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DETECTION AND ANALYSIS OF METALLURGICAL DEFECTS IN STEAM TURBINE ROTORS

by

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PHYSICAL METALLURGY DIVISION

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R.D. McDonald*

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SUMMARY OF RESULTS

This report covers research work undertaken at the request of the Rotor Forging Research and Development Committee, Royal Canadian Navy, Department of National Defence, Ottawa. The ultrasonic work was conducted by D. Jamieson, Chief Metallurgist, and staff of Trenton Works, Dominion Steel and Coal Corporation, Trenton, N.S.

Ultrasonic inspections have been conducted on two main rotors that were intended for use in the St. Laurent Class destroyer escort vessels but were rejected when boroscopic examinations revealed defects in their bores. One of the rotors was made of basic open-hearth steel and the other was made of basic electric steel. Numerous defects were detected by the ultrasonic inspection, and some of the worst were selected for trepanning for further identification.

X-ray diffraction of two large inclusions from the basic open-hearth rotor showed crystals of α-tridymite which were contained within a generally vitreous matrix. When additional information from spectrographic analyses was obtained, it appeared likely that the matrix was a metasilicate consisting mainly of oxides of manganese, magnesium and silicon. The evidence does not indicate an exogenous refractory origin. However, some reaction with refractory had probably occurred. This was indicated by some traces of aluminum and magnesium, which were believed to be of refractory origin.

The inclusions contained in the rotor made of basic electric steel were similar to those contained in the rotor made of basic open-hearth steel, differing mainly in size.

Considerable valuable development in the technique of using the ultrasonic inspection method, with a view to evolving a standard of acceptance, has been accomplished by this work.

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INTRODUCTION

The ultrasonic method of inspection for the detection of metallurgical defects in rotors has been in use for several years. However, much uncertainty regarding the meaning of indications still remains in Canada and elsewhere, and consequently the results obtained by this inspection tool are used with much caution and for information purposes. No standard of acceptability has yet been devised in Canada. Such standards are being developed elsewhere, but only after extensive experience and with the aid of long-term records on the functioning of rotors which had been inspected by this method.

Several rotors that had been rejected during the early stages of the rotor development and manufacturing in Canada were available for this program. Rejection of main rotors was traced to two major causes. These were the inadequate forging capacity of the press in use during the early stages of the manufacturing program, and the presence of non-metallic inclusions, mainly in the central region where they were revealed by boroscopic examination.

In order to gain information and experience concerning ultrasonic inspection of large forgings, and to trace, if possible, the source of the non-metallic inclusions which resulted in rejects of these quality forgings, the Rotor Forging Research and Development Committee of the Royal Canadian Navy, Department of National Defence, initiated a research project (Ultrasonic Project - Contract No. FE 717014/0059/717-22/30/767, Serial #2-L-8-59) to be conducted by the Mines Branch, with the co-operation of the Dominion Steel and Coal Corporation, under the following conditions:

"The manufacturer will

(a) provide rotors for test purposes;

(b) provide records of the manufacturing of these rotors;

(c) provide facilities for handling and inspection (by ultrasonic methods), cutting and trepanning as required;

(d) co-operate with the Mines Branch of the Department of Mines and Technical Surveys, Ottawa, in establishing the technique for locating and assessing defects;

(e) remove, by trepanning or other acceptable method, the defective portions which are to be further examined at the Mines Branch;

(f) conduct an ultrasonic inspection and remove defects, as required, from one open-hearth steel rotor and one electric furnace steel rotor."

It was recommended that the Dominion Steel and Coal Corporation should be the Contractor, since this work was essentially a continuation of previous development done by them and since its success depended upon techniques, facilities, and inspection records possessed by them. The Mines Branch of the Department of Mines and Technical Surveys "will be responsible for the technical progress, will co-operate with Trenton Steel Works of the Dominion Steel and Coal Corporation in the establishment of inspection techniques, and will be responsible for the detailed examination of samples, the analysis of data, and the preparation of a report".

PROCEDURE

The project was conducted in several phases, the most pertinent of which will be described in sufficient detail to clarify the report. The initial work was the responsibility of the staff at the Trenton Works of the Dominion Steel and Coal Corporation.

Familiarization

This was carried out at the Trenton Works. Sections of scrapped rotors containing artificial defects of known size were ultrasonically inspected with different search units, to determine for each unit the following:

(a) Sensitivity.

(b) Angle of beam spread.

(c) Approximate suitable instrument settings.

(d) The accuracy of locating defects ("pin pointing").

In this connection the straight-beam crystals of frequencies 5, 2¼ and 1 Mc, including a tandem 1 Mc crystal, were checked and the appearance of various sizes of artificial defects on the cathode-ray screen were photographed for these search units. The ultrasonic equipment and the "pin pointing" technique are described in Appendices 1 and 2, respectively.

Preparation of Equipment

This phase of the project included the adaptation of trepanning and "nip-off" tools, and trepanning trials; also, the adaptation of a thermal stability test stand, as an alternative to a lathe, for rotation for ultrasonic inspection.

Ultrasonic Inspections

These were conducted on two main rotors, M-1 and M-16, both of which had been rejected as a result of tests conducted during manufacture. Photographs of the indications observed on the cathode ray screen were taken and the defects were located (see Appendices 3 and 4 at end of report).

Trepanning

The worst defects shown by the ultrasonic indications were located, and certain ones were selected for trepanning of cores for a more detailed examination at the Mines Branch.

Detailed Examination of the Defects, at the Mines Branch

This was carried out by optical, X-ray diffraction, spectroscopic, etching, and petrographic techniques. Electrolytic separation was not used, since the particular inclusions under consideration were accessible and often could be removed without using the separation technique. In addition, electrolytic separation would have resulted in mixing other smaller inclusions, possibly differing in composition, with those under consideration. Such mixing could further complicate interpretation.

EXAMINATION OF MAIN ROTOR M-1

Ultrasonic Examination

The report contained in Appendix 3 covers the forging history, the ultrasonic examination, and the location and removal of a core from main rotor M-1. This rotor was manufactured by the basic open-hearth process and was rejected on the basis of low mechanical properties in the transverse direction. This was attributed to a high non-metallic content. The trepanned core contained the region which gave the greatest ultrasonic indication, and was judged to contain the largest non-metallic defects. The core was slightly less than five inches in length and one inch in diameter. The regions #1 and #2 containing the defects as revealed by the magnetic particle method are illustrated in Figures 33 and 34 in Appendix 3. Photographs of the ultrasonic indications (Figures 28 to 32) are also shown.

Core Examination

The core was forwarded to the Mines Branch, where further detailed examination was carried out. This examination included radiography, microscopic examination, etch tests, X-ray diffraction, spectroscopy, and petrographic examination.

Radiographic Examination

The test core was radiographed from two directions at right angles to each other. A print of the radiograph is shown in Figure 1. A group of objects can be seen, within the core, from both angles. This group was interpreted to be a cluster of non-metallic inclusions.

The radiographs were very similar, dimensionally, to the actual core, and measurements were made on the radiograph to determine where to cut the core to locate an inclusion. A cluster of inclusions beginning at a large inclusion was located 2-3/8 in. from the outer end of the core, or a radial distance 6-7/8 in. from the periphery of the rotor. The latter figure includes the depth of drilling ($4\frac{1}{2}$ in.) before trepanning was started. The cluster of large inclusions appeared to occupy a region in the core approximately $\frac{1}{2}$ in. in length.

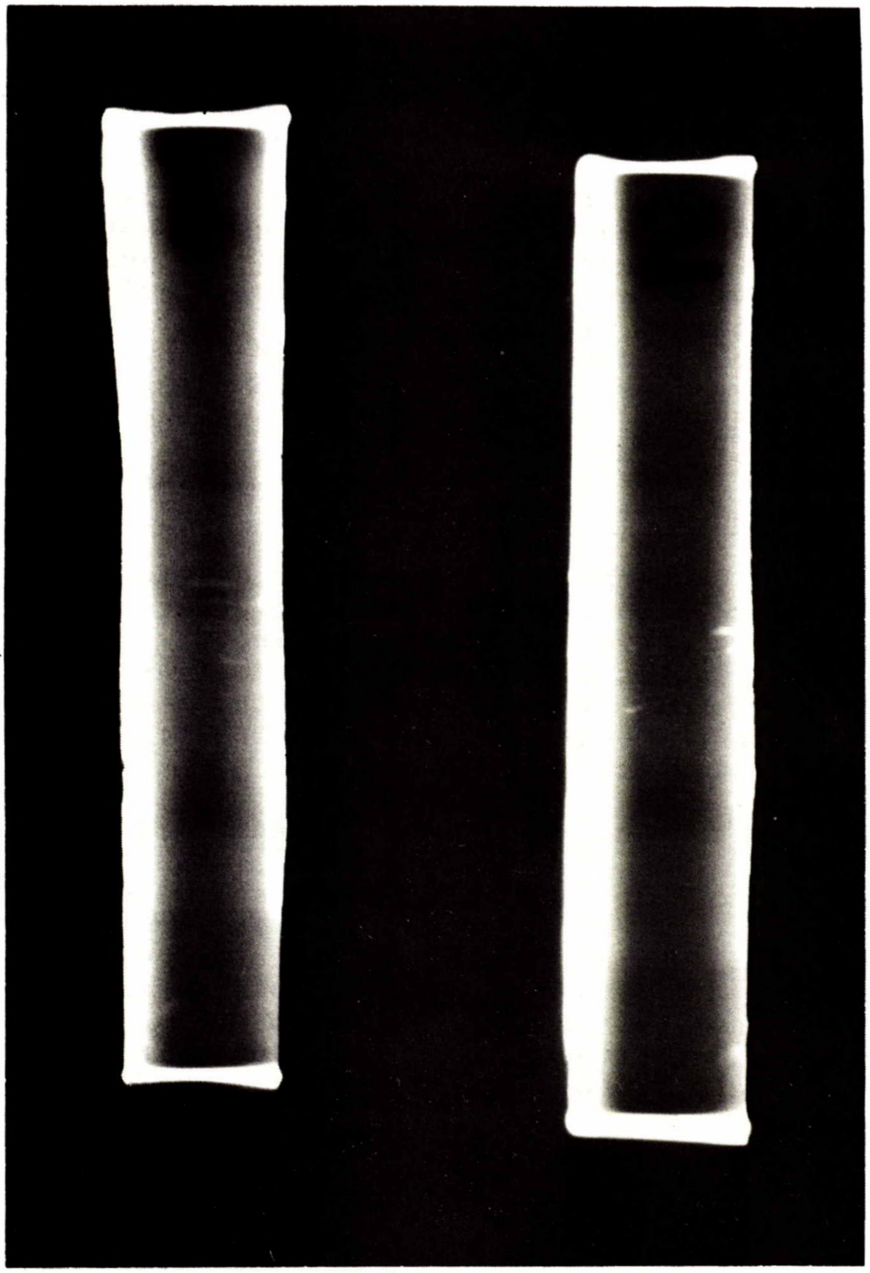
Microscopic Examination

Several of the inclusions were examined optically. However, the most complete examination was conducted on one located 2-3/4 in. from the "outer" end (Figure 2), and on two at approximately 2-7/8 in. from the same end (Figures 6 to 9). The latter two extended to the surface of the core and appeared to have been cut off by the trepanning tool.

(a) Optical Properties

When viewed stereoscopically (up to X30), the large inclusions appeared white to green or amber in colour, with a partly sugary or crystalline texture. Most of the smaller inclusions possessed a vitreous milky appearance; some had faintly darker streaks of green and brown colourations.

Under reflected white light, at higher magnifications (X100 to X500), the large inclusions consisted mainly of massive grey to greenish matrix with many darker grey crystals embedded within it. Some of the smaller inclusions contained similar darker crystals within them, although the majority appear to consist of a grey matrix with pearly-grey inclusions at the periphery.



Actual size.

Figure 1. Prints of radiographs of core trepanned from main rotor M-1.

The core is radial; the top of the radiograph represents the outermost end; the inclusion cluster (white spots) begins approximately 7 inches from the periphery; and 1 and 2 represent two radiographs on the same core, at an angle of 90° with each other.

Under reflected polarized light (crossed nicols), the large inclusions appeared colourless to slightly grey or amber, with many of the crystals appearing as slightly darker grey shadows within the main inclusion. The smaller inclusions were mainly colourless, or milky and translucent, except those which were duplexed with the darker crystals.

Under polarized light the large inclusions appeared to be weakly birefringent, although this could not be definitely determined. It appeared that the birefringence* was due to the presence of the darker crystals and would indicate their anisotropic behaviour**. The grey matrix of the smaller inclusions which contained no crystals showed only isotropic characteristics. The pearly-grey phase at the peripheries varied from green to opaque under crossed nicols. The darker or more opaque areas showed weak birefringence.

(b) Etching Tests

The standard A.S.T.M. series of etching tests was carried out on the inclusions, and photomicrographic records were made of the results that were considered pertinent. These photomicrographs are shown in Figures 2 to 5 (small inclusions) and 8 to 14 (large inclusions). The reactions to these tests are described in Table 1, and strongly indicate the identities of the non-metallic constituents.

X-ray Diffraction and Spectrographic Analysis

Two of the large inclusions shown in the radiographs of Figure 1, at 2-7/16 in. and 2-9/16 in. from the numbered end, were used for X-ray diffraction in situ and by the powder technique. A brown powder (only a small portion of the inclusion) was identified as magnetite (Fe_3O_4). The hard phase, of which most of the inclusion consisted, showed bands which were not identified. In situ, the diffractometer showed only iron lines.

Spectrographic analyses showed four major constituents, namely iron, manganese, aluminum, and silicon. Vanadium, nickel and chromium were impurities.

The results of the X-ray diffraction and spectrographic analysis suggested that the inclusions consisted mainly of glass, the composition of which probably corresponded to a mixture of the oxides of the major constituents. These particular inclusions were used up and thus could not be studied metallographically. Others in the cluster were studied by other methods (see Figures 2 to 14, inclusive).

