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Measurement and analysis

Surface inspection of hot bars during rolling

Report

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Measurement and analysis

Surface inspection of hot bars during rolling

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SURFACE INSPECTION OF HOT BARS DURING ROLLING

British Steel plc

ECSC Agreement No. 7210.GB/806

SUMMARY

The traditional method of inspecting the surface of hot steel bar has been to use surrounding coil eddy-current techniques which have inherent deficiencies. These systems of inspection are insensitive to long seam defects and also transverse defects and are generally limited to bars which are less than 75 mm in diameter. The object of this ECSC project is to develop an alternative method that can overcome these deficiencies and extend the range of bar sizes that can be tested.

The development of water cooled inspection probe assemblies which are capable of being grouped around the bar circumference and the development of very stable electronics for signal processing have been the key features associated with the success of this project.

Plant trials with a five channel inspection head confirmed the defect detection capability and the excellent signal-to-noise ratios suggest that defect detection limits may well be improved down to the 0.5mm level.

These developments indicate that an improved method of hot bar inspection is now entirely feasible which overcomes the major deficiencies of existing bar testing installations.

A proposal for a fully-engineered prototype has been submitted as an ECSC Demonstration Project for installation at the Thrybergh Works of UES Steels.

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CONTROLE DE LA SURFACE DES BARRES CHAUDES EN COURS DE LAMINAGE

British Steel plc

Accord ECSC n°7210.GB/806

RÉSUMÉ

La méthode traditionnelle de contrôle de la surface des barres d'acier chaudes fait intervenir les techniques de sondage par courants de Foucault à bobines encerclantes qui présentent des imperfections inhérentes. Ces systèmes de contrôle ne prennent pas en compte les repliures de laminage ni les criques transversales et se limitent généralement aux barres de moins de 75 mm de diamètre. Ce projet ECSC a pour objet de mettre au point une autre méthode permettant de parer à ces insuffisances et d'élargir la gamme des dimensions de barres pouvant être contrôlées.

La mise au point de sondes de contrôle à refroidissement par eau pouvant être regroupées autour de la circonférence de la barre et le développement d'équipement électronique très stable pour effectuer le traitement des signaux sont les facteurs clefs qui ont contribué au succès de ce projet.

Les essais en usine utilisant une tête de contrôle à cinq canaux ont confirmé la capacité de détection des défauts et les rapports signal/bruit excellents suggèrent qu'il est fort probable que les limites de détection des défauts soient encore améliorées pour atteindre un niveau de 0,5 mm.

Ces développements indiquent qu'une méthode perfectionnée de contrôle des barres chaudes surmontant les principales imperfections des installations de contrôle des barres existantes est à présent tout à fait envisageable.

Une proposition de prototype avec étude technique entièrement terminée a été soumise comme Projet de Démonstration ECSC en vue d'une installation à l'aciérie Thybergh de UES Steels.

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Prüfung der Oberfläche von Warmstäben während des Walzens

British Steel plc

EGKS Vertrag Nr. 7210.GB/806

Zusammenfassung

Traditionell hat man für die Prüfung der Oberfläche von Warmstahlstäben Wirbelstromtechniken mit umgebenden Wicklungen benutzt, aber diese Methode hat inhärente Mängel. Diese Prüfsysteme sind unempfindlich gegen lange Nahtdefekte und auch gegen Querdefekte, aus dem Grunde sind sie allgemein auf Stäbe mit einem Durchmesser von weniger als 75 mm begrenzt. Das Ziel dieses EGKS-Vorhabens hat die Entwicklung einer alternativen Methode betroffen, mit der man diese Mängel überwinden und den Bereich der zu prüfenden Stababmessungen erweitern kann.

Die Entwicklung wassergekühlter Sondengruppen, die an allen Seiten der Stabperipherie gruppiert werden können, und die Entwicklung sehr stabiler Elektroniksysteme für Signalverarbeitung sind die mit dem Erfolg dieses Vorhabens verbundenen Schlüsselmerkmale gewesen.

Versuche mit einem Fünfkanal-Prüfkopf im Werk haben das Defektnachweisvermögen bestätigt, und die ausgezeichneten Störabstände legen nahe, daß die Defektnachweisbegrenzungen sehr wahrscheinlich auf ein Niveau von 0,5 mm reduziert werden können.

Diese Entwicklungen deuten an, daß eine bessere Methode für Prüfung von Warmstäben heute durchaus möglich ist, mit der man die Hauptmängel existierender Stabtestanlagen überwinden kann.

Man hat einen Antrag für einen großtechnischen Prototyp als ein EGKS-Vorhaben für Vorführungszwecke zum Einbau im Thrybergh-Werk der Firma UES-Steels vorgelegt.

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SURFACE INSPECTION OF HOT BARS DURING ROLLING

British Steel plc

ECSC Agreement No. 7210.GB/806

FINAL TECHNICAL REPORT

1. INTRODUCTION

Traditional hot bar inspection systems have employed the surrounding-coil eddy-current inspection technique. This technique has fundamental defect detection limitations and these limitations have had to be tolerated by production plant in the absence of more refined methods. This surrounding-coil detection system cannot adequately resolve longitudinal seam defects unless they are short in length because of the differential action of the detection coils. In addition, defects which are purely circumferential in nature do not disturb the flow of the eddy currents and are also not detectable. There is clearly a need for an improved detection system which can overcome these shortcomings.

The purpose of this project was to develop an improved eddy-current technique for the in-line inspection of hot bar surfaces at rolling temperatures for the presence of longitudinal seam defects.

The optimum siting for a hot bar inspection system would be a position downstream of the final sizing pass before significant scale formation can take place and prior to any water quenching treatment which can lower the bar below the Curie temperature and make eddy-current inspection impractical.

The trial site at the Thrybergh Works of UES Steels included a Koch's precision sizing block and the inspection unit was located immediately downstream of this sizing block taking advantage of the excellent inherent guidance features.

The proposed inspection technique depended on the grouping of individual water-cooled probe coils around the circumference of the hot bar. These coil assemblies were mounted on ceramic wear plates which contacted the bar surface to establish the correct operating clearances and acted in an absolute detection mode to allow the detection of longitudinal and transverse bar defects. This success of this project was very much conditioned by the development and optimisation of the inspection probe assemblies and also the associated processing electronics with due regard for the bar size range rolled on this particular mill.

2. REVIEW OF DETECTION PARAMETERS

The use of single or dual excitation frequencies, the variations in the size and type of coil construction, the choice of coil construction materials and electronic processing methods all need to be optimised if the development programme is to be successful.

The successful detection of longitudinal defects implies absolute processing techniques and to obtain adequate defect detection sensitivity it is necessary to reduce the search area associated with each detection coil. An array of probe coils distributed around the product circumference provides a good basis for the design of a detection head assembly provided that the problems of sensitivity and overall stability can be resolved.

Dual frequency methods were examined early in the project but it was soon recognised that, with multiple coil inspection heads, the sheer volume of processing electronics would be unwieldy, expensive and would offer no real advantage over the simpler single frequency methods.

The choice of a single operating frequency should take due consideration of defect processing rates and offer good separation of defect information from lift-off effects. The phase angle separation between defect and lift-off vectors increases with test frequency and a practical operating frequency of 1 MHz was adopted.

2.1 Coil Winding Material

It became apparent in the early stages of the development programme that coil stability, at these enhanced operating sensitivities, was critical to the success of the project if defect signals were not to be masked by coil temperature variations. This is illustrated in the impedance plane diagram of Fig. 1 where the effects of a temperature change of 70 degrees Celsius on a coil wound with copper wire can be seen. This change was much larger than the signal produced by a 1 mm defect and would therefore impose a significant limit on defect detectability. A range of alternative coil materials was evaluated and Constantan was selected as being the most effective in reducing temperature effects. The impedance plane diagram shown in Fig. 2 indicates the measure of improvement obtained when a Constantan coil was subjected to the same temperature change. The coil temperature effects have been reduced by a factor of at least 30 by using Constantan wire and this coil material was used for all subsequent coil assemblies.

2.2 Coil Construction

Trials were also undertaken with various coil constructions to optimise the recovered defect signal relative to signals produced by variations in coil operating clearance, commonly referred to as the lift-off effect. Dual coil assemblies were examined and included orthogonal, dual-D and concentric coil configurations. The only configuration that showed any promise was the concentric coil arrangement but the overall coil size was large in relation to the sensing area and the coil construction was significantly more complicated. These are important factors where multiple coil test head assemblies are envisaged and this arrangement was therefore rejected. The examination of single coil assemblies was restricted to a single cylindrical coil of 10 mm diameter and two radially displaced coils of similar dimensions. The two radial coils offered reasonable rejection of lift-off and thermal effects but were very sensitive to lateral movement of the bar and also effects of coil tilt and, for these reasons, were discounted. The single cylindrical coil offered reasonable coverage and constructional simplicity but required the use of phase sensitive detection for lift-off cancellation. The single coil configuration was adopted to ensure that the engineering complexity of inspection head assembly was minimised.

2.3 Coil Protection

The coil assembly is designed to slide on the bar surface to provide a controlled coil clearance and the selection of a suitable facing material is an important feature in the design. The detection coil is contained in a water cooled housing faced by a ceramic shoe. Water is directed through the centre of the coil and issues through the narrow annulus between the end of the coil and the ceramic facing material into the outer collection chamber. Under normal operating conditions one side of the 2.25 mm thick ceramic facing will be in contact with the bar at 1100 degrees celsius and the other side will be in contact with cooling water at around 20 degrees celsius. The selection of a suitable ceramic will therefore depend predominantly on its ability to withstand thermal shock and also to tolerate the high thermal gradient across the the thin wall section. Table 1 lists the properties of some ceramic materials that have been considered. Silicon nitride exhibits the highest thermal shock resistance and can be machined at the green stage to produce a well toleranced component. Experience with this material during hot bar trials has confirmed its suitability for this purpose and it showed negligible wear over a period of several hours. This ceramic is also resistant to metal pick-up when in contact with molten metals and can be obtained in a glazed form to resist water absorption, which can produce breakup of the ceramic resulting from the rapid formation of steam.

2.4 Coil Characteristics

Tables 2, 3 and 4 illustrate typical coil characteristics for the two principle coil constructions considered when applied to both steel and titanium alloy test samples. The titanium test sample was selected as being similar in properties to steel at rolling temperatures. The changes in test conditions from cold steel to hot steel, as typified by the titanium alloy sample bar, incurs a loss in sensitivity of 5:1. The use of Constantan wire for the winding produces a further loss of 3:2 giving an overall loss of 15:2. With the dual coil arrangement an additional loss of 2:1 would be experienced.

The dynamic response of the preferred 10 mm diameter single cylindrical test coil is illustrated in Figs. 3 and 4. Figure 3 shows the lift-off cancellation that can be achieved by a vector rotation of 88 degrees when the coil traverses a 1 mm defect at the three specified operating clearances. The lift-off residual can be reduced even further in a practical design by allowing smaller increments in rotation than the test instrumentation limit of 1 degree. Figure 4 indicates the tolerance to lateral bar movement for displacements of ± 0.5 mm.

3. RESONANT PROBE TECHNIQUE

The test coil was initially incorporated as a tuned element in an oscillatory circuit and the reactive and resistive components were extracted by decoding the frequency and amplitude information as shown in Fig. 5. The subsequent combination of these two channels has the same effect as phase rotation in producing lift-off cancellation. Initial tests were conducted on a group of three probes but it soon became evident that probe interactions were taking place as the oscillators attempted to lock depending on their harmonic relationships - these effects can be observed in Fig. 6. It was not possible to eliminate this interaction and the use of probe commutation techniques was examined. With this technique each probe is activated in sequence allowing time for the output signal to stabilise before a reading was taken. Figure 7 shows the timing relationships and the resultant waveforms for two probes commutated at 1 kHz is shown in Fig. 8. Increased background noise was produced with this method because of interaction between the switching waveforms and the oscillator circuit caused by capacitive feedthrough and also steps in the output waveform could be observed due to asynchronous switching of the oscillator. For these reasons and because the sampling technique would only allow each coil to sample the bar at around 15mm intervals at bar speeds of 15 m/s the concept was discarded.

3.1 Plant Trials

The resonant probe technique was used to assess detection performance on hot bar at rolling temperatures with a single cylindrical test coil. The test coil was constructed along the lines discussed earlier, contained in a water cooled metal housing, and then cemented to a long silicon nitride shoe which rode on the surface of the hot bar. The probe assembly was applied to the bar with a trailing parallelogram linkage to ensure that the probe facing was maintained parallel to the bar surface during its application and retraction. The probe was applied to and retracted from the bar surface using a pneumatic cylinder.

The trial was conducted at the Thrybergh works of United Engineering Steels and the test unit was located immediately downstream of the Kochs precision sizing block which gave good control of the bar position on exit. The space available at this point in the line constrained the overall length of the test head to approximately 200 mm.

Coil cooling was provided by a peristaltic pump fed from a separate water tank at a cooling flow rate of around 7 litres/min.

The trials were restricted to bar sizes in excess of 50 mm to avoid problems associated with bar droop within the test head zone.

The two outputs from the probe channel were monitored on a multichannel FM tape recorder system to allow subsequent analysis. Coil temperature was measured by sensing the output voltage from a thermistor embedded in the coil winding and bar temperature variations along the bar were monitored with a hand-held two-colour optical pyrometer which provided an electrical output for recording purposes.

The object of this trial was to establish the suitability of the engineering materials in a practical production environment and, at the same time, to monitor the processed results from a single eddy current channel to ensure that no unexpected inspection problems were encountered.

3.2 Lift-Off Cancellation

The traces shown in Fig 9 are typical of the recordings obtained from the coil during test. The top trace relates to coil inductive variations ,the middle trace relates to coil resistive variations and the lower trace represents the final output signal after combining the two traces in the optimum ratio and applying amplification.

The underlying cyclic lift-off variations have been cancelled to good effect leaving a good datum against which to judge any defect content. Defect signals would normally be positive in polarity and the unexpected negative signal peak seen on the output trace was eventually traced to a malfunction in the tape recording system. This spurious signal occurred randomly throughout the tape recordings but, since no comparisons were being made at this stage with cold bar inspection results, this effect did not present any real problems.

The same signal recordings were then combined in the ratio which would give optimum rejection of lift-off effects based on the use of the titanium alloy reference bar which had been judged to be close in properties to that of a hot steel bar. It is evident from the results shown in Fig 10 that the titanium alloy bar cannot be used to provide the correct cancellation factor for in-line operation and it is essential that some other means must be found of determining the correct factor, to allow the resolution of harmful defects. It may be possible to use the application of the test head onto the hot bar as a means of determining the optimum cancellation ratio on a bar by bar basis.

3.3 Conveyor Induced Cyclic Variations

There is an underlying cyclic variation present on both the traces shown in Figs. 9 and 10. Further investigation showed a strong correlation between these cyclic signals and the time interval between rollers on the conveyor and therefore it has been assumed that the signals are induced by the motion of the bar nose over individual rollers along the roller table. This behaviour further endorses the need to have good lift-off cancellation as a design feature.

3.4 Furnace Induced Cyclic Variations

The recordings of bar temperature using the optical two-colour pyrometer shown in Fig. 11 indicate cycles in surface temperature along the length of the bar. After a lot of investigation this was correlated with the positions of the supports within the reheat furnace which appeared to leave cool zones along the length of the bar. The temperature depressions amounted to around 40 degrees Celsius and concern was registered that these effects may produce pseudo defect indications. Examination of other areas of the defect recordings with optimum lift-off rejection did not reveal any irregularities and it must therefore be assumed that variations in surface temperature and lift-off are similar in effect and are rejected together.

3.5 Coil Cooling

The trace shown in Fig. 12 was derived from the thermistor which was embedded within the coil assembly and was obtained during a sequence of bar tests. The initial rise is the result of heating the coil assembly from a cool condition and then the coil temperature profile stabilises and then cycles between 45°C and 50°C as bars enter and exit the test station. Cooling water flow rates of around 7 litres/h were employed with a rise in water temperature of around 20°C. These flow rates indicate that it is necessary to extract approximately 160 W of heat from the probe housing itself to maintain an internal probe temperatures of the order of 50°C. With a configuration of 32 probes in a more practical array a total heat content in excess of 5 kW would need to be extracted to maintain sensible coil temperatures.

3.6 Mechanical Considerations

The probe was located behind a 3 mm thick silicon nitride skid of approximately 100 mm in length and was applied pneumatically using a parallelogram linkage. This proved to be effective and the probe was maintained in contact with the surface at all times. After the trial period in which more than 80 bars had been processed the skid was examined to determine the extent of any wear that may have taken place. No discernible wear patterns were evident and therefore silicon nitride will continue to be used in all future trials.

4. PHASE SENSITIVE BRIDGE TECHNIQUE

The interaction of oscillatory circuits in multiprobe inspection heads requires the development of alternative electronic signal processing operating at fixed frequency with ultra-stable characteristics.

4.1 System Description

The proposed electronic processing system for multi-channel operation is illustrated in Fig. 13 where all the probes are energised from one single crystal controlled oscillator. Each coil forms part of a bridge circuit which is balanced prior to the application of the probe to the metal surface. Subsequent amplification of the bridge signals is achieved in a very stable video amplifier before being fed to the inputs of phase sensitive detector stages. These phase sensitive detectors must also be very stable in operation because any dc drift that takes place will appear as an additional component in the signal output, either enhancing or suppressing the true defect component depending on the polarity of the voltage drift. The magnitude of the problem can be appreciated by referring to Fig. 14 where the excursion in voltage from the phase detectors in moving the probe onto the test surface has been recorded together with the defect excursions produced by a 0.5 mm and 1.0 mm defect. The resultant defect signal obtained by subtracting these two waveforms in the optimum ratio equates to only 1.5% of the original step height and it will, therefore, be necessary to establish the correct cancellation factor to an accuracy of better than 0.2% to minimise residual lift-off content.

