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COLLEGE OF AERONAUTICS

DEPARTMENT OF PRODUCTION
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IN-PROCESS MEASUREMENT

by

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1. INTRODUCTION

"I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

The above statement was made by Lord Kelvin (1824-1907) about a hundred years ago and is reproduced as the main theme of the present paper. The only qualification that should be made is that when Lord Kelvin made the above statement he did not think that the philosophy he expounded was specially appropriate to engineering manufacture. The present paper will consider how this philosophy can be applied to engineering manufacture only.

Lord Kelvin would not be alone in about 1867 when he thought workshop practice was not a suitable subject for scientific analysis, but 1967 is considered to be a specially appropriate time for an all-out effort to be directed to a detailed analysis by modern scientific methods of many sections of engineering manufacture as practised under normal production conditions in the workshop. It may be that even today some persons think that the laws of nature as studied in a well-equipped laboratory have little or no relevance to the practical day-to-day affairs of a workshop. The laws of nature appear to operate with an amazing degree of consistency and reliability in every part of the known universe, including the most unsophisticated workshop. By operating in harmony with these reliable, and when thoroughly understood, beautiful laws of nature, standards of performance at present undreamed of become a possibility. The very basis of these scientific methods of analysis must be accurate "In-Process Measurement".

During the past five decades the application of the data made available by scientific analysis has improved the design of many products and this, in turn, has improved our standard of living.

There appears to be a substantial amount of evidence to support the theory that during the next five decades one, and probably the most important factor, in bringing about a further improvement in productivity will be in methods of manufacture. The contributing factors to this change are:-

(i) Many of the products developed during the past five decades are at the stage of their natural development that makes further alteration by normal design changes follow a law of diminished returns. One effect of this trend will be that the length of the period between the introduction of a completely new model and that model going out of production because it is obsolete will become longer.

(ii) The condition described in (i) above will have the effect of

(a) Creating a demand for products which will continue to operate perfectly for a longer period because the product will not be discarded after a short period due to obsolescence.

(b) The longer period between initial production and obsolescence will enable larger capital grants to be made available for the purchase of more highly developed production equipment.

(iii) In contrast to (i) above, scientific analysis into the process of engineering manufacture is relatively new. The work undertaken in the next few decades could produce results which would follow a law of increasing returns.

(iv) In the past the product of high quality has been "hand made". Mass-produced parts were considered as low-cost items of inferior quality. The next few decades will see the emergence of a range of very high value products. These products will be made from very high-quality parts produced in large quantities by automation. They will be assembled under ideal conditions in rooms where material removal devices are strictly forbidden. This is the very high value product of the future.

(v) A wide range of equipment suitable for use in the type of detailed analysis required in engineering manufacture is available and more can be made available by using transducers, electronic circuits and similar devices which have been developed at considerable cost for other purposes.

(vi) The output from suitably designed transducers can be applied in a wide range of techniques from the type of mathematical analysis used in statistical quality control to fully automatic control and continuous automatic recording.

2. ANALYSIS OF GEOMETRIC FEATURES OF AN ENGINEERING PART AND PROCESS OF ENGINEERING MANUFACTURE

By analysing the geometric features of an engineering part and the process by which it will be manufactured, it is possible to enumerate how and where the technique of "In-Process Measurement" can be applied. One example of such an analysis is given in Table T. 1. The features enumerated in Table T. 1 are divided into the following three groups:-

Group A	Geometric Features
Group B	Mean Size
Group C	Other Features

Because Group B Mean Size will be discussed in considerable detail, the groups will be examined in the present paper in the order A, C, B.

3. GROUP A. GEOMETRIC FEATURES

Engineering design and manufacture as practised by the majority of industrial organisations does not include any reorganised system of applying tolerances to, or inspecting the features listed in Group A. This practice of ignoring what appears to be important has developed and is continued because:-

(i) The technology of applying geometric tolerances is not well understood.

(ii) Errors in geometric shape are usually found to be less than 25% of the tolerance specified for size.

(iii) The geometric accuracy of the parts produced in most manufacturing operations is related to the accuracy of the manufacturing facility provided and not directly associated with the performance of the operator.

(iv) The arrangements that must be made to inspect the majority of the features listed in Group A to clearly defined geometric tolerances are elaborate and expensive.

(v) By increasing mean clearances to above what is known to be ideal, arranging for new equipment to be "run in" and similar devices, geometric errors of the magnitude normally produced can be tolerated and the only penalty is an occasional failure.

The practice as described above cannot be classified as good engineering practice. It would be more correct to say that it described a temporary phase in the natural evolution of the ideal technology. The demands of the future for higher grade engineering products is abundantly clear. Many of the facilities that are required to develop a technology that is well able to meet these future demands are available and others are becoming available. The above and other relevant data indicates very clearly that an immediate and considerable improvement can and should be made.

The present paper suggests that it is the duty of the highly qualified technical personnel engaged in the formulation of management policy to:-

(i) Establish a system of drawing office practice that will ensure that sufficient care and attention is given to these important geometric features at the design stage. Some recognised system of applying individual or group tolerances to geometric features should become

(a) An established and important part of all the educational programmes in Engineering Design and allied subjects taught in technical colleges and universities.

(b) An established and recognised part of good drawing office practice as carried out in industry.
Universities, Technical Colleges and Industrial organisations wishing to implement this recommendation can obtain much information on analysis, appli c ation of tolerances and methods of inspection from "Manual for Geometric Analysis of Engineering Designs" by Gladman.

(ii) Provida a manufacturing facility and recommend methods of manufacture that can be relied upon to keep geometric features of the type listed in Group A under good control for long periods.

(iii) By a series of well-planned, thorough and rigorous inspection operations ensure that all important geometric features are inspected by direct measurement to the tolerances specified on the drawing or an approved standard specification. The magnitude of the errors obtained from the above inspection operations should be analysed statistically to establish whether the production process can be allowed to proceed as planned. It will be noted that in carrying out the above procedure "In-Process Measurement" and not full form gauges is used. Full form gauges are unsatisfactory because:-

(a) When made and issued as new they are not accurate.

(b) In use they wear and become more inaccurate.

(c) If a complex part is rejected because when inspected by a full form gauge it does not conform to specified requirements, it is usually very difficult to state which feature is at fault. It is also impossible to state the amount by which a specified tolerance has been exceeded.

Full form gauges can only be tolerated when they are accepted as a temporary expedient during à transition period in the gradual evolution of the ideal system.