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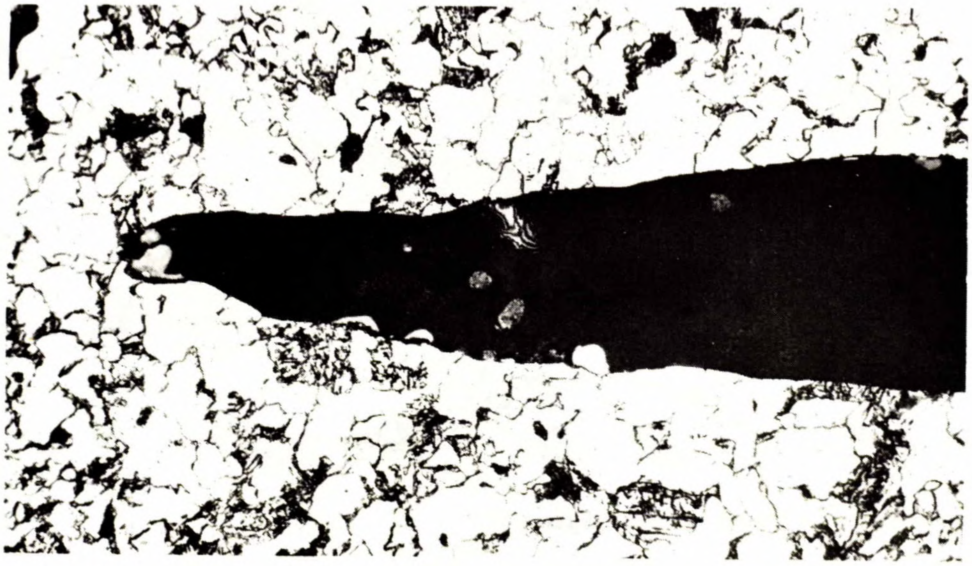
*Birefringent: having, or characterized by, the power of double refraction (therefore not a cubic system).

**Anisotropic: having different properties in different directions (therefore not a cubic lattice).

Unetched X500

Figure 2. Section of a non-metallic inclusion observed in a cluster in core from main rotor M-1.

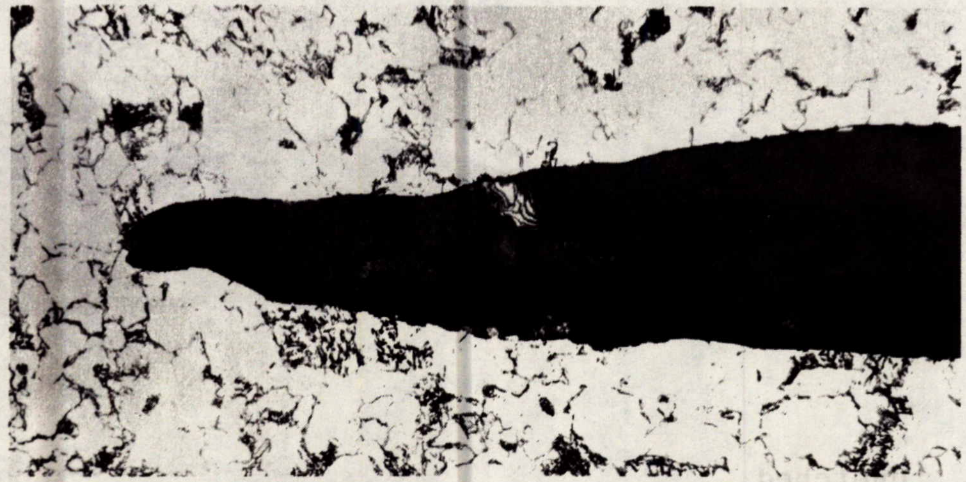
This inclusion was located within the cluster, approximately 2-3/4 in. from the outer end, and is mainly grey vitreous material with lighter pearly-grey globular or half-globular inclusions at the periphery and some within the matrix. Some darker-grey crystals can also be seen within the vitreous matrix.



After one etching X500

Figure 3. Same as Figure 2, after etching in 10% nital for 10 seconds.

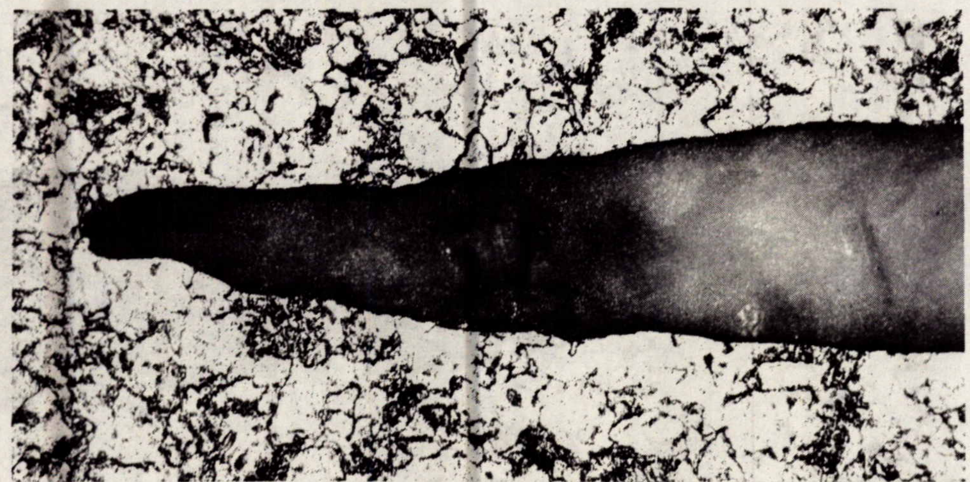
There was a slight darkening of some globular inclusions within the matrix, indicating FeO with FeS or MnO in solution. The remainder of the inclusion was not attacked.



After two etchings X500

Figure 4. Same as Figure 3, after etching for 5 minutes in 5% chromic acid in water.

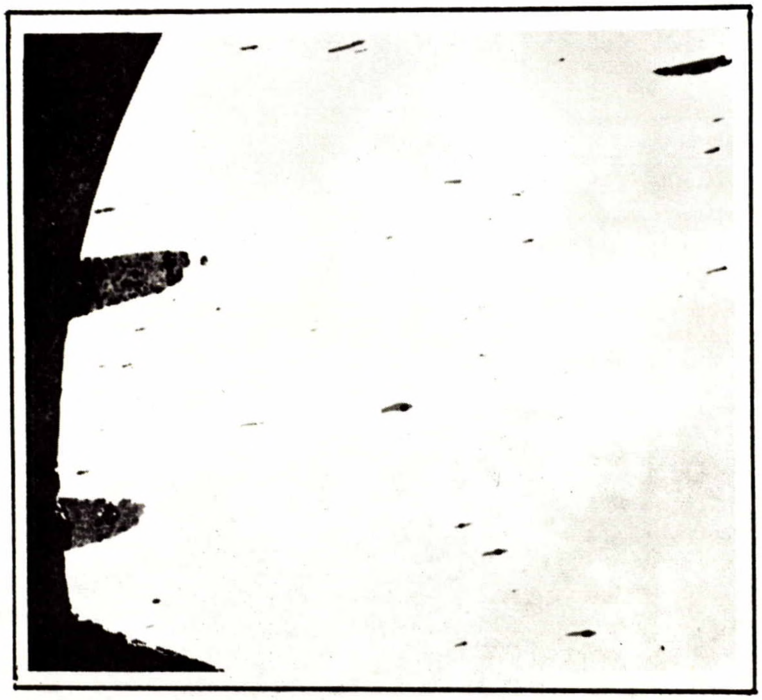
All of the globular inclusions were attacked, indicating FeS-MnS rich in MnS. Those within the matrix which were slightly attacked in nital probably contain FeO with FeS.



After three etchings X500

Figure 5. Same as Figure 4, after etching for 10 minutes in 20% aqueous solution of hydrofluoric acid.

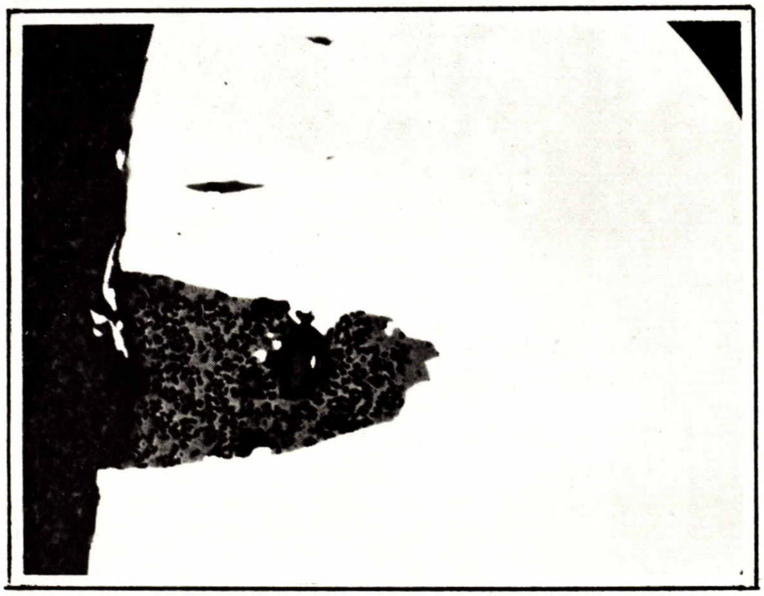
The matrix has been attacked, showing that the inclusion consists mainly of siliceous material.



Unetched X10

Figure 6. Two large inclusions located 2-7/8 in. from the end of the core from rotor M-1, shown in Figure 1.

This photomicrograph shows the difference in texture of the large inclusions as compared with the smaller inclusions nearby.



Unetched X200

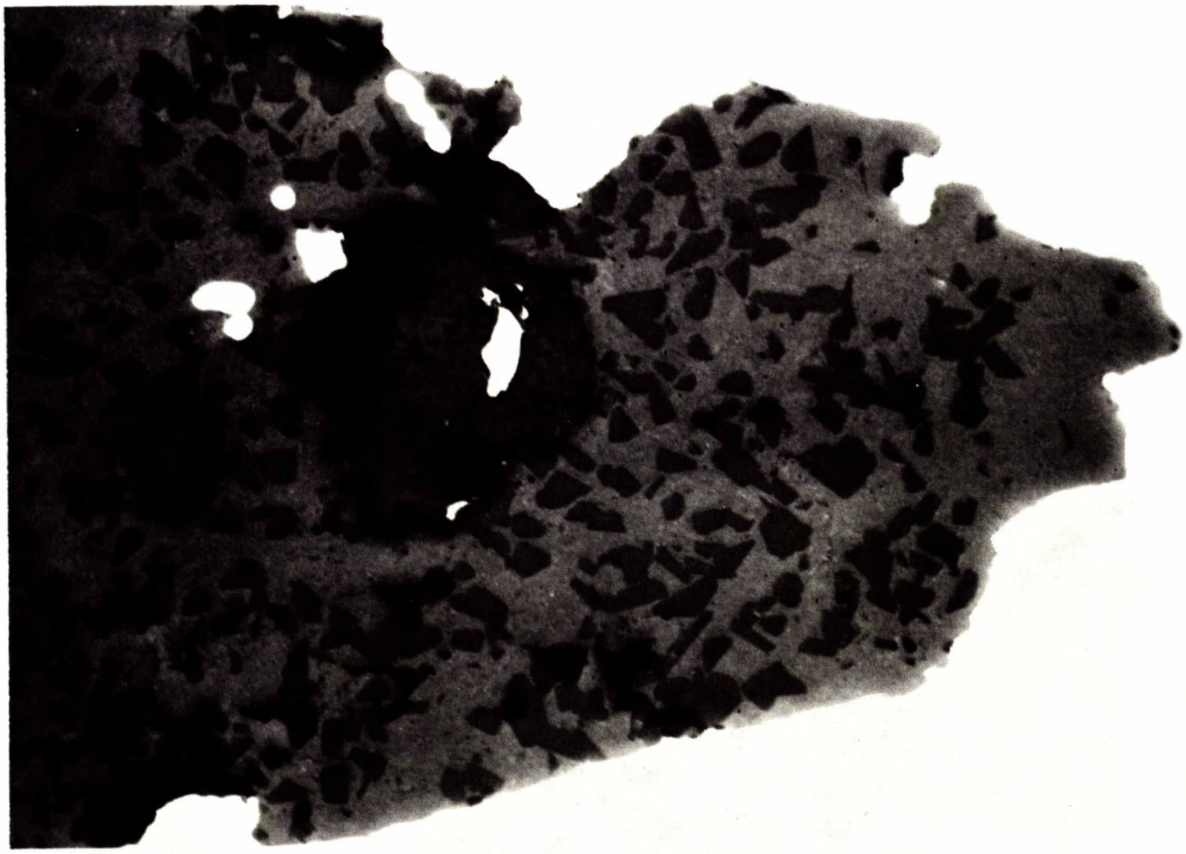
Figure 7. One of the large inclusions shown in Figure 6.

This inclusion was selected for etching tests.

Unetched X200

Figure 8. The second of the two large inclusions shown in Figure 6.

This inclusion was used for X-ray diffraction tests.



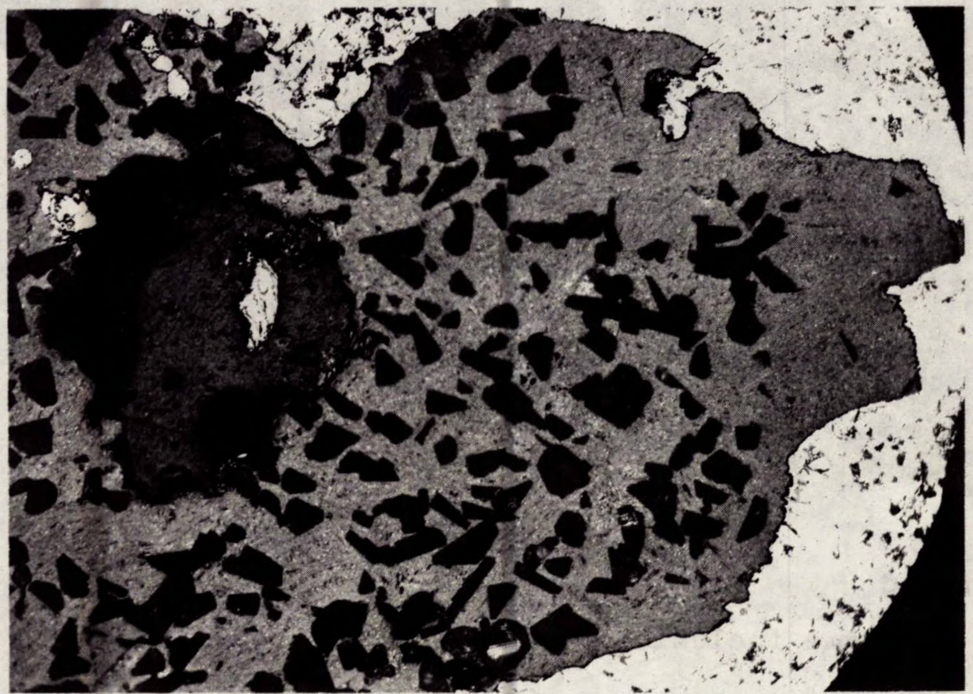
Unetched X200

Figure 9. Same inclusion as shown in Figure 7.