4.2 Automatic Lift-Off Cancellation

The inclusion of accurate automatic lift-off cancellation is a vital step in the development of this inspection system for the reasons mentioned above. Figure 15 illustrates the gross signals that can result from the use of an incorrect cancellation factor on the in-phase and quadrature signal components immediately after probe has been applied onto a hot bar surface compared to the relatively stable datum established thereafter by the use of the correct cancellation factor. These results were generated from previously recorded single-channel phase-detector outputs obtained during earlier hot bar trials. It was determined that the best form of automatic lift-off cancellation was achieved by using the voltage excursions generated by the phase detectors when the probes are applied to the bar surface. The ideal cancellation factor can be derived from the ratio of phase detector voltages with a minor correction factor which depends on surface contour. Figure 16 shows the in-phase and quadrature detector voltage excursions during probe application and the relationship between them over the duration of the application stroke. The incremental slope at the end of the application stroke is close in value to the absolute slope derived over the entire stroke and only minor corrections are required. The definition of terms used in automatic lift-off cancellation can be seen by referring to Fig. 17 which shows idealised application waveforms. The electronic processing ensures that the two wave forms are referenced to 0 V prior to head application. Immediately after probe application the maximum voltage excursions are stored and their ratio is used in the subsequent cancellation process. The voltage changes from these maximum levels are used to indicate defect or lift-off excursions at the normal coil operating clearance of 3 mm. The output signal is derived according to the formula below.

$$\text{Defect Output} = \Delta\phi \times \frac{k \, . \, j\phi_{max}}{\phi_{max}} - \Delta j\phi$$

A five channel eddy-current processing system was designed along the foregoing lines exercising great care in the design and selection of components to ensure that devices were conservatively rated and offered intrinsically very low levels of voltage drift.

4.3 Five Channel Inspection System

An exploded view of a typical eddy-current coil assembly is shown in Fig. 18 with a circular protective window ceramic window and a water cooled probe housing. A temperature measuring device is embedded close to the water chamber to ensure that cooling water flow rates are adequate. The main housing is faced with ceramic in the areas which are in contact with the bar surface.

Figure 19 shows the processing electronics developed for this trial and for technical reasons this had to be separated into a small enclosure which had to be mounted adjacent to the inspection head containing the high frequency bridge and phase detectors and a larger remote enclosure containing the remainder of the processing electronics including the automatic lift-off cancellation.

The inspection head was comprised of five eddy-current coil assemblies mounted in pantograph assemblies which were applied to the bar surface by means of pneumatic cylinders. Figure 20 shows the general construction of inspection head at the point of installation and Fig. 21 shows the unit in operation on the mill during production trials.

4.4 Production Trials

The inspection head was sited immediately downstream from the Koch's precision sizing block on the production line of the Thrybergh Bar Mill at UES Steels in Rotherham. The five probe channels allowed the inspection of one quarter of the surface of a 68 mm diameter bar. It was obviously important to ensure that defective material would pass under this close grouping of probes and that was accomplished by obtaining a prime billet of 140 mm section and machining artificial defects of known depth into all four billet faces at two zones along the 13 m length. At the first zone, a defect of 6 mm depth was machined at an angle across each face of the billet for a distance of approximately 1 m. At the second zone, the defects were similarly introduced but at the reduced depth of 3 mm. The positions of the defective zones were selected so that each of the zones would be contained in individual bar lengths of nominally 8 m.

The billet was reheated and rolled to 68 mm diameter bar and inspected with the five channel head assembly which was calibrated using a 1 mm defect standard in an austenitic bar; trials with resistively heated samples had already shown that hot steel bars and cold austenitic steel bars had comparable properties. Full monitoring of all output signals was achieved by using FM tape recorders and high speed event recorders.

The trial material was included at the end of a normal production run on the same bar size so an opportunity was taken to inspect material that should be of prime quality. The traces in Fig. 22 show the responses from each of the five probe channels on this production material. It will be noticed that some drift is evident over the full length of the bar but no measurable defect content was registered. The next bar was the trial bar with the two defective zones and the test results are shown in Fig. 23. The two defective areas showed up clearly on all five probe channels exhibiting excellent signal-to-noise ratios but the signal drift that was observed on the previous bar was still present. The second zone on probe channel 3 showed two separate indications where the probe was travelling down the bar in a position which corresponded to the original billet corner and where the billet face defects adjacent to that corner produced marginal responses.

4.5 Analysis of Trial Results

The trial bars containing the two defective zones were hand probed with conventional eddy-current equipment and the positions of the seams were marked. The bars were then sectioned at each of the two defective zones and classic longitudinal seams of nominally 1.2 mm and 2.4 mm were observed on the macrophotographs. Figure 24 shows the four 1.2 mm defects at a magnification of x 34 and Fig. 25 shows the four 2.4 mm defects at the same magnification. These results were very encouraging and suggest that defect detection sensitivities down to 0.5 mm may be practical.

Detailed tests were conducted on the inspection head assembly to determine the cause of the signal drift on the output waveforms. Eventually it was found that the radiant heating of the coil coaxial leads was predominantly responsible for this behaviour. In a final system design this problem can be overcome by routing the connecting leads through water cooled jackets and avoiding direct radiation paths wherever possible. Figure 26 illustrates the drift in signal output experienced during testing of a resistively heated austenitic calibration tube with a probe cooling water flow rate of nominally 0.1 litres/min with no protection against radiant heating. The corresponding traces shown in Fig. 27 show no significant drift when the connecting leads were lagged against the radiant heat coming from the hot tube. This test confirmed that little problem should be experienced with thermal drift providing good engineering construction practices are observed.

5. DISCUSSION OF INSPECTION SYSTEM FEATURES

The multiple probe head assembly responded well to longitudinal seams of the order of 1 mm in depth and the noise levels experienced on these trials suggest that defect detection capability might well be improved to the 0.5 mm level. These absolute detection levels are a feature of the probe coil technique and do not relate to the diameter of the bar. This allows improved inspection performance on larger bar diameters (when expressed as a percentage of bar diameter) but can be a limiting feature on small bar sizes where increased sensitivities are desirable. The following sections discuss the features of this new development and the implications of including this form of inspection system in a hot bar production line.

5.1 Product Features

Good bar guidance is an essential pre-requisite for success with this method of inspection and it will be necessary to maintain the bar position within the inspection zone to better than 2 or 3 mm of an ideal bar centreline in all planes.

It will be necessary to make provision for retaining the Koch's block in-line for all bar sizes to ensure adequate guidance is obtained throughout the production range.

The probe development has been optimised for operation over the round-bar size range rolled at Thrybergh (15 mm to 110 mm). Further probe development may well be required for reduced bar diameters.

The inspection of square or hexagonal products, whilst being a feasible proposition, would require careful thought in the design of the test head to allow for the variety of product sections and would also put constraints on the bar rotation through the inspection area; a problem not encountered in round bar testing.

The presence of excessive water on the bar surface immediately prior to test can cause spurious defect information to be generated particularly if the surface temperature is caused to reduce below Curie point. All eddy-current systems are vulnerable to this effect and encircling coil systems are often preceded by an air-knife to minimise the problem.

Scale build-up can interfere with the detection action because scale can cool rapidly below Curie levels and leave a variable magnetic layer on the bar surface. Siting the test head close to mill stand with an air-knife usually effects a cure.

5.2 Inspection Features

The limiting factors on achievable detection sensitivity relate firstly to the disproportionate fall-off in defect signal below 1 mm defect depth (a problem caused by the physics of detection), secondly to the surface condition of the hot bar or surface roughness (sensitivity is usually restricted to three times the surface roughness) and finally to the rejection of lift-off signals in the final defect output (this rejection factor is calculated automatically during probe application).

It has already been mentioned that the probe development was optimised for the range of bar sizes produced at the Thrybergh Mill of United Engineering Steels and the probe sensing area ranges from 6mm to 10mm diameter according to the size of bar being inspected. This coil size represents a compromise between detection sensitivity level and the number of coils required to cover the surface of the larger bar sizes. With the current coil design approximately 32 coils will need to be accommodated in the largest head assembly.

The probe design is omnidirectional and it should be possible to respond to most orientations of defect. A catalogue of various defect types is being gathered together with the responses that can be obtained. Figure 28 illustrates some trial results obtained from resistively heated bar samples containing natural defects. Responses have been obtained for three bar samples A, B & C and Fig. 29 contains three macrophotographs corresponding to the three defects on bar A at a magnification of x 20. All the defects in Fig. 29 are laps with a surface penetration of only 0.2 mm to 0.4 mm but they have a surface length of 2 mm to 4 mm ensuring good detection. In Fig. 30 the upper and lower macrophotographs relate to bar samples B and C respectively also shown at the same magnification of x 20. Sample B contains a 0.6 mm deep seam defect and sample C has a rough scale-filled area approximately 0.1 mm in depth. A 1 mm calibration defect would produce a 3 division shift relative to the A bar responses and a 6 division shift relative to all other responses. The signals are therefore commensurate with the defect content. The system should be capable of detecting longitudinal and transverse defects within the limits previously mentioned, rolling laps, areas of shell and roll marks which produce significant surface effects. There would be less confidence in picking up shallow surface grooves since these defects would tend to be treated as lift-off changes and would be cancelled accordingly.

5.3 Engineering Features

It has already been mentioned that bar guidance is an important factor and in that context it would be prudent and cost effective to consider the use of the Kochs precision sizing block (PSB) for that purpose. The space is quite restrictive however and a careful design study will need to be made to assess whether the test head assembly can be accommodated within the confines of the PSB. The inspection head could be accommodated in an on-line position interleaved with the limbs of the Kochs block but capable of being retracted off-line for maintenance purposes.

The alternative option is to develop an integrated bar guidance arrangement distributed throughout the inspection system. This will obviously incur a large cost penalty and it would also need to be automatic in its adjustment for varying bar diameter to effect manpower savings. This development should not be undertaken lightly since the concept is difficult to engineer.

It should also be appreciated that if the test coil assemblies are applied after the bar nose has passed then the application time of typically 0.5 s will produce an uninspected end loss related to the speed of the bar. The losses at the tail end of the bar will be significantly less because any retraction delay will keep the inspection head in contact longer.

5.4 Inspection System Costs

It is difficult, without a detailed study, to give a firm idea on the outturn cost for the design of this type of inspection system but it is anticipated that the cost would be of the order of £500 000 if the inspection system were to be incorporated into the PSB. These costs would obviously include the initial electronic and mechanical design and subsequent repeat systems would therefore be correspondingly cheaper. Without a clearer understanding of the design concept for a unit with integral guidance it would not be sensible to speculate on the outturn cost of a fully integrated inspection system.

6. CONCLUSIONS

The successful development of a stable,water-cooled, eddy-current, inspection probe has been an important aspect of this development programme. The provision of a silicon nitride ceramic protective facing has made it possible to contain the cooling water whilst at the same time allowing the probe assembly to slide on the bar surface at a predetermined operating clearance with minimal wear.

The development of ultrastable processing electronics has been an equally important feature of the overall inspection package and will allow the multichannel operation that this technique demands.

The hot bar inspection trials were very successful and good signal-to-noise ratios were obtained on all output signals suggesting that defect detection sensitivities down to 0.5 mm might be possible.

The provision of good bar guidance throughout the length of the inspection head assembly is an essential pre-requisite and costs benefits may well accrue if the guidance features of existing precision sizing blocks are integrated into the head design concepts.

A proposal for a fully-engineered prototype has been submitted as an ECSC Demonstration Project for installation at the Thrybergh Works of UES Steels.

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TABLE 1
PROPERTIES OF CERAMIC MATERIALS FOR HOT BAR INSPECTION

	Alumina Al_2O_3	Silicon Carbide SiC	Silicon Nitride Si_3N_4	Boron Carbide B_4C	Boron Nitride BN
Maximum Temperature, °C Short Term Long Term		 1600 1400	 1400 1150	 1500	 1000
Thermal Shock, °C	350	400	650		High
Thermal Expansion, $1/K.10^6$	8	4	3	5	3
Thermal Conductivity, W/m K @ 20°C @ 1000°C	 23	 150 45	 25 18	 38 18	 22 11
Density, g/cc	3.9	3.1	3.2	2.5	
Resistivity, Ω m @ 20°C @ 1000°C	 10^{12}	 10	 10^{10} 10^5	 0.1-10	 10^{11}
Tensile Strength, GPa	300	410	290	450	60
Compressive Strength, MPa	2100	2000	2000	2800	
Flexural Strength, MPa @ 20°C @ 1000°C	 300	 410 410	 650 450	 400 300	
Hardness, HV, kg/mm^2	1500	3000	1500	300	3000
Fracture Toughness, MPa $\sqrt{m}$	4	4	8		
Molten Metal Resistance		Average	Good		Good
Machinability			Green (Unfired State)		Good

TABLE 2
TYPICAL PARAMETERS FOR A SINGLE INSPECTION COIL
(COPPER WINDING)

Steel Test Sample

Test frequency is 1 MHz
All parameters are expressed as % of coil impedance
Defect size is 1 mm in a steel reference block
Lift-off excursion is ±0.5 mm around 3.0 mm nominal
Coil ID is 10 mm using copper wire
Defect vector length @ 3 mm LO is 0.215% @ 63°
Lift-off vector is 1.49% @ 125°
Included angle is 62 producing a defect factor of 0.883
Residual defect at 2.5 mm LO is 0.245% after cancellation
Residual defect at 3.0 mm LO is 0.192% after cancellation
Residual defect at 3.5 mm LO is 0.128% after cancellation
Residual lift-off is 0.032% after cancellation

Titanium Test Sample

Test frequency is 1 MHz
All parameters are expressed as % of coil impedance
Defect size is 1 mm in a titanium alloy bar
Lift-off excursion is ±0.5 mm around 3.0 mm nominal
Coil ID is 10 mm using copper wire
Defect vector length @ 3 mm LO is 0.11% @ 64°
Lift-off vector is 2.08% @ 95°
Included angle is 21 producing a defect factor of 0.358
Residual defect at 2.5 mm LO is 0.053% after cancellation
Residual defect at 3.0 mm LO is 0.037% after cancellation
Residual defect at 3.5 mm LO is 0.027% after cancellation
Residual lift-off is 0.021% after cancellation

TABLE 3
TYPICAL PARAMETERS FOR A SINGLE INSPECTION COIL
(CONSTANTAN WINDING)

Titanium Test Sample

Test frequency is 1 MHz
All parameters are expressed as % of coil impedance
Defect size is 1 mm in a titanium alloy bar
Lift-off excursion is ±0.5 mm around 3.0 mm nominal
Coil ID is 10 mm using constantan wire
Defect vector length @ 3 mm LO is 0.065% @ 86°
Lift-off vector is 0.645% @ 108°
Included angle is 22 producing a defect factor of 0.365
Residual defect at 2.5 mm LO is 0.036% after cancellation
Residual defect at 3.0 mm LO is 0.028% after cancellation
Residual defect at 3.5 mm LO is 0.022% after cancellation
Residual lift-off is 0.007% after cancellation

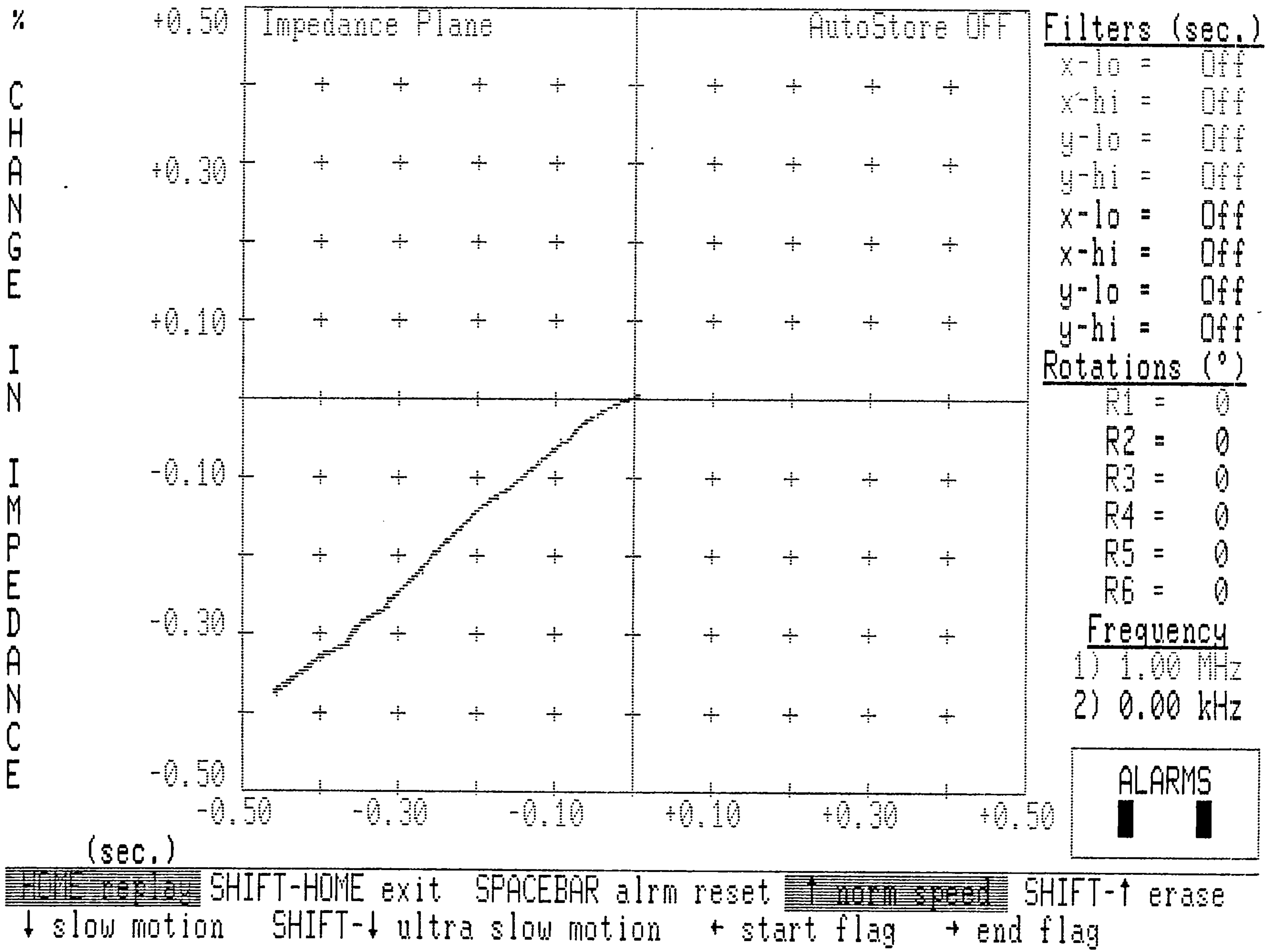
TABLE 4
TYPICAL PARAMETERS FOR A DUAL COIL DETECTION PROBE (CONSTANTAN WIRE)

Steel Test Sample

Test frequency is 1 MHz
All parameters are expressed as % of coil impedance
Defect size is 1 mm in a steel reference block
Lift-off excursion is ±0.5 mm around 3.0 mm nominal
Coil ID's of 5 mm and 13 mm using constantan wire
Defect vector length @ 3 mm LO is 0.075% @ 90°
Lift-off vector is 0.27% @ 180°
Included angle is 90 producing a defect factor of 1.000
Residual defect at 2.5 mm LO is 0.128% after cancellation
Residual defect at 3.0 mm LO is 0.075% after cancellation
Residual defect at 3.5 mm LO is 0.038% after cancellation
Residual lift-off is < = 0.012% after cancellation

