be weighed on a supporting steel frame, which is loaded vertically by a one tonne chain block running along an overhead monorail. Air flows through the stack horizontally and is not reversible. A six-bladed axial fan of 457 mm diameter, mounted in a cross-shaft arrangement is driven through a direct-coupled 5.5 HP variable speed electric motor mounted outside the kiln, the speed varies between 375 and 3000 rpm. A 24 kW heating coil is used to heat the air inside the kiln. The coil is connected in three phase star formation through a Silicon Controlled Rectifier (SCR) to a 415 v mains power supply. The SCR is used to overcome any problem of radio-frequency interference. This heater is capable of raising the circulated air temperature from ambient to 150°C. Humidification is carried out by injection of steam from a small local boiler into the kiln atmosphere. The steam line is located between the heating coil and the fan and consists of a perforated U-shaped tube, the return side of which is fitted with a thermo-dynamic steam trap to pass water condensate to a floor drain. The humidification capacity of the steam line is up to 100% relative humidity. The heating coil, steam line and the fan are accommodated in 1.98 m (long) x 0.63 m (wide) x 0.55 m (high) space which represents the back part of the air duct. This duct is accessible through a hinged top, which has two vent openings, one on each side of the fan with an area of 0.15 m x 0.15 m covered with manually controlled flaps. Two opposite vertical sides of the drying compartment are covered with screens to achieve uniformity of the air velocity through adjustable slots. The inlet side has a double layer screen, whereas the outlet has a single one, each covering an area of 1.26 m (long) x 0.55 m (wide).

The kiln is controlled, either locally by a manual set point system or remotely by a process programmer. All the control instruments are provided by Leeds and Northrup. Electromax Mark III Universal Controllers are used, one for current adjusting, producing a 0-5 milliamp output signal to control the electric power to the heating coil to achieve the DBT required and the second is a solid state switch output to adjust the position of the steam valve on the steam line through a servomotor to achieve the WBT required. Both controllers have proportional plus set point control functions with a feedback temperature sensing element fitted inside the kiln. Both dry and wet bulb temperatures are recorded by a Speedomax "M" Recorder Mark II. The remote control is carried out through a 1300 process programmer which drives the two controllers automatically according to a pre-set program. The process programmer has the facility to record the program on a module for further usage.

Photos Nos 3-11 in Appendix A give a general view of the following:-

- Experimental kiln
- Drying compartment
- Inlet side screen
- Heating duct
- Heating coils, perforated tube and fan
- Fan motor
- Steam line controlling valve

- Controlling system
- Loading arrangement

3.3 Timber Species

The species used in this investigation was quarter and back sawn silvertop stringybark (**Eucalyptus laevopinea**). This species occurs naturally on the New England tableland of New South Wales in Australia at an elevation of 700-1400 m, between latitudes of 29°S and 33°S [Turnbull **et al.** (1978)]. The species shows its best growth on well-drained basaltic soils derived from granites and rarely occurs in pure stands but typically is a co-dominant in species mixtures.

In the forest, silvertop stringybark develops a straight, slightly tapered bole, which may be up to 40 m tall and have a diameter of 1 m. The bark is rough, fibrous, dark reddish-brown, 20-30 mm thick, separating into long, shallow, narrow shreds. This species, like many other eucalypts, may produce growth stresses, tending to cause a brittle heart and flitches to split immediately upon cutting.

The timber is light brown in colour with moderate strength and durability, which has an average air dry density of 860 kg/m^3. Generally, the timber is free from kino veins and is considered one of the most important species for sawing in its area of natural occurrence. It is mainly used in building construction.

An area of 475 ha of this species was planted during the period 1966-1976. The annual planting rate in 1976 was 150 ha. The plantations are in the colder, higher, southern sites of the north coast of New South Wales. It has been used particularly in Chichester State Forest, north of Dungog, to regenerate forest which has been logged.

Twenty naturally grown trees were chosen randomly from different locations to provide the tested samples. Their diameters ranged from 0.33 to 0.91 m measured at breast height. Nine trees of these were cut from different locations in the Glen Innes district. The other eleven trees were cut from three locations in the Newcastle district.

Flitches (bark-centre-bark) from head and butt logs were quarter and back sawn to 100 x 50 and 100 x 25 mm dimensions. These dimensions represent the small scantling material used for structural purposes. Sections for determining the moisture content and the oven dry weight, were cut from each end to leave 0.6 m long samples. Samples were then end coated with bitumen emulsion to minimize drying from end grains. Samples were then grouped randomly into batches of six replicates, representing one thickness and one direction of cut. The investigation was carried out, using only the 100 x 50 mm material, which is more difficult to dry than the 100 x 25 mm.

Results of twelve tests comprising 144 samples, totalling a volume of $0.432 m^3$, laid the foundation for this investigation. The CVS process was conducted on six quarter and six back sawn samples. The same combination was dried using the conventional process.

3.4 CVS Run

The CVS run was carried out using the process programmer to control the dry and wet bulb temperatures according to a linear program for each of them. (See Fig.

3.1) The first stage of the dry bulb temperature program started at 35^{o}C and increased at a rate of 0.1^{o}C/h. The wet bulb temperature program started at 33^{o}C and the rate was 0.05^{o}C/h. This first stage lasted for 305h. At that time, it was estimated that the mean MC of all samples would be around FSP and reached 25% MC. This estimation was made on the data collected while checking the samples four times in this first stage. At the end of this stage, the DBT was 65.5^{o}C and the WBT was 48.25^{o}C. In the second stage, the DBT increased at a rate of 0.25^{o}C/h until it reached 80^{o}C during fifty-eight hours and then it was kept at 80^{o}C until the end of the drying run after a further seventy-six hours. During this stage, the WBT increased at a rate of 0.15^{o}C/h until it reached 56.95^{o}C in fifty-eight hours and was then kept at this temperature until the end of the run. During the second stage, the samples were checked once before the run was completed. At the last checking point of the samples in the first stage, region four was altered and reprogrammed, as the second stage of the programming work-sheets (See Appendix B) shows, to finish after sixty-five hours. After seventy-six hours in region six, samples were below 15% MC, thus the run was terminated with total drying time of 439 hours. The programming work-sheets of the schedule executed by the process programmer during this run are shown in Appendix B. Sheets 3 and 4 are the logic programs used to stop the process programmer during the checking points.

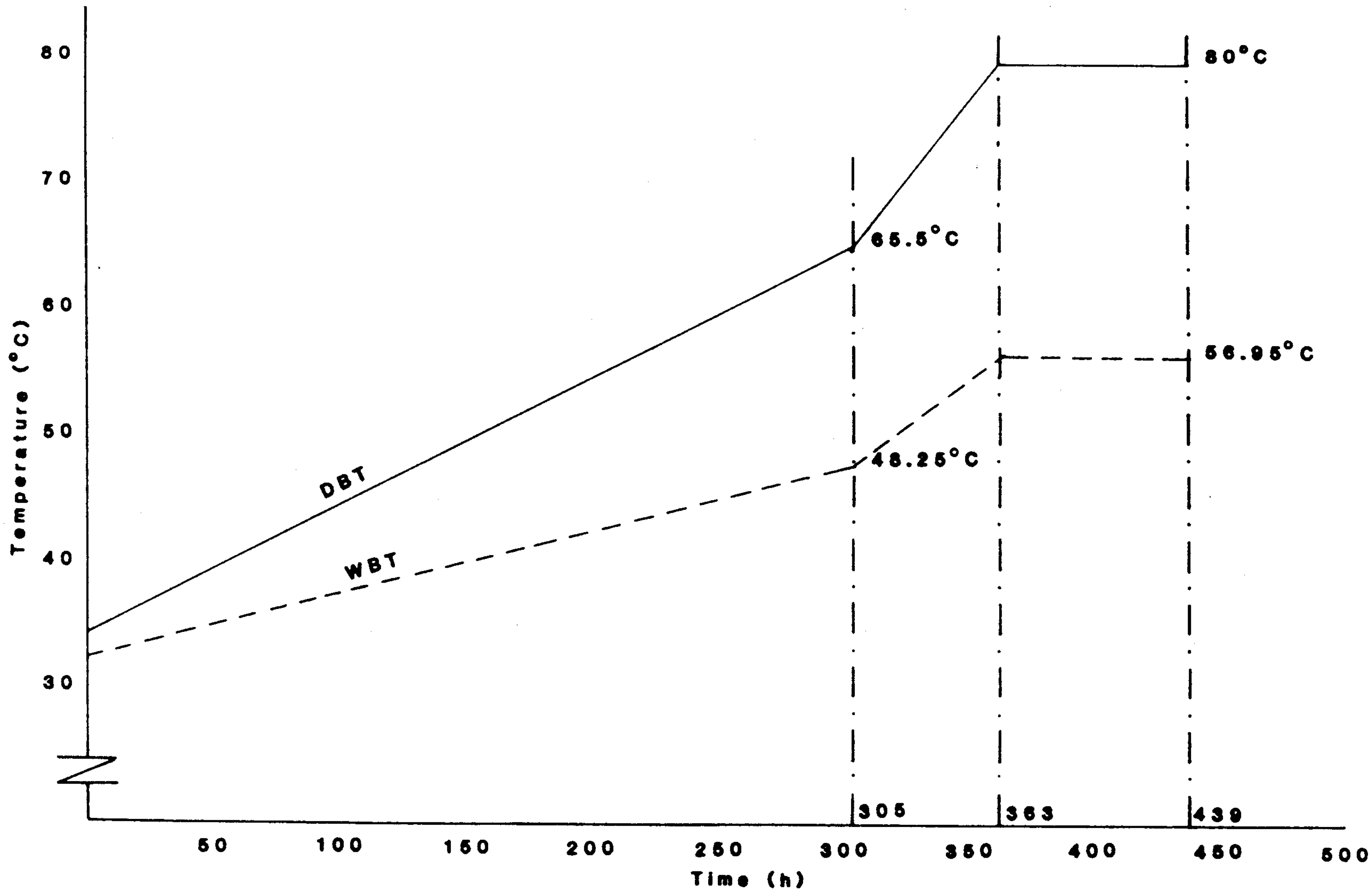


FIG. 3.1: DRYING STAGES OF THE CVS PROCESS

This program can be represented in the following equations:-

First stage: $(0 \leqslant t \leqslant 305h)$

$DBT = 35(^{o}C) + 0.1(^{o}C/h) \times t\ (h)$

range $35^{o}C \leqslant DBT \leqslant 65.5^{o}C$

$WBT = 33(^{o}C) + 0.05(^{o}C/h) \times t\ (h)$

range $33^{o}C \leqslant WBT \leqslant 48.25^{o}C$

Second stage: $(305h \leqslant t \leqslant 363h)$

$DBT = 65.5(^{o}C) + 0.25(^{o}C/h) \times t\ (h)$

range $65.5^{o}C \leqslant DBT \leqslant 80^{o}C$

$WBT = 48.25(^{o}C) + 0.15(^{o}C/h) \times t\ (h)$

range $48.25^{o}C \leqslant WBT \leqslant 56.95^{o}C$

Third stage: $(363h \leqslant t \leqslant 439h)$

$DBT = 80^{o}C$ constant

$WBT = 56.95^{o}C$ constant

The third stage was maintained to the end of the drying run.

The reading of the kilowatt-hour meter was noted before starting and after completing the run. The thickness, width, and mass of each sample were measured and noted before and after the drying process and also at every checking point during the process.

The twelve samples were stacked, four in each of three rows of the front half of the stack. The rest of the stack was filled and topped with dummy boards of a hardwood origin. The stack was baffled to the lid of the kiln, this arrangement is shown in Fig 16 of Appendix D. The air duct area through the timber stack was 0.176 m^2 using four stickers between any two layers of timber. [Nominal stickers dimensions were 25 mm (wide), 20 mm (high) and the length was equal to the width of the stack].

The fan speed was maintained at 490 rpm during the entire CVS run producing an average air velocity through the stack of 1.3 m/s.

The samples were reconditioned for five hours after drying. During the first hour, the temperature was raised from ambient temperature to 100^{o}C using saturated steam, then the temperature was kept at that level for four hours. Samples were then left exposed to the ambient conditions overnight and were then weighed and measured to evaluate the recovery in volumetric shrinkage.

3.5 Conventional Run

The conventional run was executed manually using the local control system. The required DBT and WBT were set up during the different stages of the drying schedules. The conventional schedule chosen for this run was BU as recommended and described by Campbell (1980). The letter B refers to the DBT and U to WBD in degrees Centigrade. The DBT and WBD are changed in steps according to the change in the mean MC% of the samples as follows:-

	B	U
Green	45	3
60%	45	4
40%	50	5
30%	55	8
25%	60	10
20%	70	15
15% to final	70	20

The total drying time for this run was 670 hours. The step-rise program is shown in Fig. 3.2.

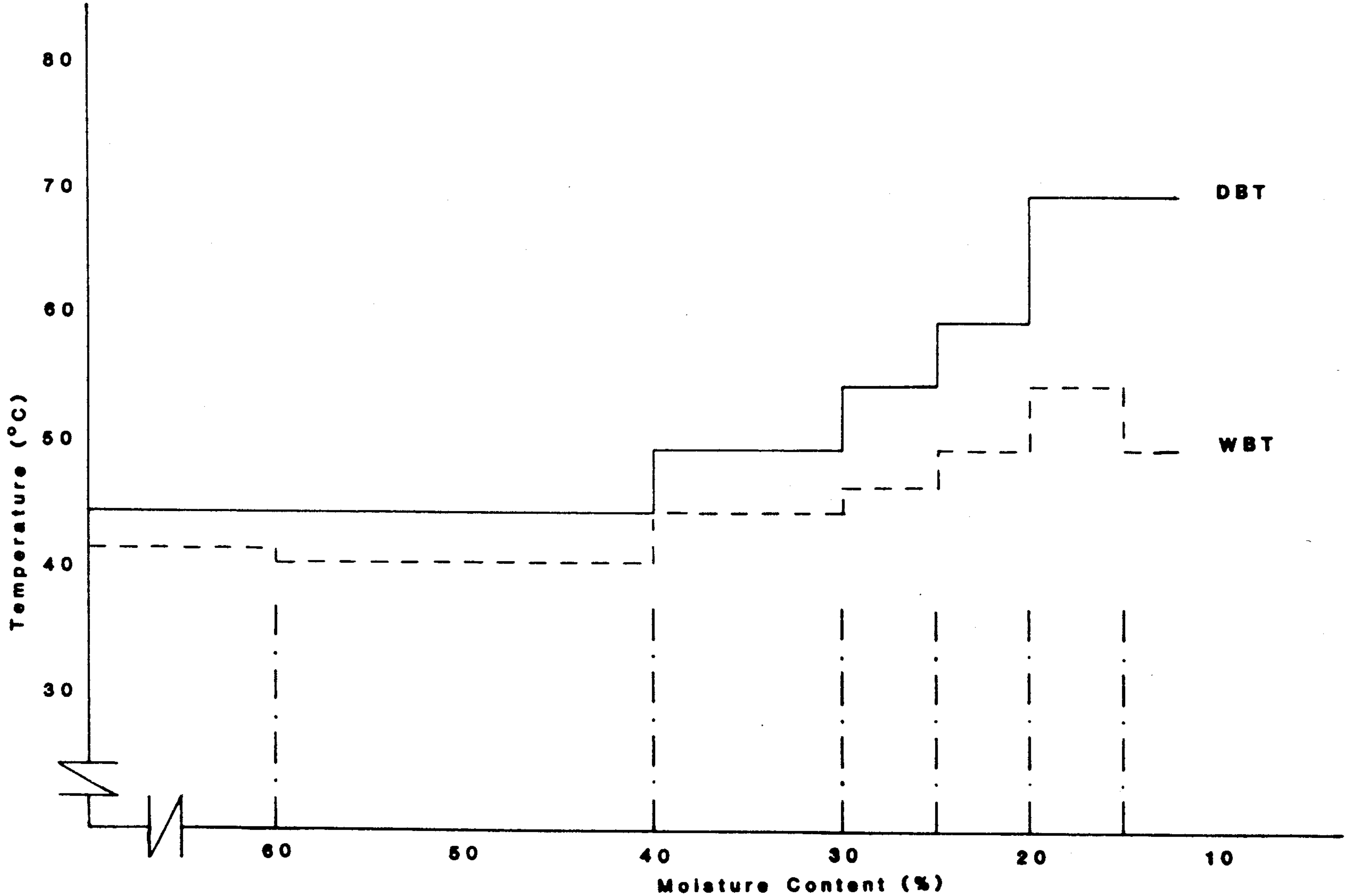


FIG. 3.2: DRYING STAGES OF THE CONVENTIONAL PROCESS

The measurement made before, during and after the drying time was the same as in CVS and samples were checked seven times during the drying process as well as at the start and the end of the run.

Stack arrangement was as in CVS with the same air duct area but the fan speed was 1200 rpm with expected air velocity of 3.3 m/s. Reconditioning treatment was the same as in CVS.

Fig. 3.3 shows the m.c % versus the drying time in hours for CVS and conventional processes. This indicates that the rate of drying during CVS was 79 % faster than the drying rate during the conventional process.

The results of the CVS and conventional runs are discussed and analysed in Chapter 5.

Chapter 4

AIR VELOCITY PROFILE

4.1 Introduction

The laminar air flow is the second principle related to the CVS feature. Theoretical estimation of the Reynolds number shows that air velocity of 1.3 m/s at the outlet side of the timber stack will keep this value well below the laminar limit. However, this estimation was not sufficient to provide detailed information about the type of air flow experienced under the configuration inside the kiln. Therefore, investigation of air velocity profile contributes to part of this thesis.

Greenhill (1936b) used a vane anemometer to measure the air flowing through a timber stack. Sharma and Jain (1977, 1978) and Jain and Sharma (1981) studied the air circulation inside a kiln using an "Alnor" velometer by inserting its probe into gaps on the outlet side of the stack. The instruments used in these previous studies had severe limitations, such as the length of time needed to carry out each single measurement. As a result, the frequency of measurements was insufficient to detect the time-variation in the velocity measured at the same position. Furthermore, the large dimensions of these instruments made it impossible to measure at sufficient positions across the small gap through which the air flows between two layers of timber in the stack to establish the velocity profile. The accuracy of these measurements also depended mainly on the skill of the operator.

From this review, it appeared that there was a lack of information regarding the profile of air velocity and the turbulence level at different positions of that profile. The work reported here is a new technique, which has been introduced to overcome the limitations experienced in the past.