This inclusion was located adjacent to that shown in Figure 8 and was used for microscopical examination and etching tests for identification. Optical properties under crossed nicols were:

Lighter grey, vitreous material - Isotropic, translucent, colourless to faint colour effects.

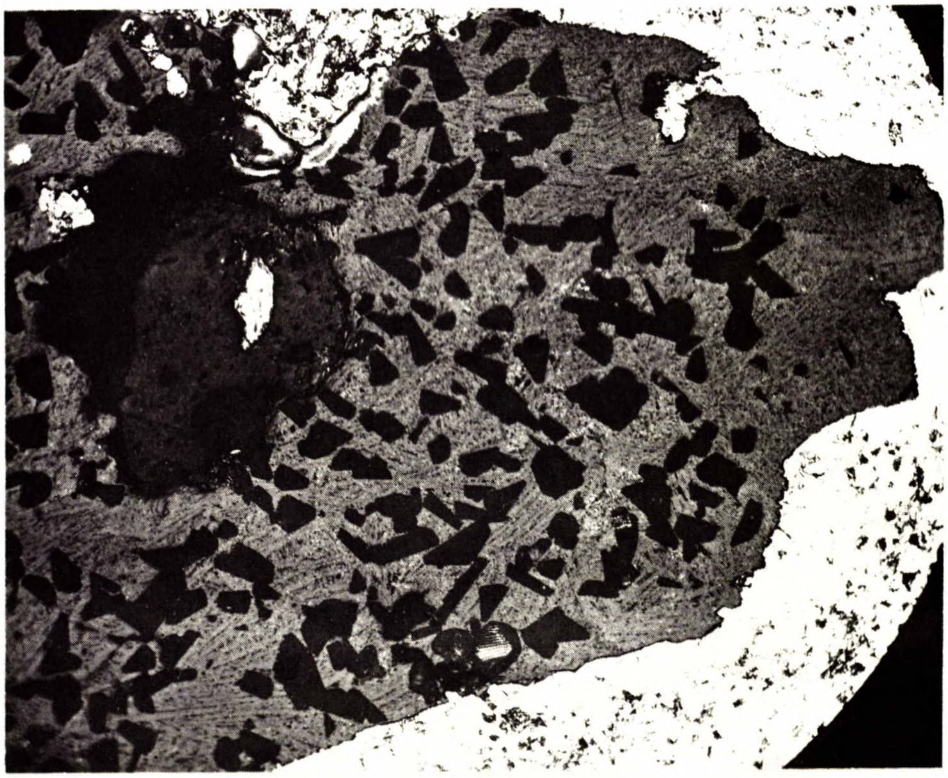
Darker grey crystals - Slight birefringence, indicating possible anisotropic behaviour; translucent to partly opaque.



After one etching X200

Figure 10. Same as Figure 9, after etching in 10% nital for 10 seconds.

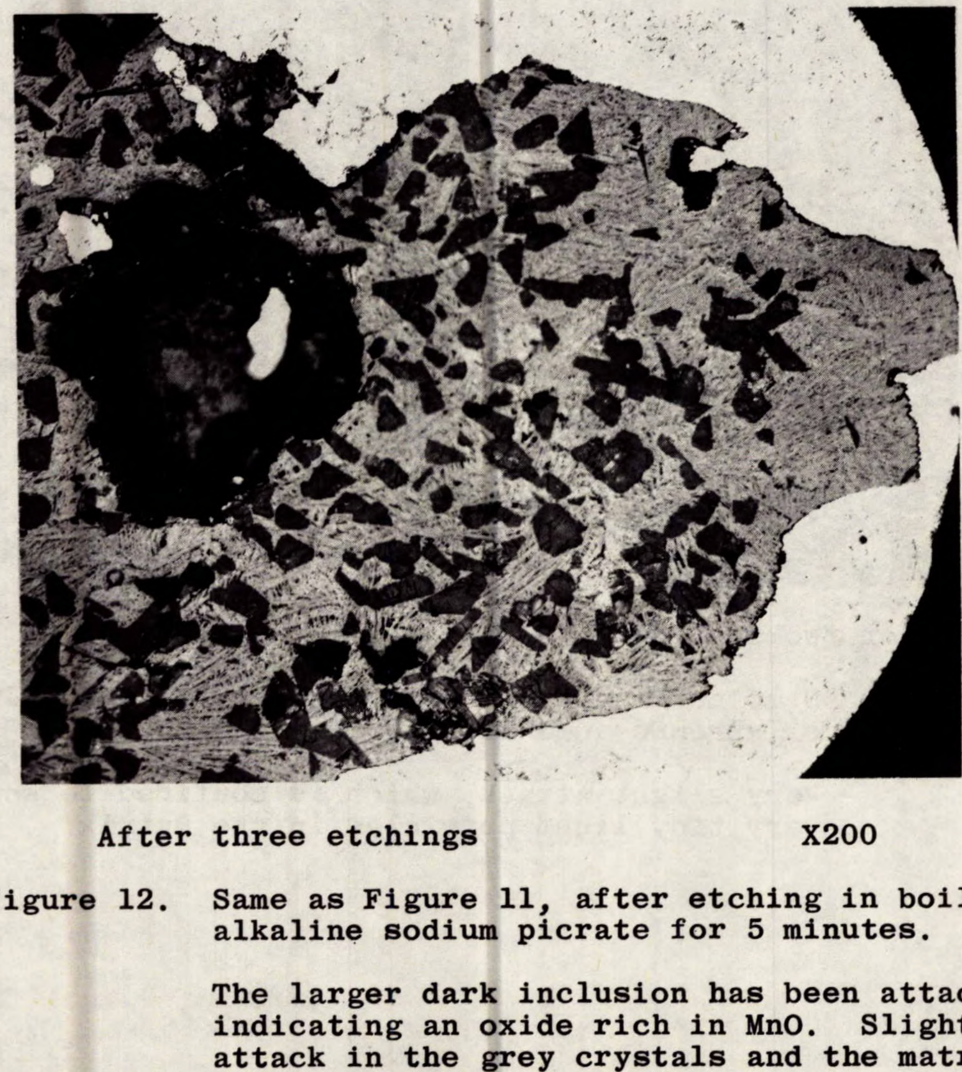
This etchant caused no significant attack.



After two etchings X200

Figure 11. Same as Figure 10, after etching in 10% solution of chromic acid in water for 5 minutes.

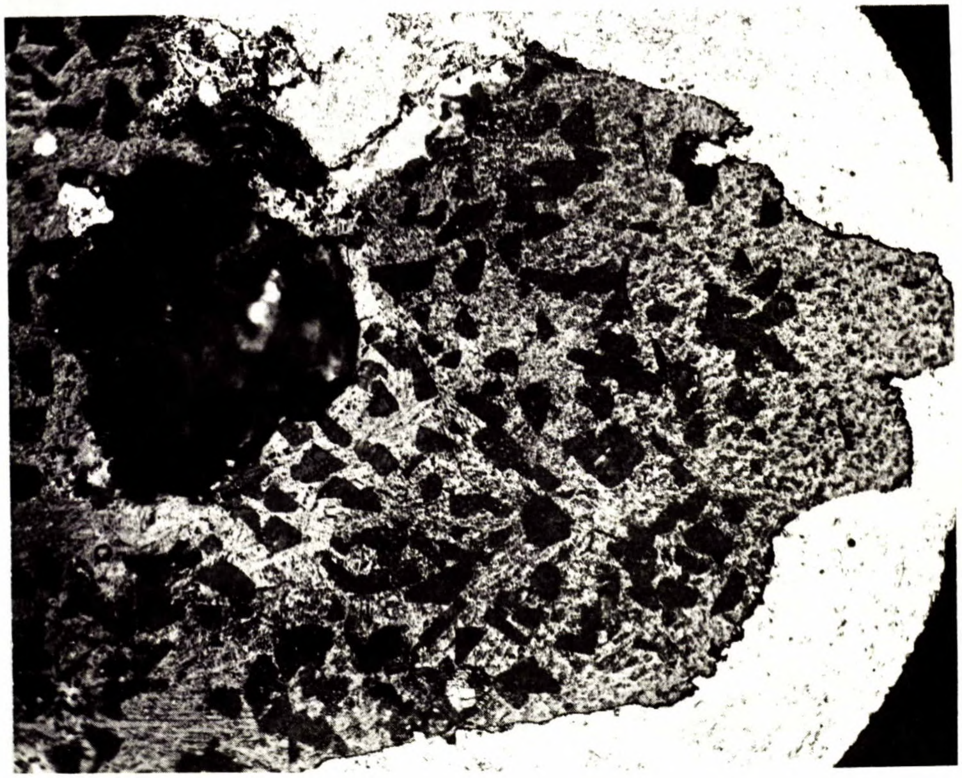
Very slight attack, which is confined to some very tiny light particles in the matrix.



After three etchings X200

Figure 12. Same as Figure 11, after etching in boiling alkaline sodium picrate for 5 minutes.

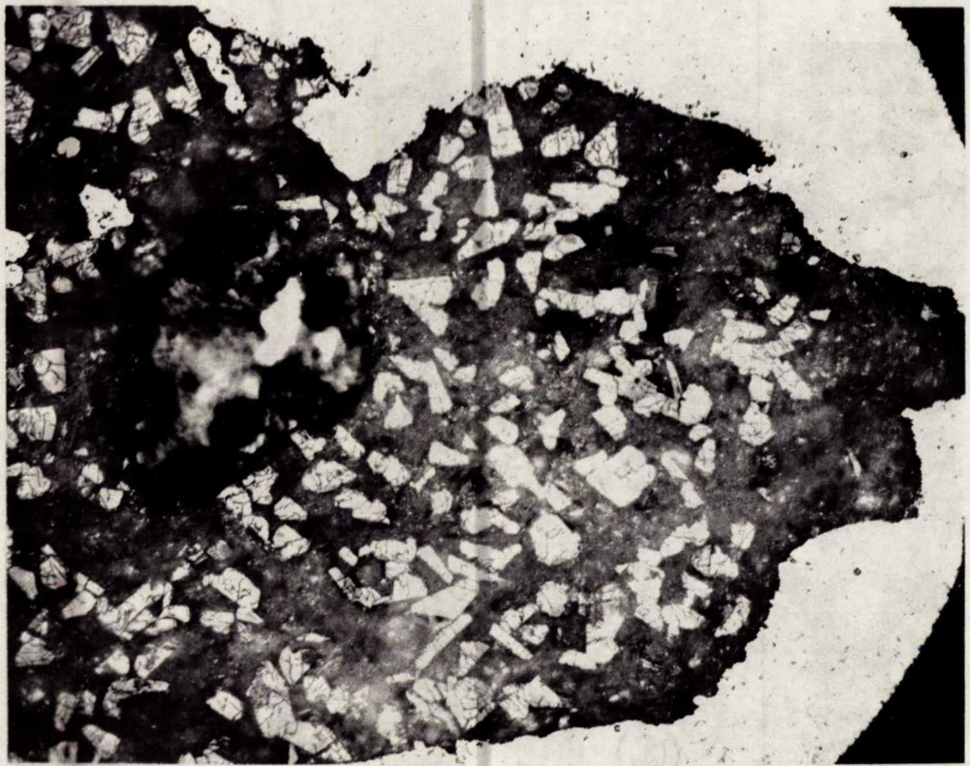
The larger dark inclusion has been attacked, indicating an oxide rich in MnO. Slight attack in the grey crystals and the matrix may indicate the presence of oxides, such as the jacobsite revealed by petrographic techniques.



After four etchings X200

Figure 13. Same as Figure 12, after etching in a saturated solution of stannous chloride in alcohol for 10 minutes.

Additional pitting attack throughout indicates the presence of compound (FeMn) oxide. The dark-grey crystals and matrix show strong resistance to the etch.



After five etchings X200

Figure 14. Same as Figure 13, after etching in a 20% aqueous solution of hydrofluoric acid for 10 minutes.

The matrix has been severely attacked. Further attack on the dark-grey crystals cannot be discerned, and it is probable that their brightness is a light effect resulting from partial dissolution of the surrounding matrix.

TABLE 1

Results of Standard Etching Tests on the Core from Rotor M-1

Description	Reaction to Etch	Identity
SMALL INCLUSIONS	(Note: No reaction with previous etchants in the series.)	
Light pearly grey globules at periphery.	Severely attacked by 10% chromic acid.	FeS-MnS rich in MnS.
Remainder of inclusion except darker grey crystals.	Severely attacked by 20% hydrofluoric acid.	Silicate.
LARGE INCLUSIONS		
None of the pearly-grey, globular inclusions at the periphery, as in smaller inclusions.	No significant attack from 10% nital. Some very slight attack by 10% chromic acid on tiny particles in the matrix which appear to have a dendritic dispersion.	
Matrix	Some further dendritic attack by boiling alkaline sodium picrate.	
Dark crystals	These show dark lines after the picrate etch, indicating slight attack.	
Matrix and crystals	Stannous chloride caused further attack on the crystals, on the matrix, and on the very large grey spherical inclusion within the matrix.	The effect of the etchants thus far indicates the presence of tiny particles of FeO, FeS, and compound FeO.MnO well dispersed.
Matrix and crystals	20% aqueous hydrofluoric severely attacked the matrix, but left the darker crystals possibly slightly attacked.	This etch indicates that the matrix is siliceous material. The crystals could be a more resistant siliceous material.

Additional tests were conducted on three inclusions at the position 2-7/8 in. from the numbered end of the core. When examined microscopically, these three inclusions two of which are shown in Figure 6, showed two major phases, consisting of angular grey crystals in a grey-green matrix. Material was extracted and analysed, both spectrographically and by X-ray diffraction using the Debye-Scherrer method. This further spectrographic analysis showed the major constituents as silicon, manganese and magnesium, along with copper as a minor constituent. Aluminum and iron were present, either as traces or as minor constituents.