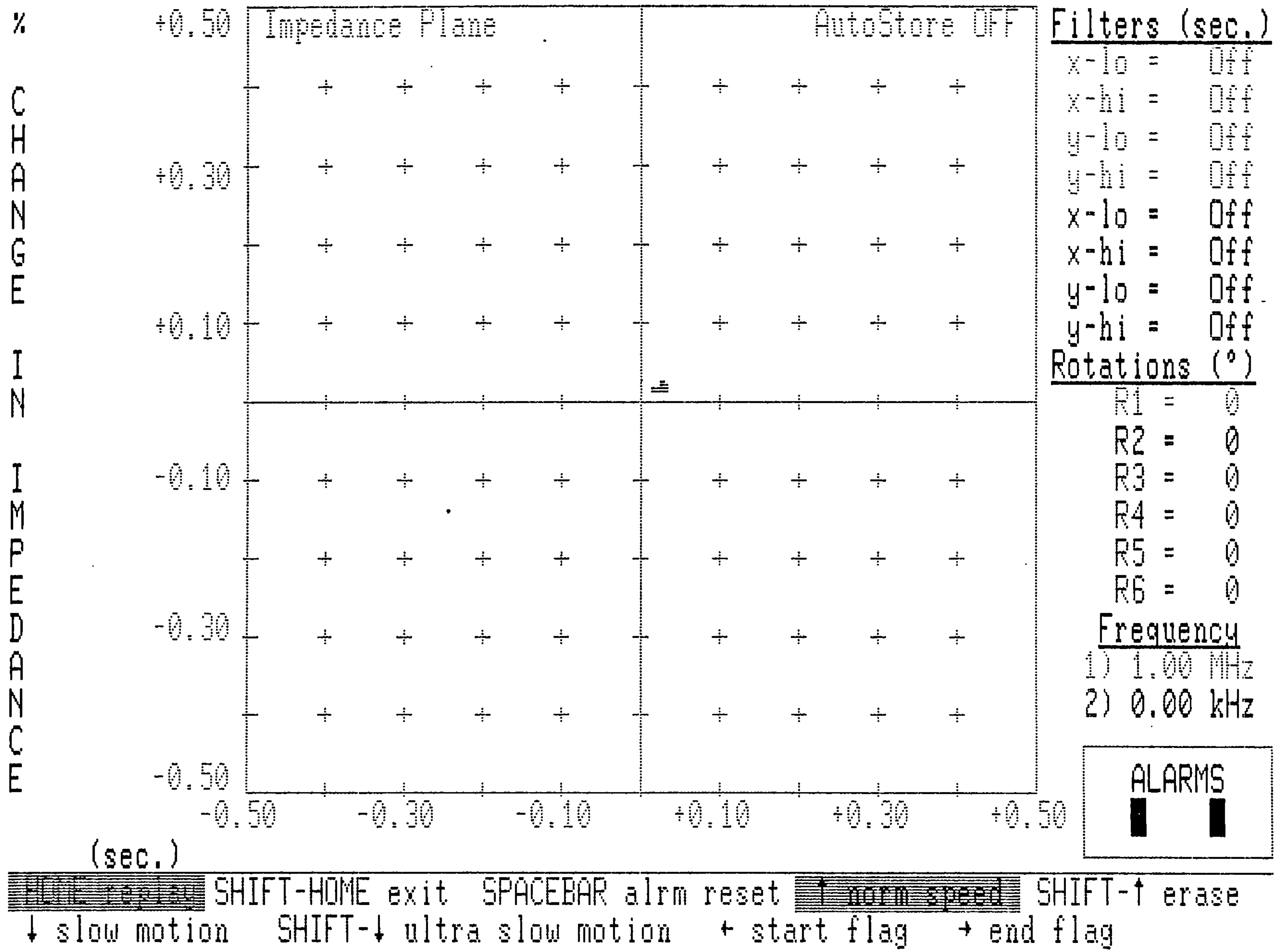
Titanium Test Sample

Test frequency is 1 MHz
All parameters are expressed as % of coil impedance
Defect size is 1 mm in a titanium alloy bar
Lift-off excursion is ±0.5 mm around 3.0 mm nominal
Coil ID's of 5 mm and 13 mm using constantan wire
Defect vector length @ 3 mm LO is 0.036% @ 98.0°
Lift-off vector is 0.26% @ 117°
Included angle is 19 producing a defect factor of 0.333
Residual defect at 2.5 mm LO is 0.022% after cancellation
Residual defect at 3.0 mm LO is 0.012% after cancellation
Residual defect at 3.5 mm LO is 0.007% after cancellation
Residual lift-off is < = 0.002% after cancellation

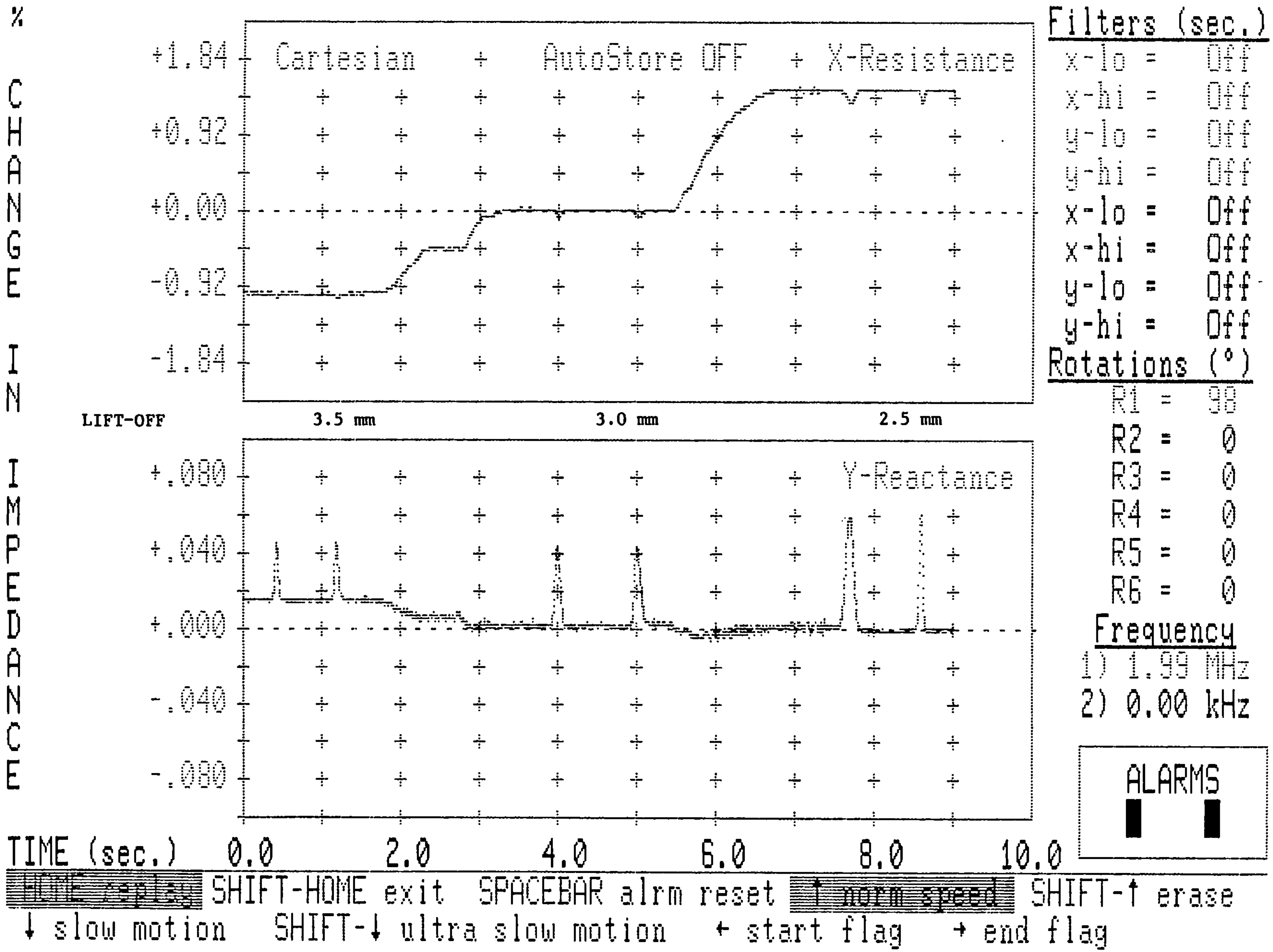


10 mm DIAMETER TEST COIL WITH COPPER WINDING
IMPEDANCE CHANGE FOR A 70°C TEMPERATURE DEPRESSION

FIG. 1

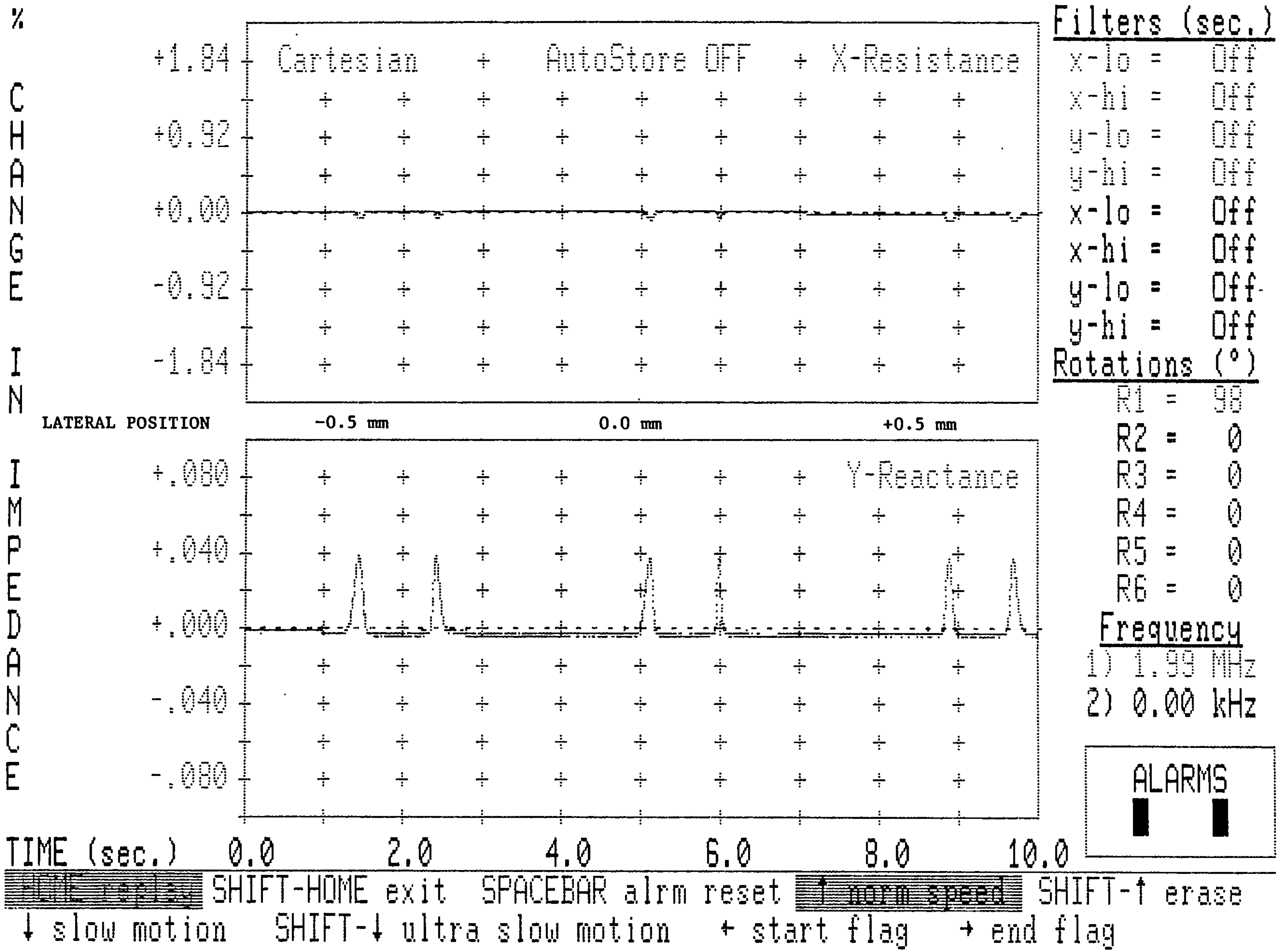


10 mm DIAMETER TEST COIL WITH CONSTANTAN WINDING IMPEDANCE CHANGE FOR A 70°C TEMPERATURE DEPRESSION **FIG. 2**



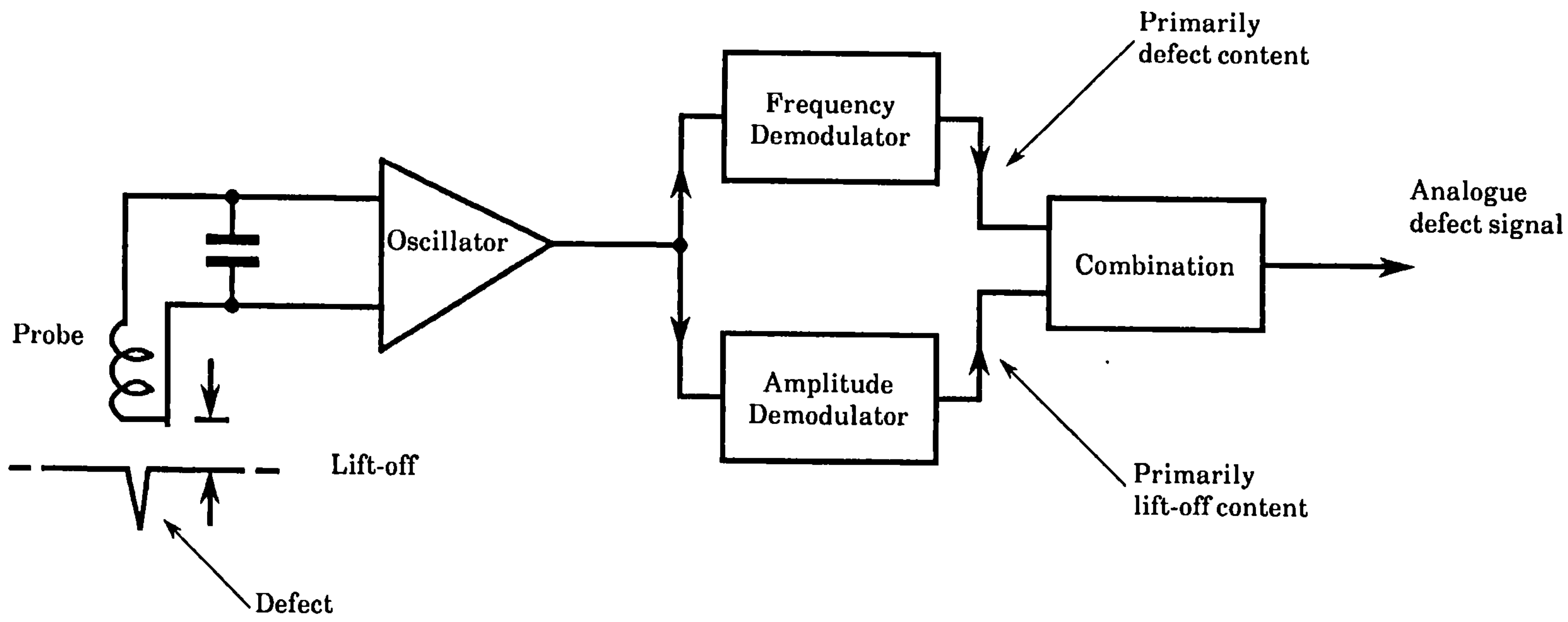
SINGLE 10 mm DIAMETER TEST COIL
1 mm DEFECT IN TITANIUM ALLOY BAR
(SHOWING VERTICAL MOVEMENT)

FIG. 3

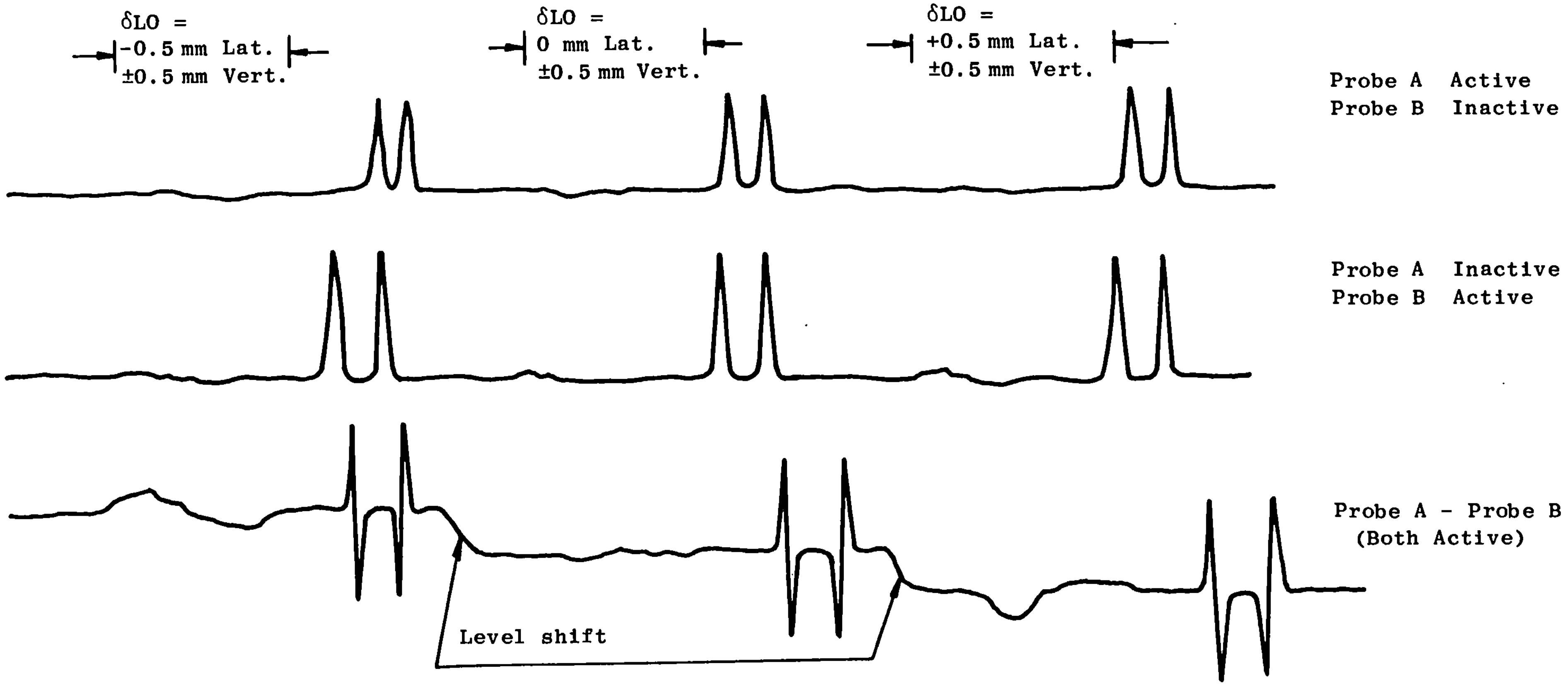


SINGLE 10 mm DIAMETER TEST COIL
1 mm DEFECT IN TITANIUM ALLOY BAR
(SHOWING LATERAL MOVEMENT)