4.2 Instrumentation

A 1.2 m long stack of timber was constructed using 100 x 25 mm rough sawn hardwood boards, four boards in each layer. The layers were separated by nominal 20 x 25 mm stickers, placed one at each end of the stack and two adjoining stickers across the centre with a total air duct area through the timber stack of a 0.176 m^2. This arrangement can be seen in Fig. 16 of Appendix D with one exception, which is replacing the 50 mm thick timber with 25 mm boards. The experimental kiln used was described in Chapter 3. The air velocity profile investigations were carried out at ambient temperature without adding any heating or humidity treatment. A Probe holder was designed to facilitate accurate vertical movement between the two layers of timber; these movements were measured by a Mercer dial gauge model No. 59A, having minor scale divisions representing 0.01 mm. The height of the air duct at the third row of column A (Fig. 16) was 20.1 mm measured by vernier calipers. Air velocity was measured at eleven vertical positions within this gap. These positions were at a distance of 0.05, 2.3, 4.3, 6.3, 8.3 mm from each surface of the two successive boards and the middle position was at 10.05 mm.

A hot wire anemometer, type DISA 55M system, which consists of the main unit 55M01, power pack 55M05, standard bridge 55M10 CTA, digital voltmeter 55D31 and a hot-film probe 55A80, was used to measure the air velocity in the form of a voltage signal; photos 12 and 13 in Appendix A show the system, probe holder and the probe. The probe was inserted 20 mm inside the air duct to avoid the end effect on the stream flow. An oscillascope, type Philips model PM 3230, was connected to the DISA 55M system to show the oscillation of the voltage signals. A thermocouple type "T" and digital thermometer type DORIC model 410A°C Trendicator were used to measure the temperature inside the kiln at the time of measuring the air velocities.

A voltage adaptor and data logger, type "Hales and Rogers" model No. DAS-1, were used to receive the voltage signal from the hot wire anemometer.

A Hewlett-Packard computer, model 75C, was used to accumulate the voltage signals through an interface, model 82165A HP-IL/GP10. These signals were then recorded by an HP digital cassette drive, model No. 82161A and the summary of voltages measured at each position as a result of the air velocities were printed by an HP printer, model No. 82905B. The layout of the instrument circuit used in these air flow measurements is shown in Fig. 19 in Appendix D. The voltage signals data were later transferred to a disc as back-up to the magnetic tape, using an HP86 computer and an HP flexible drive, model 9130A and this system was used to convert voltage signals to velocity values.

4.3 Method

A computer program was designed to collect the voltage signal from the hot wire anemometer, once every second for a two minute period. The program also calculated the mean, minimum, maximum and standard deviation of the 120 voltage signals collected at each position for every fan speed. This process was repeated at eleven positions across the 20.1 mm space between the two layers of timber in the stack to indicate the air velocity profile. Print out of the program used to collect the voltage signals is shown in Appendix C. This investigation was carried out using twelve fan speeds, which were 400, 490, 600, 700, 800, 1000, 1200, 1400, 1600, 1800, 2000 and 2200 rpm respectively.

The uniformity of the air flow along the timber stack was tested at the two fan speeds of 490 and 1500 rpm. This test was carried out with the probe fixed in the middle of the air gap at the outlet side of the stack to compare the air velocity in 16 positions, located at eight rows and four columns A-D as shown in Fig. 16 of Appendix D. This arrangement gave the opportunity of testing the air flow at a combination of eight different distances from the stickers. Columns A and C were tested in rows 2, 4, 6 and 8, while Columns B and D along rows 1, 3, 5 and 7, giving a total of 16 positions (Fig. 16 of Appendix D). The data was collected using the same program as before.

The effect of the double screen on the uniformity of the air flow at the inlet side was investigated in the empty kiln at the two fan speeds of 490 and 1500 rpm. The probe of the hot wire anemometer was placed perpendicularly at 80 mm from the screen. The air velocity was tested in eight positions along the length of the screen using the computer program to collect 120 voltage signals at each position. Position number seven was against an empty space within the screen and number eight was against one of the aluminium bars.

4.4 Calibration Test

The data collected from the various air velocity tests were voltage signals and to permit a proper interpretation of the corresponding velocities, it is necessary to calibrate the measuring system. DISA Company in Sweden, through their agent, Foss Electric (Aust.) Pty. Ltd., notified that the relationship between the voltage signal and the velocity follows a form of King's law, so that:-

$$V^2 = Vo^2 + BU^N$$

where

V = The voltage signal at a certain air velocity

Vo = The voltage signal at zero air velocity

U = Individual air velocity (m/s)

B = Constant related to the system

N = Empirical constant.

The calibration test was carried out using the same set up of the instrument circuit for air flow measurements in a wind tunnel at the New South Wales Institute of Technology, at different air velocities. These velocities were also measured by placing a pitot-static tube near the probe of the hot wire anemometer in the wind tunnel. The voltage signals of eighteen different velocities were collected by the computer program; also, the pressure due to each velocity was measured by an inclined-tube manometer manufactured by Air Flow Development Ltd. Model No. MK4.

The air velocity due to the velocity pressure was calculated taking into account the effect of humidity on air speed measurement according to Ower **et al.** (1977), British Standard 1339 (1965) and Perry (1950).

A computer program was used to determine the best fitted line between the values of the voltage signals and the air velocities in the form of the natural logarithm, as follows:-

$$\ln (V^2 - Vo^2) = \ln B + N(\ln U).$$

The coefficient of correlation ws Ø.9996 and values of B and N were as follows:-

$$F(x) = 2.44135 + (0.42652)x$$

where

$\ln (V^2 - Vo^2) = F(x)$

$\ln B = 2.44135$

$N = 0.42652$

$\ln U = x.$

These values were close to the values mentioned by Ower **et al.** (1977) and Bradshaw (1975). All the voltage signals collected during the air velocity investigation were converted to velocity values (m/s) using the computer program attached in Appendix C. This program also calculated the values of the turbulence level % according to Gostelow (1984) as follows:-

$$T_u\% = \frac{(u^2)^{0.5}}{\bar{U}} \times 100$$

where

$T_u\%$ = Turbulence level %

$$u^2 = \sum_{n=1}^{n=120} (U-\bar{U})^2/120$$

$$\bar{U} = \sum_{n=1}^{n=120} U/120 = \text{average air velocity}$$

U = individual air velocity

12Ø = n (number of samples)

4.5 Graphs

The data were transferred to a Data General MV8ØØØ computer provided with SAS package and graphs were drawn using a SAS graph program. Generally, there are four types of graphs:-

a. Air velocity profiles for fan speeds between 4ØØ and 22ØØ rpm (see Fig. 1 of Appendix D).
b. Air velocity profile and turbulence level % for each fan speed (see Figs. 2-13 of Appendix D).
c. Air velocity distribution for empty kilns at 49Ø and 15ØØ rpm (see Figs. 14, 15 of Appendix D).
d. Air velocity distribution along the timber stack to compare the front and back of the kiln at 49Ø and 15ØØ rpm (see Figs. 17, 18, Appendix D).

Chapter 5

RESULTS AND DISCUSSIONS OF DRYING

5.1 Initial Moisture Content %

The initial MC% of samples dried by CVS was compared with those from samples dried by the conventional schedule. Results of analysis of variance are presented in Table 5.1.

Table 5.1 AOV For Initial MC%

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	380.81	1	380.81	1.96
Error	4282.47	22	194.66	
Total	4663.28	23		

If $\alpha = 0.05$

at $v_1 = 1$, $v_2 = 22$ $F > 4.30$ [Walpole **et al.**, (1972)].

The initial MC% of samples dried by the CVS was not significantly different from those dried by the conventional process. This suggested that all samples belonged to the same population.

5.2 Moisture Content % After Drying

Table 5.2 shows the result of analysis of variance for MC% after drying.

Table 5.2: AOV For MC% After Drying

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	4.51	1	4.51	0.59
Error	168.13	22	7.64	
Total	172.64	23		

If $\alpha = 0.05$

at $v_1 = 1$, $v_2 = 22$ $F > 4.30$.

After drying, the MC% of samples dried by the CVS and conventional processes were not significantly different. This means that all samples dried to the same level of moisture content.

5.3 Moisture Content % After Reconditioning

The results of comparing the MC% after reconditioning for all samples dried by the two processes are presented in Table 5.3.

Table 5.3: AOV For MC% After Reconditioning

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	8.64	1	8.64	1.19
Error	160.20	22	7.28	
Total	168.84	23		

If $\alpha = 0.05$
at $v_1 = 1$, $v_2 = 22$ $F > 4.30$.

The MC% after reconditioning for samples dried by the CVS process was not significantly different from those dried by the conventional process. This indicates that all samples were within the same level of moisture content after reconditioning treatment.

5.4 Volumetric Shrinkage at End of Drying

Volumetric shrinkage % for each sample was estimated and those dried by CVS were compared with the values of samples dried by the conventional process. Results are given in Table 5.4.

Table 5.4: AOV for Volumetric Shrinkage at End of Drying

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	13.35	1	13.35	1.13
Error	263.91	22	12.00	
Total	277.26	23		

If $\alpha = 0.05$
at $v_1 = 1$, $v_2 = 22$ $F > 4.30$.

The volumetric shrinkage of samples at the end of drying by both CVS and conventional processes was not significantly different. This proves that the continuous increase of DBT and WBT during CVS had no harmful effect on the shrinkage of the samples as compared to the conventional process.

5.5 Volumetric Shrinkage After Reconditioning

The volumetric shrinkage % for samples dried by CVS was compared with that for samples dried by the conventional process. Results are shown in Table 5.5.

Table 5.5: AOV for Volumetric Shrinkage After Reconditioning

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	0.28	1	0.28	0.04
Error	140.25	22	6.38	
Total	140.53	23		

If $\alpha = 0.05$

at $v_1 = 1$, $v_2 = 22$ $F > 4.30$.

The volumetric shrinkage % after reconditioning for samples dried by CVS was not significantly different from that of samples dried by the conventional process.

5.6 Recovery in Volumetric Shrinkage

The recovery in volumetric shrinkage % was estimated for each individual sample and those dried by CVS were compared with the ones dried by the conventional process. Results are presented in Table 5.6.

Table 5.6: AOV For Recovery in Volumetric Shrinkage

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	Computed F
Treatment	18.03	1	18.03	8.52
Error	46.53	22	2.11	
Total	64.56	23		

If $\alpha = 0.01$

at $v_1 = 1$, $v_2 = 22$ $F > 7.95$.

The recovery of samples dried by CVS was significantly higher than that of samples dried by the conventional process at 1% level. This result supported the theory that the laminar boundary layer has protected the timber dried by the CVS process and prevented the wood cells from collapsing beyond the limit of recovery, as compared with those samples dried by the conventional process.

5.7 Timber Quality

The samples were planed all round and then examined by the Chief Timber Inspector from the Forestry Commission of New South Wales according to AS 2082-1979 for structural purposes. Eleven samples out of the twelve dried by CVS were graded as grade one, with the last one as grade four. Eleven samples out of those dried by the conventional process were graded as grade one and the last one as grade two.

This is a very competitive result in regard to the quality of timber form the viewpoint of the timber industry.

5.8 Energy Consumed

Table 5.7 represents the energy consumption and the amount of water evaporated from the load of the timber during each process as well as a general comparison.

Table 5.7: Comparison of Energy and Time for the Two Processes

Factors	CVS	Conventional	Saving % by CVS
1. Initial MC%	61.2	53.2	-
2. Final MC%	12.9	12.1	-
3. Drying time (h)	439	670	34.5
4. Energy used (kWh)	884	1276	30.7
5. Amount of water evaporated (g)	11585	10594	-
6. Rate of drying (MC%/h x 100)	11.0	6.1	80.3
7. Average amount of MC% reduced per unit of energy (MC%/kWh x 100)	5.5	3.2	71.9
8. Average amount of water evaporated per unit of energy (g/kWh)	13.1	8.3	57.8
9. Average amount of water evaporated per unit of drying time (g/h)	26.4	15.8	67.1

This table shows that the CVS process can save 34.5% on drying time and saves 30.7% of the electric energy used in drying. Furthermore, that the drying efficiency, as determined by the amount of water evaperated from the timber per unit of energy (g/kWh) is 57.8% better, as compared to the conventional process.

The most important advantages of the CVS process are therefore the high drying performance and the efficient usage of energy. These can be seen clearly by comparing figures of the two processes for the rate of drying and the amount of MC% reduced per unit of energy. CVS has achieved an increase of 80.3% in the rate of drying and has improved the usage of energy (MC%/kWh x 100) by 71.9% as compared to the conventional process.

Chapter 6

RESULTS AND DISCUSSION OF AIR VELOCITY TESTS

Results of air velocity investigation are discussed under four headings.

6.1 General Air Velocity Profiles

The air velocity profiles for fan speeds of 400, 490, 600, 700, 800, 1000, 1200, 1400, 1600, 1800, 2000 and 2200 rpm are shown in Fig. 1 of Appendix D. The x-axis represents the gap in mm from the bottom surface of the first board, which is referred to as top board, to the upper surface of the second board (referred to as bottom board). This gap was 20.1 mm and the velocity was measured at eleven positions which were at a distance of 0.05, 2.30, 4.30, 6.30, 8.30, 10.05, 11.80, 13.80, 15.80, 17,80 and 20.05 mm from the bottom surface of first board. The y-axis represents the air velocity in m/s.

The curves of the air velocity profiles from 800 to 2200 rpm show a flat top shape, which is a typical shape of the turbulent profile, while those below 700 rpm approximate the parabolic shape of the laminar profile.

6.2 Air Velocity and Turbulence Level

It could be worthwhile before starting to examine these results to explain why it was felt that the Reynolds number was not satisfactory to define the type of air flow. It is well established that the critical Reynolds number increases as the disturbance in the flow before the inlet side is decreased. This fact was confirmed experimentally and a critical Reynolds number of 40,000 was reached by Ekman (1910).

Table 6.1 shows the values of the mean of 120 air velocities (U) in m/s measured at each position and their turbulence level % (T_u%) for each fan speed. The velocity profile and the turbulence level % for each individual fan speed are plotted in Figs. 2 to 13 (Appendix D).

The crucial question here is whether there is a critical turbulence level separating the laminar and the turbulent flows which applies to these test conditions. Researchers working in the field have faced the same question and Gostelow **et al.** (1983) stated that Schlichting **et al.** (1970) indicated that such a critical level exists. He added also, that unpublished work performed at Cambridge University is fully consistent with the concept of a critical turbulence level. These turbulence level measurements were made under adverse pressure gradient conditions which varied up to 4.5%. Schlichting (1968) stated that Dryden **et al.** (1947) undertook extensive measurements on the effect of placing fine-mesh screens in a wind tunnel. Dryden concluded that the addition of a single screen reduces the turbulence level by a factor relating to the resistance coefficient of the screen. Generally speaking the critical value for the turbulence level depends to a large extent on the conditions under which the test is carried out. In our case these conditions involve an inherited effect due to the design of the kiln, fan position, resistance coefficient of the screen, stack configuration and finally the surface roughness of the timber.

The establishment of this critical value under these particular conditions requires time and resources to carry out fundamental studies which are beyond our present capacity.

Table 6.1: Mean Air Velocity and Turbulence Level at Each Position and Fan Speed

rpm	Values \ Distance from top board in mm	0.05	2.30	4.30	6.30	8.30	10.05	11.80	13.80	15.80	17.80	20.05
400	$\bar{U}$	0.44	0.70	0.93	1.09	1.14	1.14	1.14	1.08	0.96	0.62	0.40
	T_u%	2.13	13.66	10.57	5.83	4.48	4.54	4.54	6.55	9.45	16.92	1.97
490	$\bar{U}$	0.48	0.97	1.20	1.35	1.43	1.44	1.42	1.35	1.24	0.83	0.43
	T_u%	2.89	12.86	9.68	6.13	4.32	4.10	5.65	5.80	9.17	15.49	3.08
600	$\bar{U}$	0.50	1.26	1.56	1.68	1.75	1.75	1.72	1.66	1.56	1.15	0.46
	T_u%	3.34	12.53	8.15	6.05	4.52	4.36	5.00	5.54	8.31	13.04	2.68
700	$\bar{U}$	0.54	1.54	1.69	1.89	1.97	1.98	1.98	1.94	1.83	1.47	0.49
	T_u%	3.38	12.49	9.80	6.60	4.94	4.83	4.65	4.88	7.74	11.64	3.07
800	$\bar{U}$	0.59	1.83	1.97	2.19	2.28	2.30	2.30	2.23	2.17	1.66	0.51
	T_u%	4.27	11.95	10.14	5.37	5.23	5.07	4.26	6.10	6.60	14.93	4.14
1000	$\bar{U}$	0.71	2.39	2.54	2.82	2.89	2.90	2.89	2.85	2.69	2.29	0.60
	T_u%	5.09	9.56	9.82	6.36	4.29	4.23	5.02	5.10	6.79	11.89	7.43
1200	$\bar{U}$	0.87	2.85	2.95	3.25	3.30	3.36	3.38	3.33	3.13	2.76	0.73
	T_u%	7.09	10.30	10.89	5.80	4.84	5.44	5.14	6.32	6.86	12.46	9.32
1400	$\bar{U}$	1.03	3.28	3.71	3.95	4.06	4.04	4.08	3.99	3.80	3.36	0.88
	T_u%	8.58	10.49	7.57	5.18	4.54	4.87	5.13	5.18	6.79	10.85	10.27
1600	$\bar{U}$	1.16	3.44	3.94	4.26	4.26	4.31	4.30	4.25	3.98	3.66	1.02
	T_u%	8.48	12.25	7.80	5.68	4.94	4.86	4.82	5.66	7.48	10.46	14.29
1800	$\bar{U}$	1.33	3.80	4.40	4.48	4.55	4.69	4.51	4.58	4.34	3.97	1.14
	T_u%	11.86	13.23	25.43	18.92	16.99	28.80	19.06	7.38	7.28	9.61	14.90
2000	$\bar{U}$	1.42	3.97	4.28	4.73	4.83	4.88	4.91	4.73	4.59	4.16	1.27
	T_u%	10.57	16.54	22.78	10.71	7.65	11.77	14.92	10.01	6.99	9.23	15.44
2200	$\bar{U}$	1.52	4.36	4.75	4.97	4.90	4.99	5.07	5.03	4.82	4.36	1.40
	T_u%	12.63	35.09	11.28	5.98	12.67	16.25	10.24	8.19	7.13	9.80	16.21

On the other hand, Schlichting (1968) stated that "an increase in the turbulence level causes an increase in the rate of heat transfer which is characteristic of a turbulent as compared with a laminar boundary layer". If the air flow which passed through the timber stack during the CVS process at a fan speed of 490 rpm was a turbulent flow, we should expect the heat transfer to occur at a high level, therefore exposing the timber to a severe condition of drying. A poor quality dried product would be expected. The result of timber quality which was indicated in Chapter 5 was completely contrary to that expected under turbulent flow conditions.