The X-ray patterns revealed α-tridymite (SiO_2). However, all lines were not accounted for by known standards. The presence of halos suggested glassy silicates, and the presence of manganese and magnesium as major constituents suggested the existence of complex oxides or silicates of those elements.

Examination by Petrographic Techniques

In the petrographic examination, a diffuse X-ray powder diffraction pattern of the inclusion shown in Figures 6 and 8 was obtained, and one of the major constituents was identified as α-tridymite (high temperature SiO_2). A few extra lines on the pattern indicated that some material was not identifiable. A microscopical examination of a powder of the inclusion in immersion oils confirmed the X-ray results. Polished section studies showed that a few very small grains of a metallic mineral are also present in the inclusion and have optical properties resembling those of jacobsite ($MnO.Fe_2O_3$) or magnetite (Fe_3O_4).

EXAMINATION OF MAIN ROTOR M-16

Ultrasonic Examination

The examination of rotor M-16, which was made by the basic electric furnace process, was a duplication of the examination of main rotor M-1. The report contained in Appendix 4 provides the forging history, the description and records of the ultrasonic inspection, and other pertinent data concerning the core which was trepanned from the region that was considered to give some of the strongest indications of defects.

This rotor was one of two made from a 37-ton ingot, both of which were rejected because of non-metallic content.

Core Examination

The core was forwarded to the Mines Branch and was examined by the same techniques as were described previously for main rotor M-1.

Radiographic Examination

Radiographs revealed one centrally located inclusion at 2-5/16 in. from the bore end of the core (see Figure 15). It could correspond to the two inclusions identified as #2 and #3 on the core surface shown in Figures 36 and 37 of Appendix 4. On sectioning the core at that location, a long and continuous, although apparently fragmented, inclusion was found. The largest single particle of this inclusion was only about 1/16 in. long and was oblong in shape. Also in the group were some inclusions, smaller and less fragmented but having individual particles slightly longer than 1/16 in. Many similar inclusions extended to the surface, some of them being stringer-like in appearance.

The radiographs did not reveal the defect that is shown as #1 on the core in Figure 37 of Appendix 4. This might have been due to the particular orientation, since a long (1/2 in. or more) group of inclusions was located by sectioning the core at the #1 position. This inclusion was similar to that located at the #2 and #3 positions.

Microscopic Examination

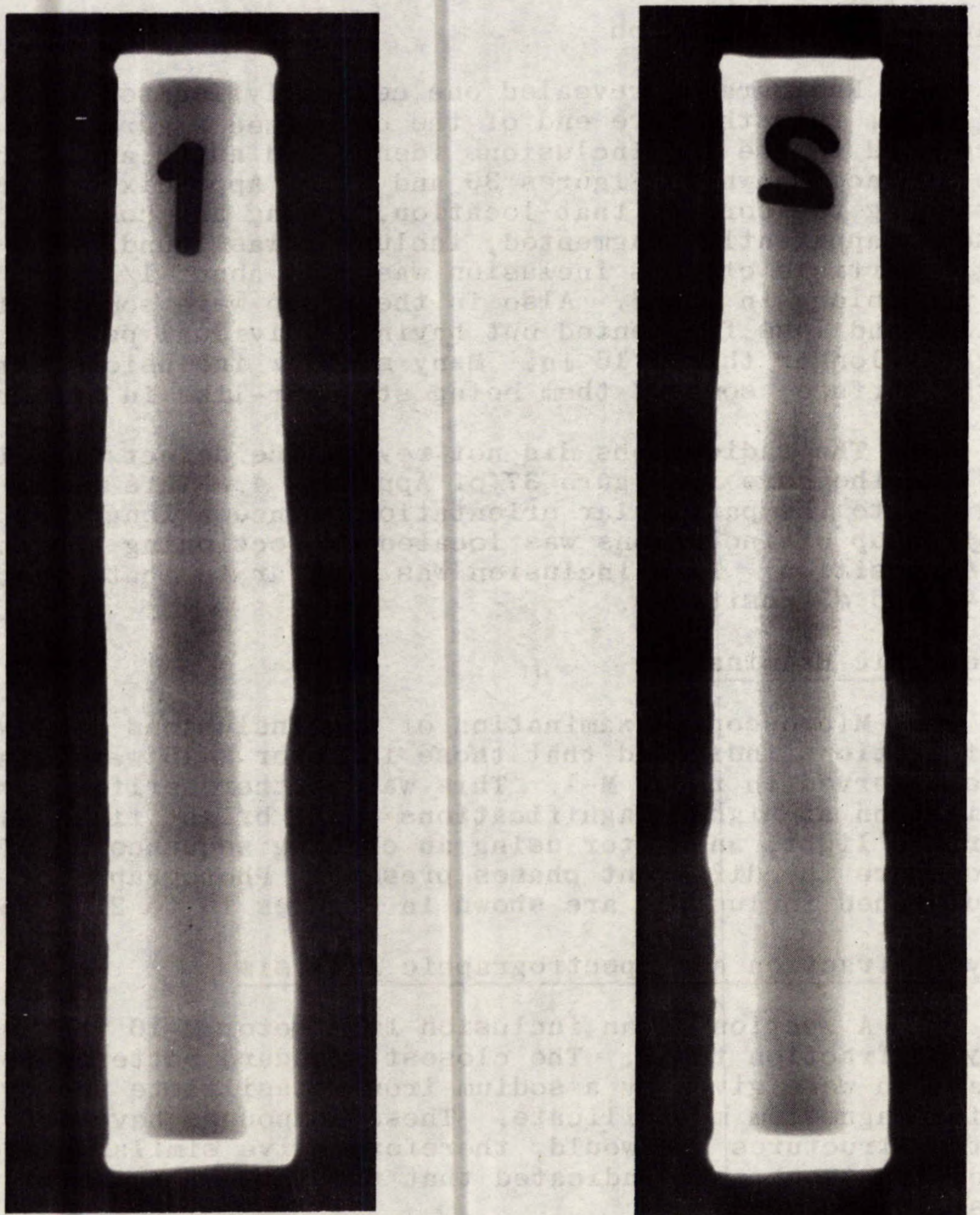
Microscopic examination of the inclusions at low magnifications indicated that those in rotor M-16 were similar to those observed in rotor M-1. This was further verified by examination at higher magnifications using bright field and polarized light, and after using an etching sequence to distinguish and compare the different phases present. Photographs of etched and unetched inclusions are shown in Figures 16 to 21, inclusive.

X-ray Diffraction and Spectrographic Analysis

A section of an inclusion from rotor M-16 was used for X-ray diffraction tests. The closest standard patterns for comparison were given by a sodium-iron metasilicate and by a calcium-magnesium metasilicate. These compounds have very closely related structures and would, therefore, give similar patterns. The diffraction tests indicated that the inclusion was a metasilicate.

A spectrographic analysis showed major constituents to be magnesium, manganese, silicon and aluminum, with calcium and vanadium as minor components.

The results of the X-ray diffraction tests and of the spectrographic analysis suggest that the inclusions correspond to a mixture of the oxides of the major constituents.



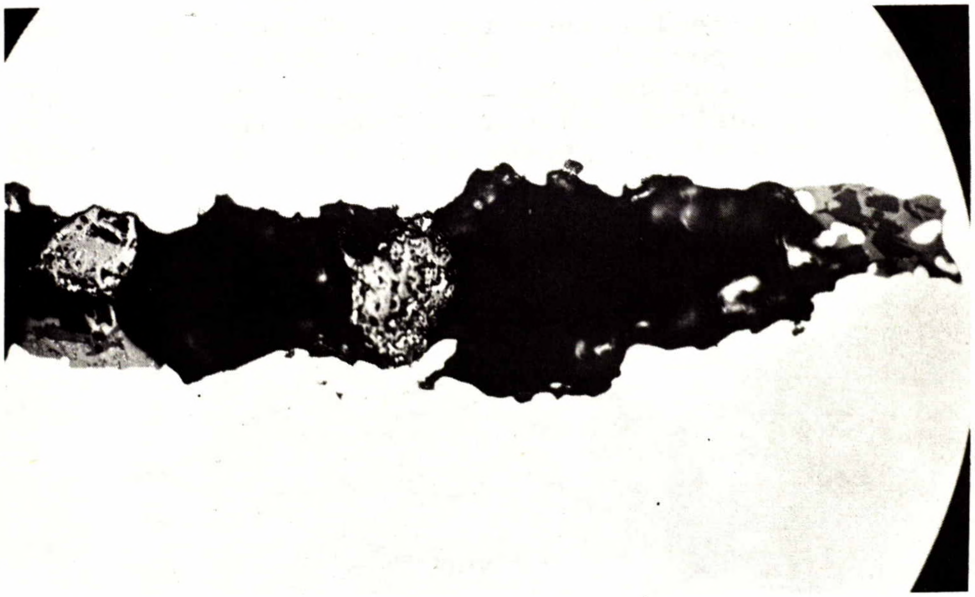
Actual size.

Figure 15. Prints of radiographs of the core trepanned from main rotor M-16.

The core is radial, and the tops of the prints are adjacent to the bore of the rotor. The numbers were used on the core to orient the radiographs at 90° with respect to each other. The light streak in the dark area of the print is evidence of the group of inclusions located 2-5/16 in. from the bore (shown as defect area No. 2 in Figure 36 of Appendix 4). The other group one inch from the core cannot be detected on these prints.

Unetched X35

Figure 16. One of the largest inclusions observed in the group located 2-5/16 in. from the bore. (This corresponds to defect area No. 2 shown in Figure 36 in Appendix 4.)



Unetched X125

Figure 17. Same as in Figure 16, at higher magnification.

This inclusion has been partly removed for diffraction tests. Note dark grey crystals within lighter matrix at end. Note, also, some spherical or hemispherical globules of pearly-grey material.

Unetched X500

Figure 18. Inclusion from group located in core from M-16 one inch from the bore end. (This corresponds to defect area No. 1, shown in Figure 37 in Appendix 4.)

This inclusion, like all of those observed at this position, contains a dark-grey matrix, vitreous in appearance; pearly-grey globular inclusions, mainly at the periphery; and a crystalline phase, within the matrix, which is darker grey.

After one etching X500

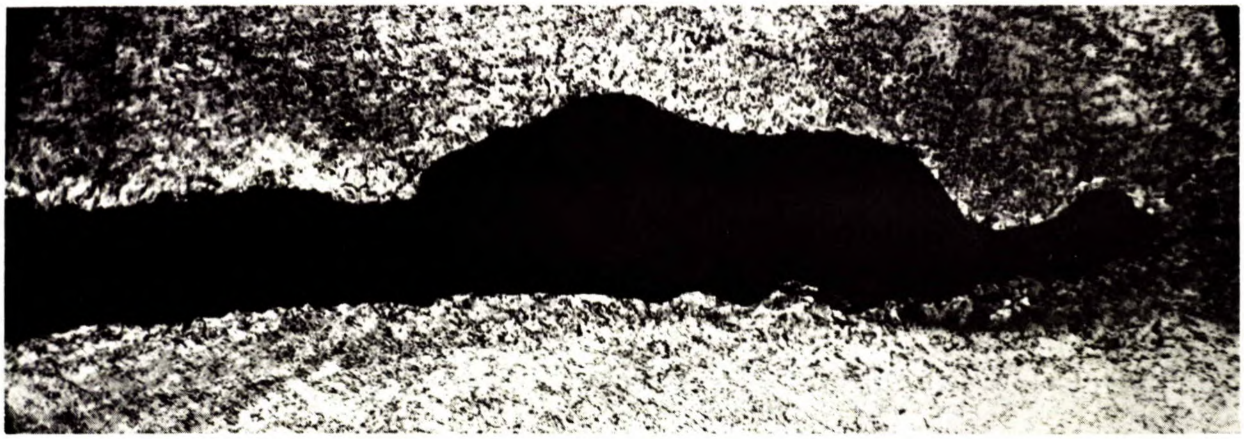
Figure 19. Same as Figure 18, after etching in 10% nital for 10 seconds.

The only change might be a slight attack on some of the globular inclusions, indicating FeO-FeS or FeO-MnO.

After two etchings X500

Figure 20. Same as Figure 19, after etching in 10% solution of chromic acid in water for 5 minutes.

The remaining grey globular inclusions were attacked, showing that they consist of FeS-MnS rich in MnS. Some staining has occurred on the lower half of the inclusion.



After three etchings X500

Figure 21. Same as Figure 20, after etching for 10 minutes in a 20% aqueous solution of hydrofluoric acid.

The matrix has been attacked, indicating that it consists of siliceous material. The long dark crystal remained apparently unattacked, but had been loosened in the matrix and was lost before photographing.

Examination by Petrographic Techniques

Petrographic studies were conducted mainly by X-ray diffraction techniques. A small amount of the material from two large inclusions was removed and subjected to X-ray powder diffraction studies. Although microscopical examination showed the presence of two minerals in the inclusions, only α-tridymite was identified. A similar technique was used on small inclusions but did not provide a pattern; this indicates a glassy type of inclusion.

SUMMARY AND COMMENTS

1. The ultrasonic method of inspection has been used very effectively to detect and locate defects ranging in size from very small (in clusters) to individual defects 1/8 in. diameter or larger. Also, it has been found possible to identify these defects as non-metallic in nature or as voids or porosity.

2. The size and nature of the inclusions were judged by the ultrasonic indication with a reasonable degree of accuracy -- i.e., a single inclusion, a cluster of inclusions, or voids -- by comparison with and indications received from artificial defects of known size.

3. The smaller inclusions in the clusters were principally vitreous silicates that exhibited isotropic properties when optically examined. The matrix of the large inclusions also reacted isotropically, but the darker grey crystals within the matrix appeared to exhibit some birefringence. The matrix was identified as principally a glassy metasilicate which may contain iron, manganese, magnesium, silicon and aluminum as major constituents, probably in oxide form. A definite pattern of α-tridymite was given by inclusions from both M-1 and M-16. The grey angular inclusions are believed to provide this pattern, since this would be consistent with etch and optical tests carried out during the microscopical examination. The small vitreous inclusions appear to have been more plastic at forging temperatures than were the larger, more complex inclusions. Many inclusions may have small amounts of other types of inclusions associated with them, such as complex sulphides (FeS-MnS), magnetite (Fe_3O_4) and jacobsite ($MnO.Fe_2O_3$).