FIG. 4



BLOCK DIAGRAM OF RESONANT PROBE CONCEPT **FIG. 5**

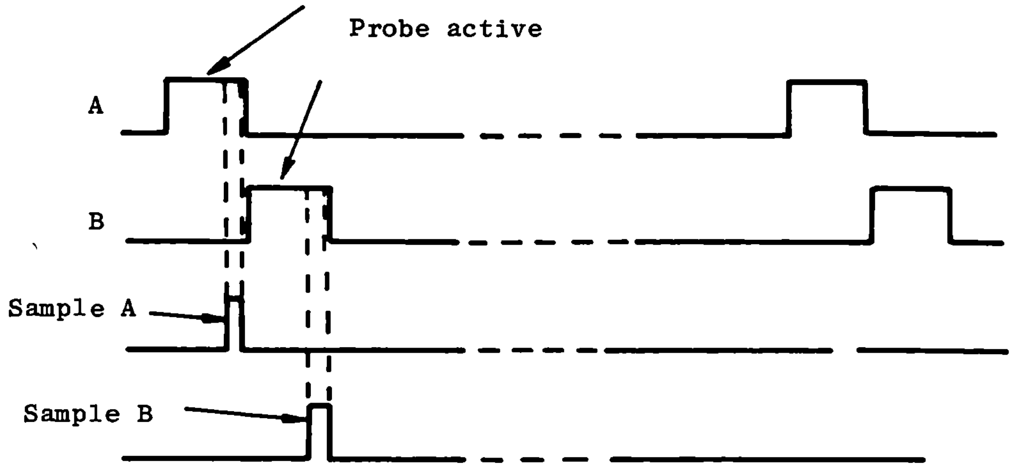


All defects = 1 mm

Nominal Lift-off = 3.5 mm

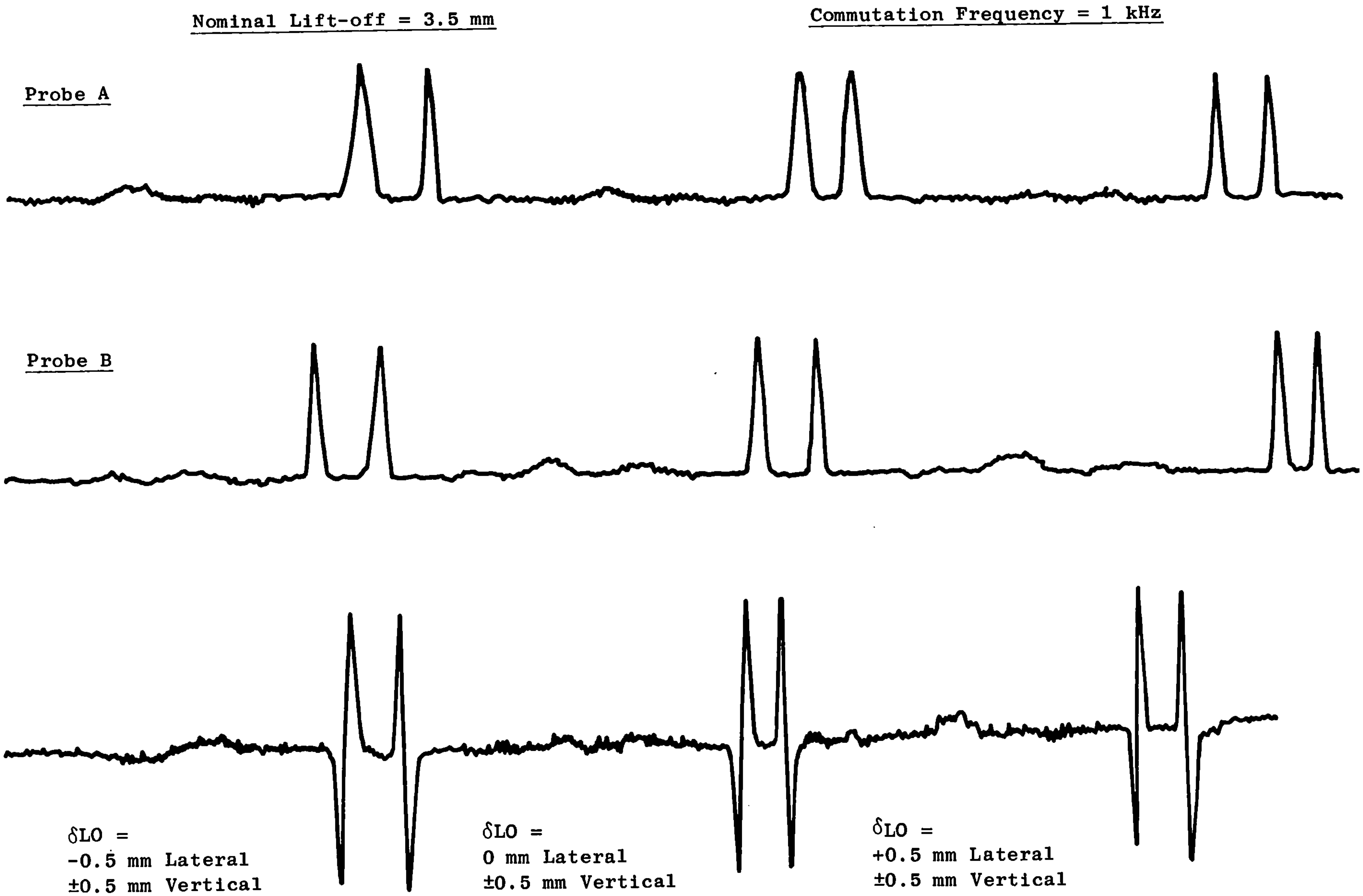
INTERACTION OF ADJACENT PROBES SUBJECT TO
VERTICAL AND LATERAL LIFT-OFF

FIG. 6
(R3/6160)



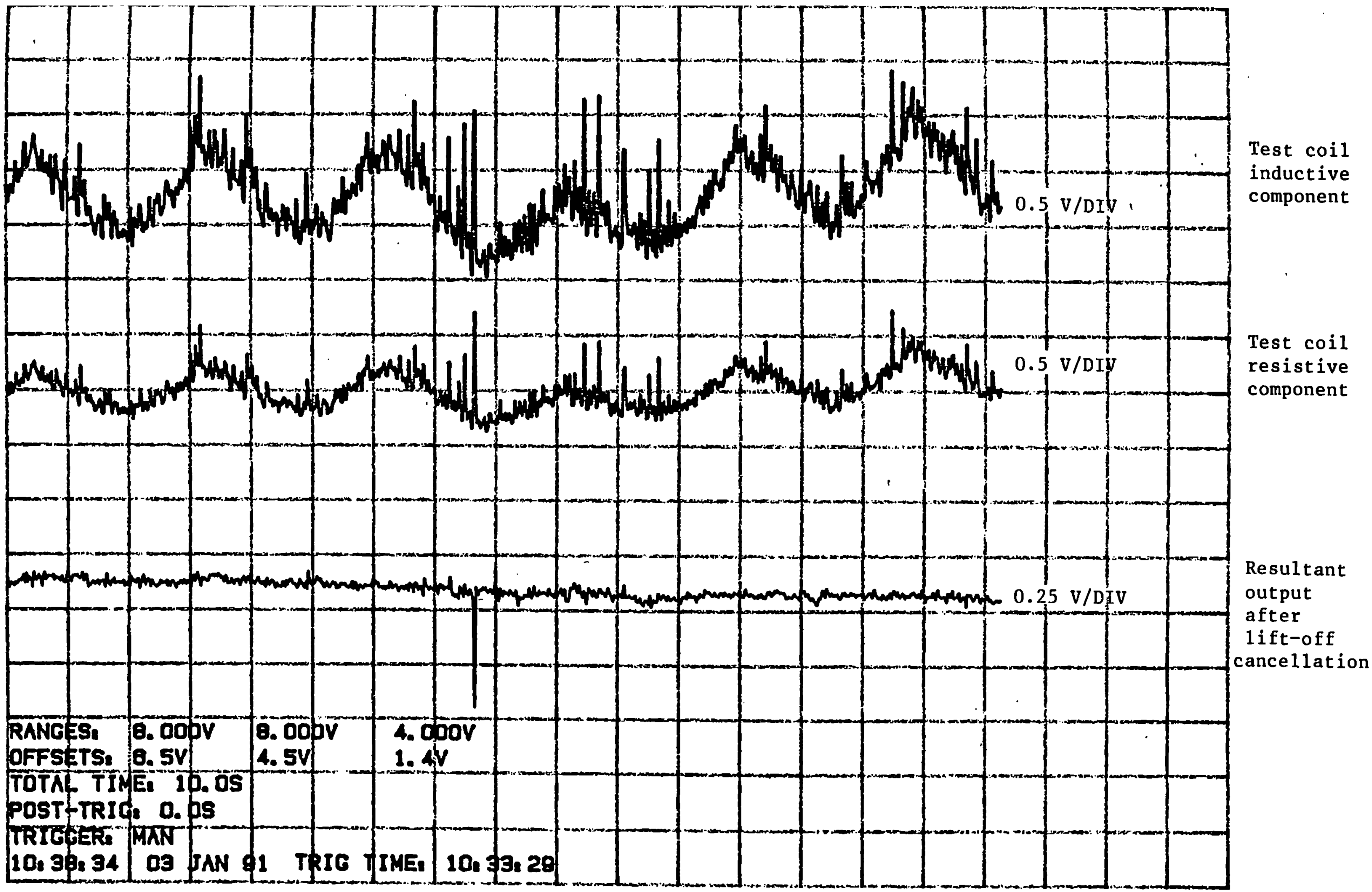
PROBE COMMUTATION SAMPLING SEQUENCE
(NOT EMPLOYED IN FINAL DESIGN)

FIG. 7
(R3/6161)



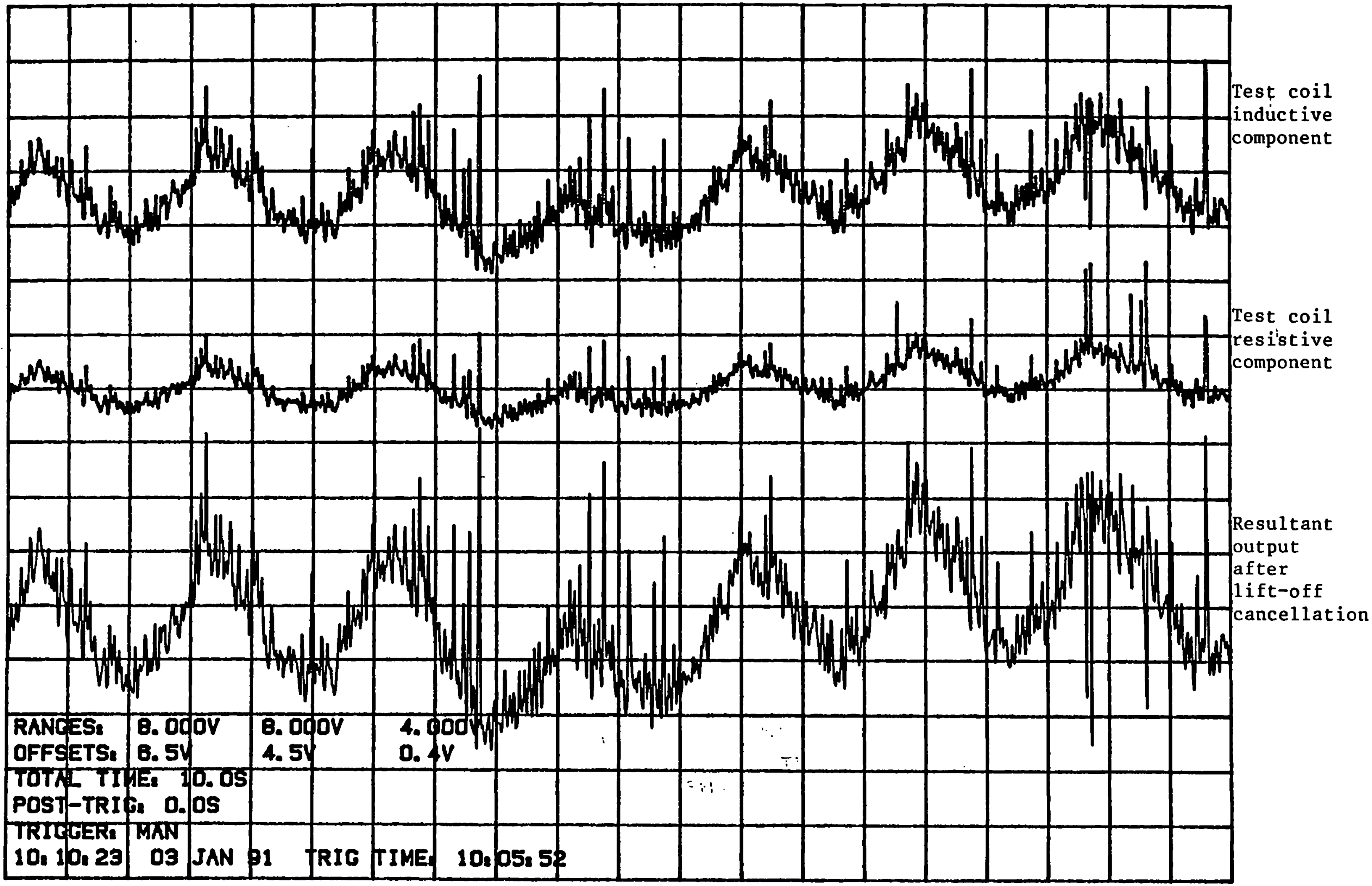
2 PROBE COMMUTATION SYSTEM

FIG. 8
(R3/6162)