Finally, my expectation is that due to the high friction between the rough surface of the timber and the flowing air, a laminar boundary layer exists on the two surfaces. This appears to be an acceptable explanation of the low values of the turbulence level near the surfaces. The high values of turbulence level which are observed at the next position outwards from timber surface (2.3, 17.8 mm), probably occur as a result of the breaking away of the air flow from the boundary layer. Consequently, the maximum turbulence level for all velocity profiles for fan speeds from 400 to 1600 rpm (Figs 2 to 10, Appendix D) remains about the same in the range of 11 to 17 percent. Over this range the maximum flow velocities have increased from 1.14 to 4.31 m/s.

On the other hand, beyond a fan speed of 1600 rpm (Figs. 11 to 13, Appendix D) there is a sharp increase in the maximum turbulence level to 23-35 percent, i.e. by a factor of more than 2. This range corresponds to maximum flow velocities of 4.7 to 5.1 m/s, and is probably due to the formation of major free stream turbulence.

6.3 Air Velocity Distribution in the Empty Kiln

In an attempt to establish the uniformity of the air velocity distribution due to the double screen in the empty kiln, measurements of mean air velocity and turbulence level were taken 80 mm behind the inlet screen at fan speeds of 490 and 1500 rpm. These results are summarized in Table 6.2. Eight positions were tested along the screen, with position 1 located near the front of the kiln.

Table 6.2: Mean Velocity and Turbulence Level in Empty Kiln

Position	490 rpm		1500 rpm	
	Mean Velocity m/s	Turbulence Level %	Mean Velocity m/s	Turbulence Level %
1	0.55	12.45	1.88	17.03
2	0.36	22.00	1.37	22.59
3	0.31	26.62	1.18	28.33
4	0.52	15.50	1.87	18.43
5	0.40	17.46	1.50	19.49
6	0.44	17.12	1.66	17.54
7	0.45	15.02	1.48	16.25
8	0.43	14.08	1.49	15.98
Overall Mean	0.43	-	1.55	-

Figures 14 and 15 (Appendix D) are a graphical representation of the mean velocity results in Table 6.2

at each position and the overall mean velocity for the empty kiln at the two fan speeds.

The high values of the turbulence level % at the two fan speeds support my expectation of an inherited turbulence effect due to kiln screen design. Therefore, this factor no doubt has some disturbing effect on the air flow entering the stack, which affects the air flow at the outlet side of the stack.

Figures 14 and 15 (Appendix D) show a difference in air velocity along the screen. This indicates that the screen design needs to be improved to facilitate better air flow uniformity and a lower base level of turbulence.

6.4 Air Velocity Distribution Along the Timber Stack

Results for the uniformity of air velocity distribution along the timber stack at speeds of 490 and 1500 rpm are shown in Table 6.3, where the mean velocity and the turbulence level are compared between the front and the back halves of the stack.

Figures 17 and 18 in Appendix D are a graphical representation of the mean velocity in Table 6.3 at each row in comparison between the front and back along the outlet side of the stack and the overall mean velocity at two fan speeds.

From Table 6.3 it is clear that the turbulence level % is lower than the values shown in Table 6.2, despite the fact that the air velocity through the stack is much higher than the velocity through the screen.

Table 6.3: Mean Velocity and Turbulence Level Along Timber Stack Front v. Back at 490 and 1500 rpm

Row No.	490 rpm				1500 rpm			
	Front		Back		Front		Back	
	Mean Vel. m/s	Turb. Level %	Mean Vel. m/s	Turb. Level %	Mean Vel. m/s	Turb. Level %	Mean Vel. m/s	Turb. Level %
1	1.21	5.58	1.19	4.00	3.79	5.88	3.52	4.69
2	1.13	7.02	1.29	5.09	3.58	6.18	3.99	4.66
3	1.30	6.07	1.30	3.83	3.88	6.23	3.91	3.53
4	1.17	4.63	1.27	4.10	3.69	4.86	3.73	4.54
5	1.22	5.38	1.28	3.70	3.76	5.42	3.94	4.01
6	1.33	4.91	1.20	4.78	4.22	4.82	3.71	5.04
7	1.27	4.45	1.23	3.65	3.86	4.86	3.70	3.88
8	1.22	4.72	1.26	4.68	3.73	4.72	3.77	5.13
Overall Mean	1.23	-	1.25	-	3.81	-	3.78	-

This comparison supports my expectation that the surface roughness of the timber surface creates a frictional resistance which absorbs the turbulence energy of the air flow.

The graphical presentation of the results in Figs. 17 and 18 shows some difference in the air velocity between the front and the back halves of the stack, which can be overcome by improving the screen function and requires more attention to the method of stacking the timber.

The distances between the stickers and the measured positions under columns A, B, C and D (Fig. 16, Appendix D), were chosen to minimize any direct effect on the measured velocities, but their effect on the velocity was not a major part in the investigation.

Chapter 7

CONCLUSIONS

7.1 CVS Process

CVS process proved to be a more efficient technique than any currently used for kiln drying green medium to high density hardwood. Results of comparison between the CVS and the conventional kiln drying process reveals the following:-

a. CVS reduced drying time by 34.5%.

b. The high drying performance of the CVS process achieved an increase in rate of drying (MC%/h x 100) by 80.3%.

c. The mass of the water evaporated from the timber per unit of drying time (g/h) during the CVS was 67.1% higher than the conventional process.

d. Energy wise, the CVS was more economical, since the amount of energy used during drying (kWh) was 30.7% less than that used by the conventional process.

e. The CVS had demonstrated a highly efficient usage of the energy, as the amount of moisture content reduced per unit of energy (MC%/kWh x 100) was 71.9% higher than the conventional process.

f. The mass of water evaporated from timber per unit of energy used by the kiln during the CVS process (g/kWh) was 57.8% higher than that of the conventional.

g. The quality of the timber dried by CVS process was very competitive as compared with that dried by the conventional process.

h. The CVS can be applied fully automatically using a process programmer to drive the kiln controller according to a pre-programmed schedule, subject to the accumulation of enough knowledge regarding the drying conditions of different timber species.

Generally, the CVS has achieved great progress towards the goal of efficient kiln drying of medium to high density hardwood. It is a three-fold advantage of one drying process to reduce the drying time, the amount of energy consumed and to produce a competitive quality of the dried timber. To the best of the author's knowledge, no other currently used process is capable of performing as fast or as efficiently as CVS.

7.2 Air Flow

A new technique was reported in this thesis to examine the air flow through the duct of the timber stack inside the kiln. This technique involves the combination of a hot wire anemometer, data logger, computer and computer peripherals to accumulate and analyse the data of the air velocity and turbulance level at different fan speeds. The turbulence levels were estimated for 120 air velocity samples measured in each of the eleven positions between the 20.1 mm gap, which represents the duct height. The same technique was used to examine the uniformity of the air flow at eight different positions along the double screen at the inlet side. The air flow distribution along the timber stack was also examined in four different vertical columns along eight different horizontal rows.

The investigations of the air velocity profile, turbulence level, effect of the screen and the air distribution through the outlet side of the timber stack, has accumulated a reliable bank of information, which to the author's knowledge is the first in this field.

The results indicate that to differentiate between laminar and turbulent flow, the value of the critical turbulence level has to be established, especially as there is an inherited effect due to the design of the system, which increases the turbulence level of the air entering the timber stack. It is recommended that further investigations should be carried out in this field.

It is the author's conclusion, that due to the high friction between the rough surface of the timber and the air flow, a moisture-laden laminar boundary layer forms on the two surfaces which protects the timber being processed against the severe temperature conditions during the CVS process. Evidence for this conclusion is circumstantial, rather than absolute. The results of the drying tests carried out under CVS, representing a combination of high rate of temperature increase and low air velocity, could not have produced the high quality of dried timber, had the timber not been protected by such a moisture-laden laminar boundary layer.

7.3 Energy

The author has made suggestions towards the more efficient use of energy during the drying process. Integration of a dehumidifier and a solar-powered system backed up with an electric or wood-waste fired booster was recommended as an economical and low energy cost drying plant.

Recovery of waste energy from conventional drying kilns was also discussed. Heat exchangers may be useful to recover energy from the exhaust air of the kiln and can supply supplementary heat to another process in the timber processing plant, especially in localities having low ambient temperatures. A saving of 12 to 15% over the conventional method was claimed by using heat exchanger.

The CVS has an energy saving of 30.7% as compared with the conventional process, without any major change to the drying plant. This is double the saving which the addition of the heat exchanger could achieve.

A conventional drying plant could quite easily and cheaply be converted to operate under CVS. All that would be required is some modification to the fan system and the addition of a programmable control system for temperature and humidity control.

Sources of energy other than the petroleum-based energy were also discussed, which was initiated by the fact that cost of petroleum products has been constantly rising in recent years.

APPENDIX - A

"PHOTOS"

Photo no. 1: The Portable Hand-Held Velocity Meter .

Photo no. 2: Velocity Meter Probe .

Photo no. 3: Experimental Kiln .

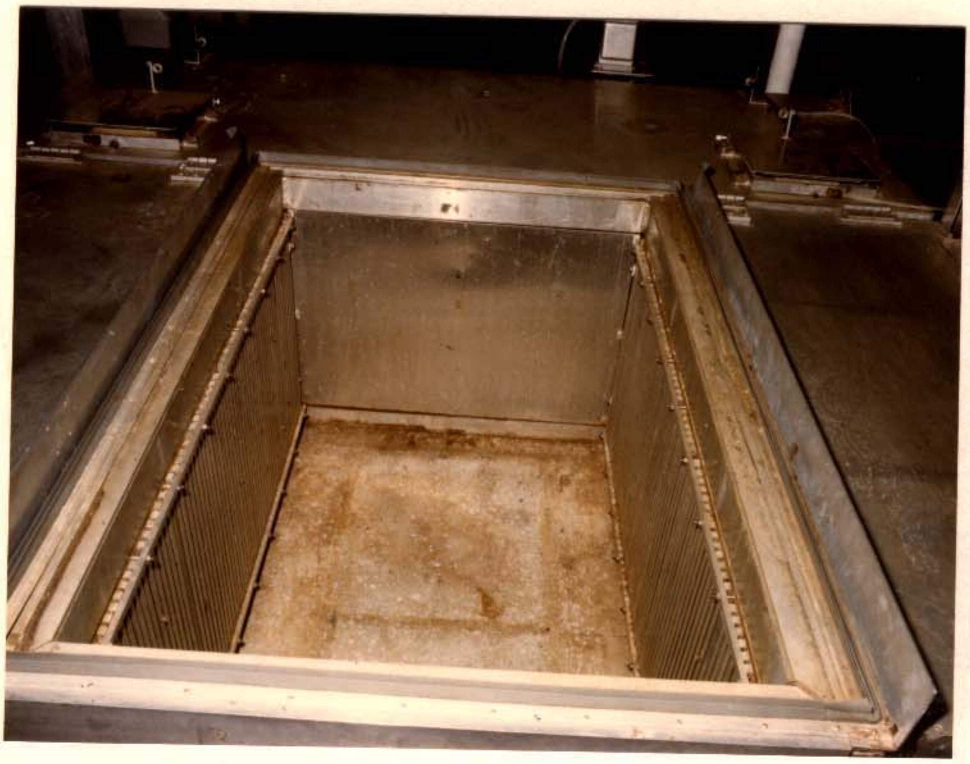


Photo no. 4: Drying Compartment .

Photo no. 5: Inlet Side Screen .

Photo no.6: Heating Duct .

Photo no. 7: Heating Coils, Perforated Tube and Fan .

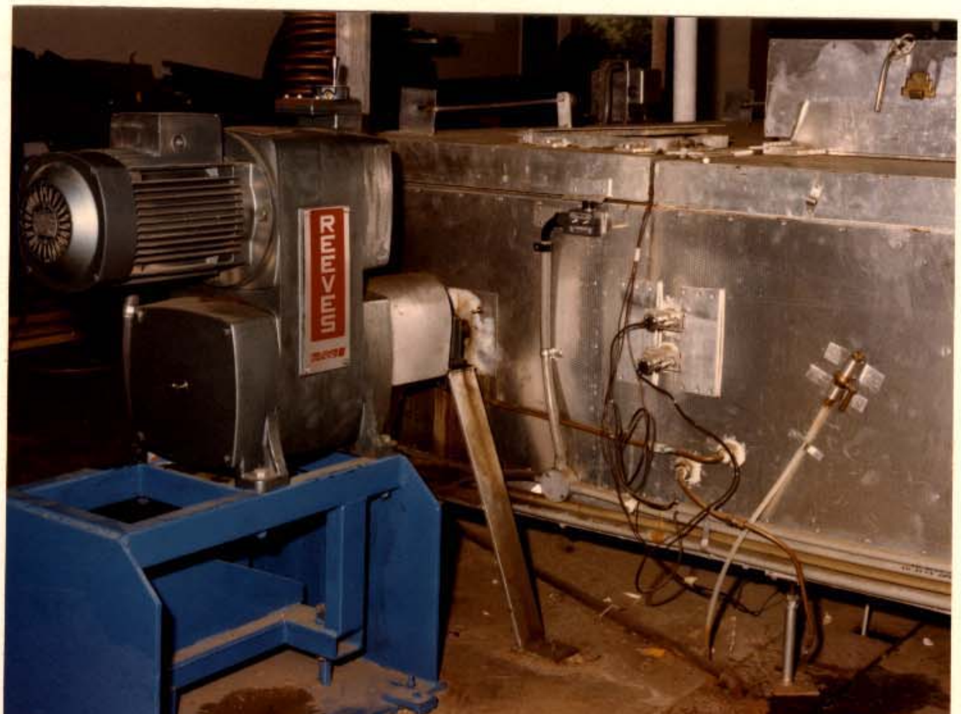


Photo no. 8: Fan Motor .

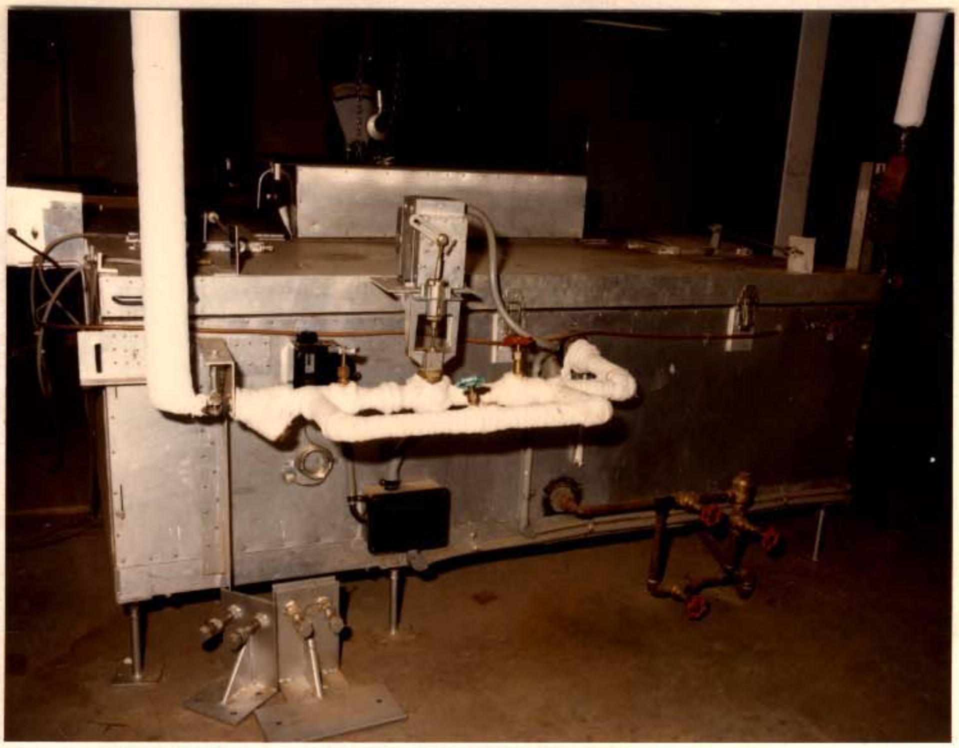


Photo no. 9: Steam Line Controlling Valve .

Photo no. 10:

Controlling System .

Photo no. 11:

Loading

Arrangement .

Photo no. 12: Hot Wire Anemometer,

Oscillascope And Probe Holder .

Photo no. 13: Probe Of Hot Wire Anemometer .

APPENDIX - B

"PROGRAMMING WORK-SHEETS"

SET POINT PROGRAMMING WORK-SHEET

Sheet 1 of 6

SELECT: [✓] OUTPUT 1 or [ ] OUTPUT 2

PROGRAM DESCRIPTION: CVS Run - Stage I

MODULE NO.

ENTER RANGE: LOW END: 0 °C HIGH END: 200°C

PROGRAM REGIONS:

REGION	SOAK AT / RAMP TO		TIME / EVENT
REGION: 0	[✓] SOAK AT: 35°C	or	[✓] TIME: 00 HRS. 01 MIN. / or [ ] EVENT: [ ] NOT
	or [ ] RAMP TO:		TIME: HRS. MIN.
REGION: 1	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [✓] RAMP TO: 43°C		TIME: 80 HRS. 00 MIN.
REGION: 2	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [✓] RAMP TO: 51°C		TIME: 80 HRS. 00 MIN.
REGION: 3	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [✓] RAMP TO: 59°C		TIME: 80 HRS. 00 MIN.
REGION: 4	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [✓] RAMP TO: 67°C		TIME: 80 HRS. 00 MIN.
REGION:	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [ ] RAMP TO:		TIME: HRS. MIN.
REGION:	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN. / or [ ] EVENT: [ ] NOT
	or [ ] RAMP TO:		TIME: HRS. MIN.

SET POINT PROGRAMMING WORK-SHEET

Sheet 2 of 6

SELECT: [ ] OUTPUT 1 or [✓] OUTPUT 2

PROGRAM DESCRIPTION: CVS Run - Stage I

MODULE NO.