The above carefully-planned inspection operations should be carried out at regular and specified intervals. Their frequency must be decided upon during initial planning and adjusted as found to be necessary by experience. In a well-planned and operated engineering organisation inspection of the majority of the geometric features listed in Group A would occur once, or at the most four, times per month.

The above is one phase of "In-Process Measurement" that is seriously neglected. Machine operators, foremen, planning engineers, managers and others would all become much better informed about the dynamic and other important characteristics of the machine tools they use if they analysed geometric errors. This, in turn, would generate a range of improved specifications for machine tools of high accuracy and low rates of deterioration. This is specially important at a time like the present when all the ingredients necessary to produce these improved machines are available. The only requirement is a more critical demand from the purchasers of machine tools based on the accurate information the above analysis would provide.

4. GROUP C. OTHER FEATURES

In any comprehensive system of inspection designed to ensure full control of quality, all the features that are known to have an influence on quality should be enumerated and suitable systems of control arranged. Examples of other features that are important but not directly dimensional are listed in Group C.

In the present paper no direct attempt will be made to describe in a comprehensive manner how these features may be controlled but this should not be taken as an indication that their control is difficult or unimportant.

5. GROUP B1 CONTROL OF MEAN SIZE (GRINDING)

Example 1. Simple Cylindrical Grinding Operation

Consider the finish grinding operation for the part shown in Fig. 1. "In-Process Measurement" can be applied in a simple and effective manner and high accuracy obtained by:-

(i) Using a measuring caliper and associated indicator of the type shown in Fig. 2.

(ii) Establishing basic size by an accurately calibrated setting master of the type shown in Fig. 3.

The machine operator is instructed to place the setting master in the grinding machine and when rotating and flooded with a full flow of coolant the instrument must be adjusted to read the value corresponding to the known error in the setting master. Fig. 4 shows the pointer at the position on the scale where it indicates the known error in the setting master. When required, the output from the transducer can be arranged to operate an automatic control device of the type shown in Fig. 5 and if required a separate measuring circuit attached to the measuring caliper can be arranged to record automatically the size of each part produced and show this size in relation to the tolerance boundaries as illurtrated in Fig. 6.

Example 2. High Precision Cylindrical Grinding

One only part required. No setting master available.
Care required to reduce errors due to temperature.

In cases where a one-only, highly-accurate part must be produced, where the part is seriously affected by temperature and where no setting master is available, the following technique may be used:-

(1) After turning, heat treatment, and preliminary stabilizing, round-grind to dimensions shown in Fig. 7.

(2) Stabilize.

(3) Intermediate-grind to tolerances shown in Fig. 7.

(4) After the part has been in the standards room and at uniform temperature for about two days, make very careful measurements on each of the dimensions to be finish-ground and tabulate the results to the nearest 0.00001 in. as shown in Fig. 7.

(5) Plot a calibration curve for grinding gauge-indicator system.

(6) Place the part in the grinding machine and allow coolant to flow over the part as will occur during the finish-grinding operation. Fit grinding gauge as shown in Fig. 2 and allow part to run as shown, until for a period of 2 minutes there is no observable change in size as shown on the indicator.

(7) Set the indicator to read a value corresponding to the amount of metal to be removed as shown in Fig. 7, corrected for errors of calibration as shown by calibration curve obtained in (5) above.

(8) Very carefully and without causing the part to increase in temperature reduce the size of the part until the indicator reads zero.

(9) Repeat operations 7 and 8 for all other dimensions requiring finish-grinding.

(10) Transfer part to standards room and after about two days, when the temperature has become stable, carefully inspect all important diameters.

Example 3. High Precision through-feed centreless grinding

As an example of "In-Process Measurement" arranged for use on a through-feed centreless grinder, consider the case illustrated in Fig. 8. This system is designed to provide:-

(i) Automatic in-feed of grinding wheel.

(ii) Automatic recording of mean size of parts produced.

(iii) If parts are produced very near or outside tolerance, the sorting unit is operated so that no faulty parts are passed into the container for finish-ground parts. The hopper feed is also automatically stopped and a signal device operated.

Example No. 4. Control of fit in high precision parts

Where the total fit tolerance between two parts is one micron (0.00004") or less and the parts are not produced in quantities that enable the matching of graded parts on assembly, the following arrangement may be used. Fig. 9 illustrates a differential pneumatic circuit that enables a piston to be ground to a size that will make it produce a predetermined fit with the cylinder placed on the air measuring mandril. In using this system the setting master is a pair of parts having the required fit or a fit in which the amount by which it is different from the required fit is known in magnitude and in sense. Electronic transducers and the associated electronic circuits can be used to produce the same result.

The control of lengths and internal diameters by grinding operations is possible by methods substantially similar to those described.

6. GROUP B2 MEAN SIZE (TURNING AND BORING)

In turning, boring and similar operations the amount of material removed during the final cut of the finish machining operation is, in most cases, more than the total tolerance on the part. This condition prevents the use of a system in which the gradual change of size is observed by the operator or an automatic control device and arrangements are made for the material-removing device to be withdrawn when the part is found to be the correct size. Control of size by turning and similar operations creates a demand for a facility that will enable the machine operator to place the cutting tool in the correct position, engage the feed mechanism, produce the finished surface and the operator must know before the final measurement is made that the part is correct. The above condition can be satisfied on parts that must be turned to small tolerances by "In-Process Measurement". Fig. 10 illustrates in diagramatic form a part that must be finish-turned to a tolerance of 20mm $\pm$ 0.002 mm. It is possible, by normal turning methods, to turn the part to a tolerance of 20 mm $^{+0.075\text{ mm}}_{+0.050\text{ mm}}$. Let it be assumed that when the cut before the finishing cut has been taken the tool is withdrawn along a line parallel to the axis of the part but not moved in a radial direction. The part is then measured and let it be assumed that by careful measurement of the type illustrated in Fig. 11 and using the calibrated setting master technique already described the part is found to be 20.064 mm diameter. This measurement establishes the fact that to produce an accurate part the tool must be moved 0.032 mm nearer the centre line about which the part is rotating, a final cut must be taken and the tool and its support mechanism must behave in the same manner as occurred on the previous cut. By fitting a suitable transducer to measure the movement of the cross-slide in relation to the main saddle of the machine, the movement of the tool in a radial direction can be controlled to a high order of accuracy. The above technique can be of considerable assistance to a skilled operator and by avoiding the formation of a built-up edge on the cutting tool and allowing for small differences in the calibration characteristics of the transducers used to measure the part and to measure the movement of the slide accuracies of $\pm$ 0.002 mm from basic size can be attained on external and internal diameters and on distances between faces by turning.