4. The presence of magnesium and aluminum in the inclusions, when none was added to the steel, is indicative of reaction with refractory material, probably occurring near the end of the steelmaking process or in the ladle. However, the inclusions do not differ in appearance and constituents from those which might result from the deoxidation of a steel which contains residual quantities of aluminum. The size of the inclusions does indicate that slag entrapment has occurred.

CONCLUSIONS

1. The examination of the rejected rotors by the ultrasonic method and by sectioning of cores has confirmed the inspection records which show that rejection was based on non-metallic content. The inclusions were identified; and it was confirmed that location, general identification, and size estimation can be obtained by ultrasonic means.

2. The origination of the inclusions was principally from entrapped slag and deoxidation products. The presence of traces of aluminum and magnesium in the inclusions indicates that these inclusions had been modified by reactions with refractory material, but no inclusion examined was truly representative of an exogenous refractory material.

3. It should be possible, with continued experience and the maintenance of careful records, to attain sufficient proficiency to judge the internal quality, in terms of its serviceability, without resorting to sectioning.

4. Ultrasonic testing of large forgings is a method of inspection which should be considered of great importance for the attainment of high quality throughout.

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(Appendices 1-4, including)
(Figures 22-39 and Tables 2-6,)
(follow on pages 26-51.)

APPENDIX SECTION

ULTRASONIC DATA SUPPLIED BY THE DOMINION STEEL AND COAL CORPORATION, TRENTON WORKS, TRENTON, NOVA SCOTIA

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Appendix 1 -	Description of Ultrasonic Equipment........................ (Figures 22-23)	27-28
Appendix 2 -	"Pinpointing" of Defects in Rotor Forgings.................. (Figures 24-26)	29-31
Appendix 3 -	Open-Hearth Rotor M-1............. (Tables 2-3. Figures 27-34)	33-41
Appendix 4 -	Electric Furnace Rotor M-16...... (Tables 4-6. Figures 35-39)	43-51

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APPENDIX 1. - DESCRIPTION OF ULTRASONIC EQUIPMENT

A Sperry "Reflectoscope", type U.R., was used, capable of testing at frequencies of $\frac{1}{2}$, 1, $2\frac{1}{4}$, 5 and 10 megacycles.

Normally, a single search unit is used with the instrument, the search unit acting as a transmitter and a receiver. It is possible, however, to employ a double or tandem search unit, where one crystal acts as a transmitter and another acts as a receiver.

The surface of the rotor to be tested is usually machined to a finish of 125 micro-inches or better.

In the ultrasonic testing of rotors, the 1 Mc, $2\frac{1}{4}$ Mc and 5 Mc frequencies are usually employed. The rotor is rotated in a lathe during testing, although careful examination of individual defects is conducted while the rotor is stationary.

Figure 22 illustrates the front panel of the Reflectoscope. The tuning controls, the screen of the cathode ray tube and a $2\frac{1}{4}$ Mc single-type search unit are all visible.

To record the indications, a 35 mm camera was attached to the reflectoscope screen by an adjustable bezel. The adjustment permits accurate focusing. Figure 23 is a photograph of the Reflectoscope with the camera in position.

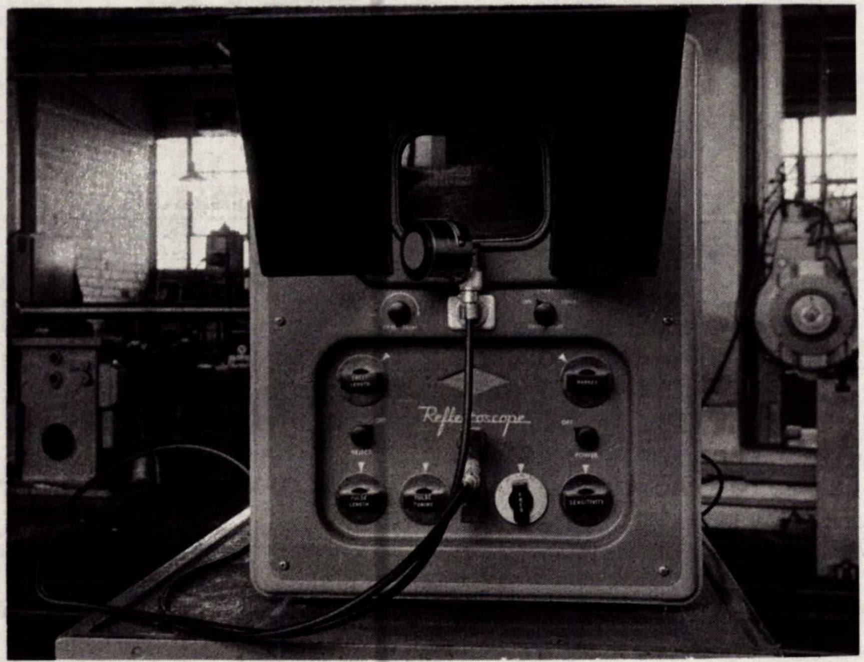


Figure 22. Front panel of Reflectoscope.

Figure 23. Reflectoscope with camera in position.

APPENDIX 2. - "PINPOINTING" OF DEFECTS IN ROTOR FORGINGS

"Pinpointing" is the term which describes the method used to locate rotor defects ultrasonically with sufficient accuracy to permit their removal in a core trepanned from the forging. The procedure was developed at the General Electric Company by Messrs. R. Fitzgerald and G.E. Lockyer. Briefly, the procedure consists of:

(a) Locating the 1 Mc crystal position from which the maximum indication from the defect is obtained. The location coincides with the point where some part of the beam is normal to the defect. See Figure 24.

(b) Locating the 5 Mc crystal position where the maximum loss of bore reflection, due to the defect, occurs. The most radial portion of the beam is responsible for the bore reflection; therefore, when the greatest loss of bore reflection occurs, the defect is in direct radial line (minimum distance) with the defect. See Figure 25.

(c) Plotting the results of steps (a) and (b) on a cross-section of the rotor. See Figure 26. From the plot shown in Figure 26, the exact location of the defect is given by the 5 Mc data, and the plane of the defect is given by a line constructed at right angles to the line joining the defect location and the 1 Mc crystal location.

The above method of "pinpointing" was used in locating the defects in both the open-hearth and electric furnace rotors used in the investigation.

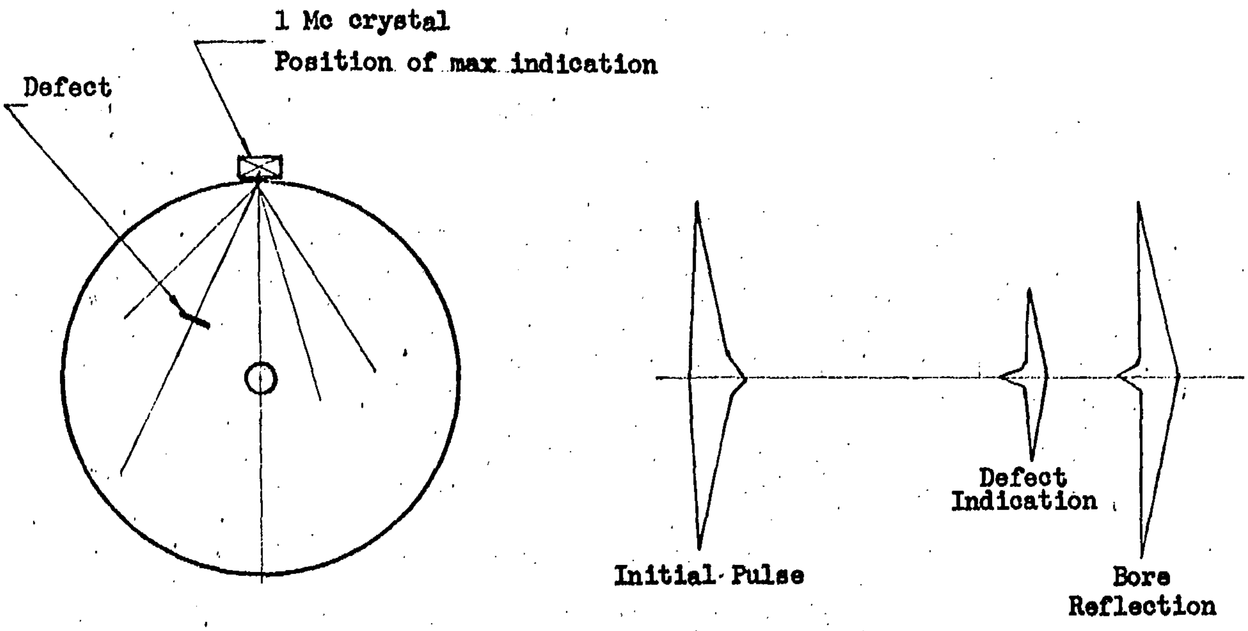


Figure 24. Step (a) in ultrasonic pinpointing to locate rotor defects.

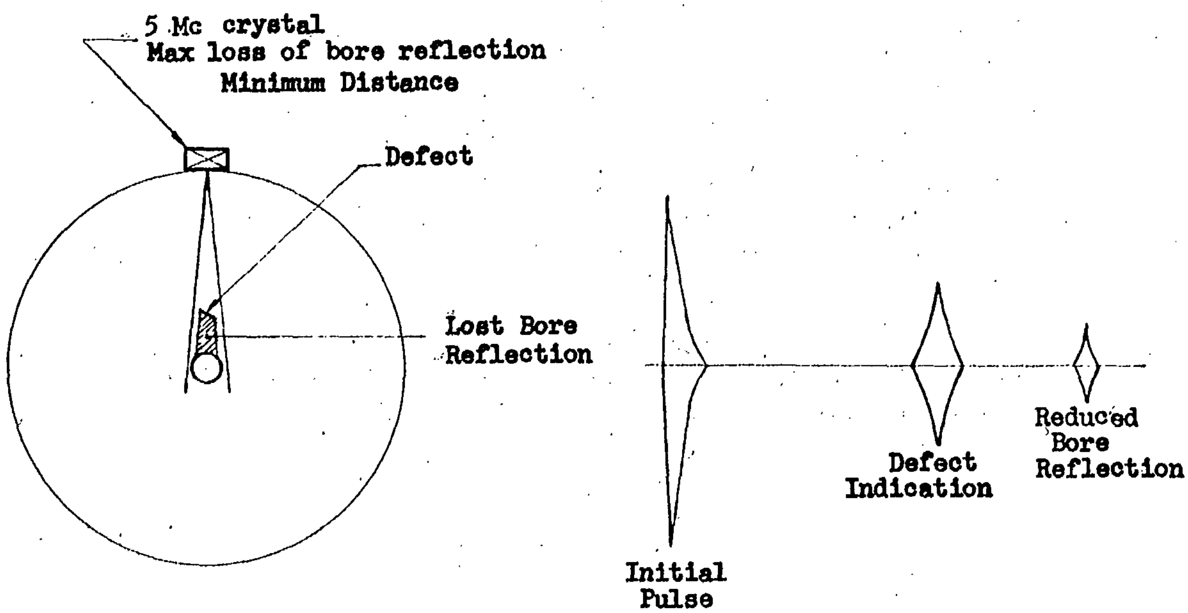


Figure 25. Step (b) in ultrasonic pinpointing to locate rotor defects.

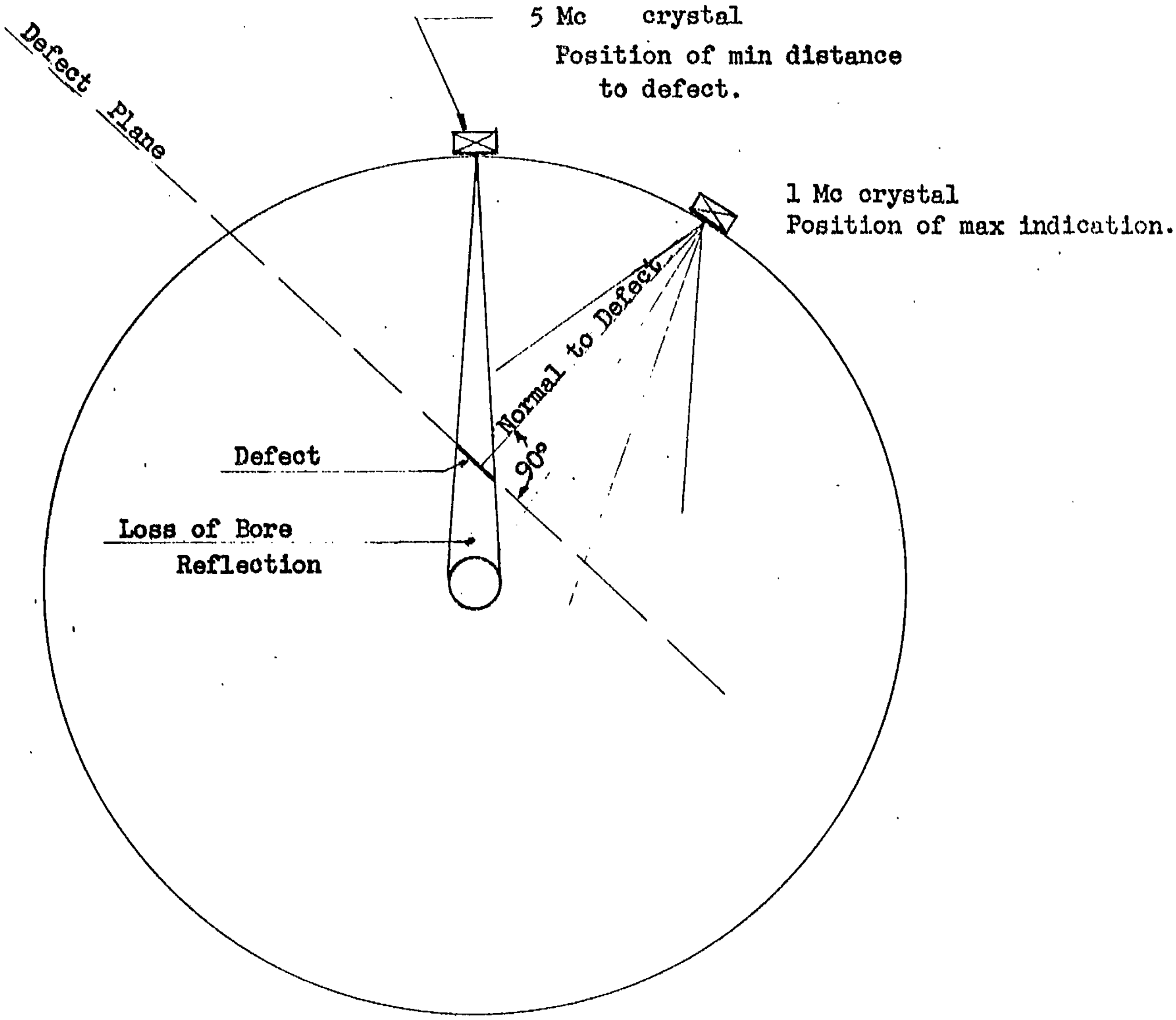


Figure 26. Step (c) in ultrasonic pinpointing: plotting results of steps (a) and (b) to obtain location and plane of defects.