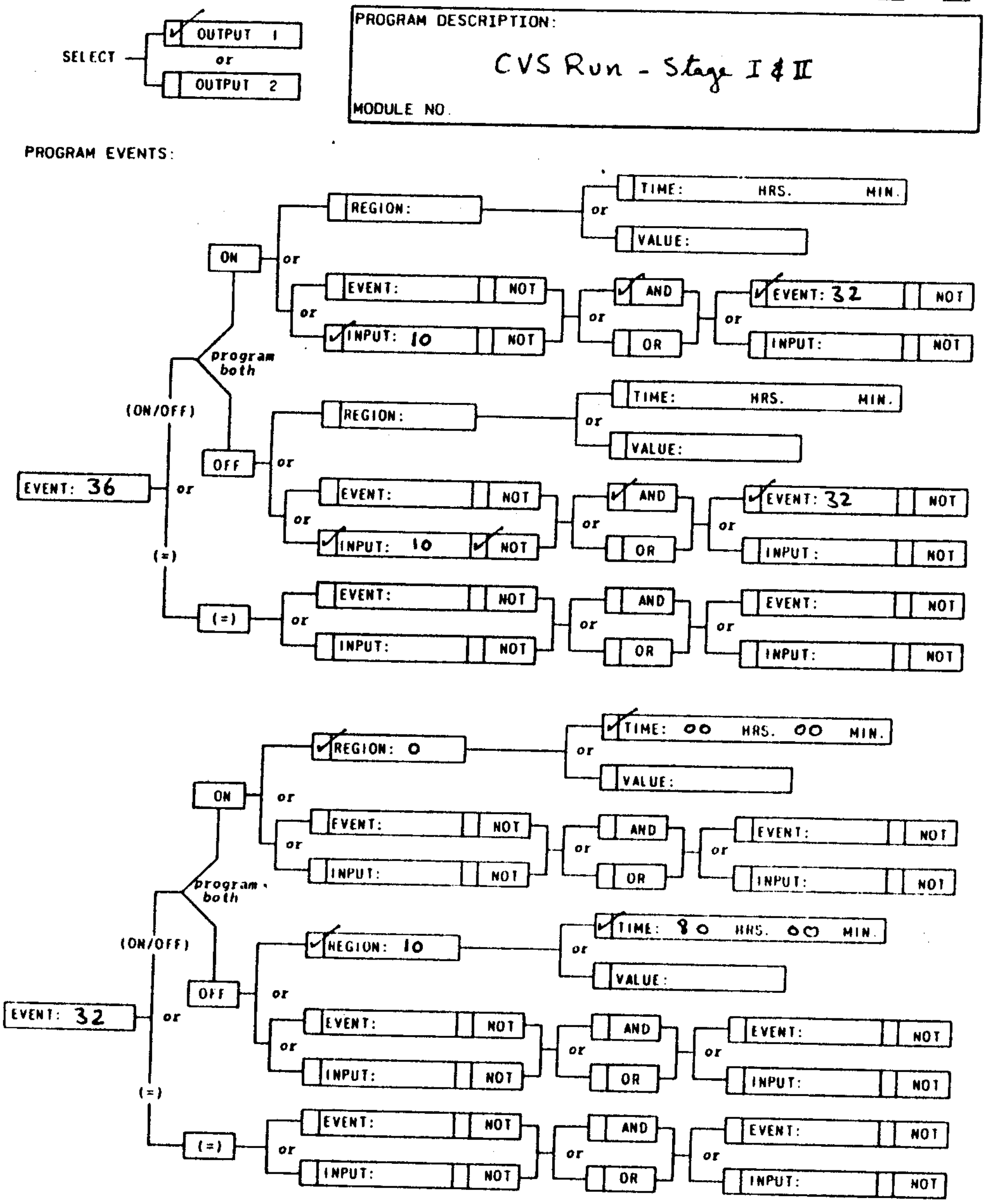
ENTER RANGE: LOW END: 0°C HIGH END: 200°C

PROGRAM REGIONS:

REGION				
REGION: 0	[✓] SOAK AT: 33°C	or	[✓] TIME: 00 HRS. 01 MIN.	or [ ] EVENT: [ ] NOT
or	[ ] RAMP TO:		TIME: HRS. MIN.	
REGION: 1	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[✓] RAMP TO: 37°C		TIME: 80 HRS. 00 MIN.	
REGION: 2	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[✓] RAMP TO: 41°C		TIME: 80 HRS. 00 MIN.	
REGION: 3	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[✓] RAMP TO: 45°C		TIME: 80 HRS. 00 MIN.	
REGION: 4	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[✓] RAMP TO: 49°C		TIME: 80 HRS. 00 MIN.	
REGION:	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[ ] RAMP TO:		TIME: HRS. MIN.	
REGION:	[ ] SOAK AT:	or	[ ] TIME: HRS. MIN.	or [ ] EVENT: [ ] NOT
or	[ ] RAMP TO:		TIME: HRS. MIN.	

LOGIC PROGRAMMING WORK-SHEET

Sheet 3 of 6



LOGIC PROGRAMMING WORK-SHEET

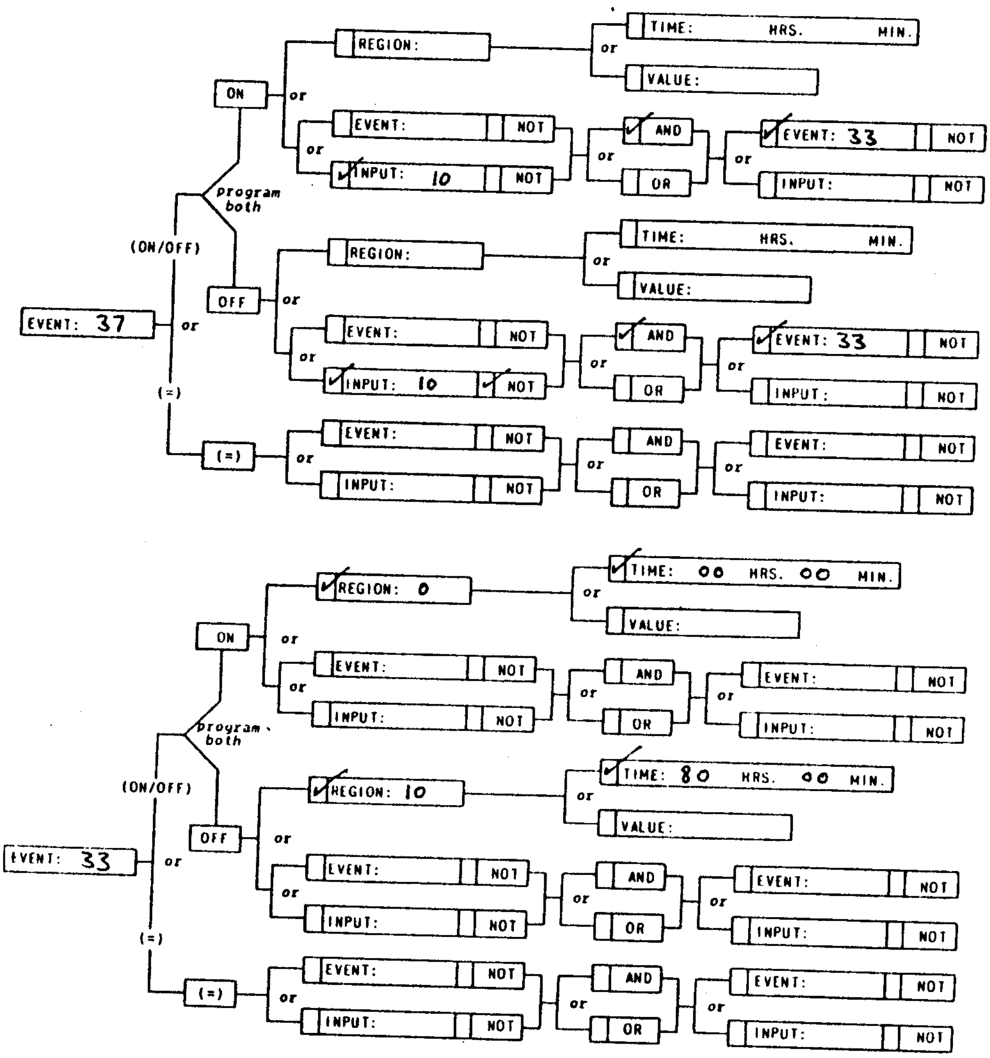
Sheet 4 of 6

SELECT — OUTPUT 1 or ✓ OUTPUT 2

PROGRAM DESCRIPTION: CVS Run - Stage I & II

MODULE NO.

PROGRAM EVENTS:



SET POINT PROGRAMMING WORK-SHEET

Sheet 5 of 6

SELECT
- [✓] OUTPUT 1
- or
- [ ] OUTPUT 2

PROGRAM DESCRIPTION: CVS Run - Stage II

MODULE NO.

ENTER RANGE: LOW END: 0 °C HIGH END: 200 °C

PROGRAM REGIONS:

REGION: 4
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [✓] RAMP TO: 65.5 °C — TIME: 65 HRS. 00 MIN.

REGION: 5
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [✓] RAMP TO: 80 °C — TIME: 58 HRS. 00 MIN.

REGION: 6
- or
  - [✓] SOAK AT: 80 °C — or — [✓] TIME: 80 HRS. 00 MIN. / [ ] EVENT: [ ] NOT
  - [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- or
  - [ ] SOAK AT: — or — [ ] TIME: HRS. MIN. / [ ] EVENT: [ ] NOT
  - [ ] RAMP TO: — TIME: HRS. MIN.

SET POINT PROGRAMMING WORK-SHEET

Sheet 6 of 6

SELECT: [ ] OUTPUT 1 or [✓] OUTPUT 2

PROGRAM DESCRIPTION: CVS Run - Stage II

MODULE NO.

ENTER RANGE: LOW END: 0°C HIGH END: 200°C

PROGRAM REGIONS:

REGION: 4
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [✓] RAMP TO: 48.25°C — TIME: 65 HRS. 00 MIN.

REGION: 5
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [✓] RAMP TO: 56.95°C — TIME: 58 HRS. 00 MIN.

REGION: 6
- [✓] SOAK AT: 56.95°C — [✓] TIME: 80 HRS. 00 MIN. or [ ] EVENT: [ ] NOT
- or [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [ ] RAMP TO: — TIME: HRS. MIN.

REGION:
- [ ] SOAK AT: — or [ ] TIME: HRS. MIN. or [ ] EVENT: [ ] NOT
- or [ ] RAMP TO: — TIME: HRS. MIN.

APPENDIX - C

"COMPUTER PROGRAMS"

The program used to collect the voltage signals - 1.

```
10 REM * AIR VELOCITY PROGRAMME "PRIMEAIR"
20 REM * WRITTEN FOR RESEARCH PROJECT
30 REM * CONTROLS ACQUISITION OF DATA FROM HOT WIRE ANEMOMETER BY
40 REM * DATA LOGGER DAS-1, STORES VOLTAGE DATA FILE ON CASSETTE,
50 REM * INPUTS & PRINTS ANEMOMETER & KILN PARAMETERS, &
60 REM * CALLS STATISTICAL PROGRAMME "RESULTS"
70 REM * OCTOBER 1983
80 REM * REVISED DECEMBER 1983

90 REM * HP-75C BASIC.
100 REM * FOLLOWING FILES MUST BE PRESENT;
110 REM * HP-IL "UTILITIES","RESULT"
120 REM * PROGRAMME MUST BE RE-RUN FOR EACH PROBE LOCATION.
130 REM ***********************************************************
140 REM * INITIALISE STORED VARIABLES;
150 DISP "INITIALIZATION"
160 ASSIGN # 2 TO "TDAT" ! Data file for storing voltage readings.
170 OPTION BASE 1
180 RESTORE IO
190 CLEAR LOOP
200 C=0
210 K=0
220 DIM A$[2]
230 PRINT CHR$(27)&"&l1L"; ! SKIP PRINTER PERFs.
240 REM ***************************************************
250 REM * GPIO CONTROL REGISTER DATA PLACED IN R$ & S$.
260 REM * DATA FOR R$ and S$ "INTERLEAVED"
270 DATA 64,64,152,144,221,221,5,5,0,0
280 R$=''
290 S$=''
300 FOR I=1 TO 5
310 READ X
320 R$=R$&CHR$(X)
330 READ X
340 S$=S$&CHR$(X)
350 NEXT I
360 REM **********************************************
370 REM * ENTER KILN & ANEMOMETER PARAMETERS
380 DIM B$[40]
390 DISP "ENTER TYPE OF TEST";
400 INPUT B$
410 DISP "ENTER TEMP. INSIDE KILN";
420 INPUT A
430 DISP "ENTER COLD RESISTANCE";
440 INPUT B
450 DISP "ENTER HOT RESISTANCE";
460 INPUT D
470 DISP "POSITION/ROW NO.";
480 INPUT C$
```

The program used to collect the voltage signals - 2.

```
490 DISP "ENTER LOCATION";
500 INPUT E$
510 DISP "ENTER Vo";
520 INPUT E
530 DISP "ENTER PROBE TYPE";
540 INPUT D$
550 DISP "ENTER FAN SPEED";
560 INPUT F
570 VO=.86*E
580 REM ************************************************
590 REM * PROCEDURE READS  DAS-1.
600 ON TIMER # 1,1 GOSUB 620 ! Read DAS-1 every one second.
610 GOTO 610
620 SENDIO '','LAD1,DDLO',S$ ! SET CONTROL REGISTERS
630 SENDIO '','LAD1,GET','' ! RESET CHANNEL COUNTERS
640 SENDIO '','LAD1,DDLO',R$ ! SET *RDYO* CONTROL LINE
650 A$=ENTIO$('','TAD1,SDA') ! LOAD TRANSFER BUFFER INTO CHAR. STRING
660 IF LEN(A$)=0 THEN 750
670 SENDIO '','LAD1,DDLO',S$ ! TURN OFF *RDYO*
680 V=NUM(A$[1,1])*64+NUM(A$[2,2])
690 V=V*2.5/1000
700 C=C+1 ! C= no. of readings.
710 DISP C
720 PRINT # 2 ; C,V ! Store each counter & voltage reading in "TDAT".
730 IF C=120 THEN 800 ! Number of readings = 120
740 GOTO 770
750 BEEP
760 DISP "PROBLEM, GPIO BUFFER EMPTY"
770 RETURN
780 REM ************************************************
790 REM * TRANSFER VOLTAGE DATA FILE TO CASSETTE
800 X=9999
810 PRINT # 2 ; X ! Delineates end of data for each probe location.
820 OFF TIMER # 1
830 F$=DATE$
840 G$=TIME$
850 BEEP 220,2 ! Calls operator when readings completed.
860 DISP "ENTER NAME OF FILE"; ! Operator names current set of data.
870 INPUT Z$
880 RENAME "TDAT" TO Z$
890 COPY Z$ TO Z$&":CA" ! Current data file stored on tape under new name.
900 REM ************************************************
910 REM * PRINT DATE, TIME, KILN & ANEMOMETER PARAMETERS, & CURRENT FILE NAME
920 PRINT F$,G$
930 PRINT
940 PRINT "TYPE OF TEST : ";B$
950 PRINT
960 PRINT "TEMPERATURE INSIDE KILN = ";A;"C"
```

The program used to collect the voltage signals - 3.

```
970 PRINT "COLD RESISTANCE = ";B;" OHMS",
980 PRINT "HOT RESISTANCE = ";D;" OHMS"
990 PRINT "POSITION/ROW NO.= ";C$,
1000 PRINT "LOCATION : ";E$
1010 PRINT "FAN SPEED = ";F;"Rpm",,"Vo =";E
1020 PRINT "PROBE TYPE : ";D$,,"Vo' =";VO
1030 PRINT
1040 PRINT "FILE HOLDING DATA ";Z$
1050 PRINT
1060 PRINT
1070 PRINT
1080 PRINT
1090 REM ***********************************************
1100 REM * CALL STATISTICAL PROGRAMME
1110 ASSIGN # 4 TO "TITLE"
1120 PRINT # 4 ; Z$ ! Store current voltage data file name in "TITLE".
1130 CALL "RESULT" ! Call statistical programme.
1140 PURGE Z$ ! Purge current voltage data file from memory.
1150 PRINT CHR$(12) ! Form feed.
1160 END
```

The program used to convert the voltage signals to verlocity values - 1.

```
10 REM * AIR VELOCITY PROGRAMME "CONVERT"
20 REM * WRITTEN FOR RESEARCH PROJECT
30 REM * CONVERTS VOLTAGE DATA AT EACH PROBE LOCATION TO VELOCITY
40 REM * USING EQUATION DERIVED BY N.M. NASSIF,
50 REM * CALCULATES STATISTICAL SUMMARY, COMBINES STATISTICS FROM
60 REM * ALL PROBE LOCATIONS INTO AN ARRAY FOR EACH FAN SPEED, &
70 REM * STORES EACH ARRAY IN A SEPARATE RECORD WITHIN APPROPRIATE DATA FILE.
80 REM * PROGRAMME IS RE-RUN FOR EACH FAN SPEED CHANGING LINE 810.
90 REM * MARCH 1984
100 REM * HP86A BASIC
110 REM ****************************************************
120 REM * INITIALISE PARAMETERS
130 OPTION BASE 1
140 DIM A(120),B(10,6)
150 REM * A()=ARRAY FOR VOLTAGE DATA FROM ONE PROBE LOCATION
160 REM * B(,)=ARRAY FOR VELOCITY STATISTICS FROM ALL PROBE LOCATIONS FOR ONE
170 REM * FAN SPEED
180 ASSIGN# 2 TO  "VELPROFILE" ! name corresponds to appropriate data file.
190 FOR J=1 TO 10 ! 10 probe locations
200 PRINT CHR$ (27)&"&l1L"
210 PRINT @ PRINT @ PRINT
220 REM * INITIALISE STATISTICAL VARIABLES
230 SUMY,SUMY2,CNT,MX,SUMDEV2=0
240 MINM=9999
250 REM ****************************************************
260 REM * ENTER VOLTAGE DATA FILE DETAILS FROM ONE PROBE LOCATION
270 DISP "ENTER FILENAME";
280 INPUT B$
290 DISP "ENTER Vo";
300 INPUT VO
310 REM ****************************************************
320 REM * READ VOLTAGE DATA INTO A(), CONVERT TO VELOCITY, &
330 REM * CALCULATE STATISTICS
340 ASSIGN# 1 TO  B$
350 READ# 1 ; A()
360 FOR I=1 TO 120
370 X=A(I)
380 Y=(LOG (X^2-VO^2)-2.44135)/.42652
390 Y=EXP (Y)
400 MX=MAX (MX,Y)
410 MINM=MIN (MINM,Y)
420 SUMY=SUMY+Y
430 SUMY2=SUMY2+Y^2
440 CNT=CNT+1
450 NEXT I
460 MEAN=SUMY/CNT
470 FOR I=1 TO 120
480 X=A(I)
490 Y=(LOG (X^2-VO^2)-2.44135)/.42652
500 Y=EXP (Y)
```