Two types of measuring device suitable for measuring the movement of the tool-holding device will be described. Fig. 12 illustrates a measuring unit on which the transducer can be adjusted so that the associated indicator reads a value corresponding to the adjustment that must be given to the tool-holding device. When the tool-holding device is moved the amount of movement is shown on the indicator to an accuracy of 0.001 mm. One further and useful feature of this device is that the moving element is attached to the moving member on the lathe by electro-magnetic attraction. By operating a switch the two parts can be held together or separated. This facility of connecting and releasing the device from the moving member on the lathe enables the device to be used for the final adjustment of the cutting tool on several diameters on the same part. By fitting two such units to a lathe as illustrated in Fig. 12 lengths as well as external and internal diameters can be turned by the technique described. The one limitation to the above scheme is that the comparator or other accurate system of measurement must be used for each size to establish the amount by which the tool must be moved prior to taking the finishing cut. A further development of the above idea is to employ an accurate measuring device that will also cover a wide range. One good example of this is the "Digiturn" equipment illustrated in Fig. 13. Consider the turning of the part illustrated in Fig. 14. The 1.500" diameter can be turned using normal methods to a tolerance of $1.500^{+0.012''}_{+0.008''}$. The part can then be measured by the comparator system already described. Let it be assumed that the size is found to be 1.5100". This dimension can be set up on the small pre-set indicator shown in the centre and lower part of the panel. The adjacent button is depressed and the display on the pre-set indicator is transferred to the right-hand display unit on the panel. The slide is adjusted to make the display unit read 1.5000 by slide movements of 0.0001" causing the display unit to register a change of 0.0002". The final cut is taken, the size remeasured, and, if necessary, the display unit finally adjusted. It is now possible to finish-turn the four other diameters of 0.750", 1.000", 1.250" and 1.750" without any further measurements being made. The technique is to adjust the slid e so that the display reads the diameter required and take the finishing cut which should be about the same thickness as that taken on the 1.500 diameter. The speed of the lathe should also be adjusted to give a surface speed approximately equal to that used on the 1.500 diameter. In a similar way a datum can be established for lengths and internal diameters. The accuracy obtained on the dimensions not measured is not so high as where the comparator system of measurement is used but by taking suitable precautions the difference is small.

7. GROUP B3 MEAN SIZE (LARGE QUANTITY PRODUCTION) (LARGE AND SMALL TOLERANCES)

"In-Process Measurement" as described in the examples given has been mainly associated with the production of parts made in small quantities to small tolerances. The introduction of "In-Process Measurement" to the manufacture of parts made in large quantities and to large as well as small tolerances provides additional and valuable information which enables the production process to be optimised. One example only will be described in considerable detail but the technique can be applied to a wide range of products.

The diagram Fig. 15 illustrates a part produced on a five-spindle automatic lathe. The drawing shows that ten dimensions must be made to the tolerances specified. In a simple experiment fifteen parts made consecutively on the machine were accurately measured. The measured sizes were plotted and the result is shown on the chart Fig. 15.

The facts that emerge from a detailed study of the above results taken in conjunction with the tool layout are as follows:-

(Note: In some instances the data reported below as actual must be predicted because suitable in-process measuring equipment must be designed and made at the same time as the special tooling. A good planning engineer can predict to a high standard of accuracy the probable performance of the range of machine tools for which he is a recognised specialist.)

1. Dimensions Nos. 1 and 2 are made by the same tool. The tolerance on dimension 2 is smaller than on dimension 1. Good control of dimension 2 would, under normal circumstances, keep dimension No. 1 in satisfactory control.

2. Dimensions Nos. 3 and 4 are made by the same form tool. They are unstable and steps should be taken to improve the performance of the part of the equipment responsible for this dimension.

3. Dimensions Nos. 5, 6 and 9 are produced by the same form tool. Dimension No. 9 is, and should be, very stable and control of dimension No. 6 to ± 0.003 should, under normal circumstances, keep dimension No. 5 to ± 0.005 under good control.

4. The two faces measured for dimension No. 7 are made by the same form tool. The degree of variability in the size of this dimension is, and should be, very small in relation to the tolerance.

5. Dimension No. 8 is affected by the interrelationship of two tools. It is only fairly stable and very close attention to the size of this dimension is required.

6. Dimension No. 10 can be considered as fairly stable but only because of the wide tolerance.

When a manufacturing process has been analysed by a method of the type described above, it is possible to classify all the dimensions in relation to the type of control that is required to ensure the production of a very high percentage of satisfactory parts. The following three categories describe the systems of control that are considered satisfactory for the example selected.

<u>Group 1. Dimensions Nos. 1, 5, 7 and 9</u>

This group of dimensions can be considered as very stable because the random distribution of the process in relation to the tolerance is small. Inspection by very simple measuring equipment (not fixed anvil gauges) at widely-spaced intervals is all that is required to keep the size of these dimensions under good control.

<u>Group 2. Dimensions Nos. 2, 3, 4, 6 and 10</u>

In this group the random distribution is about 30% of the tolerance. The manufacturing process must, therefore, be classified as only fairly stable. To keep these dimensions under good control, a system of frequent percentage inspection is required. The ideal equipment should be rapid in operation and bring to the notice of the operator or setter any change occurring inside the tolerance boundary that if left uncorrected would result in faulty parts being produced. Inspection of this group of dimensions should be carried out at frequent predetermined intervals as dictated by the resuirements of the process.

Group 3. Dimension No. 8

This group is made up of those dimensions on which it is seen that the random distribution of the process absorbs a substantial part of the tolerance or for some other reason such as rapid drift of size in relation to tolerance causes them to be classified as unstable. These dimensions require 100% inspection and in the ideal arrangement this inspection operation should be included as part of the manufacturing process. The result of inspection should also be recorded, faulty parts should not be allowed to enter the work container for finished components and if a predetermined number of faulty parts is produced consecutively or in a predetermined number of manufacturing cycles, the manufacturing process should be automatically stopped.

The type of "In-Process" measuring equipment recommended for the three types of control in the manufacture of the part illustrated in Fig. 15 is as follows:-

Group 1 (Dimensions 1, 5, 7 and 9)

Dimensions in which the random distribution of size is found to be a small percentage of the tolerance can be controlled much more effectively by very simple in-process measurement techniques and equipment than by fixed anvil gauges. The measuring equipment can be very simple indeed and in most cases would be a simple fixture to which a mechanically-operated dial gauge is fitted. The periods between inspection can also be relatively long but the equipment must show the position of the size as established by measurement and its relation to the boundaries of tolerance. By this means, full advantage can be taken of drift of size inside the tolerance boundary due to tool wear, temperature changes in the machine, etc.