APPENDIX 3.- OPEN-HEARTH ROTOR M-1

History

Heat No. 6507 (M-1) was melted in a basic open-hearth furnace located at Sydney Works (Nova Scotia). This heat was tapped on January 5, 1951 (see Table 2 for the melt practice employed), and the ingot was shipped hot to Trenton. The temperature of the ingot was 835°C (1535°F) on removal from the hot box, and the ingot was then immediately transferred to a furnace for heating to forging temperature 1260°C (2300°F).

The forging operation, in which a 2000-ton press was used, consisted of separating the ingot into three sections after blocking (M-1, M-2, M-3). Each section was then forged to the required dimensions. This was a straight draw-down without an upset operation. The forgings were then placed in a car-type furnace for the dehydrogenizing treatment.

Following this treatment the rotor was rough-machined and heat-treated to develop the desired physical properties.

M-1, one of three main turbine rotors from heat No. 6507, was rejected for an unsound center axis. M-2 and M-3 were also rejected for the same reason.

Analysis of Ingot:

	%
Carbon	- 0.29
Manganese	- 0.36
Phosphorus	- 0.019
Sulphur	- 0.014
Silicon	- 0.140
Nickel	- 2.37
Chromium	- 0.45
Molybdenum	- 0.45
Vanadium	- 0.10

TABLE 2

Melt Practice, Heat 6507 (M-1), tapped January 5, 1951

Charge:

Iron ore	-	Nil
Limestone	-	11,250 lb
Steel scrap	-	82,600 "
Cold pig	-	17,200 "
Hot metal	-	36,000 "

Refining Additions:

Lime	-	9 boxes	- Approx.	13,500 lb
Spar	-	1/3 box	- Approx.	600 "

Furnace Alloys:

Nickel anodes	-	3,800 lb	
Ferrochromium	-	1,500 "	
Calcium molybdate	-	1,430 "	(Equiv. to 650 lb Mo)
Ferromanganese	-	1,100 "	
Silicomanganese	-	450 "	

Ladle Additions:

Coke	-	240 lb
CaMnSi	-	750 "
FeV	-	175 "
Lime	-	120 "

Refractories:

The refractories used during 1951 were:

Ladle: "Swank" fireclay ladle brick.

Nozzle: Ordinary fireclay - not 'high cone'.

Ultrasonic Survey

Three large-diameter sections of the rotor (shown in Table 3) were machined and polished in preparation for testing. The center axis bore, which was already smoothly finished, was cleaned.

The main survey was conducted at $2\frac{1}{4}$ Mc frequency, using a single-type search unit. Many indications were received, but 29 of them were separated as being larger and more significant than the others. The magnitude of the 29 indications, together with the corresponding search unit location for each, was recorded.

A further survey was made with a 1 Mc frequency tandem search unit. This type of low-frequency search unit, with its characteristic wide angle of beam spread, is well suited to the detection of defects which are oriented in a radial or partially radial direction. Such defects are usually first detected by the side waves of the beam, and as the rotor is rotated, the defect passes through the entire beam. As it does so, the distance between the defect and the search unit varies, and this changing distance results in the defect indication moving laterally across the screen. Such indications are known as "travelling indications".

The results of the surveys are presented in Table 3.

The results indicate that the rotor contained many small longitudinally-oriented defects which tended to be concentrated towards the top end of the forging. The appearance of the indications was typical of that obtained from clusters of non-metallic inclusions, as opposed to cracks, ruptures, cavities, or other large, single-type defects.

Selection of Defects for Physical Examination

The twenty-nine (29) defects recorded were all similar in appearance on the screen and varied only in magnitude. Therefore, the question of selecting indications believed to represent various types of defects did not exist. Defect No. 27 was chosen because it existed in a section of the rotor otherwise defect-free; by selecting this defect, the pinpointing could be conducted without interference from nearby defects.

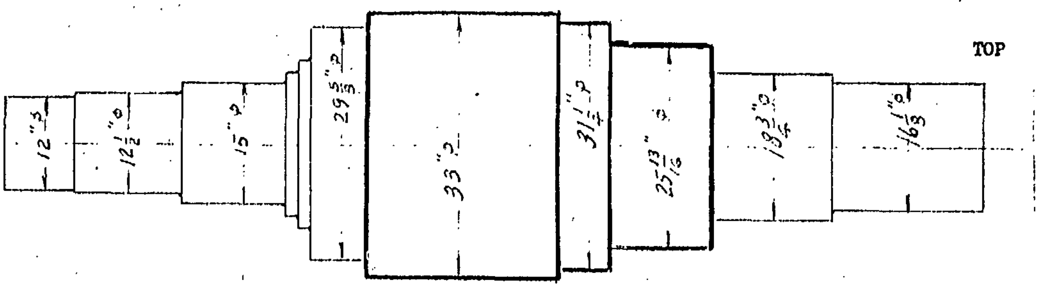
Pinpointing of Defect No. 27

The procedure outlined in Appendix 2 was followed. In this case, two separate 5 Mc locations were found for the greatest loss of back reflection and the minimum distance from search unit to defect. This may be explained by the fact that the defect under examination was thought to be a cluster of non-metallic inclusions rather than one large defect. The results

TABLE 3

Results of Ultrasonic Survey on Open-Hearth Rotor M-1

Dimensional Diameters Submitted to Ultrasonic
Survey at 2¼ Mc and 1 Mc: shown in heavy line



Instrument Settings at 2¼ Megacycles:

Sweep length, 4.9; pulse length, 4.3;
pulse tuning, 3.8; sensitivity, 2.2.

The above settings produced a two-division (0.2 in.) indication from a 1/16 in. diam. flat-bottomed hole 13 in. from the search unit (rotor material test block with radiussed ends).

Defects Shown with 2¼ Megacycles:

Indication No.	Rotor Diam., in.	Approx. Clock position	Dist. from Search unit, in.	Magni-tude, Divs.	Dist. from Top of Diam., in.
1	25-13/16	9.00/9.30	5	10	3/5
2	"	10.00	4	6	4
3	"	10.30	4	10	2-1/2
4	"	10.30	4	6	3¼/4-3/4
5	"	12.00	2-1/2	10	3
6	"	2.00	3	8	2-1/4
7	"	2.30	5-1/2	5	2
8	"	4.00	6-1/2	4	7
9	"	6.30	10-1/2	3	6
10	"	7.30	6	6	4
11	"	8.00	7/8	4/6	2
12	"	9.00	4-1/2	10	2/5
13	31-1/4	1.00	10-1/2	3	5-1/2
14	"	3.30	9	3	4
15	"	7.30	9	4	3
16	"	8.00	10	3	1-1/2
17	"	8.30	5	3	1
18	33	12.00	8-1/2	4	5-1/2
19	"	12.00	6-1/2	5	6
20	"	1.30	6-1/2	3	22
21	"	2.00	7-1/2	3	1-1/2
22	"	3.00	5-3/4	6	16
23	"	3.30	8-1/2	3	7-1/2
24	"	4.00	5/6	5	8
25	"	6.30	6-1/2	4	1-1/2
26	"	8.00	3	9	1-1/4
27	"	8.00	7	4	16-1/2
28	"	8.30	11-1/4	2	6
29	"	9.30	11	4	6

Instrument Settings at 1 Megacycle:

The reflectoscope was adjusted so that a 2 in. back reflection was received from the bore while the rotor was rotating.

Defects Shown with 1 Megacycle:

No travelling indications were detected.

of the pinpointing are shown in Figure 27. A series of reflectograms was made, illustrating the appearance of the indications at the various locations in the pinpointing procedure. The reflectograms are shown in Figures 28 to 32 inclusive. Since the three search unit locations were all practically coincident, it was concluded that the defect did not have any radial orientation.

Removal of Defect No. 27

A 1-15/16 in. diameter drill was centred on a point 16-3/4 in. from the top of the 33 in. diameter section at 7.35 on the rotor clock. (This was the location of greatest loss of bore reflection at 5 Mc frequency.) A radial hole was drilled $4\frac{1}{2}$ in. deep. From this point on, a coring or trepanning tool was substituted for the drill, and a 5 in. long core was removed. Since the outside end of the core was actually $4\frac{1}{2}$ in. from the outside surface of the rotor, the defect was expected between two points, 2-3/4 in. ($7\frac{1}{4}$ in. - $4\frac{1}{2}$ in.) and $3\frac{1}{4}$ in. (7-3/4 in. - $4\frac{1}{2}$ in.), from the outside end of the core.

Examination of Core Containing Defect No. 27

On the surface of the core, non-metallic inclusions could be readily seen. The inclusions passed right through the core from one side to the other. The defects appeared at a point 2-3/8 in. from the outside end of the core and extended over a 5/8 in. length. The appearance of the defects after magnetic particle testing is illustrated in Figures 33 and 34.

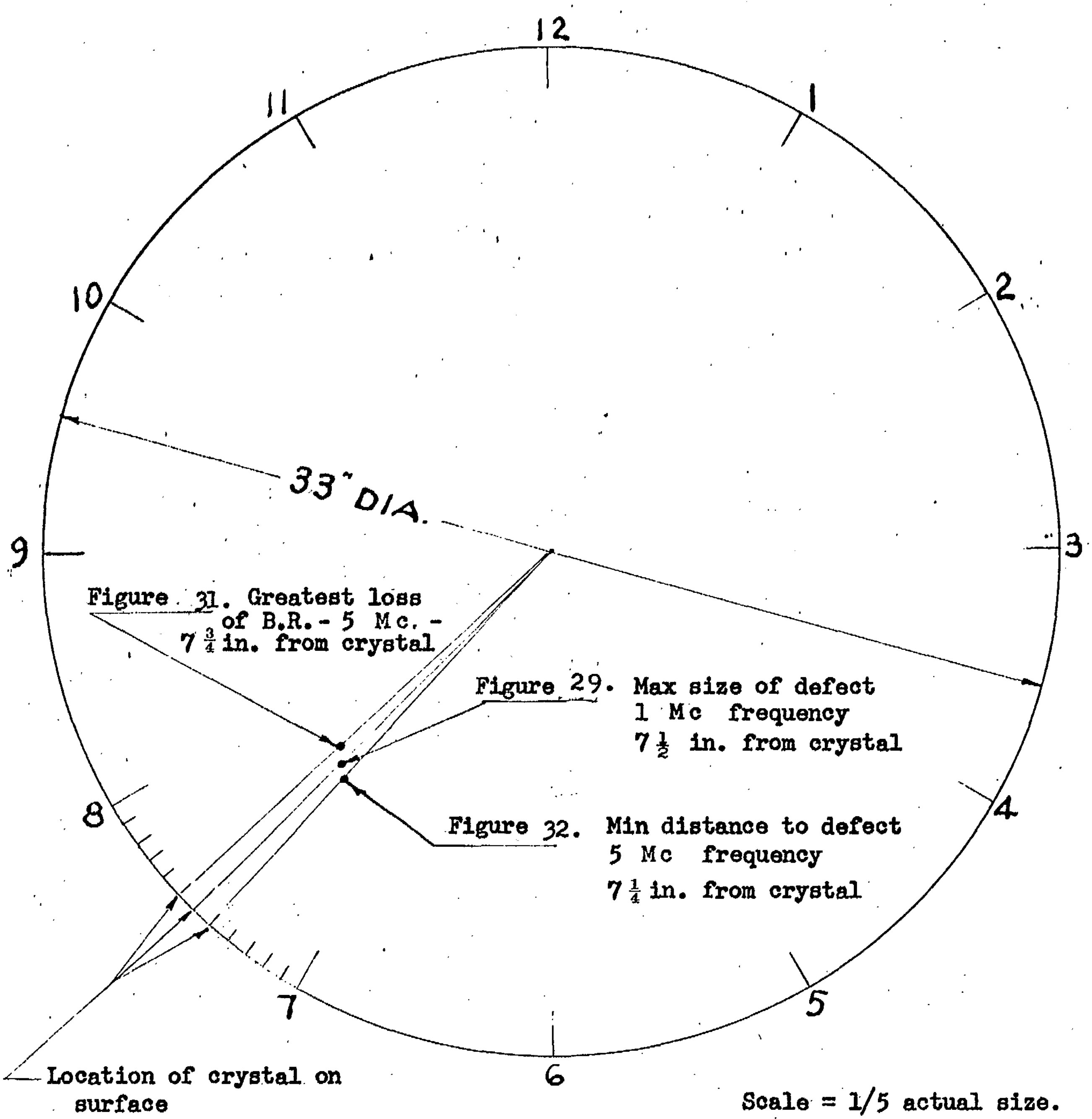


Figure 27. Cross-section of rotor, located 16½ in. from top end of 33 in. diam.

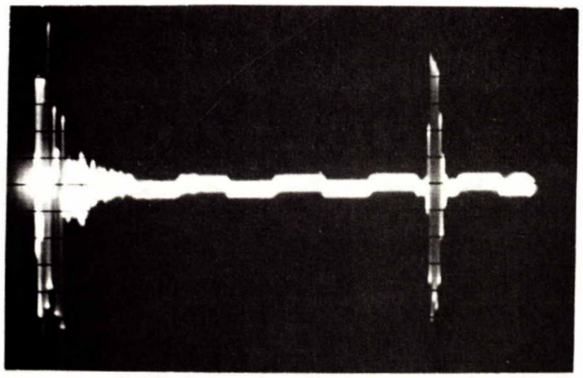


Figure 28. A defect-free area in the 33 in. Ø section.
1 Mc Frequency.