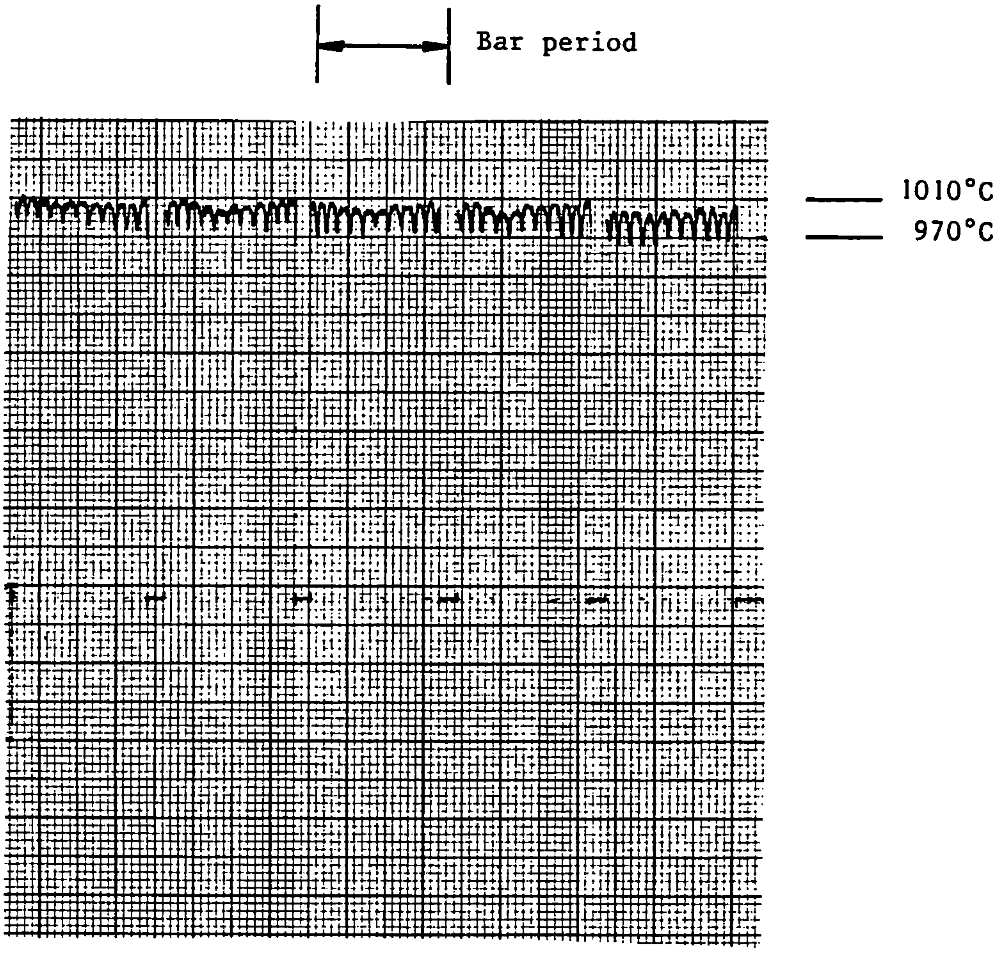
HOT BAR INSPECTION SIGNALS USING CANCELLATION FACTOR BASED ON HOT STEEL BAR

FIG. 9

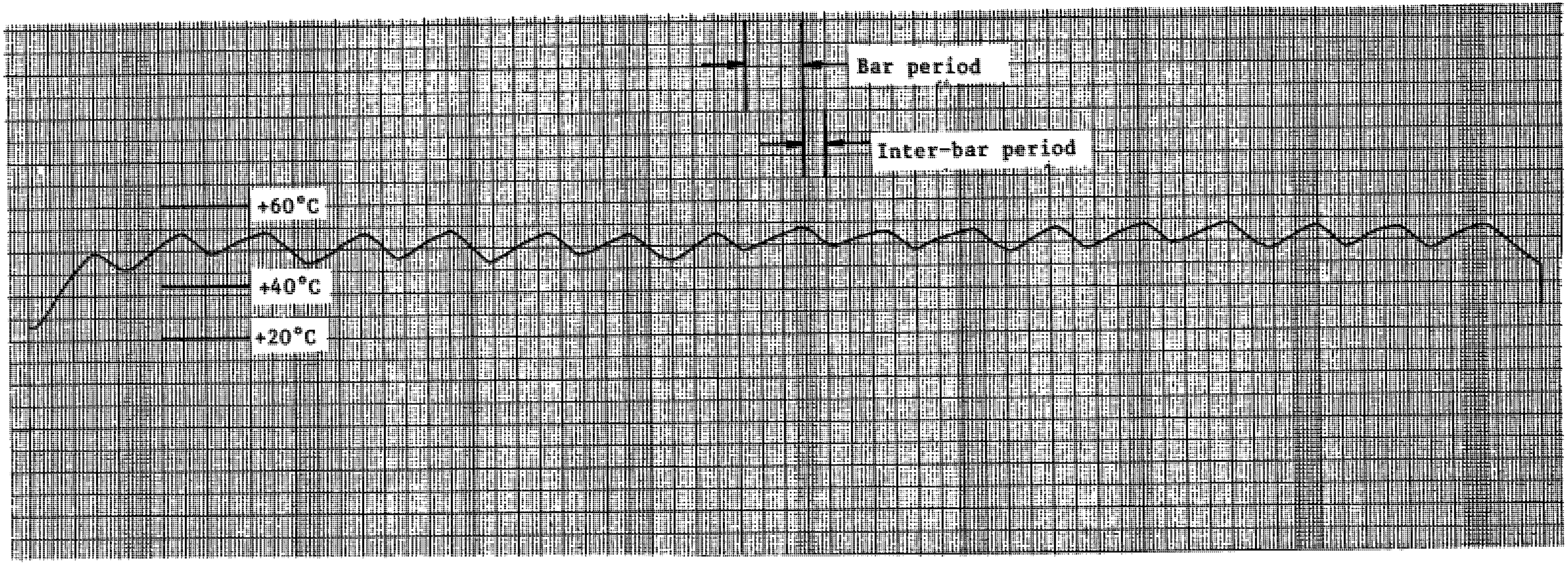


HOT BAR INSPECTION SIGNALS USING CANCELLATION FACTOR BASED ON TITANIUM ALLOY BAR

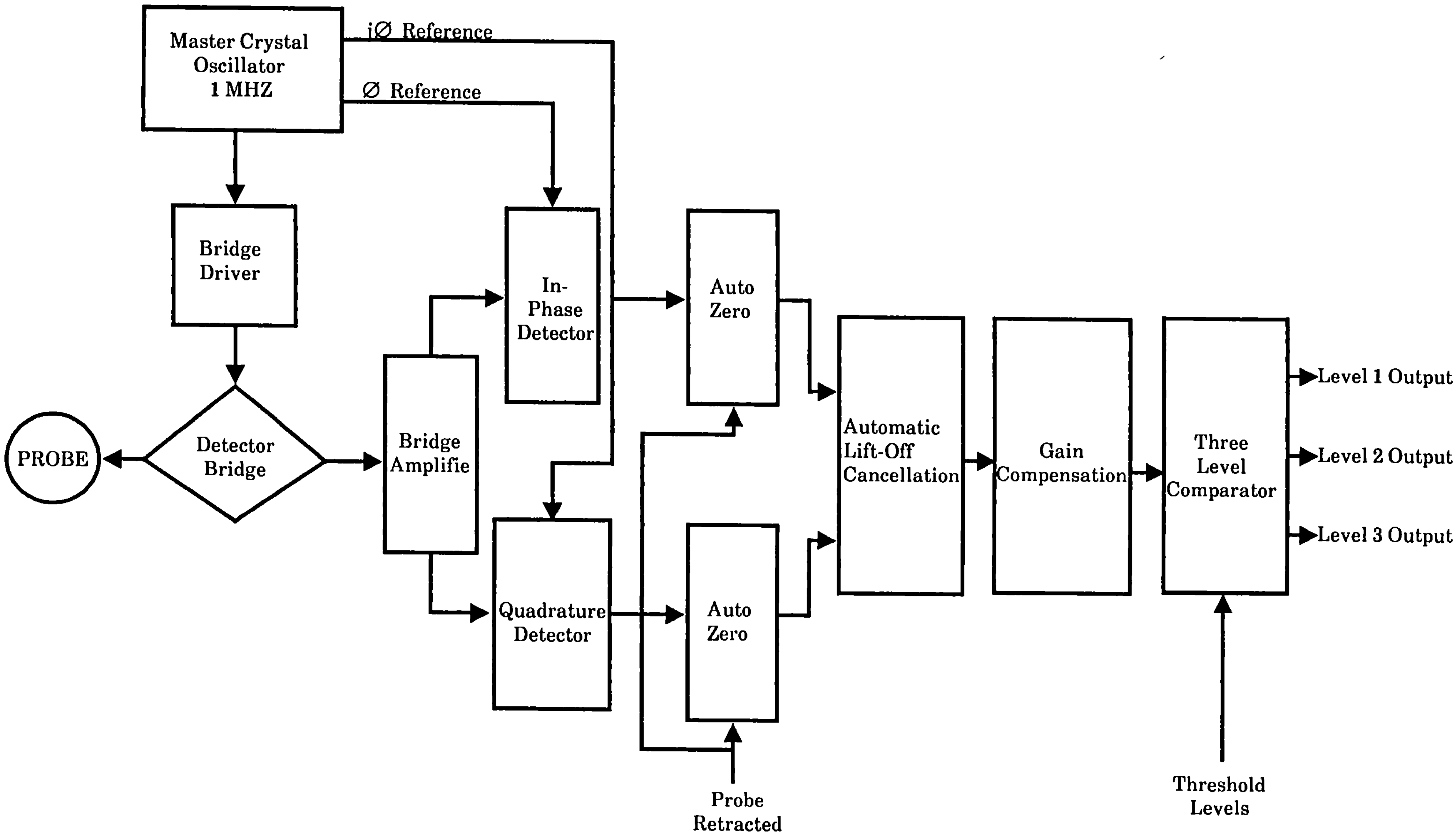
FIG. 10



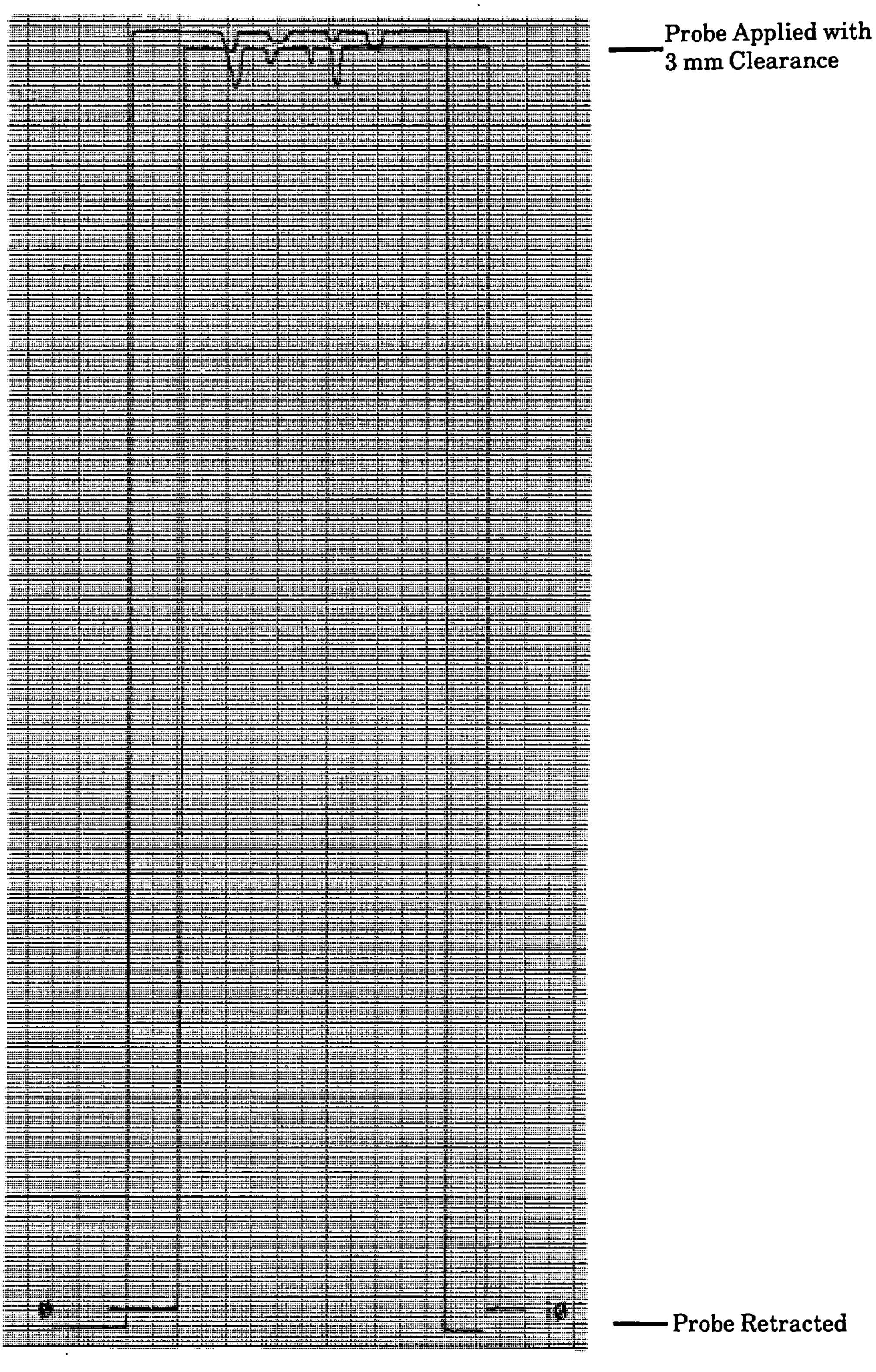
BAR TEMPERATURE PROFILES DURING HOT BAR TRIALS **FIG. 11**



VARIATIONS IN TEST COIL TEMPERATURE DURING HOT BAR TRIALS FIG. 12

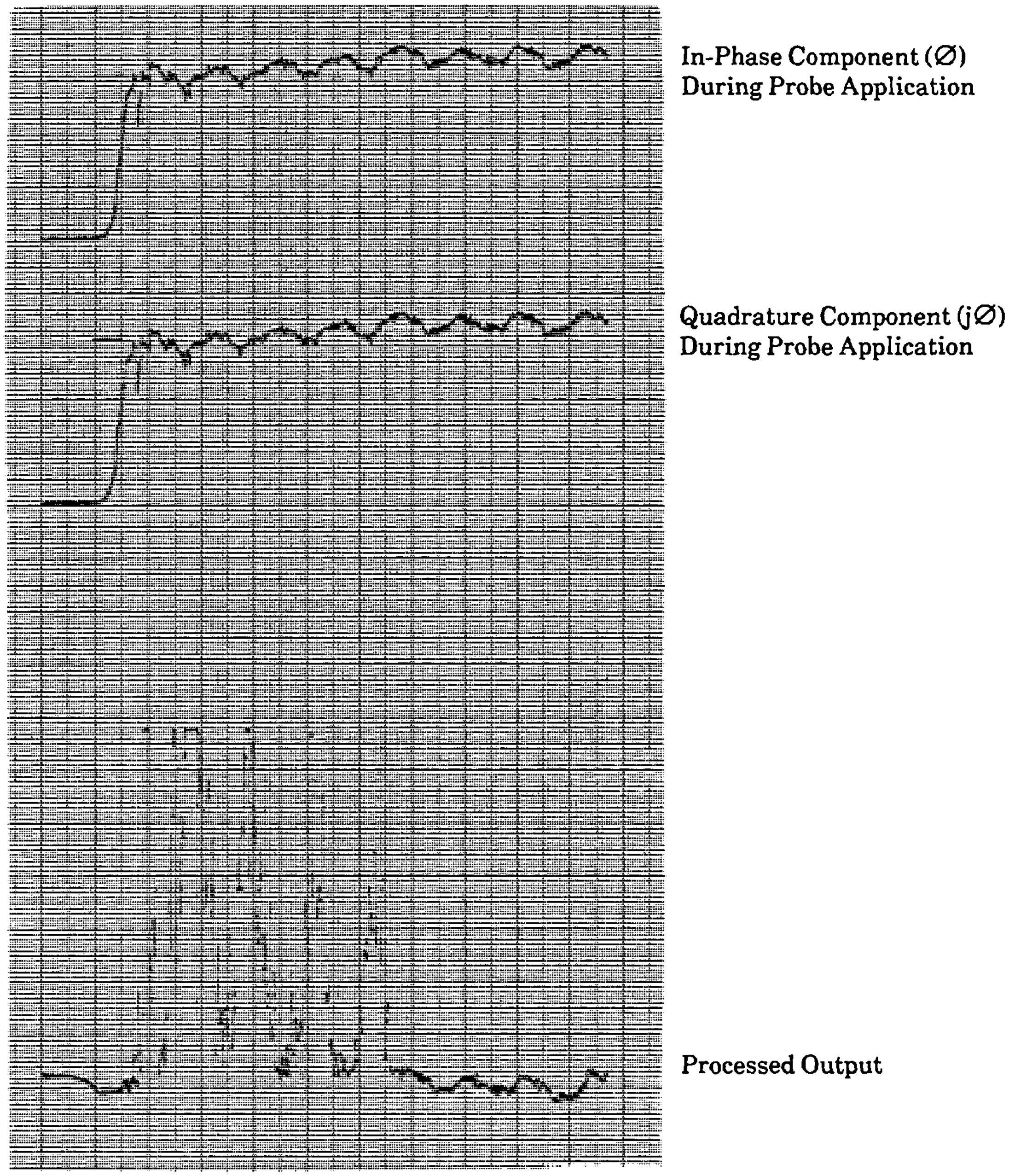


ELECTRONIC SIGNAL PROCESSING FIG. 13



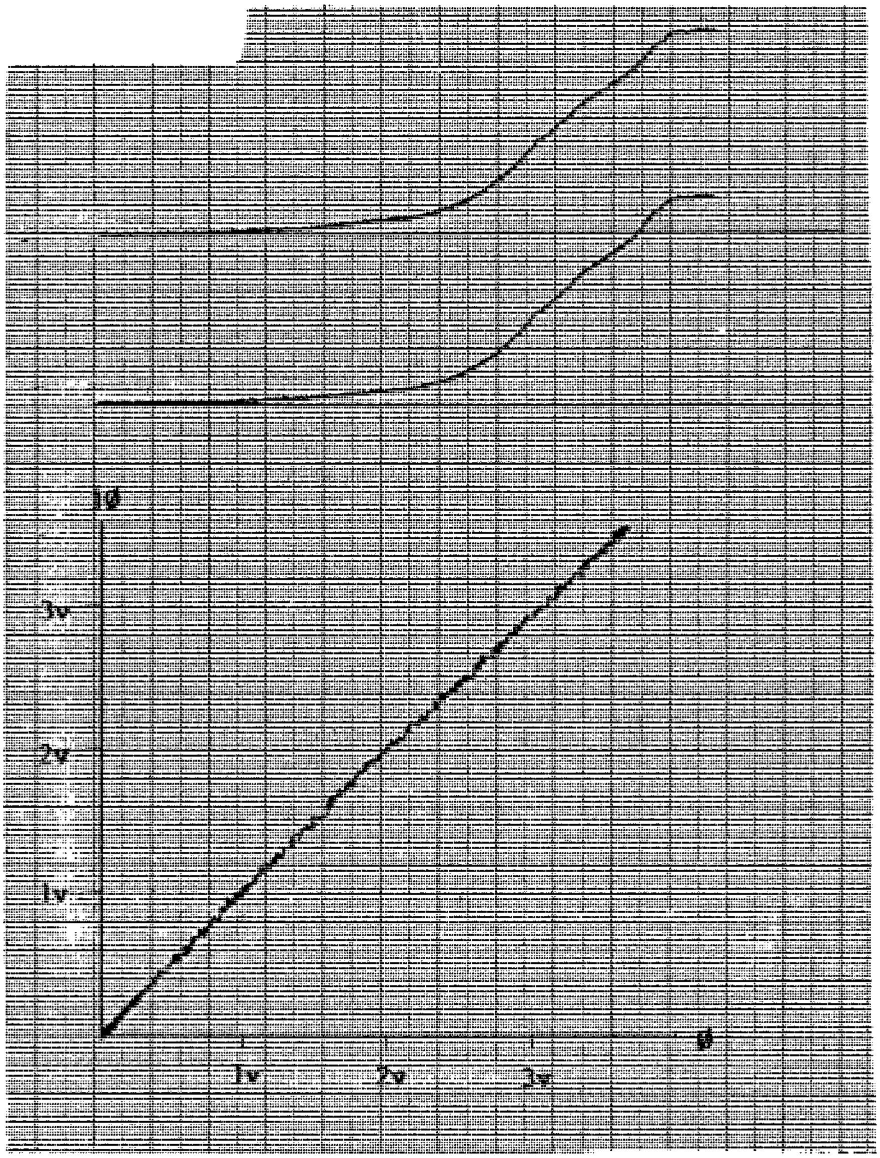
RELATIONSHIP BETWEEN VOLTAGE CHANGE DURING PROBE APPLICATION AND VOLTAGE CHANGE FOR A 0.5 mm AND 1.0 mm DEFECT