Group 2 (Dimensions Nos. 2, 3, 4, 6 and 10)

For the rapid and frequent percentage inspection of the dimensions that are classified as between the extremes of very stable (group 1) and unstable (group 3) the following rather exacting conditions should be satisfied:-

1. All dimensions must be inspected simultaneously.

2. Tolerance boundaries for all inspected dimensions must be clearly shown.

3. The measured size of each dimension inspected must be shown clearly and accurately and the disposition of this size in relation to the boundaries of tolerance allocated to each dimension.

4. The direction in which the size of each measured dimension can be expected to drift as production proceeds must be shown.

5. The dimensional stability of the manufacturing process for each dimension inspected must be shown.

6. Arrangements must be made that will enable the basic size and the boundaries of tolerance for each inspected dimension to be established to a high standard of accuracy by means of a relatively inexpensive setting master.

7. Errors due to gauge-maker's tolerance and gauge wear or their equivalent, must be reduced to a degree that makes errors from these causes of no commercial significance.

An inspection fixture of the type illustrated in Fig. 16 and an associated display unit of the type illustrated in Fig. 17 satisfies all the above conditions in the following manner:-

1. Condition No. 1 is satisfied because all dimensions are inspected simultaneously by the inspection fixture illustrated in Fig. 16.

2. Condition No. 2 is satisfied because, as illustrated in Fig. 17, a clearly-marked tolerance band is provided, which is never narrower than 4" and never wider than 6". This tolerance band forms part of an indicator panel carrying uniformly divided scales with an effective length of 10". The above conditions are made possible by the use of standard transducers which provide magnifications varying in small steps from 100 to 10,000.

3. Condition No. 3 is satisfied because the indicating device incorporates a multi-tube manometer unit, as illustrated in Fig. 17. The measured size of each inspected dimension and its disposition in relation to the tolerance boundary can be clearly seen by observing the height of the liquid in each of the manometer tubes and this height in relation to the line indicating the tolerance boundary.

4. Condition No. 4 is satisfied by the sign illustrated in Fig. 17 and shown just beyond the tolerance lines towards which size is expected to drift as production proceeds. When there is no consistent drift of size in one direction, the sign is not used.

5. Condition No. 5 is satisfied in the following manner:-

   When a part is placed in the inspection unit, the size of each dimension inspected is indicated by the height of the liquid in each of the separate manometer tubes. By means of a signal-retaining device, it is possible to retain the result of inspection on the indicator display panel after the part has been withdrawn from the inspection unit. When the second part to be inspected is inserted in the inspection unit, the section of each of the pneumatic circuits connected to the measuring units takes up a pressure corresponding to the size of the part being measured, while the section of the pneumatic circuit incorporating the indicator display tubes remains at a pressure corresponding to the size of the first part. By depressing a foot pedal, both sections of the pneumatic circuits take up pressures corresponding to the size of the dimensions inspected on the second part, and as this change occurs the height of the liquid in each of the manometer tubes moves from the position where it accurately indicated the size of the first part to the position where it accurately indicates the size of the second part. By observing the magnitude of this movement and its relation to the magnitude of the tolerance, it is possible to observe the difference in size between two parts made consecutively and by comparing this difference with the tolerance the stability of the manufacturing process associated with each inspection dimension can be assessed.

6. Condition No. 6 is satisfied by using the technique illustrated in Fig. 18 and Fig. 19. Fig. 18 is a reproduction of a standards room report on a good quality part selected as suitable for use as a setting master. Each inspected dimension on the selected part has been very carefully measured by the standards room staff and the deviation from nominal size tabulated. Marks corresponding to the carefully measured size on each dimension are indicated on the diagram panel by means of the small marker lines, as shown in Fig. 19. The illustration shows the operation of adjusting the height of the liquid in each of the manometer tubes to correspond to these marker lines. This operation is carried out when the calibrated setting master is placed in the inspection position. The indicator unit is adjusted so that it indicates to a high standard of accuracy the known size of all inspected dimensions on the part selected as a setting master. As stated in 2 above, the ten inch length of scale is linear and the boundaries of the tolerance for each dimension can be marked as shown.

7. The section of Condition 7 dealing with toolmaker's tolerance is satisfied by using the technique described in 6 above, and the section dealing with gauge wear is satisfied by periodically placing the setting master in the inspection unit and if drift has occurred due to wear on gauge anvils, or from any other cause, the effect of this can be eliminated by resetting the indicator unit as already described and illustrated in Fig. 19.

<u>Group 3. (Dimension No. 8)</u>

Dimension No. 8 is listed as requiring the 100% inspection described in Group 3. The tool layout should be prepared on the basis of including this inspection operation as part of the manufacturing process. This inspection operation can, in many cases, be carried out by an attachment which collects the part and places it into a simple inspection unit and then into the work shute. Arrangements can be made for a sorting unit to be incorporated in the work shute and rejects on the dimension inspected deflected into a separate work container. By this arrangement only those parts that are 100% satisfactory on the unstable dimension No. 8 enter the container for good parts. If the machine produces any predetermined number of faulty parts in a specified time it can be automatically stopped and a prominent signal light illuminated.

A strip recorder can automatically produce a very valuable record of the type shown in Fig. 20 and the operator can be encouraged to make the majority of the parts near the centre of the tolerance and very few near the boundaries of size at which they would be rejected.

If several machines are engaged on the manufacture of the same part the permanent record will show the amount of random variation and the drift of size of one machine in relation to another. The differences can be analysed and in many cases the performance of the inferior machines can be made equal to, and in some cases better than, the performance of the best.

Alterations can be made in speed of machining, type of cutting tool used, type of workpiece material, coolant used etc., and the effect of these changes observed by comparing the difference in recordings taken over a long period.

If improvements of the type described above can be obtained on a manufacturing process that was previously declared as seriously unstable it may be reclassified as stable and transferred to Group 1 or 2. The rather elaborate recording equipment can then be released and used for investigations on some other unstable manufacturing operation. The basis of this philosophy is to use "In-Process Measurement" in the most simple form that will provide the type of control that is required. In some cases this most simple form may be 100% inspection and the automatic recording of the individual size of each part as a temporary measure only.