APPENDIX - D

"GRAPHICAL FIGURES"

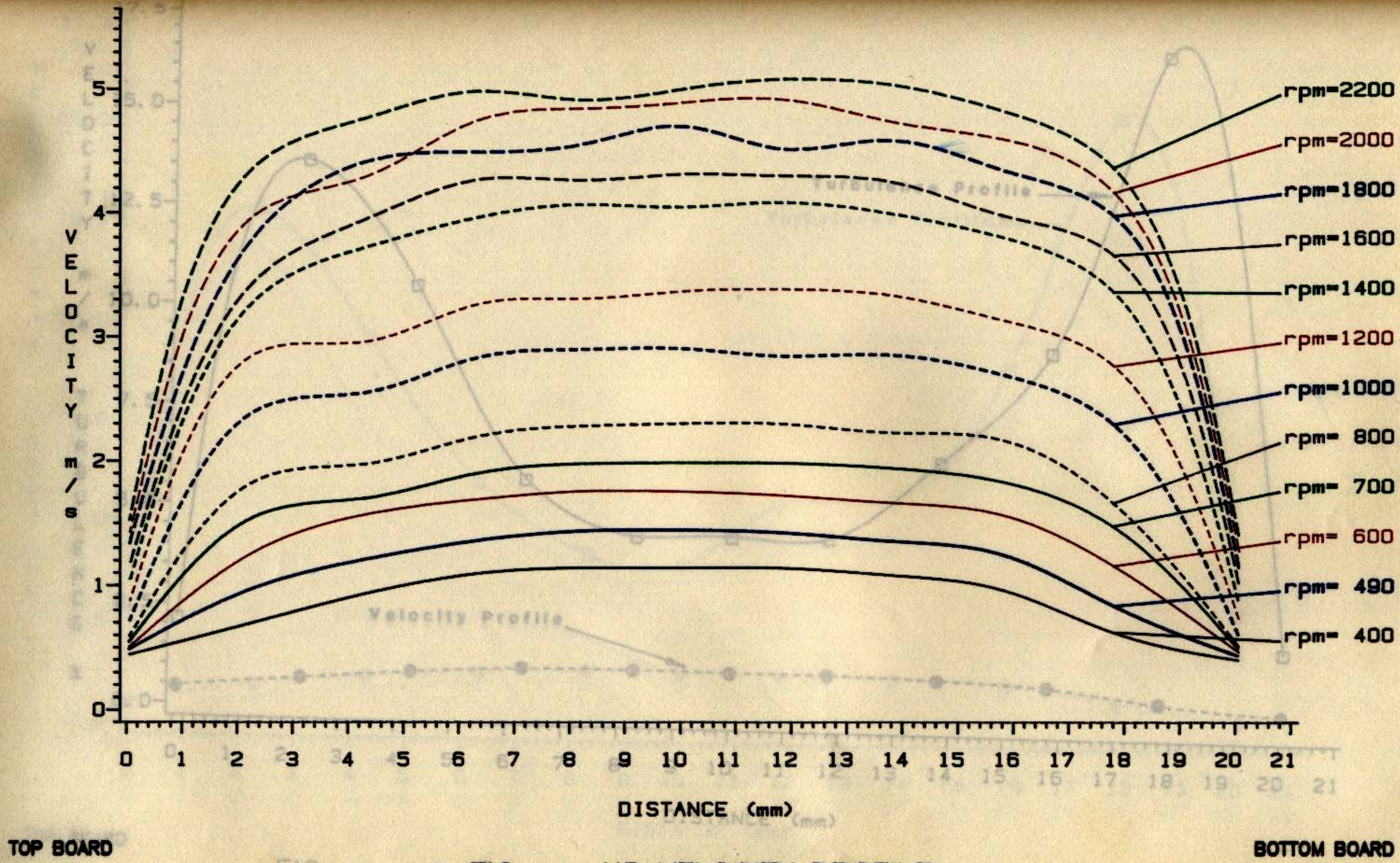


FIG. 1 : AIR VELOCITY PROFILE

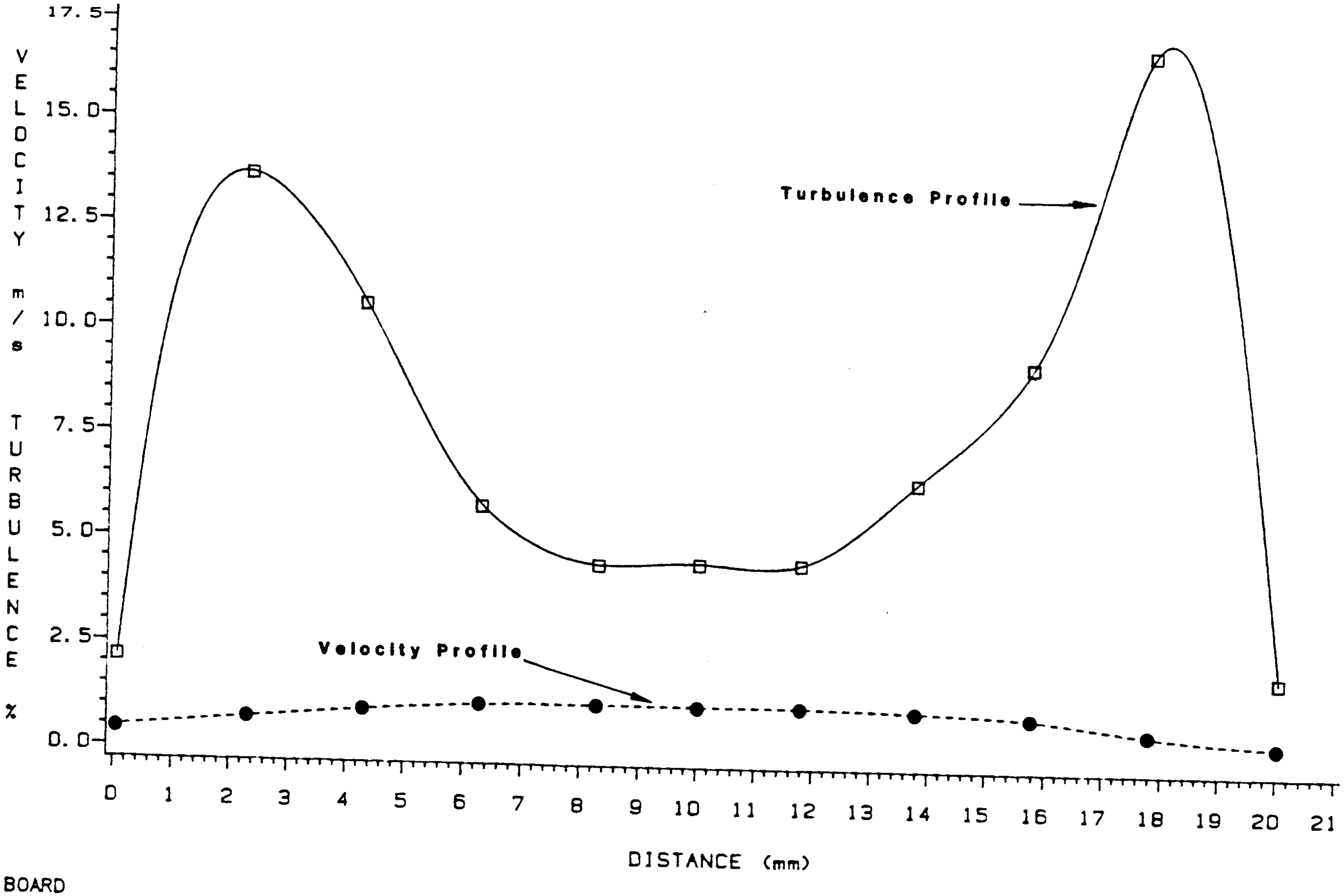


FIG. 2: AIR VELOCITY & TURBULENCE LEVEL AT 400 rpm

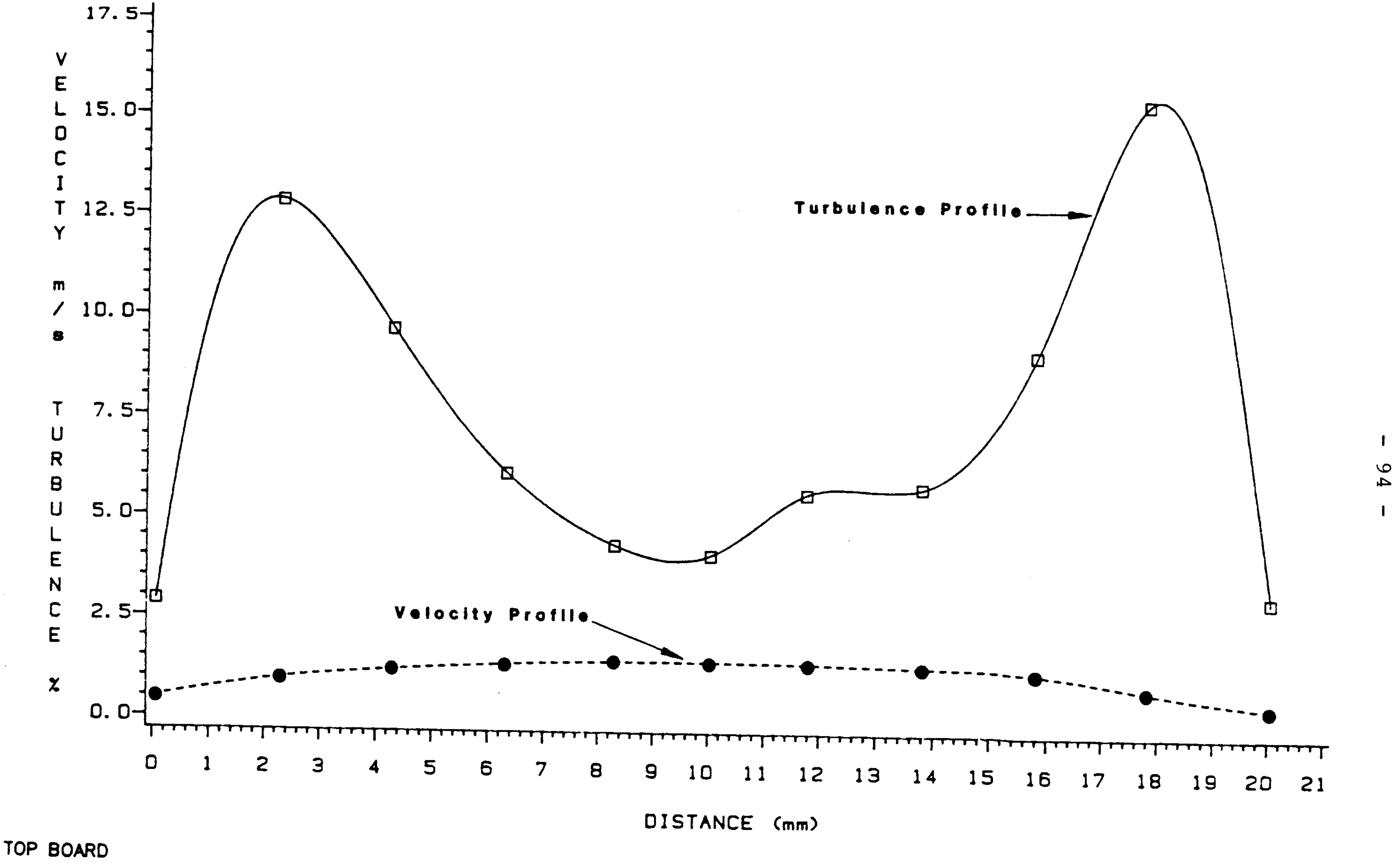


FIG. 3: AIR VELOCITY & TURBULENCE LEVEL AT 490 rpm

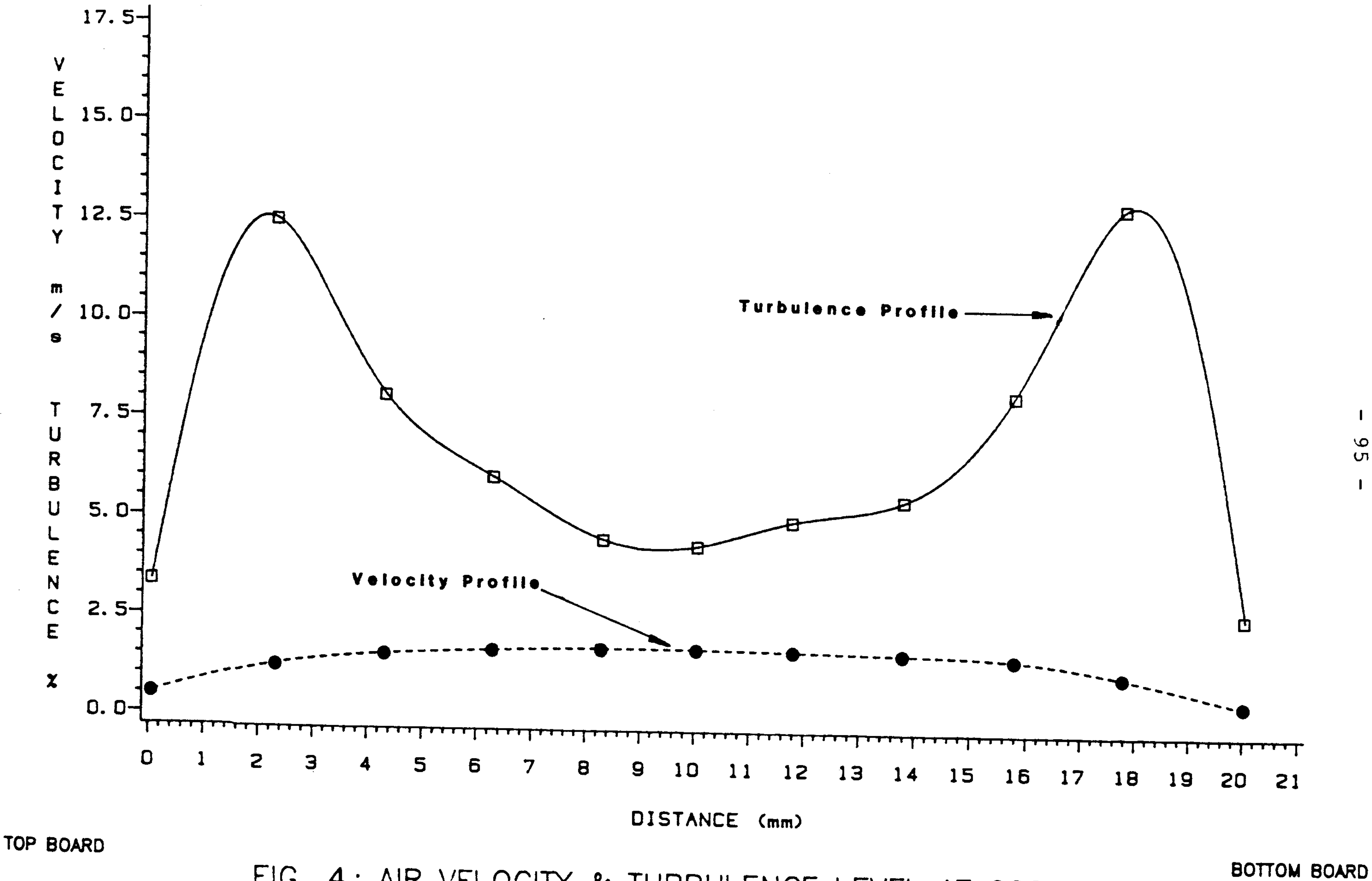


FIG. 4: AIR VELOCITY & TURBULENCE LEVEL AT 600 rpm

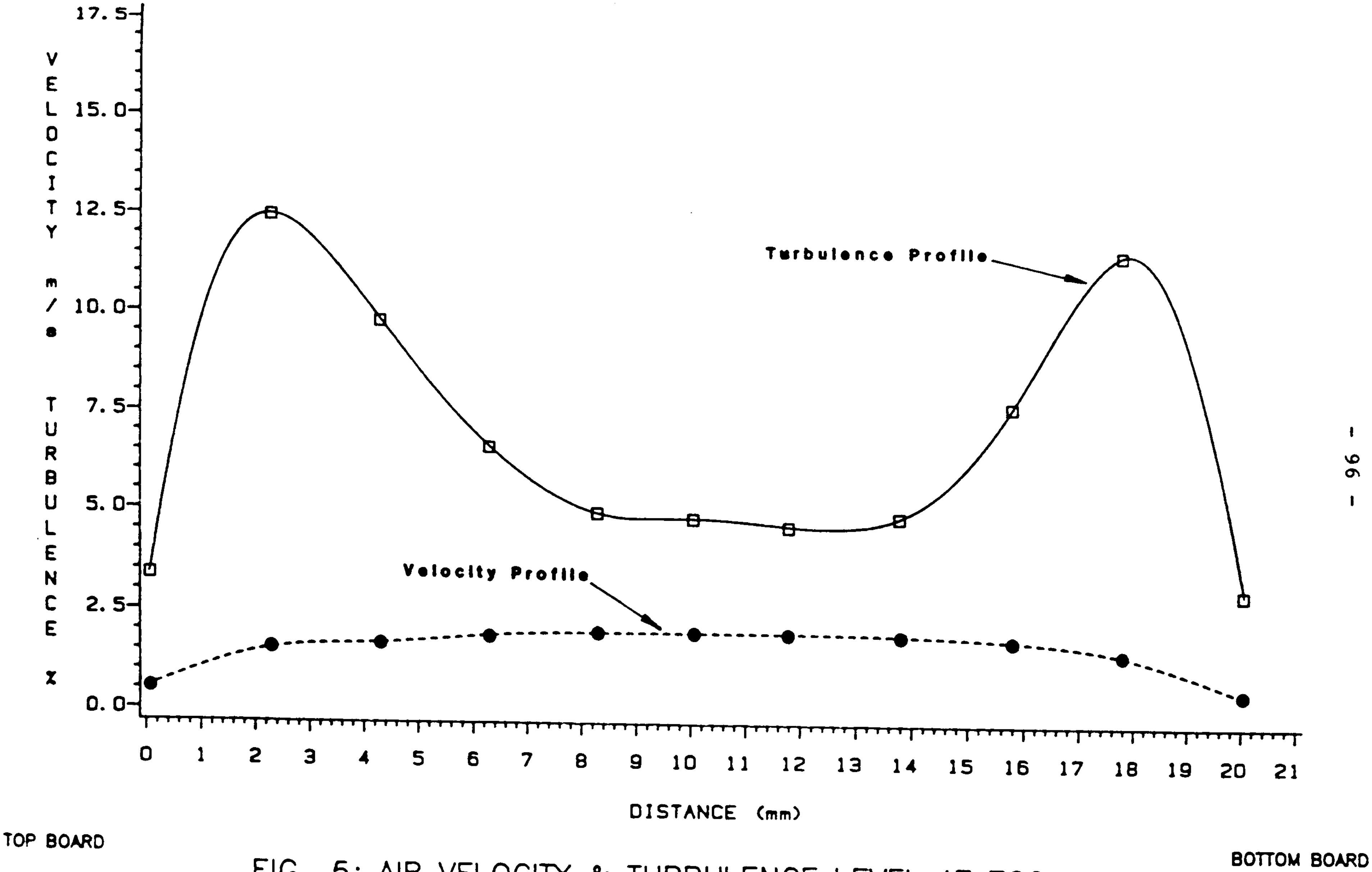
