Evaluation of EM rope testers: joint Canada/US work paper for ASNT conf., Oct. 8-12, 1990, Seattle, WA

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MRL report #90-052 (OP) June, 1990

EVALUATION OF EM ROPE TESTERS: JOINT CANADA/US WORK

by

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For presentation at the ASNT Oct. 8-12, 1990, Seattle, WA, Conference on "NDT for Today's Application"

ABSTRACT

The authors describe results obtained in the course of extensive cooperative work in Canada. It was undertaken by the Canada Centre for Mineral and Energy Technology's (CANMET) Mining Research Laboratories (MRL), in close cooperation with the US Department of Labor's Mine Safety and Health Administration (MSHA), and with the support of Canadian mines, their regulatory authorities, and the wire-rope manufacturing industry.

The basic project objective was to examine, analyse, and clarify the reasons for continuing mine-shaft wire-rope failures (or near failures) that occur despite routine non-destructive testing (NDT) with electro-magnetic (EM) instruments. The project is a first both as to its depth and its scope.

Project goals were attained. It was concluded that, at this time, the principal problem area with EM testing is more of a human than of a hardware-related nature. An overview of the test results, and of our conclusions, is given in this paper. Complete details are provided elsewhere, in referenced reports.

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Keywords: US; Canada; mine-shaft; wire-ropes; Non-destructive-testing; Electro-magnetic instruments

ÉVALUATION DES APPAREILS D'ESSAI ÉLECTROMAGNÉTIQUES (AE) DE CÂBLES : PROJET CONJOINT RÉALISÉ PAR LE CANADA ET LES ÉTATS-UNIS

par

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Pour une présentation à la conférence "NDT for Today's Application" (Les END et les applications d'aujourd'hui) organisée par l'ASNT, du 8 au 12 octobre, à Seattle, Washington.

RÉSUMÉ

Les auteurs décrivent les résultats obtenus dans le cadre d'importants travaux menés conjointement au Canada. Ces travaux ont été entrepris par les Laboratoires de recherche minière du Centre canadien de la technologie des minéraux et de l'énergie (CANMET), en étroite collaboration avec le Department of Labor's Mine Safety and Health Administration (MSHA) des États-Unis et avec l'appui des mines canadiennes, des organismes responsables de leur réglementation et de l'industrie de la fabrication de câbles métalliques.

À l'origine, le projet avait pour but d'examiner, d'analyser et de clarifier les raisons des ruptures (ou quasi-ruptures) de câbles métalliques utilisés dans les puits de mine, malgré les

d'essais non destructifs (END) de type courant auxquels ces câbles sont soumis au moyen d'appareils électromagnétiques (AE). Ce projet constitue une première, à la fois en raison de son étendue que de son objet.

Les objectifs du projet ont été atteints. On a conclu qu'à l'heure actuelle, le principal problème relatif aux essais réalisés à l'aide d'AE est davantage imputable à des défaillances humaines que mécaniques. Le présent document donne un aperçu des résultats de l'étude et de nos conclusions. Les résultats complets sont fournis dans d'autres rapports plus détaillés.

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Mots clés : États-Unis, Canada, puits de mine, câbles métalliques, essais non destructifs, appareils électromagnétiques.

CONTENTS

INTRODUCTION

Cooperative work by US and Canadian Federal, as well as Provincial, organizations in the field of hoisting technology has been ongoing for close to a decade. One area of special interest is concerned with the NDT of mine-shaft wire-ropes. At the request of the Canadian mining industry, and of its regulatory authorities, CANMET undertook a major research project in 1986. Its principal objective was to investigate why, on occasion, mine-shaft wire-ropes continue to catastrophically fail, or almost fail, despite several decades of mandatory testing with EM instruments on a routine basis.

CANMET's project consisted of both in-house and contracted work phases. Their in-house project-phase covered an in-depth examination, and analysis: (1) of the instrument charts and test-reports obtained in the course of their contracted project-phase, (2) of extensive data-banks, containing results of previous destructive (DT) and non-destructive (NDT) wire-rope tests. Most of these data were provided by Canadian provincial authorities, the USBM, and MSHA, (3) of the mine-shaft wire-rope discard criteria, as mandated by various regulatory agencies, (4) of the relevant training and certification aspects, that apply to both the EM instruments and to their operators, and (5) of the constructional details of Canadian mine-shaft ropes.

CANMET also assembled an extensive data-bank of its own in the course of its contracted project-phase. These data cover non-destructive, as well as destructive tests. They were obtained with three Canadian (the Magnograph, Rotescograph, and Rotesco AC), and one American (LMA-250 series), commercially available, instruments. A West German prototype instrument of WBK design was also used. Its test results are, however, not available as yet. Many of the tests were performed with instruments, and staff, from Canadian mines and from MSHA. Others were undertaken by service companies. All instrument operators were known to, and approved by, the instruments' makers/designers. All tests were performed completely independently of each other. Results were not disclosed to any of the operators before being submitted to CANMET.