FIG. 14



PROCESSED DEFECT OUTPUT WITH DELAYED LIFT-OFF CANCELLATION

FIG. 15

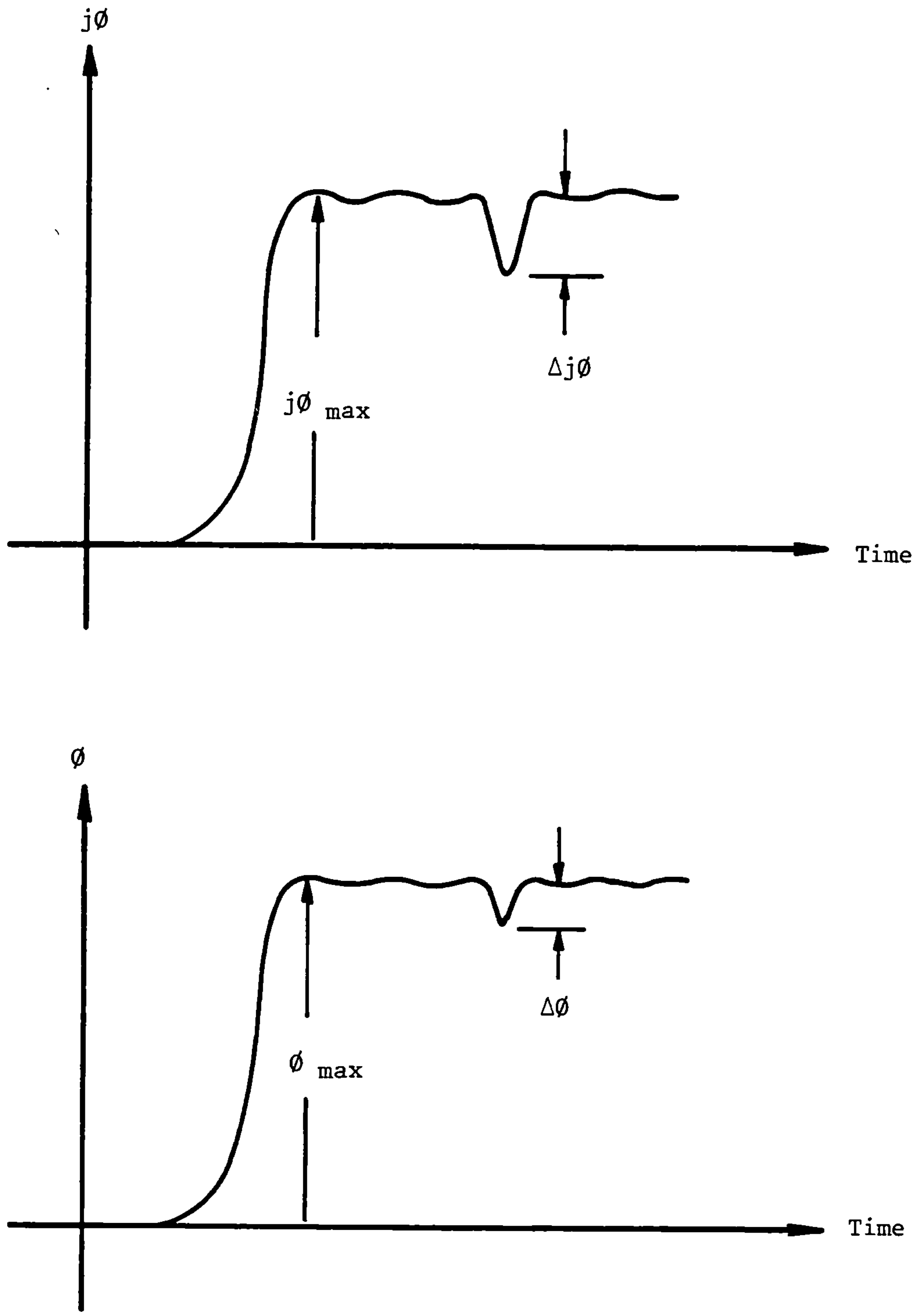


Quadrature Component (jØ) During Probe Application

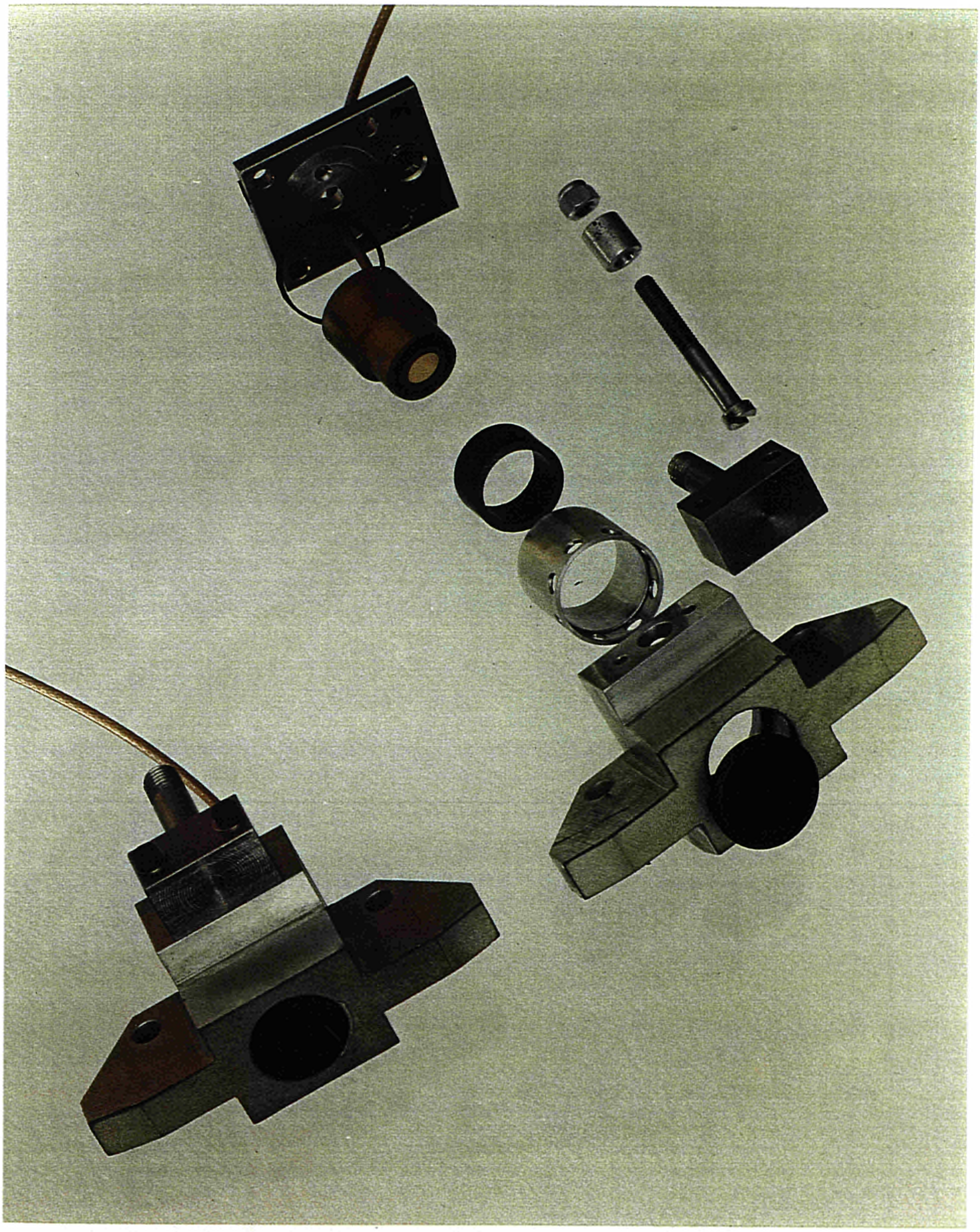
In-Phase Component (Ø) During Probe Application

Plot of Ø versus jØ

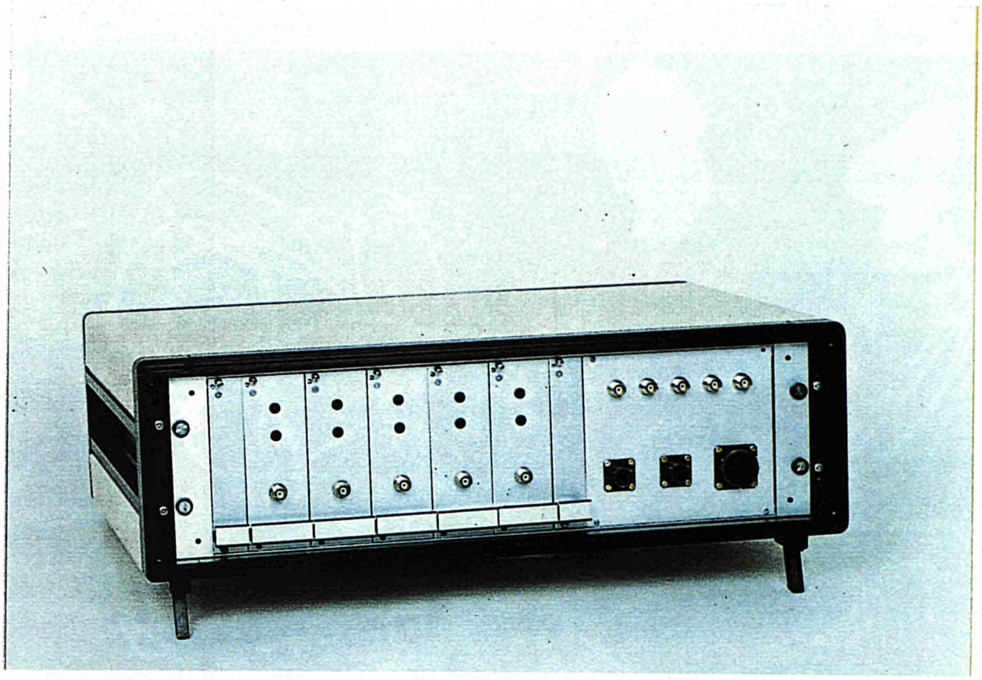
RELATIONSHIP BETWEEN IN-PHASE AND QUADRATURE COMPONENTS DURING PROBE APPLICATION **FIG. 16**