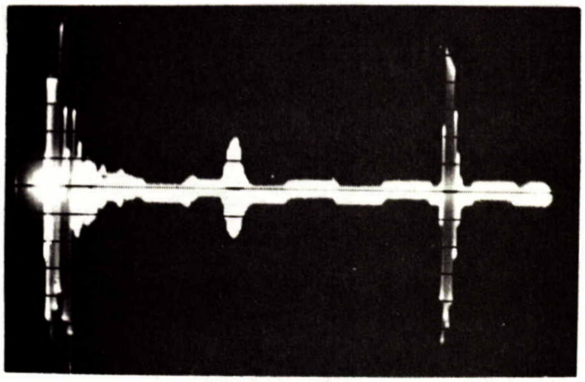


Figure 29. Defect #27 at location of max. size.
Clock reading, 7.30.
Distance from crystal, 7-1/2 in.
Distance from top of 33 in. Ø section, 17 in.
1 Mc Frequency.

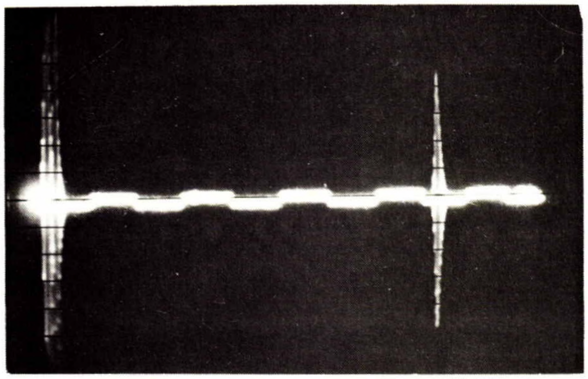


Figure 30. A defect-free area in the 33 in. Ø section.
5 Mc Frequency.

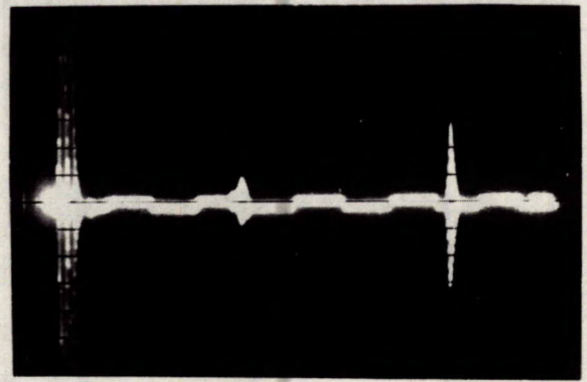


Figure 31. Defect #27 at location of greatest loss of bore reflection.
Clock reading, 7.35.
Distance from crystal, 7-3/4 in.
Distance from top end of 33 in. Ø section, 16-3/4 in.
5 Mc Frequency.

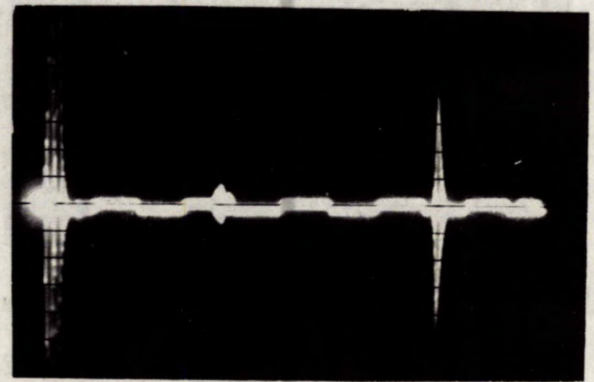


Figure 32. Defect #27 at location of min. distance of defect to crystal.
Clock reading, 7.25.
Distance from crystal, 7-1/4 in.
Distance from top end of 33 in. Ø section, 17-3/8 in.
5 Mc Frequency.

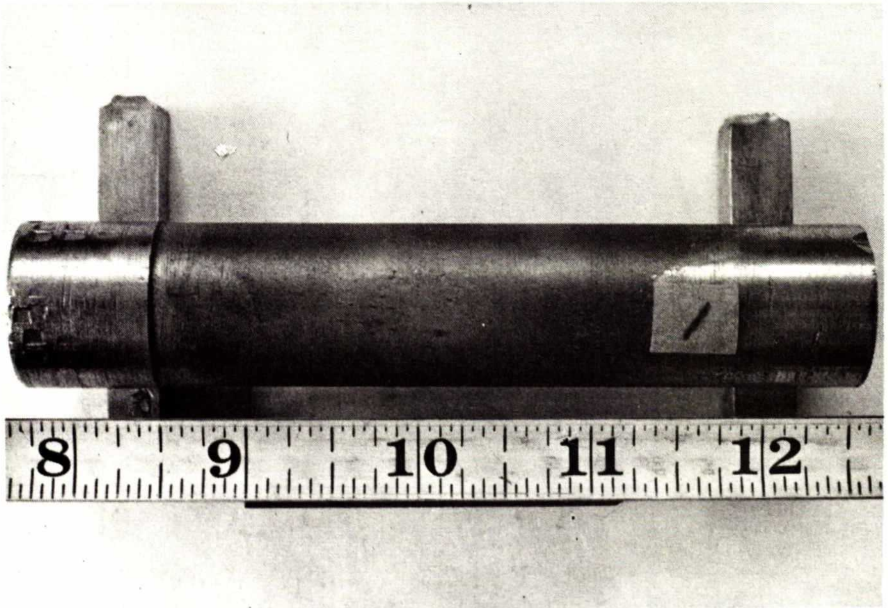


Figure 33. Core piece containing defect No. 27, after magnetic particle testing.

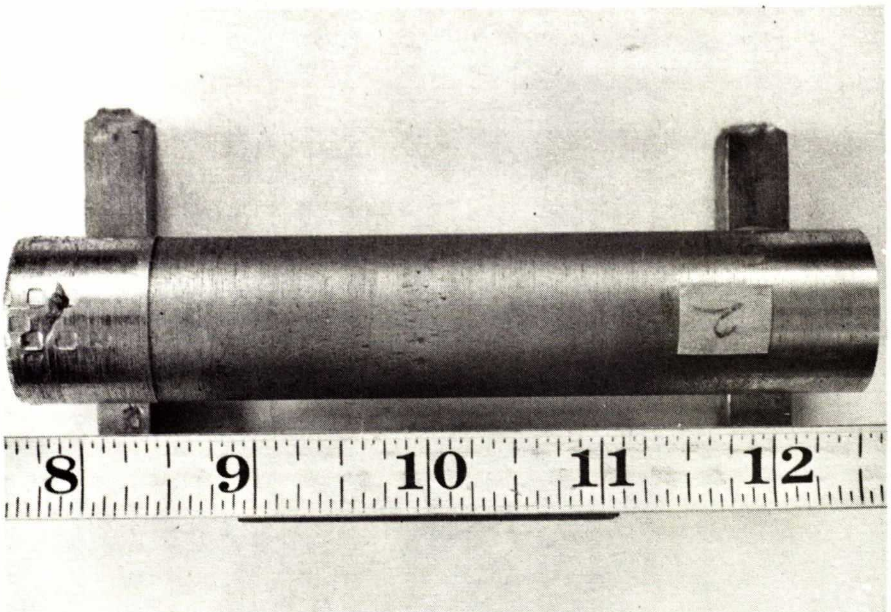


Figure 34. Core piece containing defect No. 27, after magnetic particle testing; the core is turned 180° from the view shown in Figure 33.

APPENDIX 4. - ELECTRIC FURNACE ROTOR M-16

History

Heat No. 5D 175 (M-16) was melted in a 30-35 ton, basic electric furnace located at Montreal Works. This heat was tapped on March 24, 1955 (see Table 4 for the melting practice employed), and the ingot (37 tons) was shipped hot to Trenton. The temperature of the ingot was approximately 565°C (1050°F) on removal from the hot box and the ingot was then immediately transferred to a furnace for heating to forging temperature, 1260°C (2300°F).

The forging operation, in which a 7000-ton press was used, consisted of separating the ingot into two sections after blocking (M-16 and M-17). Each section was upset, and then forged to the required dimensions using V-dies. The forgings were then placed in a car-type furnace for the dehydrogenizing treatment.

Following this treatment, rotor M-16 was rough-turned and then heat-treated in a pit-type furnace to develop the desired physical properties.

The rotor was rejected for sand patches on the outer surface and for zones of poor ductility.

Analysis of Ingot:

	%
Carbon	- 0.31
Manganese	- 0.67
Phosphorus	- 0.007
Sulphur	- 0.011
Silicon	- 0.275
Nickel	- 2.65
Chromium	- 0.166
Molybdenum	- 0.55
Vanadium	- 0.09

TABLE 4

Melt Practice, Heat 5D 175 (M-16), tapped March 24, 1955

Charge:

Iron ore		Nil
Lime	-	5,000 lb
Fluorspar	-	450 "
Carbon steel scrap	-	67,360 "
Alloy steel scrap	-	15,240 "
Electrodes	-	450 "
Nickel anodes	-	1,816 "
Ferromolybdenum	-	629 "

Refining Additions:

Lime	-	1,350 lb
Swedish ore	-	2,700 "
Fluorspar	-	370 "
Sand	-	180 "
Fine petroleum coke	-	285 "

Furnace Alloys:

Nickel anodes	-	60 lb
Ferromolybdenum	-	24 "
Ferromanganese (H.C.)	-	210 "
Ferromanganese (M.C.)	-	400 "
Ferrovanadium	-	175 "
Ferrosilicon	-	550 "

Ladle Additions: - Nil

Pouring:

Nozzle - $1\frac{1}{4}$". (Rate of rise, 4.87 in./min in ingot body. 16 min.)

Stream and stopper - good.

Skull - almost nil.

Refractories:

Ladle: Dande ladle firebrick.

Nozzle: High cone nozzle surrounded with high refractory cement "Helspot".

Ultrasonic Survey

The larger-diameter sections of the rotor (32-7/8 in. and 31-11/16 in., shown in Table 5) were machined and polished in preparation for testing. The center axis bore, like that of M-1, required only cleaning.

The main survey was conducted at 5 Mc frequency, using a single-type search unit. The indications were so small that surveying at the lower frequencies of 1 Mc and $2\frac{1}{4}$ Mc was not considered suitable. Only six indications were considered worthy of any attention, and these even at the 5 Mc frequency were all smaller than that received from a 1/8 in. diameter flat-bottomed hole drilled in a suitable rotor material test block. (This test block was part of a sectioned rotor.)

A survey was also made with a 1 Mc frequency tandem search unit. No travelling indications were detected.

The results of the survey are presented in Table 5.

From the results of the survey it was realized that the rotor did not contain any large defects. The indications that were detected resembled those received from small non-metallic inclusions or clusters of inclusions. Before selecting one of the six defects for removal, they were all "pinpointed" so that the ultimate selection could be governed by the further information derived.

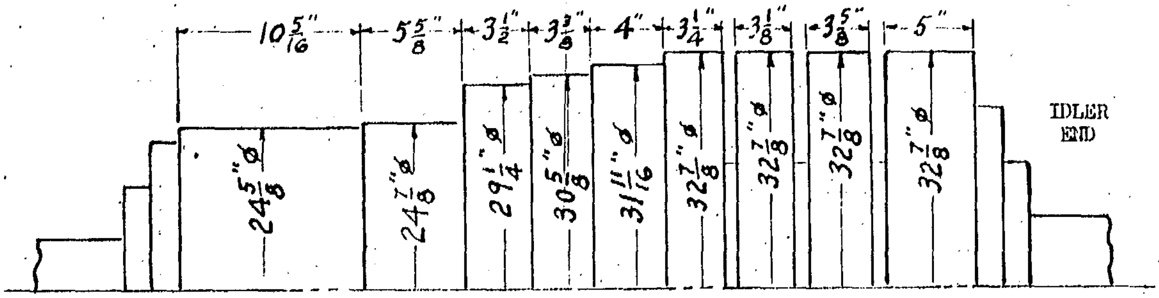
Pinpointing of Six Defects

The procedure outlined in Appendix 2 was followed. However, with rotor M-16 the defects were so small that they had no visible effect on the bore reflection, and thus the search unit location corresponding to the maximum loss of bore reflection could not be found for any of the indications. Table 6 lists the results of the pinpointing, and illustrates with appropriate reflectograms the appearance of each indication at the various search unit locations and frequencies. The reflectograms in the extreme right hand column of Table 6 provide an idea of the size of each defect. The reflectograms shown in this column were made with settings which would render a two-division (0.2 in. high on screen) indication from a 1/8 in. diameter flat-bottomed hole, located close to the bore of a rotor similar to M-16.

TABLE 5

Results of Ultrasonic Survey on Electric Furnace Main Rotor M-16

Dimensional Diameters Submitted to Ultrasonic Survey at 1 Mc, 2 1/4 Mc, and 5 Mc:



Instrument Settings and Results:

1 Mc, single, 1-1/8 in. diam. crystal

Settings: Sweep length, 4.9; pulse length, 5.2; pulse tuning, 3.1; sensitivity, 4.1.

Results: The indications obtained were small. Surveying at this frequency was not considered feasible, because the signals were obscured by base line hash.

1 Mc, tandem crystal

Settings: Sweep length, 4.9; pulse length, 5.2; pulse tuning, 10.5; sensitivity, 3.1.

Results: No travelling (radially oriented) defects.

2½ Mc, single, 1-1/8 in. diam. crystal

Settings: Sweep length, 4.9; pulse length, 4.5; pulse tuning, 3.1; sensitivity, 1.8.

Results: A few indications were detected, but the signals were so small that the possibility of missing some existed. Rapid surveying at this frequency was not considered feasible.

5 Mc, single, 1-1/8 in. diam. crystal

Settings: Sweep length, 4.9; pulse length, 3.9; pulse tuning, 4.9; sensitivity, 1.7.