CONCLUSIONS

The type of inspection recommended for dimensions in Group 2 has been described in considerable detail as one example of a system that appears to satisfy all the stated requirements. Other systems may be used and the equipment illustrated in Fig. 21 is given as an example of how several dimensions may be inspected simultaneously by electronic equipment. The information provided is satisfactory for many purposes but when the display presented to the operator or setter is analysed critically against the background of proved ergonomic principles the pneumatic system appears to be superior. A further alternative would be to use one of the recognised methods of statistical quality control based on data obtained by suitable "In-Process Measurement".

Many additional examples could have been described in the paper, products quite different from the ones selected could have been chosen. The subject is vast and it is thought that enough has been described to expound a worthwhile and exciting philosophy. Only two further observations will be made.

1. The paper has emphasized that the type of "In-Process Measurement" advocated must be made in the workshop under normal production conditions. This inevitably involves the machine operator. This is very desirable for several reasons and one good reason is that the operator is a person and persons are very important. Management should endeavour to organise the activities under its control so that everyone has the opportunity of making a contribution which is near the maximum of which he is capable. If "In-Process Measurement" is suitably applied, it can result in the operator becoming personally involved in the control of quality. When, as was common less than five decades ago, many persons lived well below subsistence level, money and food were the only real incentives. Now, and even more in the future, Management must appeal to the heart and the mind. If the persons on the shop floor were given suitable leadership, the majority would enjoy being engaged on difficult, attainable tasks.

2. Having started the present paper with a statement from one British physicist, it seems appropriate to end it with a statement from another. It is said that Sir Isaac Newton was once congratulated on the number of important discoveries he had made. He replied "I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me".

   It is not claimed that the examples given in this paper are in any way superior; they are, in fact, too briefly and inadequately described. It is claimed, however, that the planning and management of engineering manufacture as practised in the workshop is a large, important, exciting and relatively undiscovered area of Technology. Much benefit can be obtained by analysing the process of manufacture in the machine tool laboratory, but now, and to an increasing extent in the future, the place from which the richest harvests will be reaped will be from experiments with the machines and the men engaged on actual manufacture and the analytical tools that should be used in this investigation are noble behaviour and "In-Process Measurement".

JL/bw
4th April, 1967

No	GROUP	DESCRIPTION OF FEATURE OR POSSIBLE SOURCE OF ERROR.	RECOMMENDED FREQUENCY OF INSPECTION ONCE PER				
			HOUR	DAY	WEEK	MONTH	3 MONTHS
1	A	STRAIGHTNESS (PLANE SURFACE)				×	
2	A	FLATNESS			×		
3	A	STRAIGHTNESS (CYLINDRICAL SURFACE)		×			
4	A	CIRCULARITY			×		
5	A	CYLINDRICITY				×	
6	A	ANGLE BETWEEN FLAT SURFACES			×		
7	A	ANGLE BETWEEN A CYLINDRICAL SURFACE AND IT'S AXIS		×			
8	A	ANGLE BETWEEN AXES OF TWO OR MORE CYLINDRICAL SURFACES			×		
9	A	CONCENTRICITY BETWEEN AXES OF TWO OR MORE CYLINDRICAL SURFACES			×		
10	A	SURFACE TEXTURE		×			
11	B	MEAN SIZE	×				
12	C	ESTABLISHMENT OF BASIC SIZE AT PLACE OF MANUFACTURE				×	
13	C	INSTRUMENTAL ERRORS (REPEATABILITY CALIBRATION)				×	
14	C	PRESENTATION AND DISTORTION ERRORS DUE TO DIFFERENCE BETWEEN SETTING MASTER AND PART TO BE MEASURED					×
15	C	ERRORS DUE TO TEMPERATURE			×		
16	C	HUMAN ERRORS				×	

TABLE T.1.

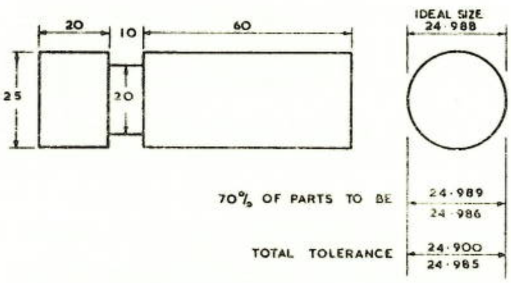


FIG.1. TEST PIECE


FIG.2. CALIPER AND INDICATOR.

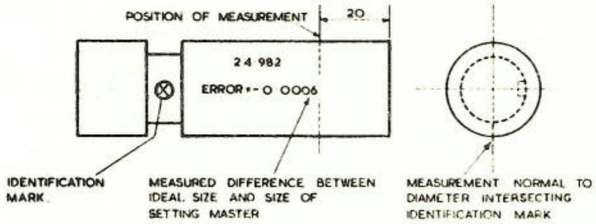


FIG.3. CALIBRATED SETTING MASTER.

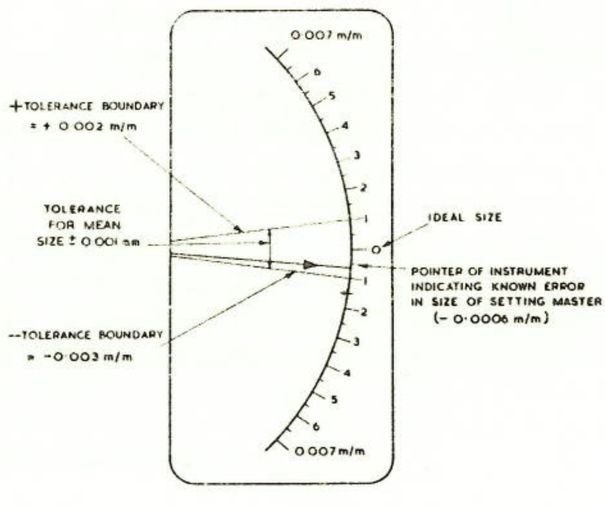


FIG.4. SCALE OF MEASURING INSTRUMENT.

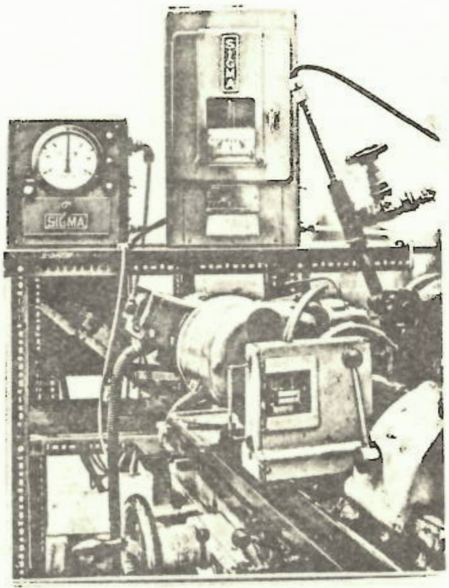


FIG.5. AUTOMATIC CONTROLLER.