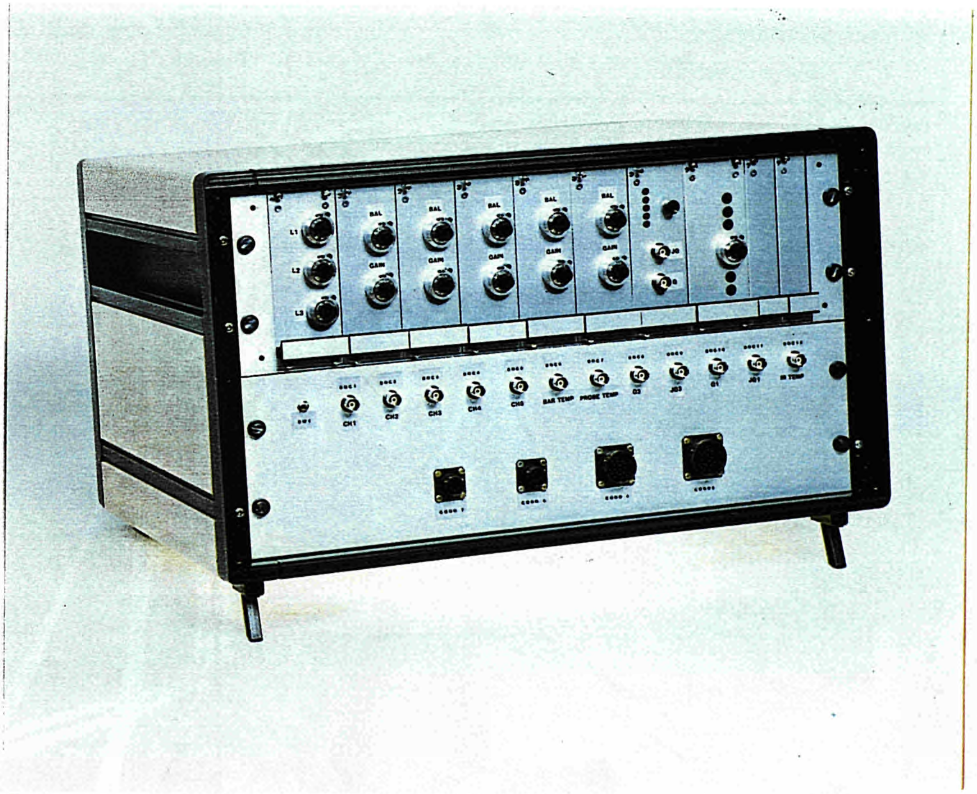


DEFINITION OF TERMS USED IN LIFT-OFF CANCELLATION **FIG. 17 (R3/8404)**

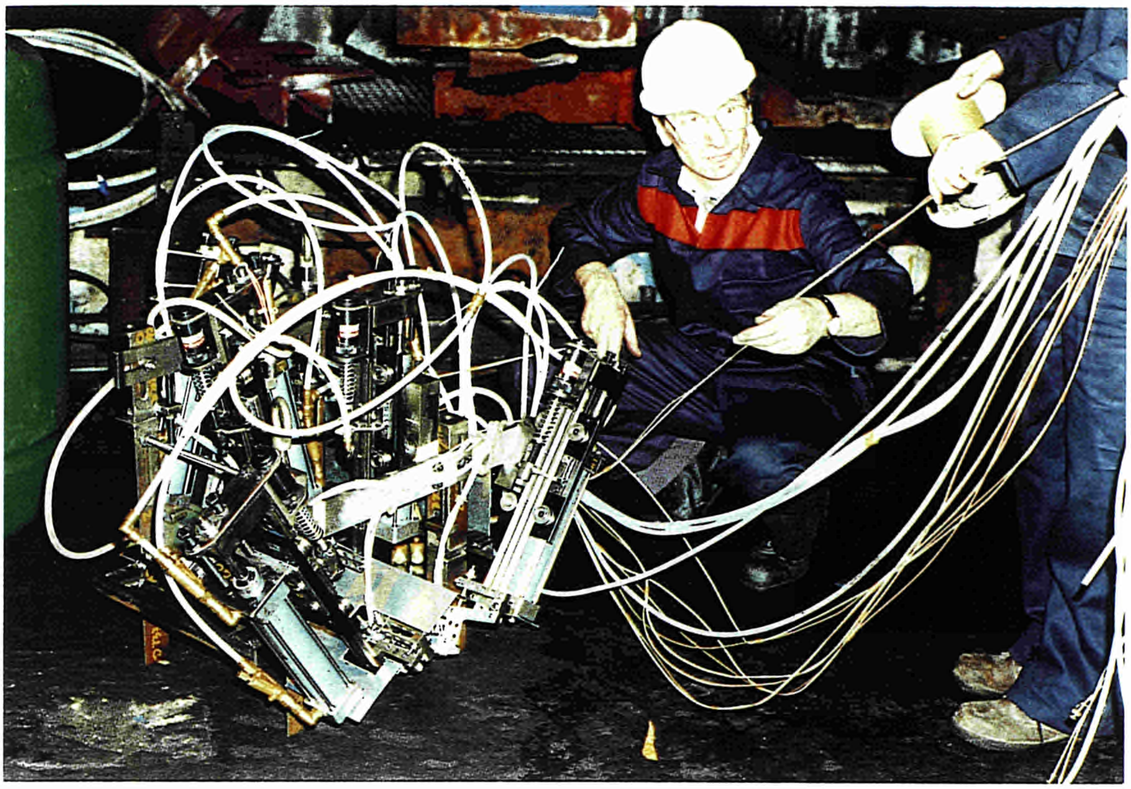


EXPLODED VIEW OF INSPECTION COIL ASSEMBLY FIG. 18

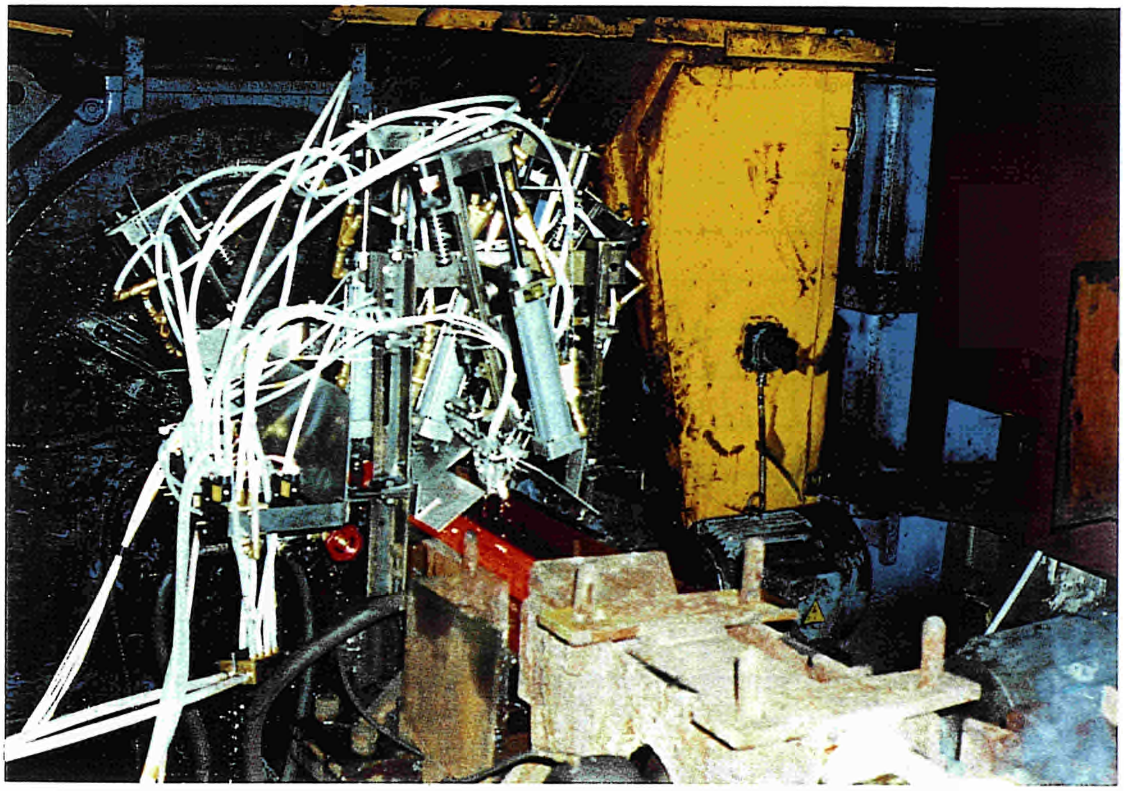




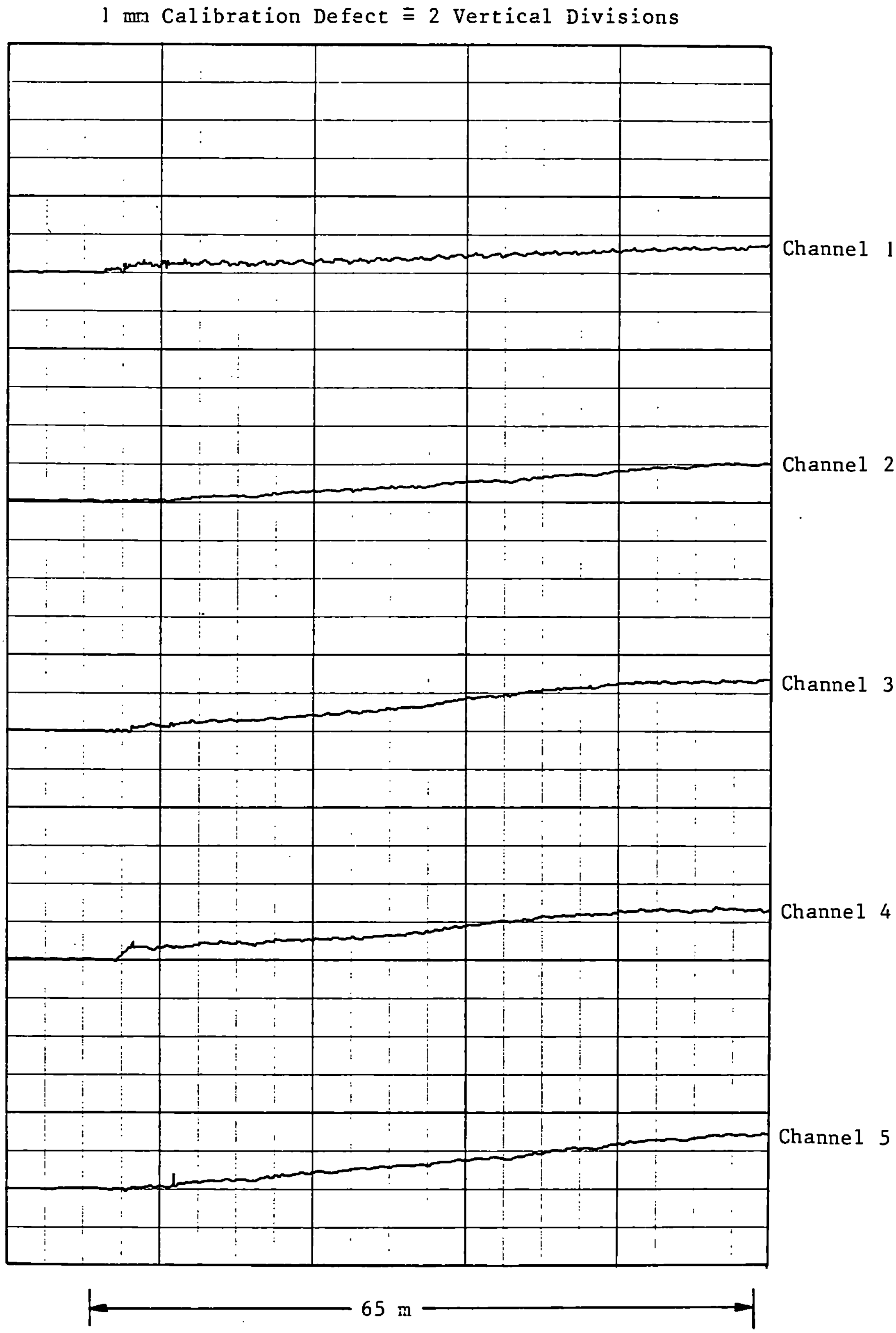
LOCAL AND REMOTE ELECTRONIC SIGNAL PROCESSING UNITS **FIG. 19**



TEST HEAD ASSEMBLY DURING INSTALLATION FIG. 20

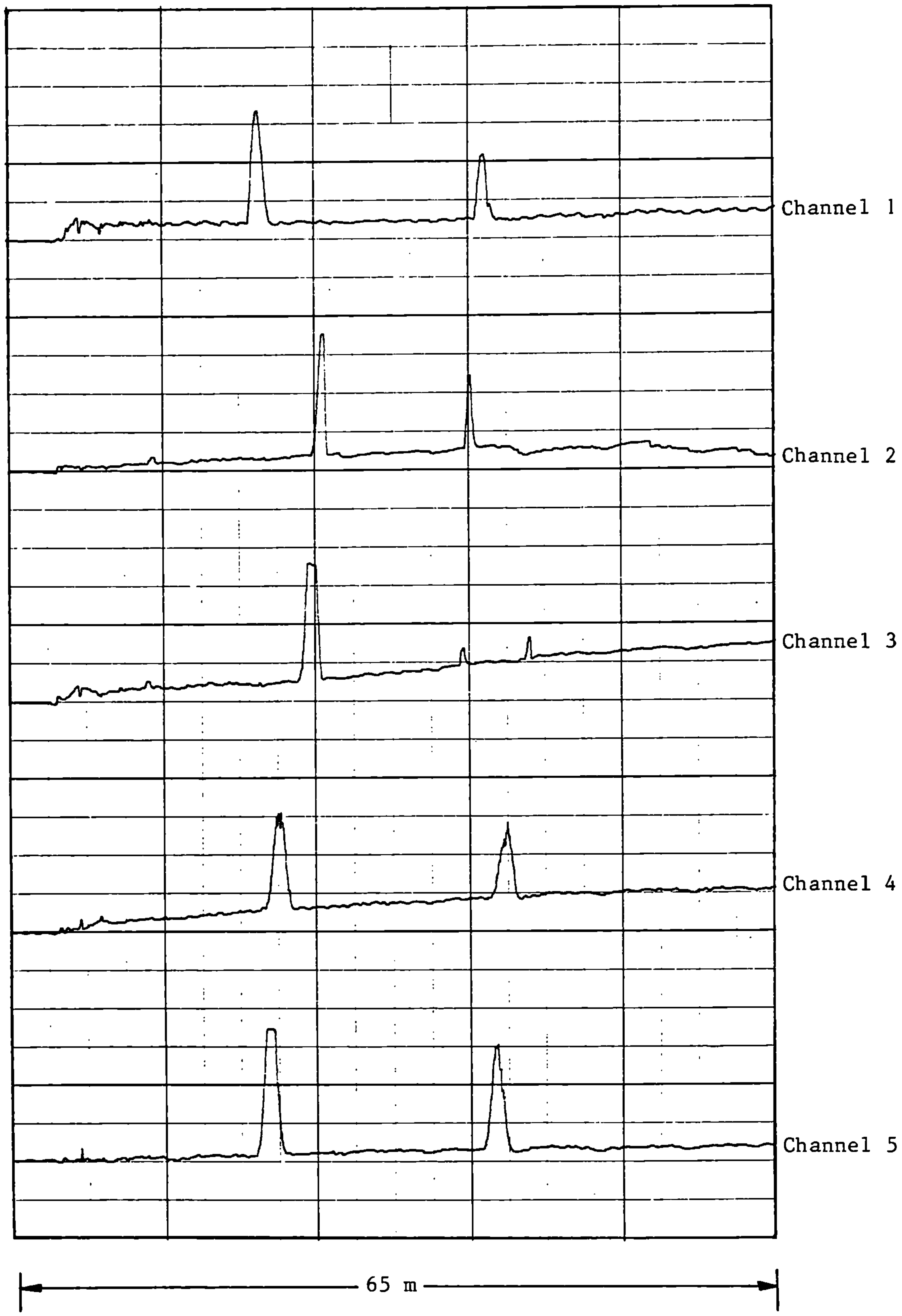


TEST HEAD ASSEMBLY DURING PRODUCTION TRIALS FIG. 21



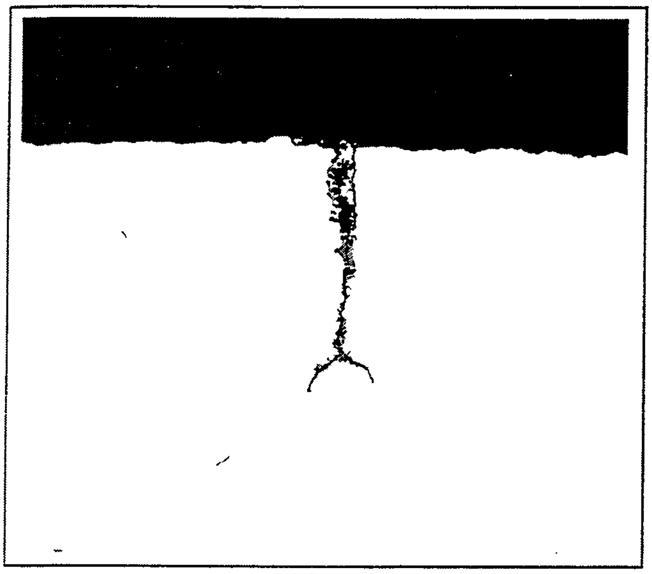
EDDY-CURRENT INSPECTION RESULTS FOR PRIME PRODUCTION BAR **FIG. 22**

1 mm Calibration Defect ≡ 2 Vertical Divisions

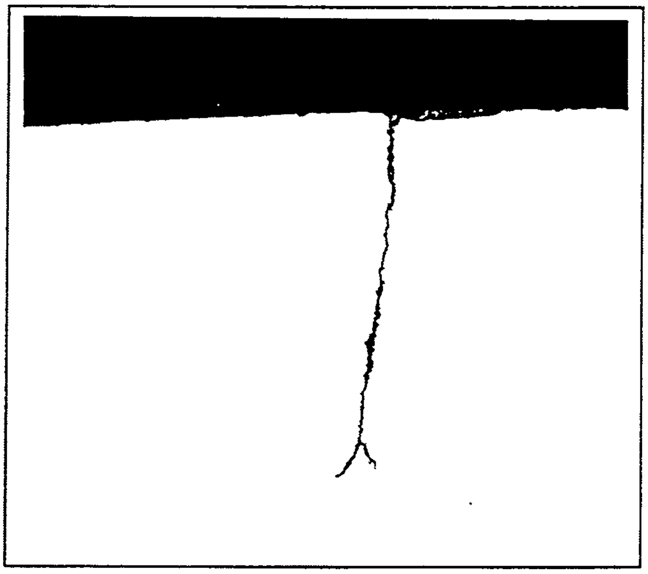


EDDY-CURRENT INSPECTION RESULTS FOR DEFECTIVE TRIAL BAR

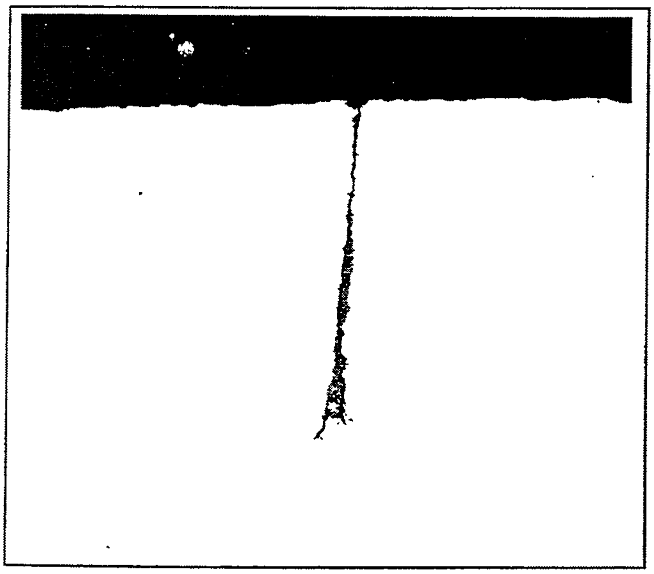
FIG. 23



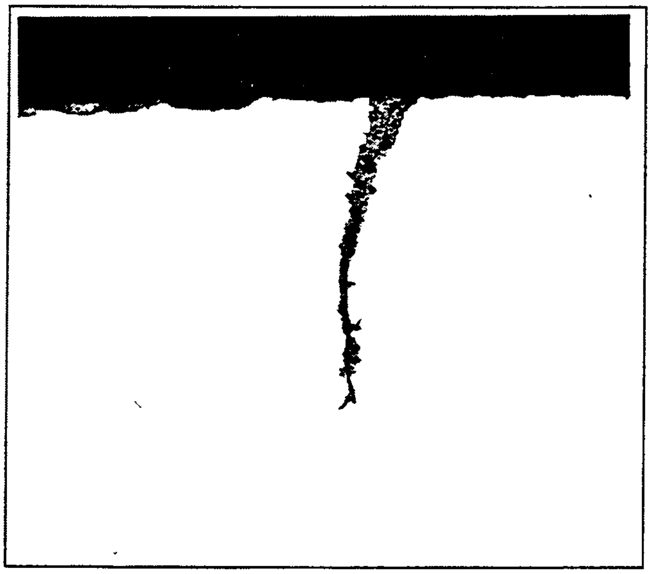
x 34



x 34

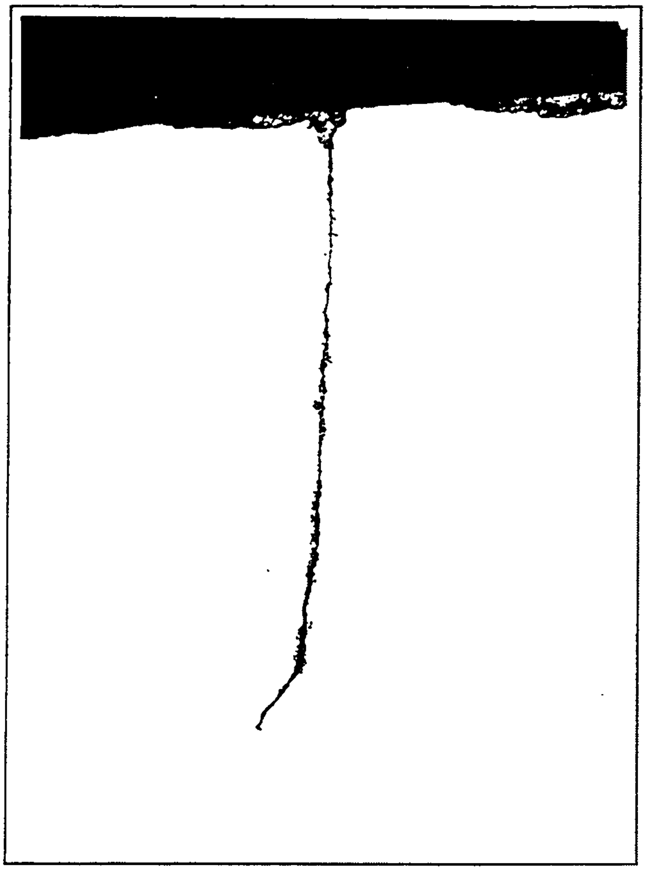


x 34

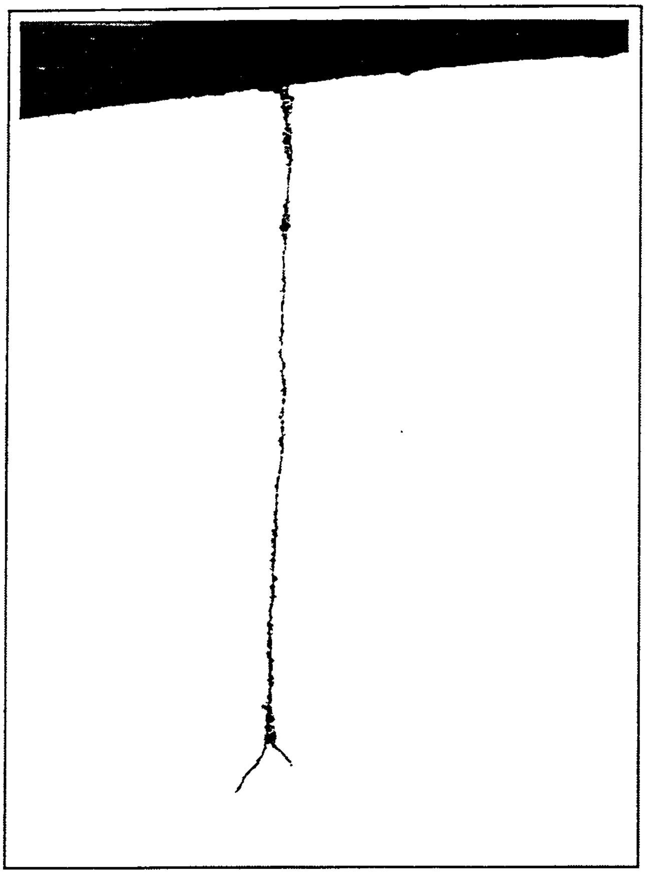


x 34

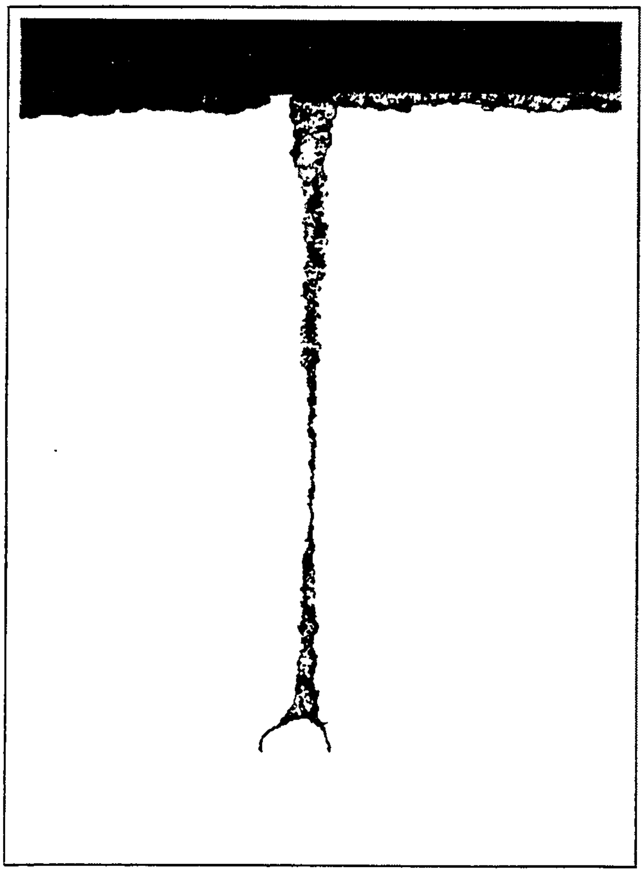
TYPICAL MACROPHOTOGRAPHS OF THE NOMINAL 1.2 mm DEFECTIVE ZONE **FIG. 24**



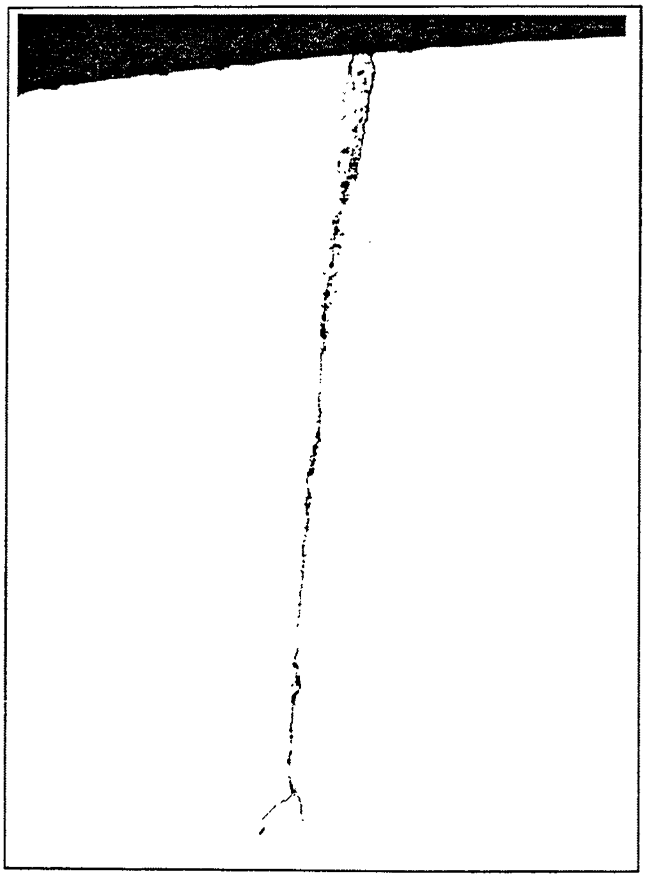
x 34



x 34

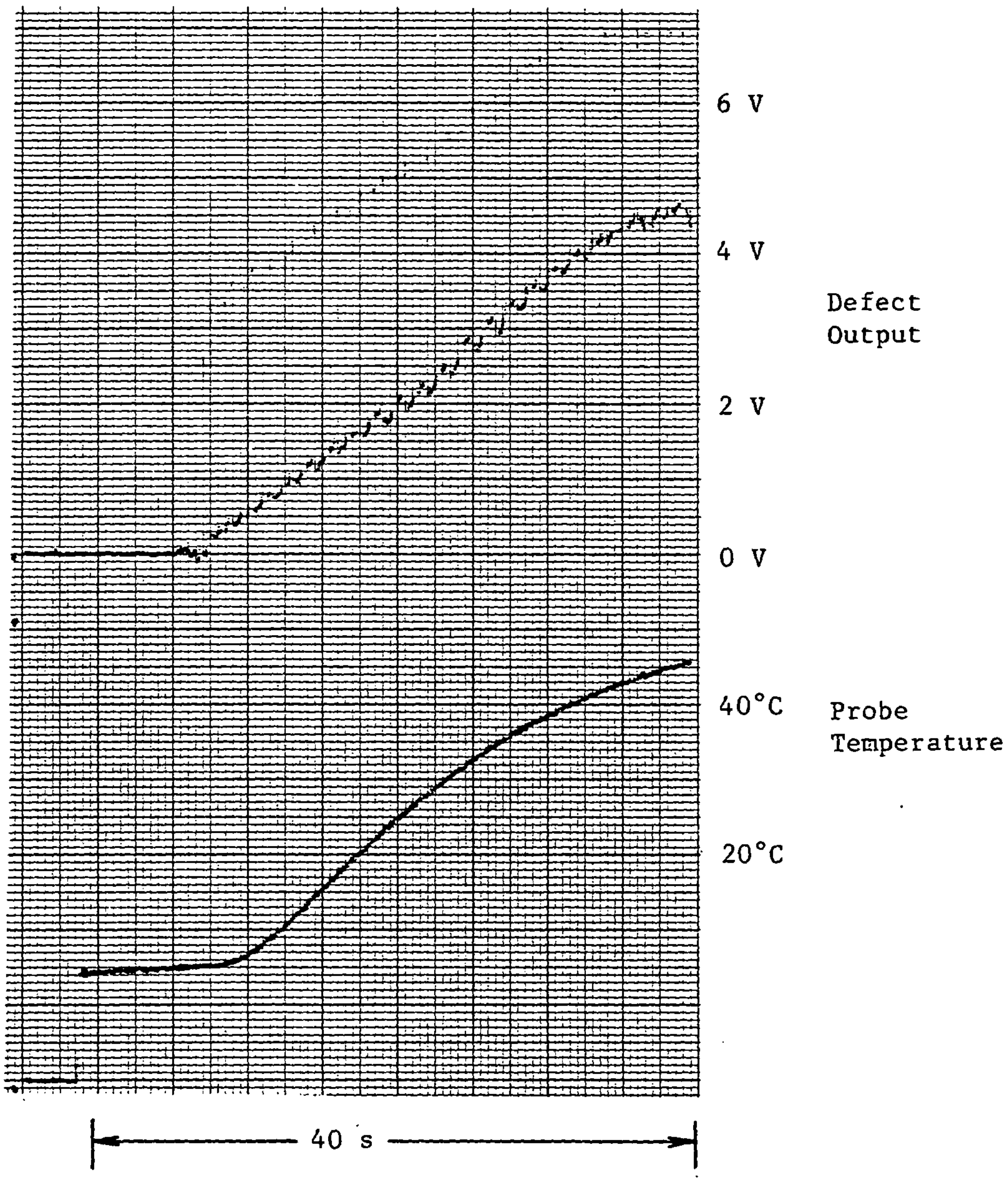


x 34

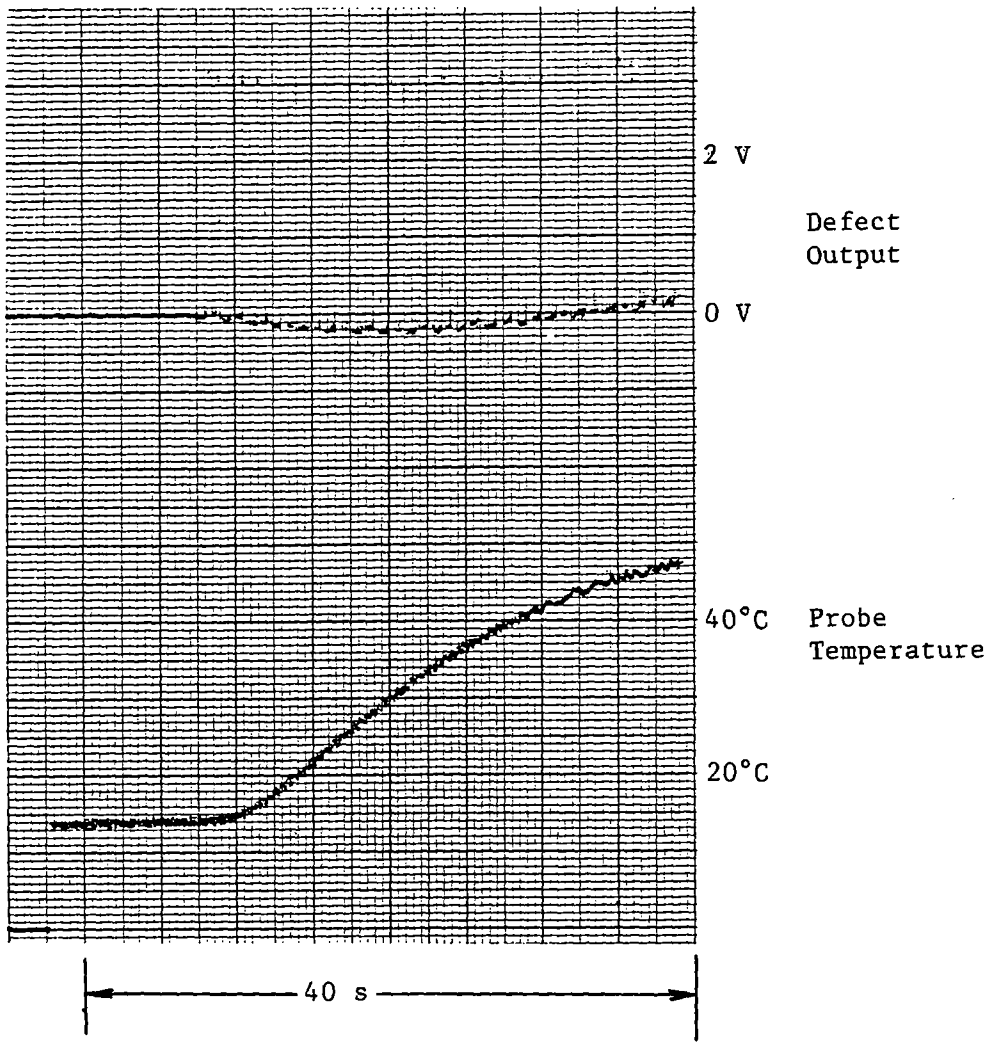


x 34

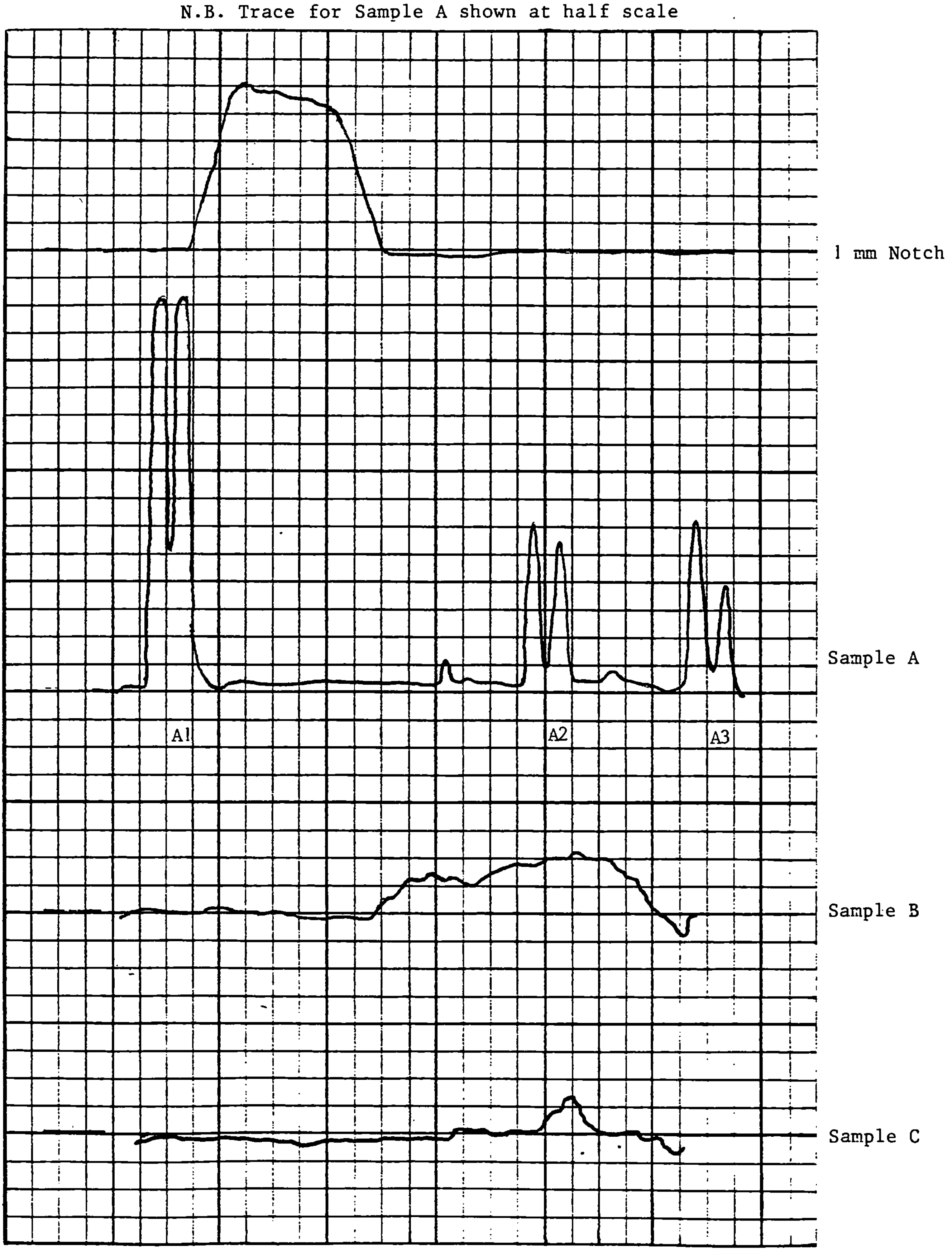
TYPICAL MACROPHOTOGRAPHS OF THE NOMINAL 2.4 mm DEFECTIVE ZONE **FIG. 25**



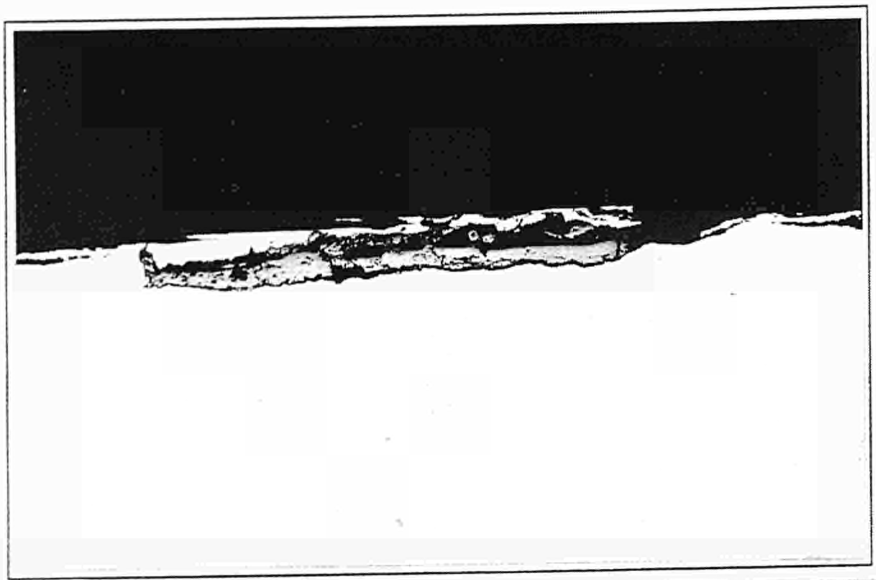
PLOTS OF DEFECT OUTPUT AND PROBE TEMPERATURE v TIME DURING REPEATED TRAVERSE OF THE CALIBRATION NOTCH IN HOT STEEL WITH UNLAGGED LEADS **FIG. 26**



PLOTS OF DEFECT OUTPUT AND PROBE TEMPERATURE v TIME DURING REPEATED TRAVERSE OF THE CALIBRATION NOTCH IN HOT STEEL WITH LAGGED LEADS **FIG. 27**



DEFECT RESPONSES FROM RESISTIVELY HEATED SAMPLES FIG. 28



Sample A1

x 20

Sample A2