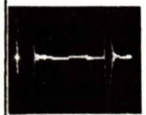
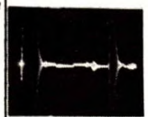
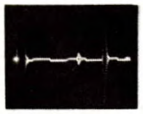
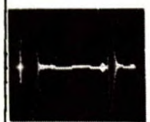
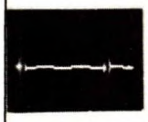
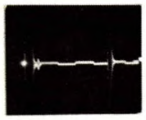
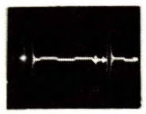
Results: The above settings are those which revealed a two-division indication from a 1/8 in. diam. flat-bottomed hole drilled in a test block made from rotor material. No indications over 2 divisions were found. The six largest indications were selected for more attention, and details of these follow:

Defects Shown with 5 Megacycles:

Indication No.	Rotor Diam., in.	Approx. Clock Position	Dist. from Crystal, in.	Magnitude, divs.	Distance from Idler End of 32-7/8 in. Diam. Section
1	32-7/8	5.58	11	less than 2	1-3/8
2	32-7/8	5.35	10-1/4	2	13/16
3	32-7/8	9.50	12-3/4	2	1-7/16
4	32-7/8	5.10	14-1/4	2	12-1/4
5	31-11/16	8.45	2	2	20-9/16
6	31-11/16	12.20	11-3/4 and 13-1/2	2	20-1/2

TABLE 6

Results of Pinpointing, and Appearance of Six Defects, in Rotor M-16

	Shortest Distance Search Unit/Defect		Largest Defect Signal		Indications rec'd with settings for 2 Divisions from 1/8" dia. F.B. Hole	
	Frequency - 5 Mc Settings: S.L.-4.9 P.T.-4.9 P.L.-3.9 Sens.-3.7		Frequency - 1 Mc Settings: S.L.-4.9 P.T.-3.1 P.L.-5.2 Sens.-3.2		Frequency - 2.25 Mc Settings: S.L.-4.9 P.T.-3.1 P.L.-4.5 Sens.-1.8	
	Markers 6 - 1 Up and 1 Down - 6"					
	Location	Reflec-togram	Location	Reflec-togram	Location	Reflec-togram
DEFECT 1	L = 1-3/8" C = 5.58 D = 11"		L = 2" C = 5.50		L = 1-7/8" C = 5.55	
DEFECT 2	L = 13/16" C = 5.35 D = 10-1/4"		L = 1-1/4" C = 5.30		L = 7/8" C = 5.35	
DEFECT 3	L = 1-7/16" C = 9.50 D = 12-3/4"		L = 2" C = 10.05		L = 2" C = 9.53	
DEFECT 4	L = 12-1/4" C = 5.10 D = 14-1/4"			No Signal		Only .3" thickening of sweep line at back reflection visible
DEFECT 5	L = 20-9/16" C = 8.45 D = 2"			No Signal	L = 20 3/4" C = 8.45	
DEFECT 6	L = 20-1/2" C = 12.20 D = 11-3/4" 13-1/2"		L = 20-3/4" C = 12.15		L = 21" C = 12.20	

LEGEND:

L = Distance from centre of search unit to idler edge of 32-7/8" Ø.

C = Clock position of search unit on surface of Rotor.

D = Distance between search unit and defect.

Selection of Defect for Physical Examination

In selecting one defect out of the six for physical examination, there was not much to choose from. In each case, the defect did not have any appreciable length, and the pinpointing locations for both the 5 Mc and 1 Mc search units were close together. The defects were short and of a type which did not lend itself to orientation determination. Defect No. 6 was interesting in that it yielded two indications, was close to the bore, had a reflecting area approaching that of a flat-bottomed 1/8 in. diameter hole, and probably was the largest of the six. A further interesting feature about this defect was that it yielded an indication larger than that yielded by a 1/8 in. diameter hole, but only when a frequency of 1 Mc was used. It was decided that this defect, No. 6, would be removed for examination.

Removal of Defect No. 6

A 1-15/16 in. diameter drill was centered on a point 20½ in. from the idler edge of the 32-7/8 in. diameter, at 12:20 on the rotor clock. (This was the location of the shortest distance from the search unit to the defect as determined by the 5 Mc search unit.) A radial hole was drilled from this point until the drill tip was only 6 in. from the bore surface. From this point on, a coring tool was substituted for the drill, and a core 5-7/8 in. long was removed. The innermost end of the core was the bore surface. Since the defect occurred at 11-3/4 in. and 13-1/2 in. from the surface of the rotor, and since the outside surface to bore surface distance was 14.53 in., the defects in the core itself were expected over a 1-3/4 in. length, starting 1 in. from the bore surface.

Examination of Core Containing Defect No. 6

On the surface of the core, two defects--identified as No. 1 and No. 3 -- could be seen (see Figure 35). After a magnetic particle test was applied, an additional defect -- identified as No. 2 -- was evident at approximately 180° from defect No. 3 (see Figure 36). The distances from the bore to the three core defects were measured as:

Defect No. 1 - 1 in. from bore surface.
Defect No. 2 - 2-3/8 in. from bore surface.
Defect No. 3 - 2-3/8 in. from bore surface.

Defects Nos. 1 and 3 stood out more clearly after magnetic particle testing, as illustrated in Figure 37.

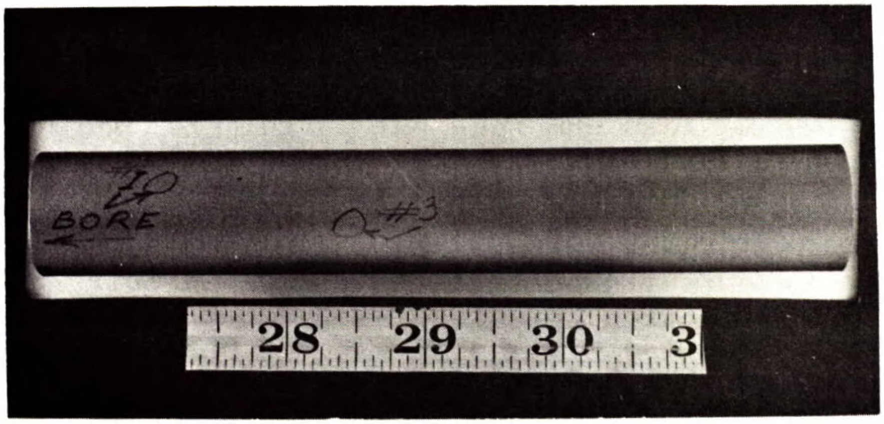


Figure 35. Core piece as removed from rotor M-16, in the non-magnafluxed condition. Defective areas Nos. 1 and 3 are outlined.

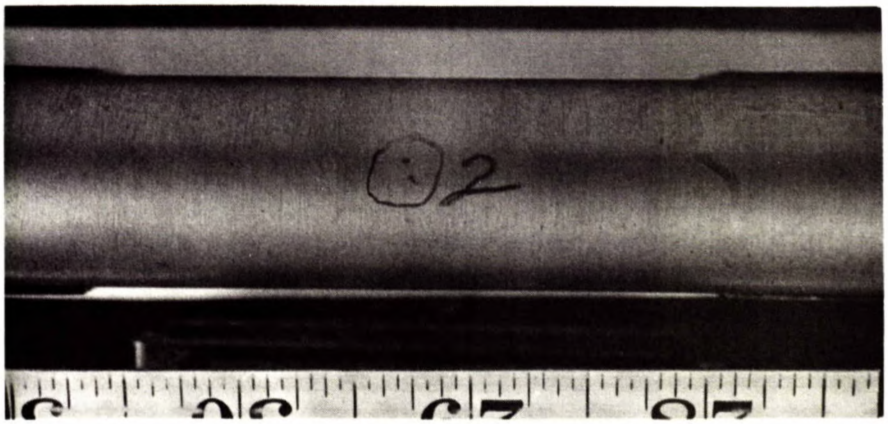


Figure 36. Core piece as removed from rotor M-16, in the magnafluxed condition, turned 180° from the view shown in Figure 35. The No. 2 defect area is located approximately opposite to defective area No. 3. This defective area is invisible without magnetic particle inspection.

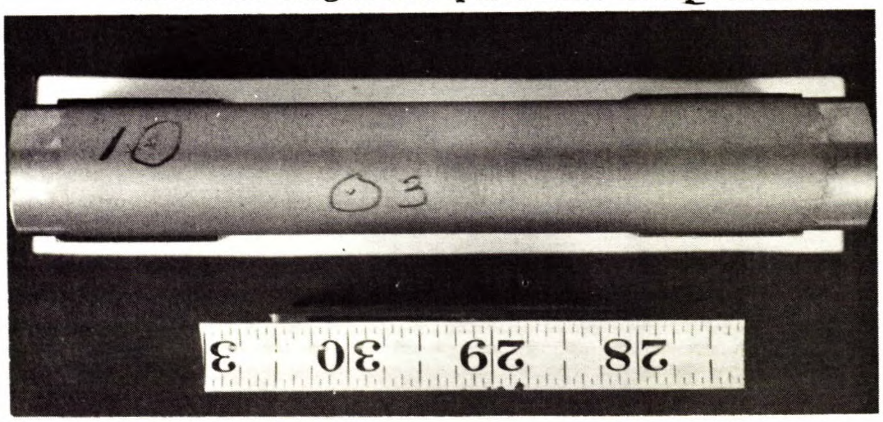
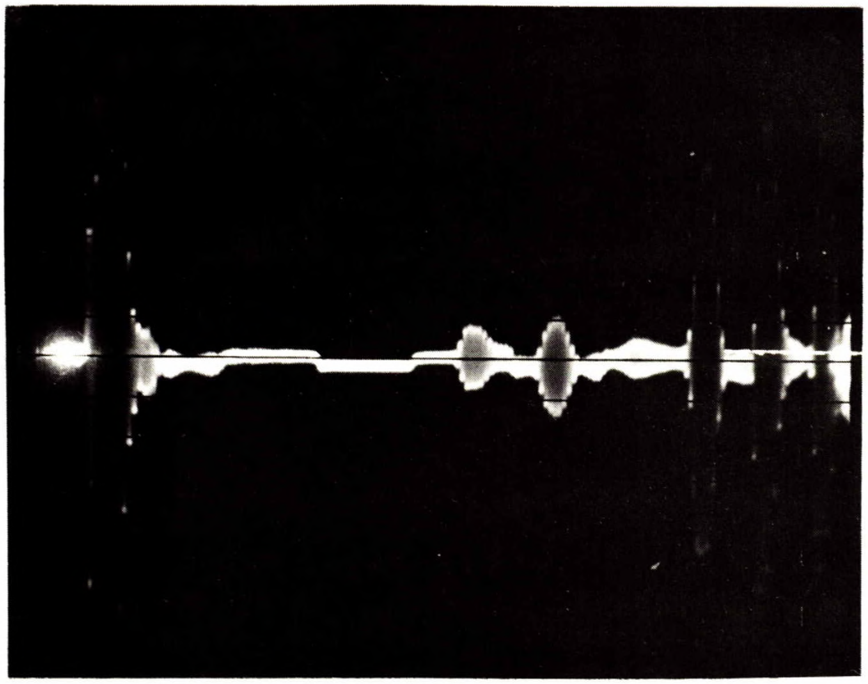


Figure 37. Core piece as removed from rotor M-16, in the magnafluxed condition. Defective areas Nos. 1 and 3 are outlined.

The core itself was tested ultrasonically. At 5 Mc frequency, the defective area yielded a multitude of small indications which changed their shape and size upon only slight movement of the search unit. At $2\frac{1}{4}$ Mc frequency, the indications became less numerous but larger; Figure 38 illustrates the indications visible. It is believed that the lower $2\frac{1}{4}$ Mc frequency was less able than the 5 Mc frequency to separate the small defects, but did give a more general picture of the defective condition. Returning to Figure 38, and using the distance markers, it was established that the first and third indications from the back reflection coincided with areas #1 and #2 at 1 in., and #3 at 2-3/8 in. from the bore. The second indication, which is the highest of the three visible, stems from a point 1-5/8 in. from the bore surface. This indicates the presence of a further defect within the core at this point.

To provide a means of assessing the size of the three defects, Figure 39 may be used. This is a reflectogram illustrating the size of indication produced by a 1/16 in. diameter flat-bottomed hole when located 3 in. from the search unit, all other conditions being equal to those used for the reflectogram in Figure 38.



Back reflection from end of core corresponding to bore surface.

Figure 38. Reflectogram illustrating indications from core containing defect No. 6. $2\frac{1}{4}$ Mc setting.

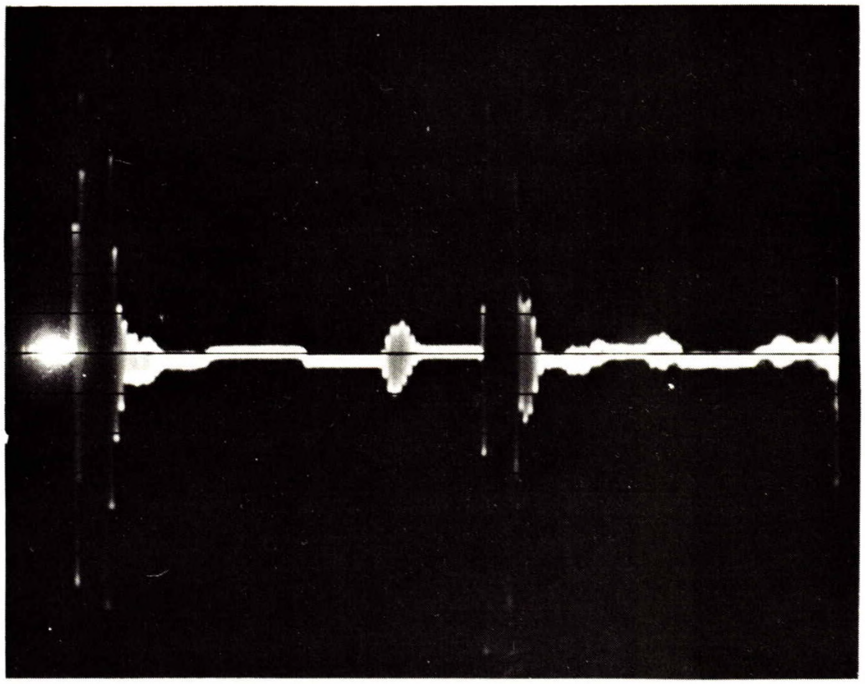


Figure 39. Reflectogram illustrating indications from a rotor test block containing a 1/16 in. diam. flat-bottomed hole 3 in. from the search unit. $2\frac{1}{4}$ Mc setting as for Figure 38.

NOTE: Each step on base line represents 1 inch of beam travel.

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