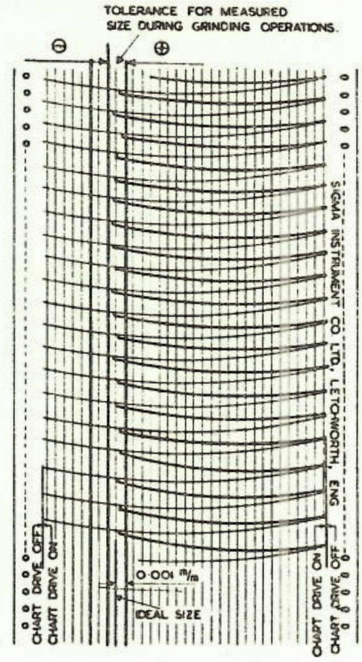
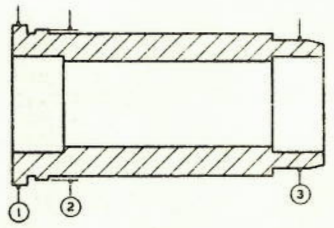


FIG.6. CHART RECORDING



DIMENSIONS	FINISH GRIND SIZE	MEASURED SIZE	METAL TO BE REMOVED
1	4·62100	4·62159	0·00059
2	4·37100	4·37162	0·00062
3	4·27700	4·27766	0·00066

COMPONENT		SETTING MASTER MADE TO NOMINAL DIMENSIONS		
DIMENSION	SIZE AND TOLERANCE	FINISH GRIND SIZE	INTERMEDIATE GRIND TOLERANCE	ROUGH GRIND TOLERANCE
1	4·622 4·620	4·621	4·6217 4·6215	4·628 4·626
2	4·372 4·370	4·371	4·3717 4·3715	4·378 4·376
3	4·278 4·276	4·277	4·2777 4·2775	4·284 4·282

FIG.7. SETTING MASTER.

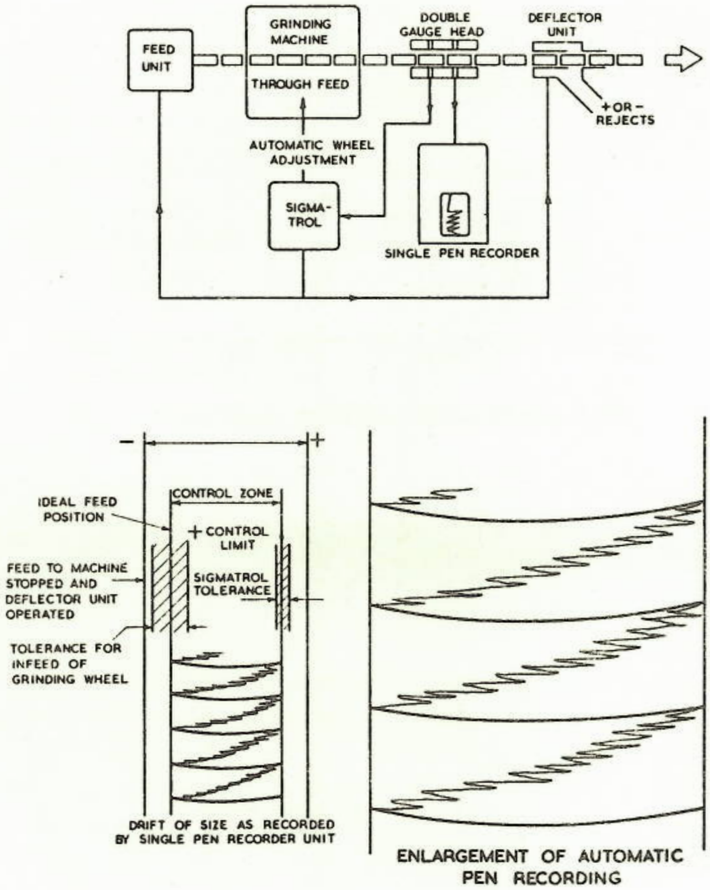


FIG.8. CENTRELESS GRINDER.

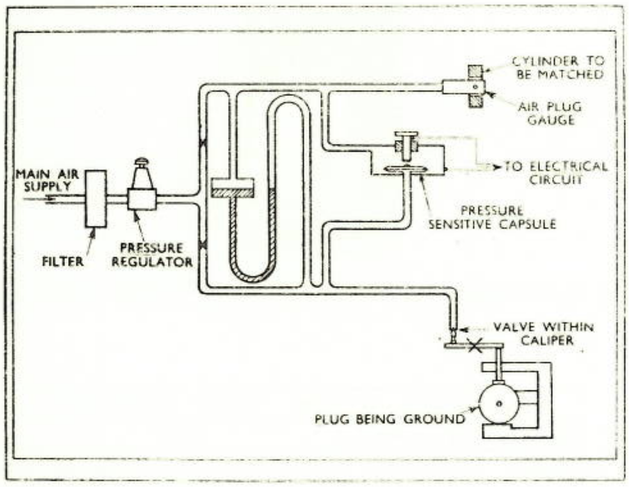


FIG.9. DIFFERENTIAL CIRCUIT.

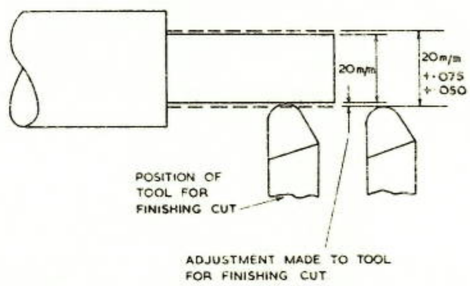


FIG.10. DIAGRAM OF PART TURNED TO 20 mm $^{+0{\cdot}075}_{+0{\cdot}050}$

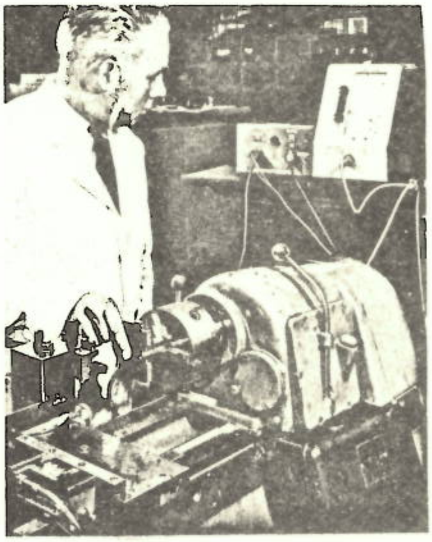


FIG.11. HAND CALIPER MEASURING TURNED PART.