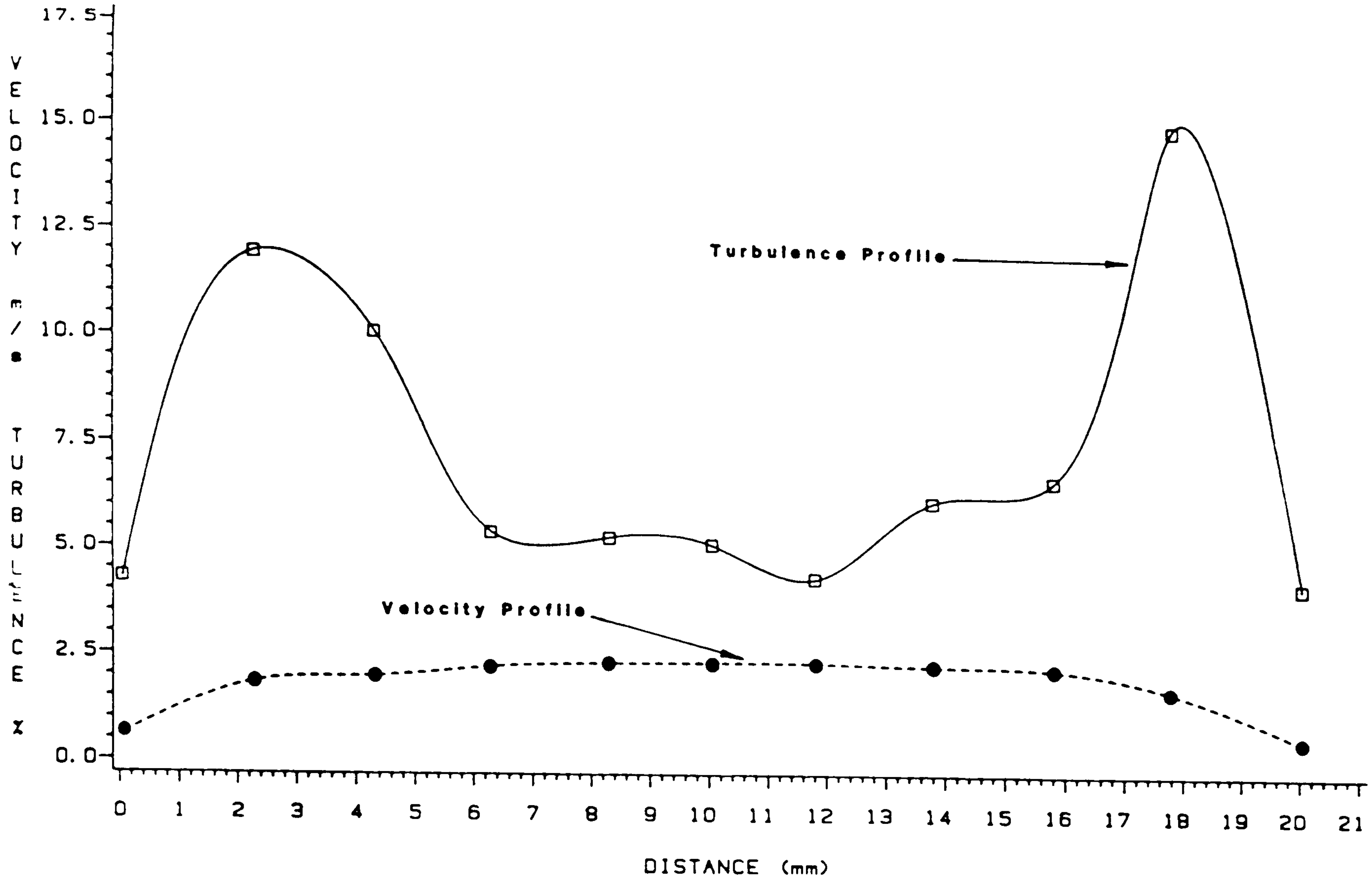


FIG. 5: AIR VELOCITY & TURBULENCE LEVEL AT 700 rpm



TOP BOARD

BOTTOM BOARD

FIG. 6: AIR VELOCITY & TURBULENCE LEVEL AT 800 rpm

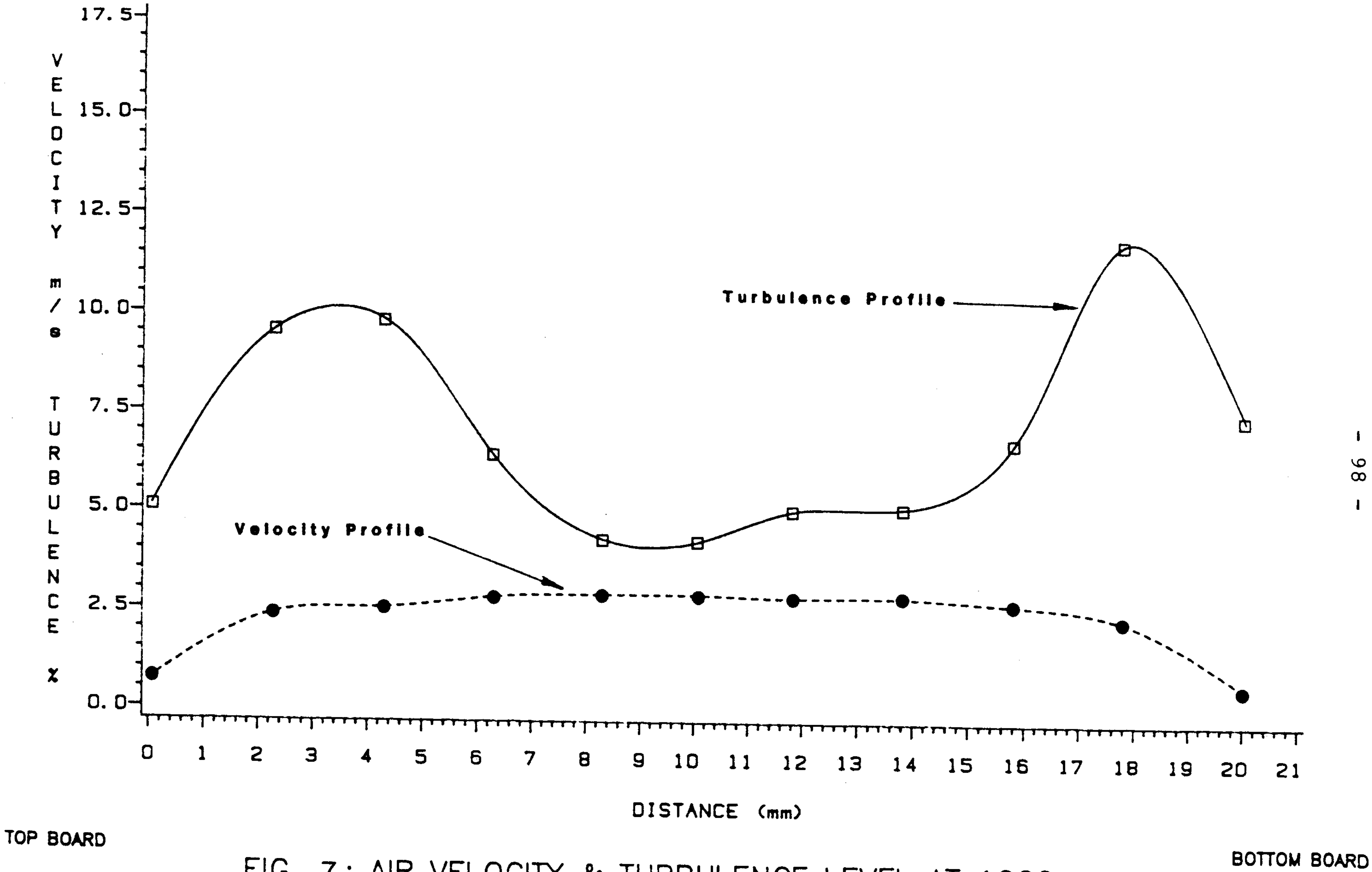
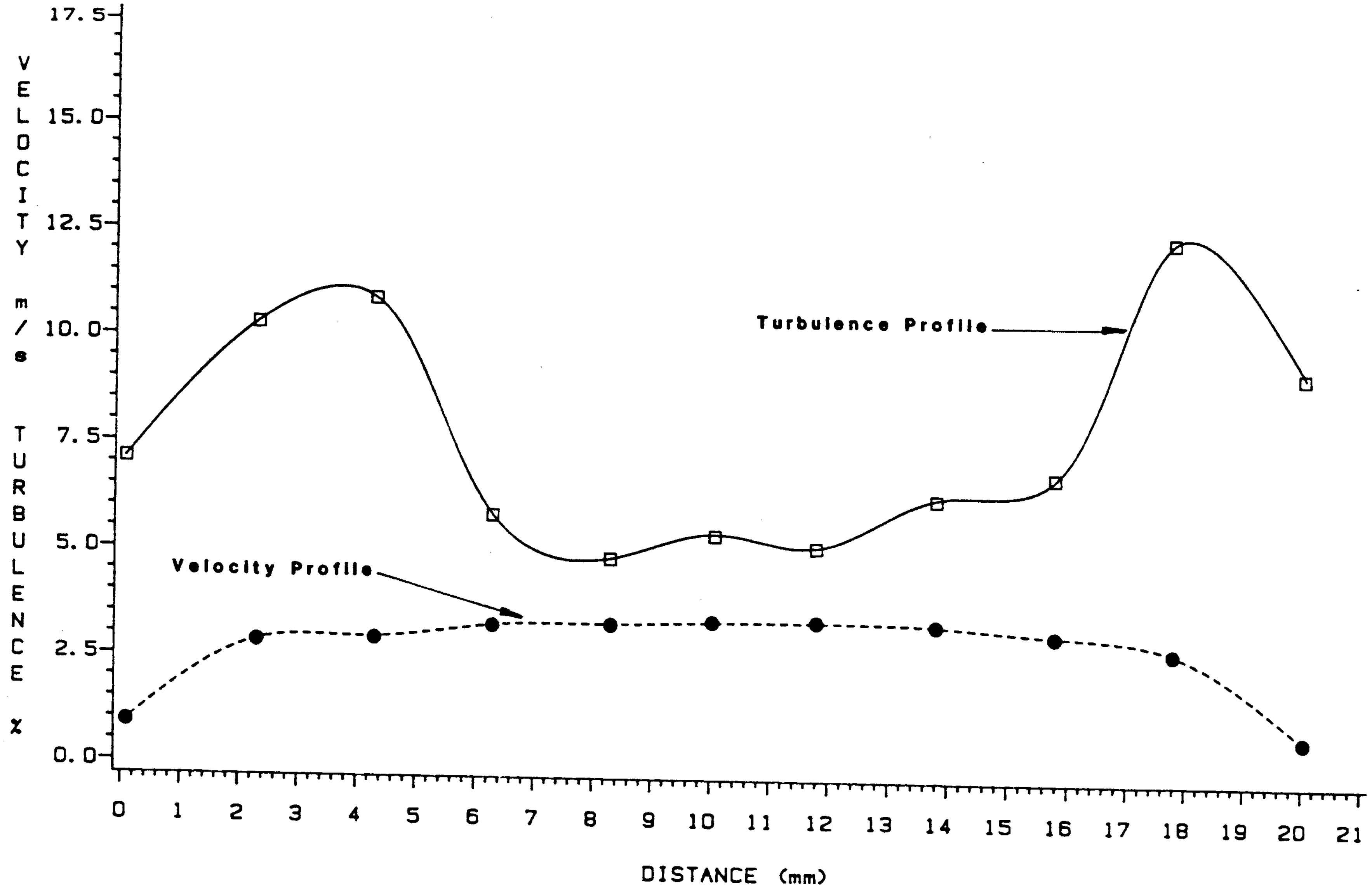


FIG. 7: AIR VELOCITY & TURBULENCE LEVEL AT 1000 rpm



TOP BOARD

BOTTOM BOARD

FIG. 8: AIR VELOCITY & TURBULENCE LEVEL AT 1200 rpm

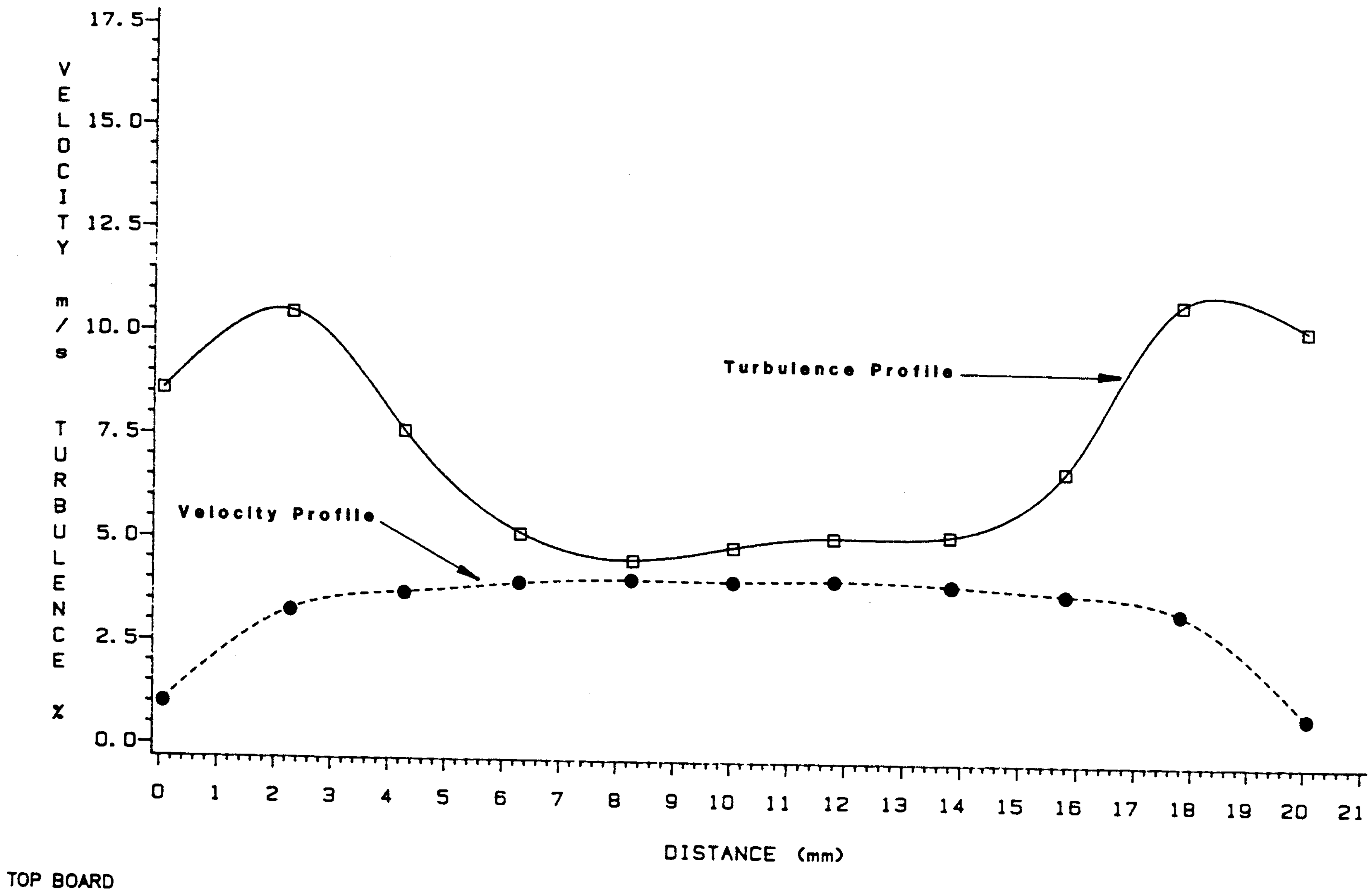
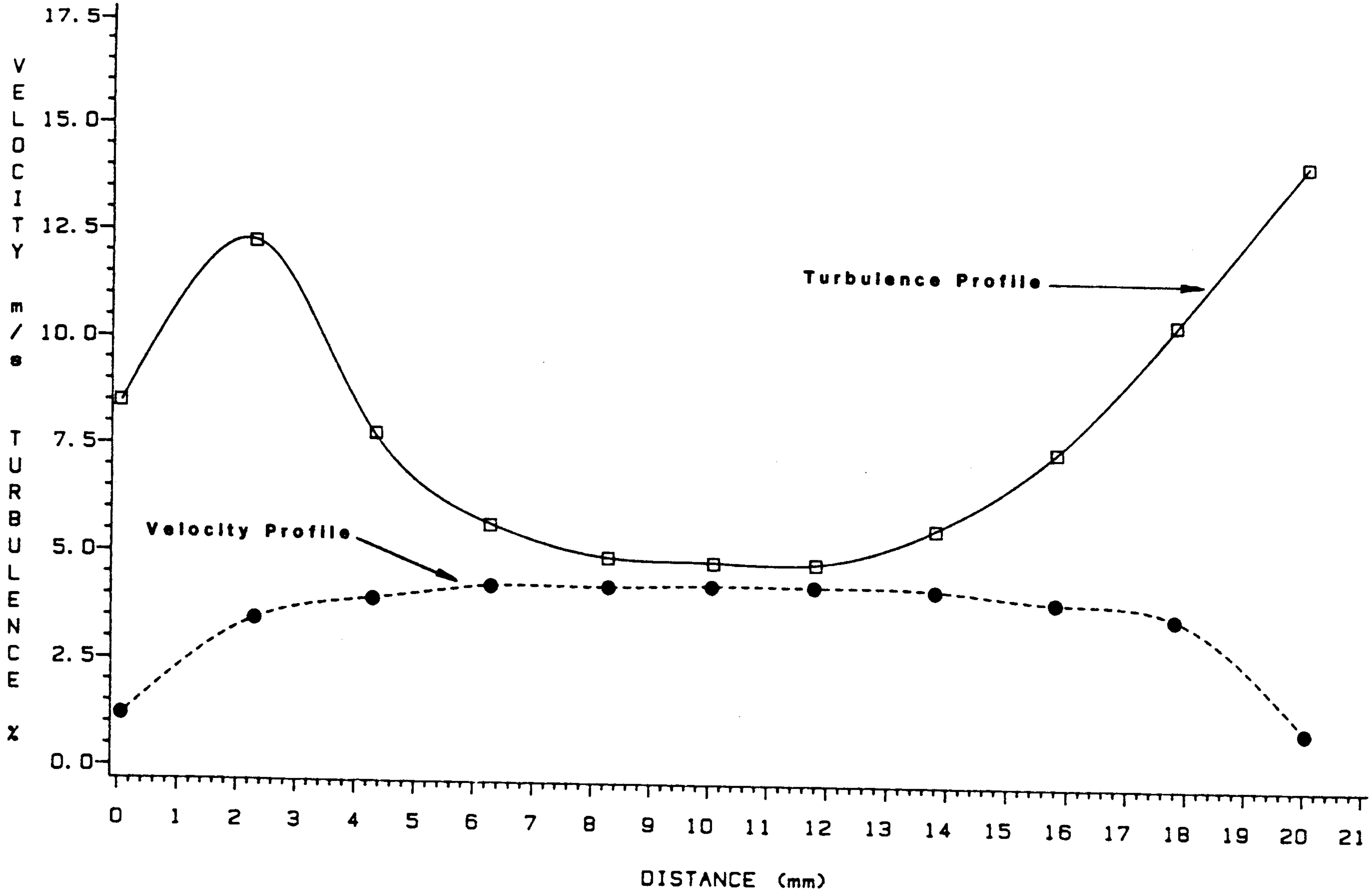