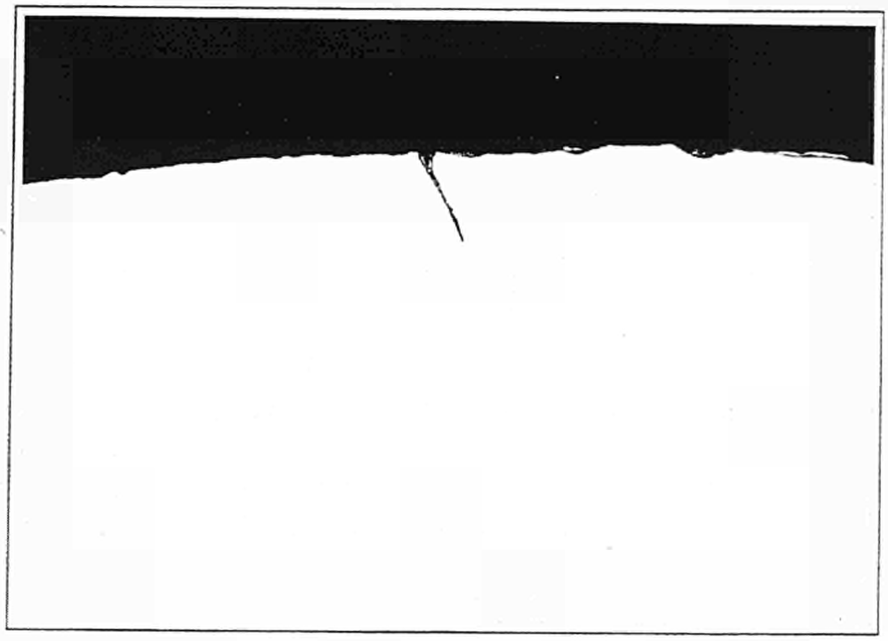
x 20

Sample A3

x 20

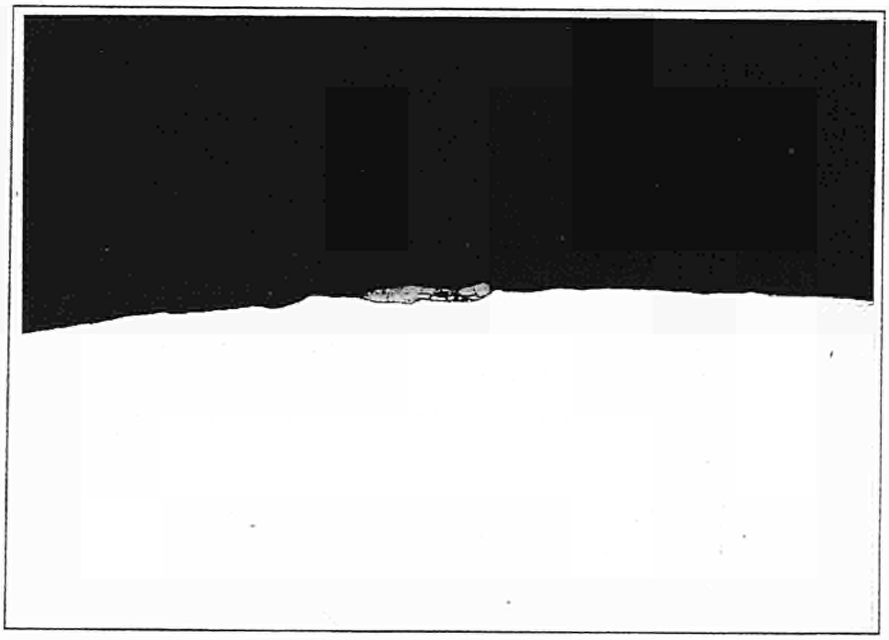
MACROPHOTOGRAPHS OF RESISTIVELY HEATED DEFECT SAMPLES

FIG. 29



Sample B

x 20



Sample C

x 20

MACROPHOTOGRAPHS OF RESISTIVELY HEATED DEFECT SAMPLES **FIG. 30**

European Commission

EUR 15814 — Measurement and analysis
Surface inspection of hot bars during rolling

D. Savidge

Luxembourg: Office for Official Publications of the European Communities

1996 — XVIII, 41 pp. — 21.0 x 29.7 cm

Technical steel research series

ISBN 92-827-7122-9

Price (excluding VAT) in Luxembourg: ECU 7

The traditional method of inspecting the surface of hot steel bars has been to use surrounding coil eddy-current techniques which have inherent deficiencies. These systems of inspection are insensitive to long seam defects and also transverse defects and are generally limited to bars which are less than 75 mm in diameter. The object of this ECSC project is to develop an alternative method that can overcome these deficiencies and extend the range of bar sizes that can be tested.

The development of water-cooled inspection probe assemblies which are capable of being grouped around the bar circumference and the development of very stable electronics for signal processing have been the key features associated with the success of this project.

Plant trials with a five channel inspection head confirmed the defect detection capability, and the excellent signal-to-noise ratios suggest that defect detection limits may well be improved down to the 0.5 mm level.

These developments indicate that an improved method of hot bar inspection is now entirely feasible which overcomes the major deficiencies of existing bar testing installations.

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