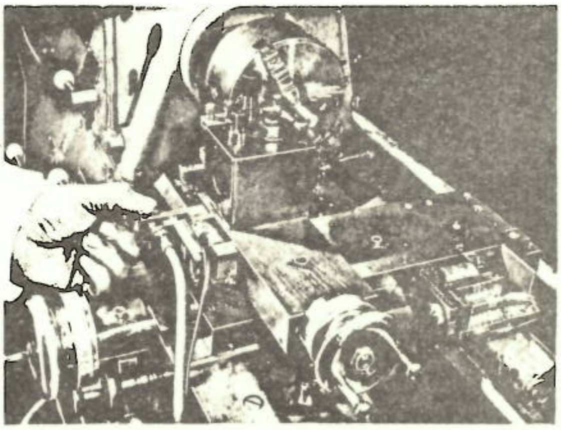


FIG.12. MEASURING UNIT FITTED TO CROSS SLIDE OF CENTRE LATHE

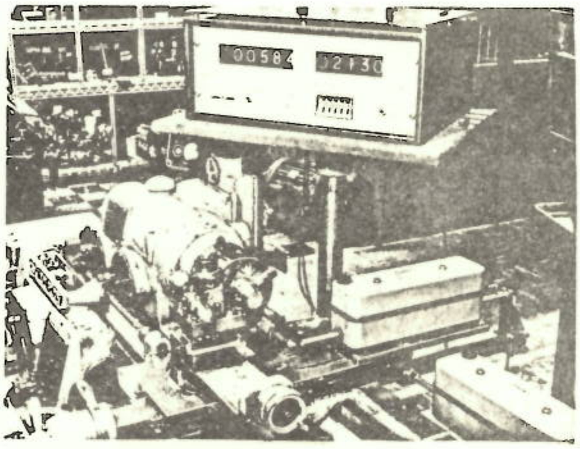


FIG.13. "DIGITURN" MEASURING EQUIPMENT FITTED TO CENTRE LATHE.

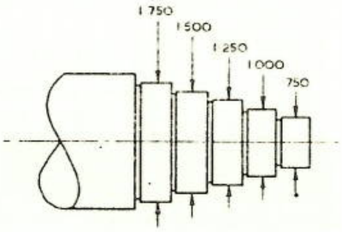


FIG.14. DIAGRAM OF PART TURNED ON FIVE DIAMETERS.

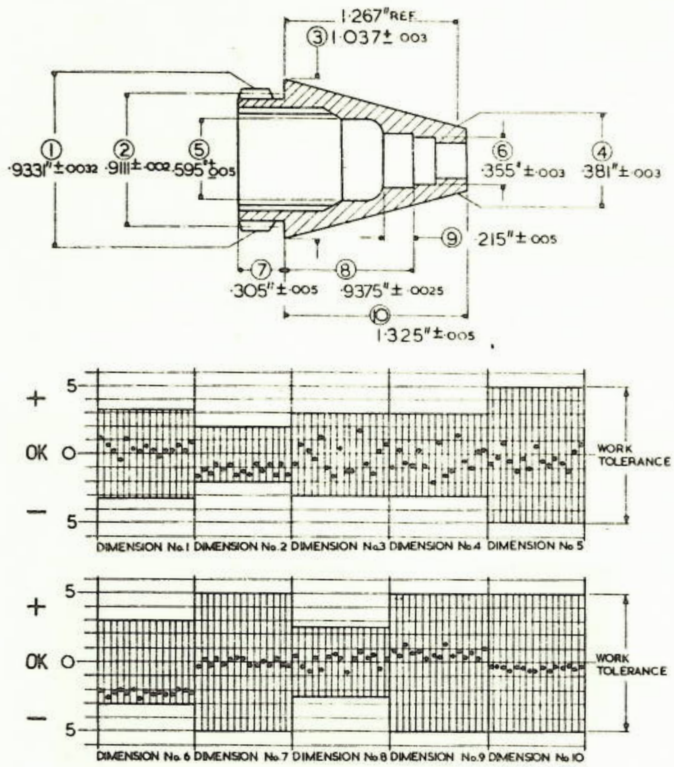


CHART SHOWING RESULT OF INSPECTING TEN DIMENSIONS ON FIFTEEN PARTS PRODUCED CONSECUTIVELY ON THE SAME MACHINE.

FIG.15. DIAGRAM OF PART REQUIRING INSPECTION ON TEN DIMENSIONS.

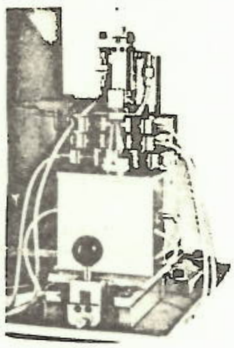


FIG.16. FIXTURE FOR INSPECTION OF FIVE DIMENSIONS.

STANDARDS ROOM TEST REPORT.				
DESCRIPTION OF PART.		BODY.		
DIMENSION NUMBER	BASIC SIZE	+ TOLERANCE	−	MEASURED DIFFERENCE FROM BASIC SIZE.
1	·9131"	+ 0	− ·004"	+ ·0002"
2	·384"	+ 0	− ·006"	− ·0005"
3	1·04"	+ 0	− ·006"	+ ·0005"
4	·59"	+ ·010"	− ·0	+ ·002"
5	1·32"	+ ·010"	− ·0	− ·0015"
6	·940"	+ 0	− ·005"	+ ·0002"
7	·300"	+ ·010"	− ·0	+ ·0015"
8	·220"	+ 0	− ·010"	+ ·0015"
9	·9363"	+	− ·0064"	− ·0005"
10	·354"	+ ·004"	− ·002"	+ ·0005"

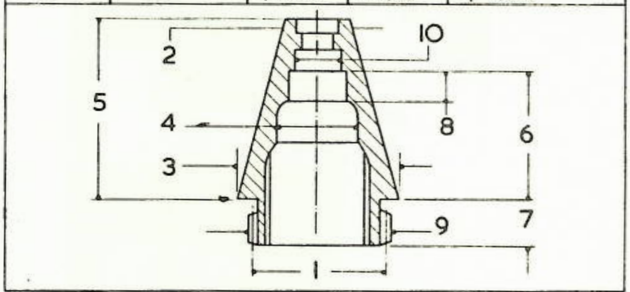


FIG.18. STANDARDS ROOM REPORT ON MEASUREMENT OF SETTING MASTER.