FIG. 9: AIR VELOCITY & TURBULENCE LEVEL AT 1400 rpm



TOP BOARD

BOTTOM BOARD

FIG.10: AIR VELOCITY & TURBULENCE LEVEL AT 1600 rpm

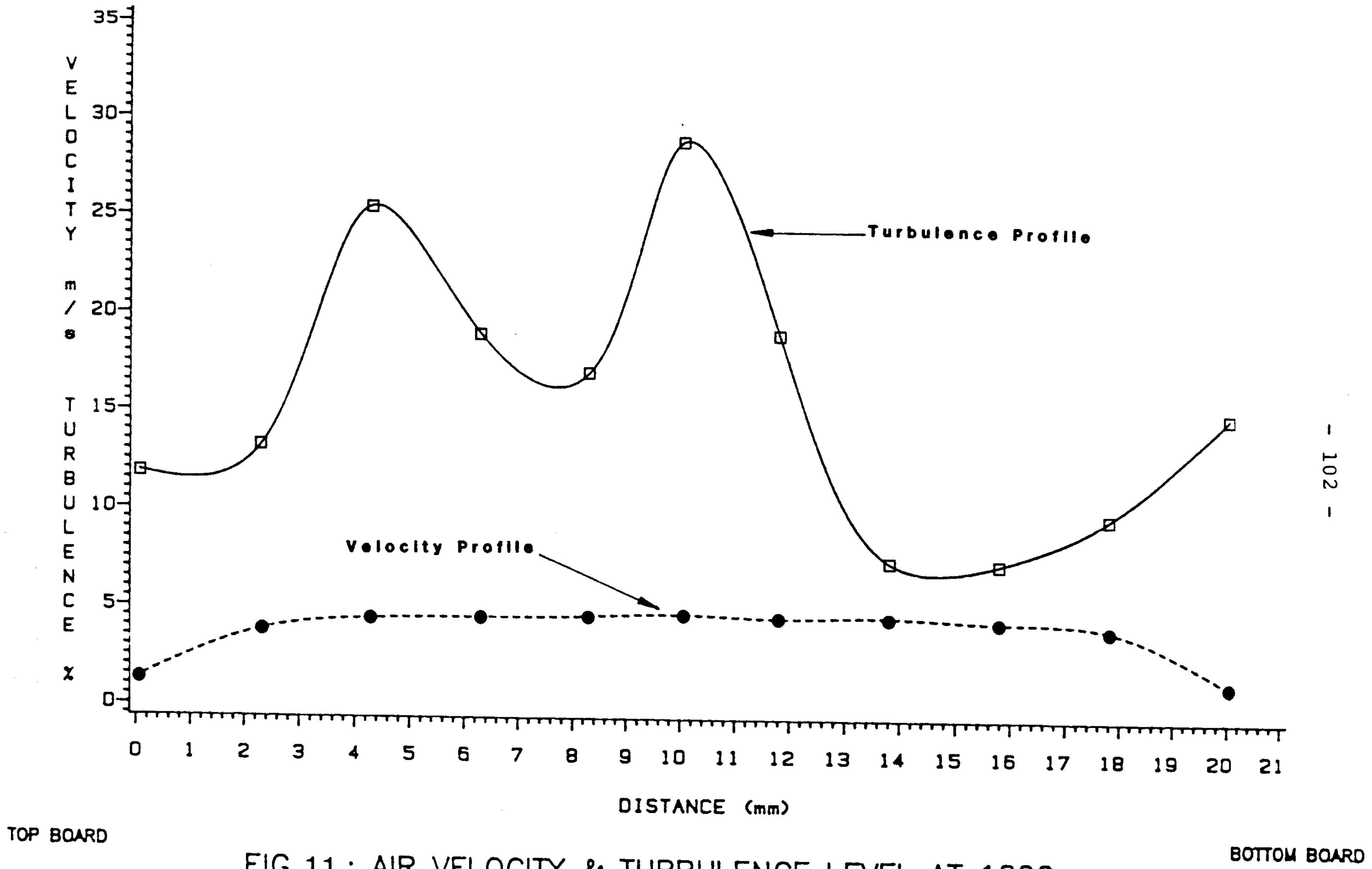


FIG. 11 : AIR VELOCITY & TURBULENCE LEVEL AT 1800 rpm

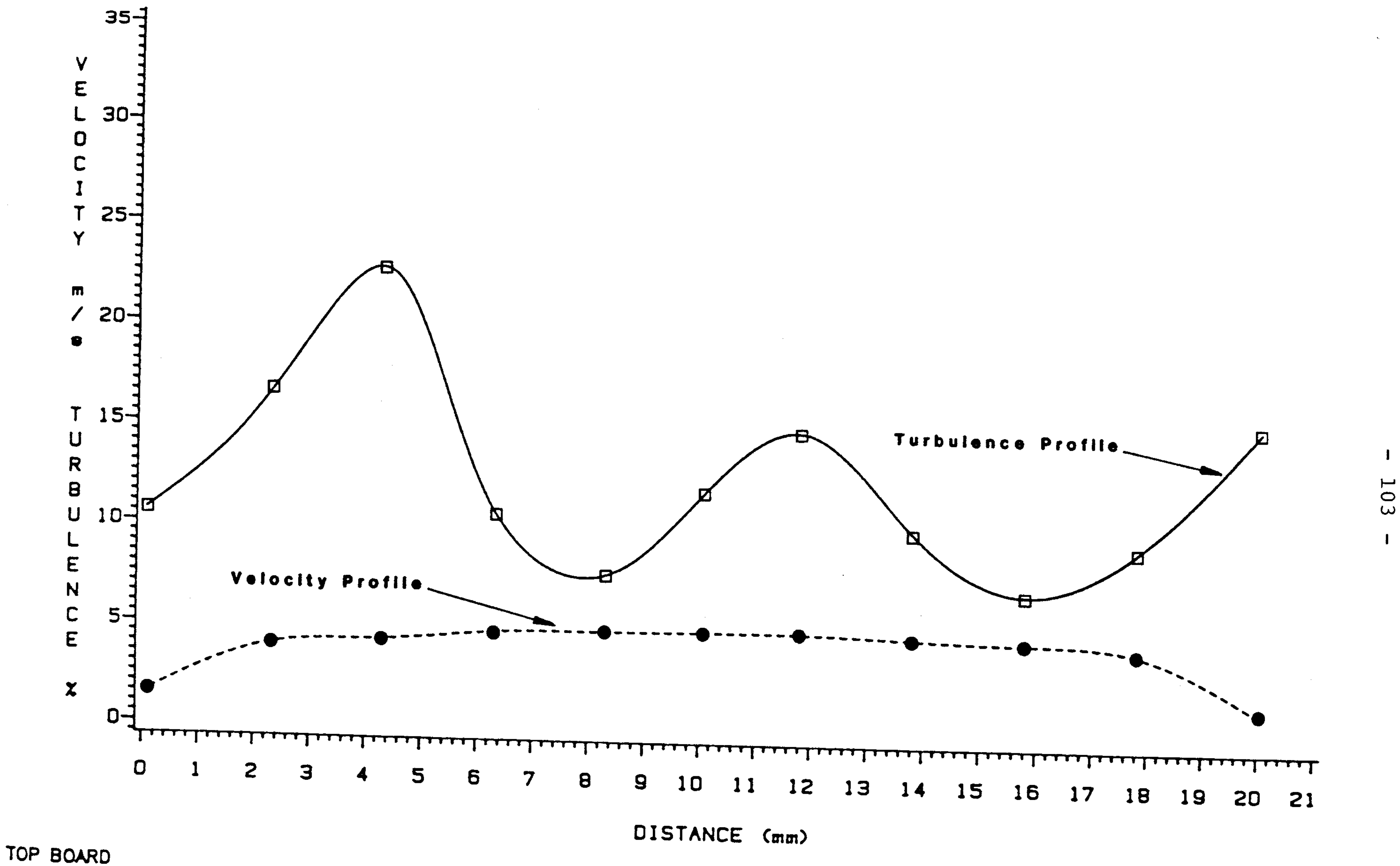


FIG. 12: AIR VELOCITY & TURBULENCE LEVEL AT 2000 rpm

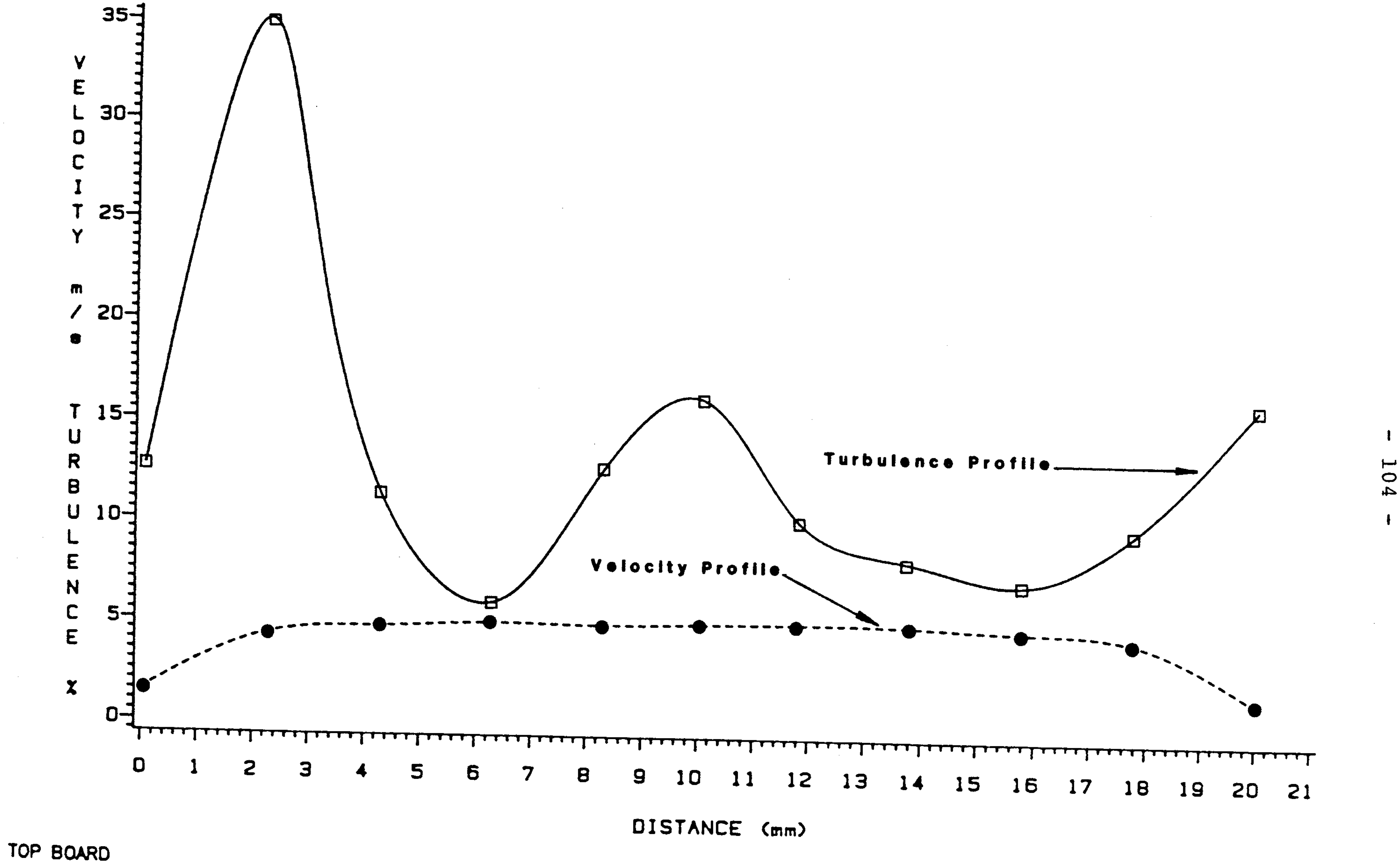


FIG. 13: AIR VELOCITY & TURBULENCE LEVEL AT 2200 rpm

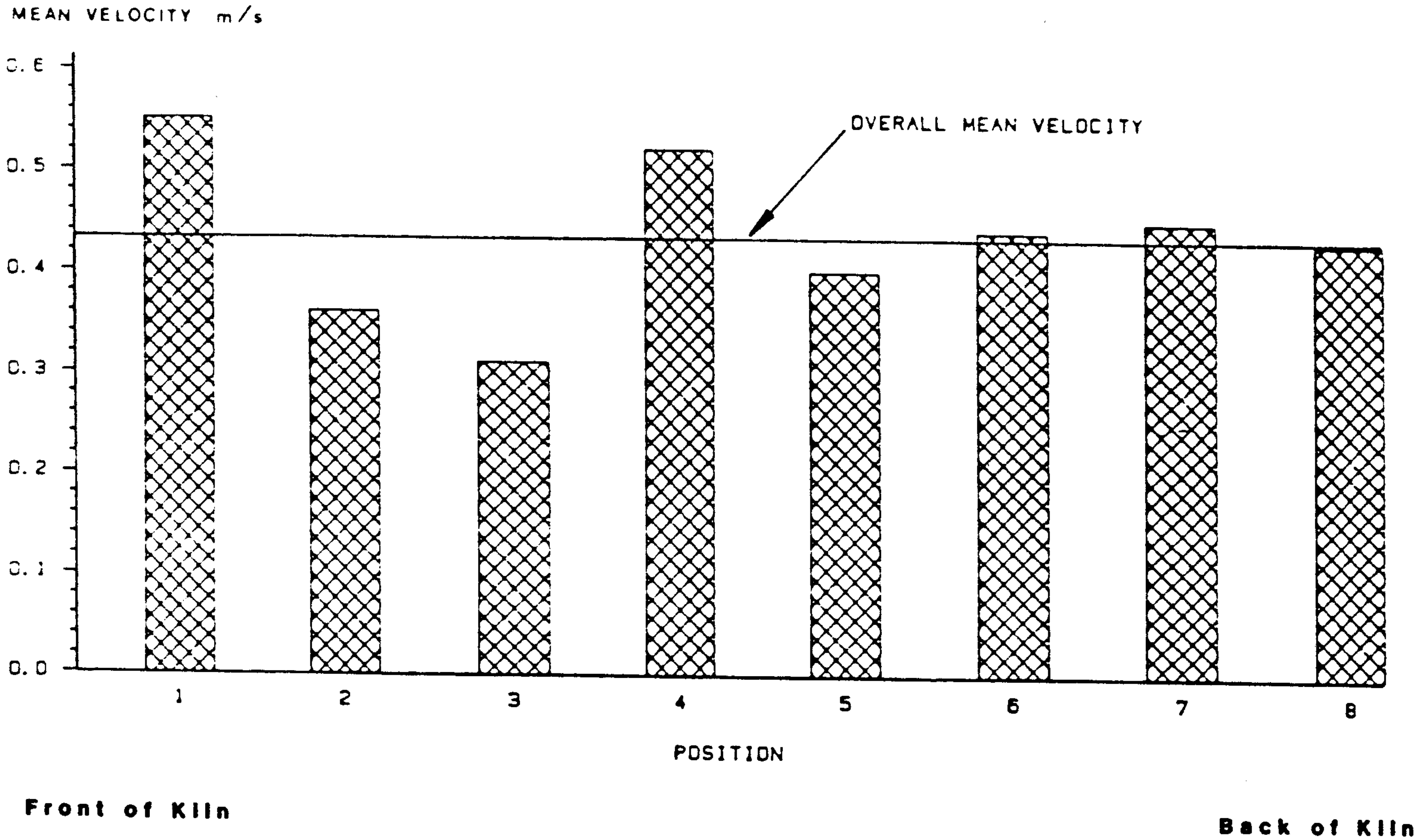


FIG.14 : AIR VELOCITY DISTRIBUTION FOR EMPTY KILN AT 490 rpm

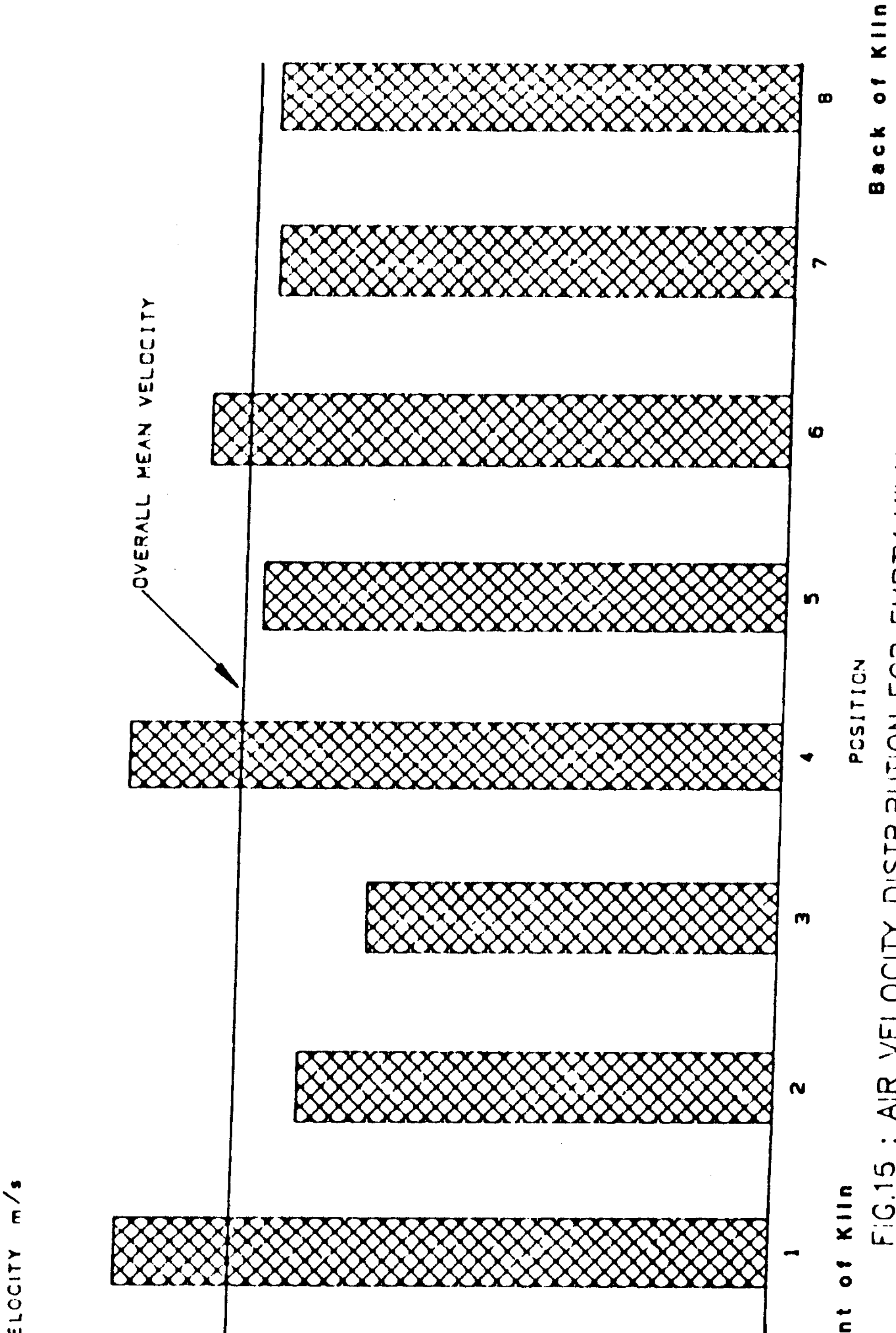


FIG.15 : AIR VELOCITY DISTRIBUTION FOR EMPTY KILN AT 1500 rpm