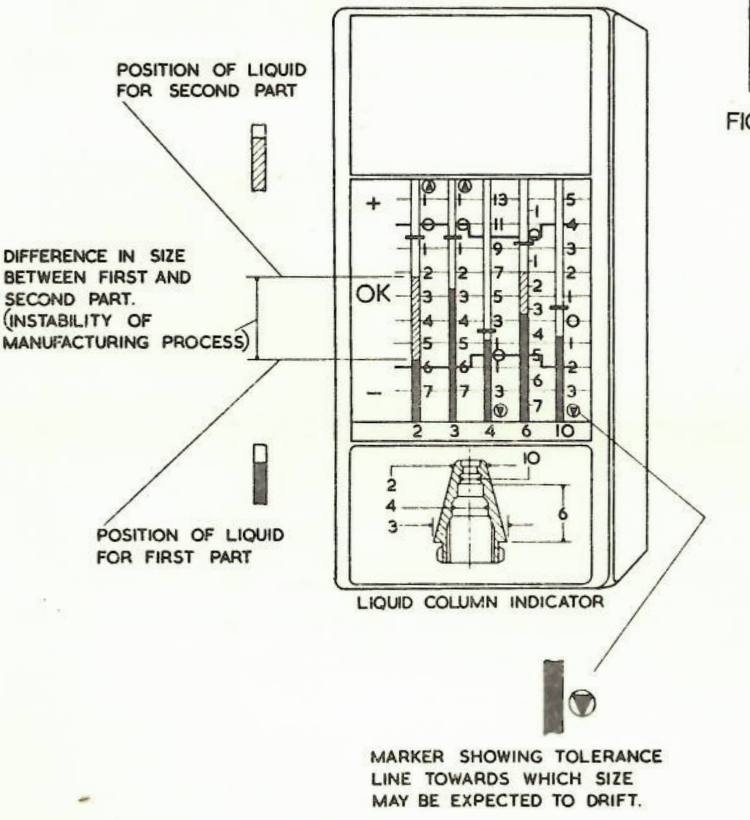


FIG.17. INDICATOR PANEL FOR FIVE DIMENSIONS INSPECTED.

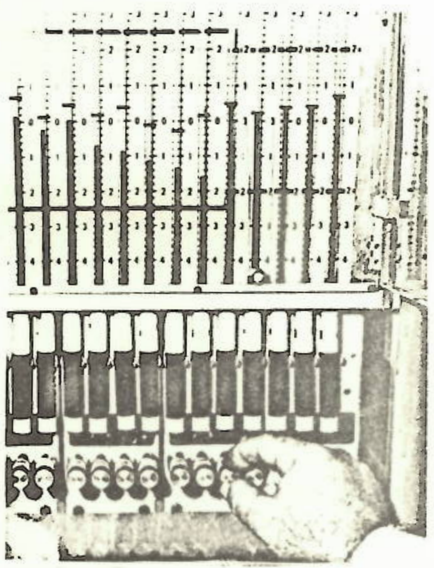
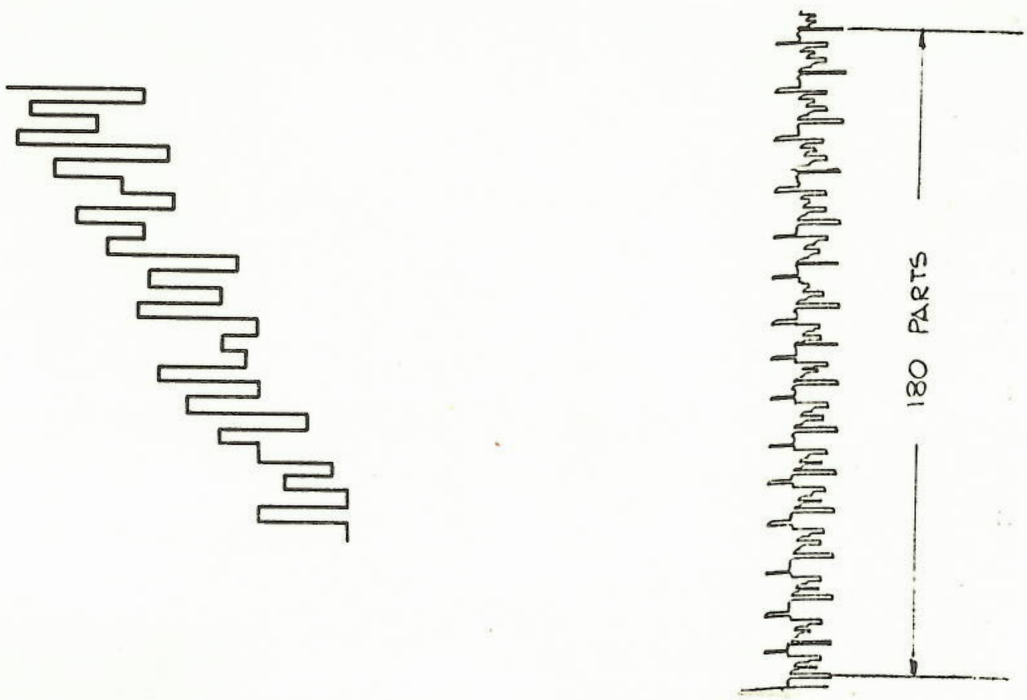


FIG.19. MARKER LINES ON DISPLAY PANEL.



DIAGRAMMATIC REPRESENTATION OF RECORDING SHOWING DRIFT OF SIZE.

ACTUAL RECORDING SHOWING CYCLIC VARIATION IN PRODUCTION PROCESS.

FIG.20. STRIP RECORDER.

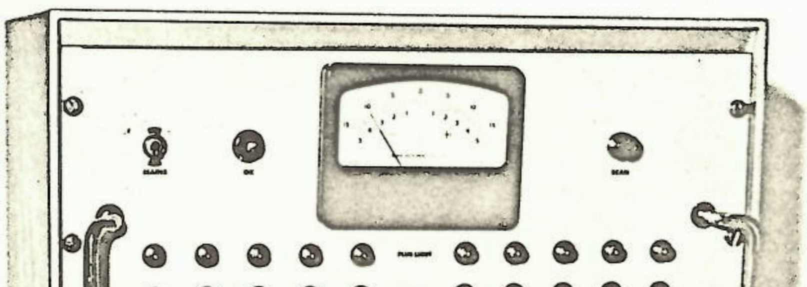


FIG.21. ELECTRONIC MEASURING UNIT.