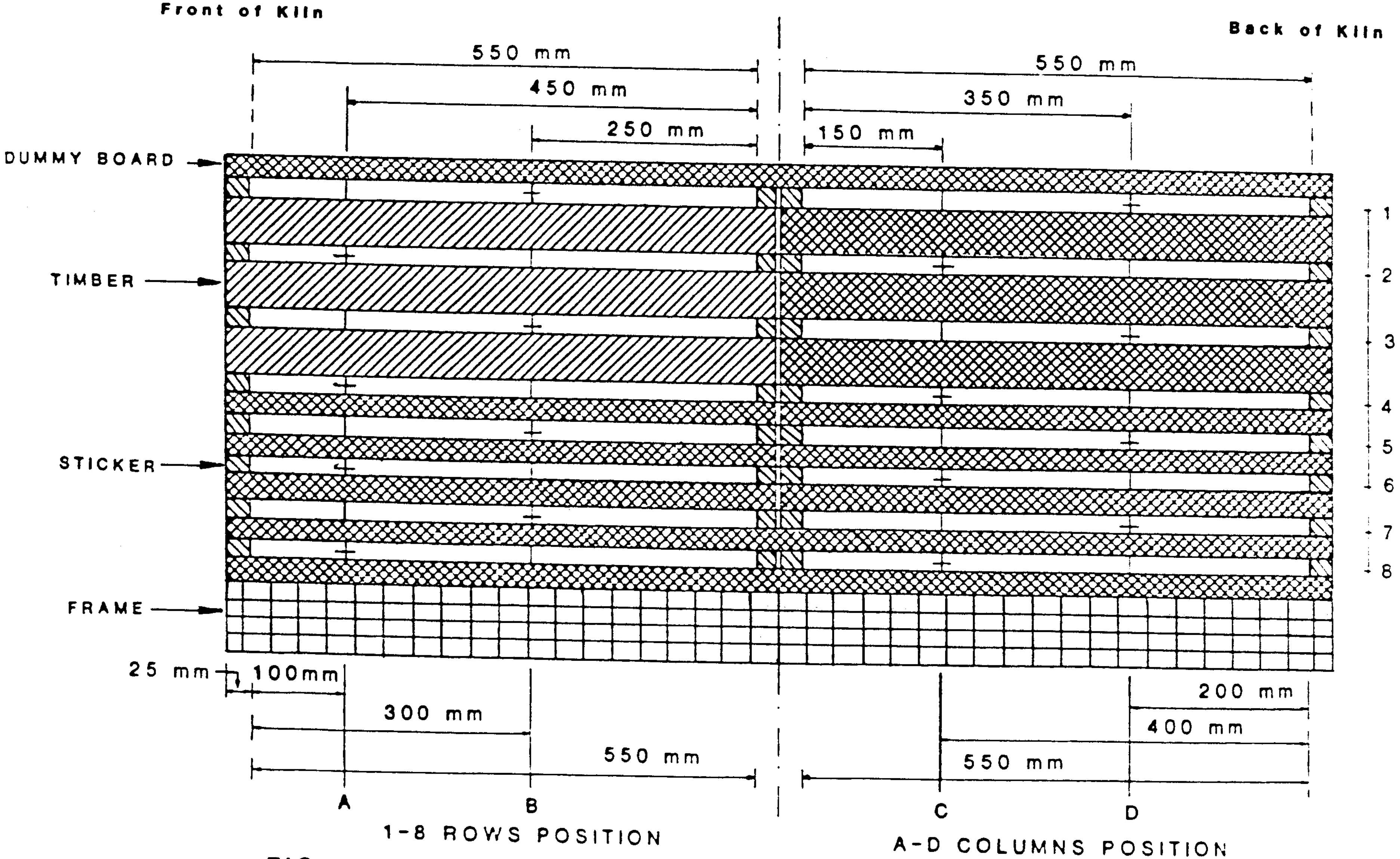


FIG 16 : SIDE VIEW OF THE STACK SHOWING ROWS & COLUMNS POSITION

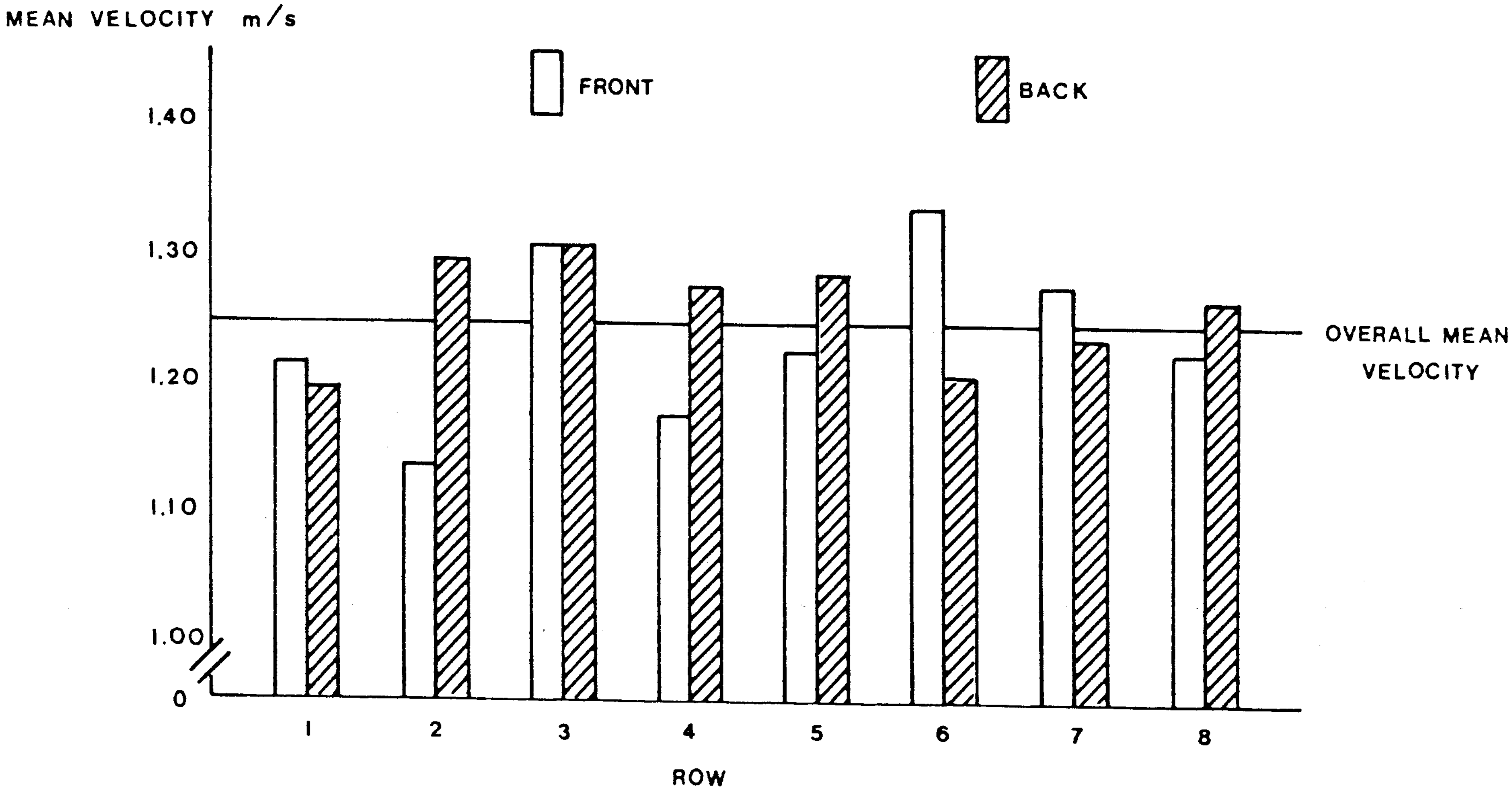


FIG.17: AIR VELOCITY DISTRIBUTION ALONG THE TIMBER STACK
COMPARISON OF FRONT v. BACK OF THE KILN
AT 490 rpm

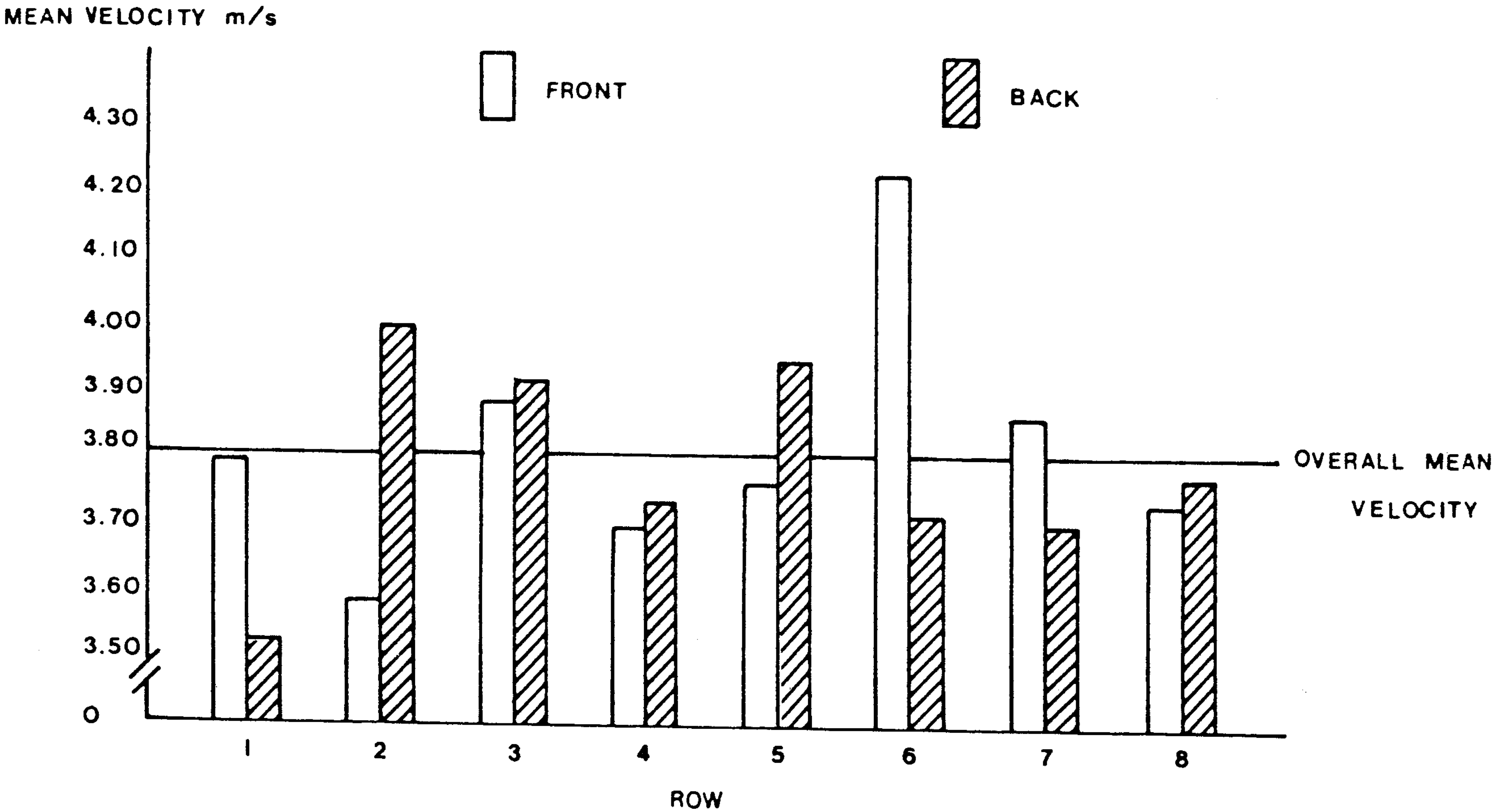


FIG.18: AIR VELOCITY DISTRIBUTION ALONG THE TIMBER STACK
COMPARISON OF FRONT v. BACK OF THE KILN
AT 1500 rpm

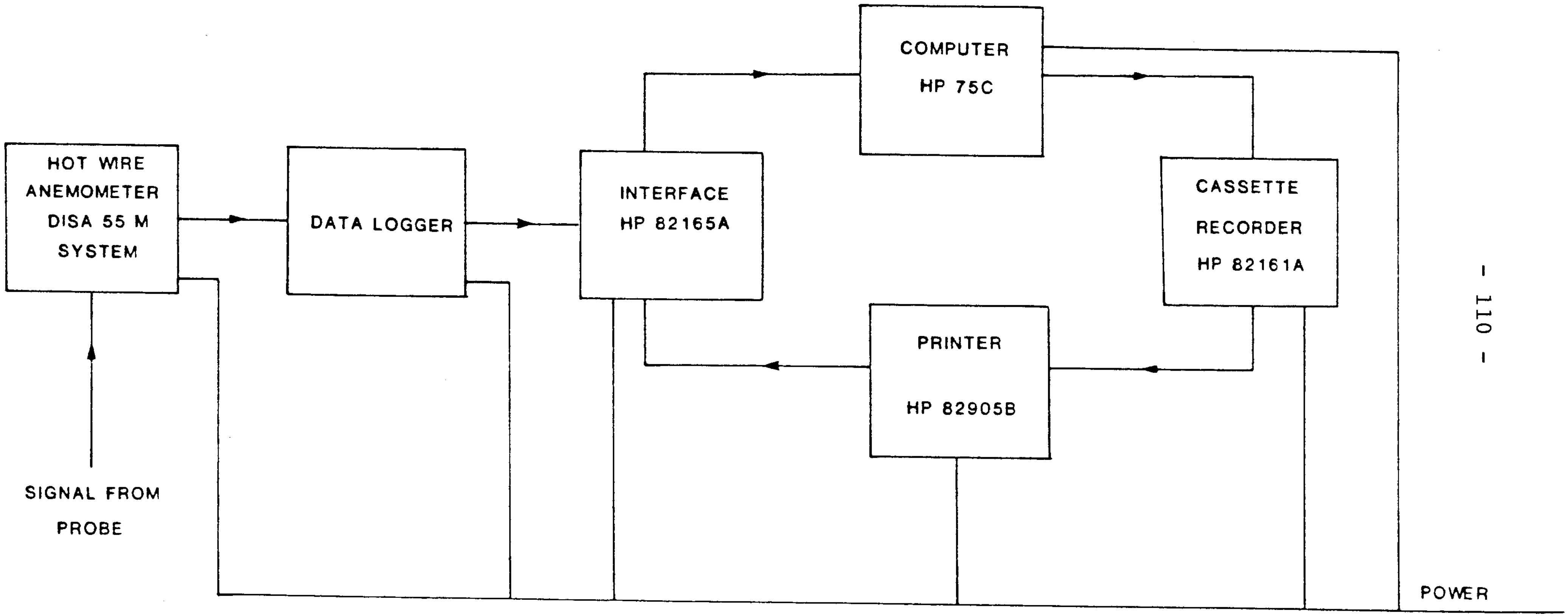


FIG. 19 : LAYOUT OF THE INSTRUMENTS CIRCUIT USED IN AIR FLOW MEASUREMENTS

REFERENCES

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