Rope sizes ranged from 7/8 in. to 2 1/4 in. Rope constructions included stranded, locked-coil, and spin-resistant designs. Tests were undertaken on four specially manufactured ropes with artificial defects, and on 14 operational ropes. The latter were tested both in the field and, subsequently, reel-to-reel on the shop-floor of Wire Rope Industries Ltd. at Pointe Claire, Quebec.

On the shop-floor the Rotesco AC was tested first, on its own, in order to make sure that the ropes were effectively demagnetized before, and remained so during, the tests. The other instruments, with their powerful permanent magnets, were then tested together. After carefully testing for their polarities, they were appropriately aligned in series on a wooden table. General views of the test procedure are presented in Figure 1. Complete details of both the in situ and shop-floor tests are provided elsewhere (1, 2, 3).

RESULTS

In this report we have insufficient space to provide complete details of our project-results. These are covered in the referenced (1 to 6) CANMET reports already published. Additional ones are in the process of preparation. In this paper we provide an overview of the major results.

Accuracy of LBS estimates

As discussed in detail elsewhere (1, 2, 3), an excessive number of EM instrument-based loss-of-breaking-strength (LBS) estimates are outside the ±4.0% benchmark parameter of Ontario's "Performance Requirements of EM Mine Shaft Rope Testing Devices". This is illustrated in the error distribution bell-curves, and in the cumulative DT vs NDT test-result diagrams of Figures 2 to 5. One could, perhaps, question: (a) our choice of the ±4.0% benchmark parameter, and (b) our reasons for restricting the analysis of the DT/NDT data pairs to those that were obtained from the worst rope sections only — while ignoring the large number available from other rope sections. In reply we state that: (a) we were unaware of any other benchmark parameter we could have used instead, and (b) the accuracy of the LBS estimates for the worst rope sections is the vital one; that for the better rope segments is of somewhat less importance.

Interestingly, the data in Fig. 5 indicate that in a number of cases the "true" LBS values (i.e., the ones obtained destructively) greatly exceeded the limits set by the regulatory authorities. Often, in fact, they also much exceeded the corresponding LBS estimates. It can also be seen (Table 1 and Figures 2-5) that the LBS estimates based on chart readings obtained with "dual-function" instruments — such as the Magnograph, Rotescograph, and LMA-250 — are better than the ones based on "single-function" testers, such as the Rotesco AC. Consequently, we see no justification in limiting official testing to the latter instrument only. In this context "dual-function" means instruments whose charts record both the local-fault (LF) and the loss-of-metallic-area (LMA) signals, while single-function testers only display one of these.

We wish to emphasize, though, that the safety of mine-hoisting has been much enhanced by the use of any one of the abovementioned instruments; within their physical-design imposed limitations all performed satisfactorily during our test series. These limitations represent one of those aspects we feel some instrument operators are not sufficiently aware of.

To assist instrument users, and prospective users, in assessing the performance of the various commercially available testers, we assembled a "list of desirable instrument characteristics" (5). Individual users' special needs and particular requirements must, of course, be the determining factor when making final choices.

Reasons for inaccurate LBS estimates

As mentioned earlier, we feel that, at this time, the major cause for inaccurate test-results is of human, rather than hardware related origin. We base our conclusion on a careful analysis of our project results. These proved that the crux of the matter involved the operator. Test results were equally good, or bad, no matter which instrument was used, and whether it was operated by a service company, mine, or the instrument maker. However, only limited reliance can be placed on results, unless they are obtained by an operator: (a) who has an in-depth understanding of his instrument's capabilities and limitations, as well as of the entire measuring process as a whole — including instrument calibration, gain-settings, chart-reading and splicing procedures, LBS calculations, etc., (b) is fully committed and motivated, (c) is well aware of the technical and operational background of the rope being tested, that of its predecessors' and companion-ropes, as well as of all relevant matters concerning the general hoisting procedures and shaft-layout in use.

In our opinion the single, major, cause for the inaccurate LBS estimates can be found in the ill-understood and nebulous process used to convert measured LF and LMA, as obtained from the chart recordings, into the LBS estimates called for by the mining regulations. We are unaware of any relevant, properly documented, algorithm in the public domain for doing this. In fact some service companies refuse to provide LBS estimates (contending that it is impossible to accurately estimate LBS), while others refuse to disclose just exactly what research their method is based on. Only one company was willing to discuss this problem with us in detail. We shall revert to it in a future publication.

Reasons for inaccurate LMA reporting

From what we said in the foregoing it might appear that mandated rope discard criteria should, in fact, not even call for NDT based LBS estimates — a proposition often advocated. At this time we are unable to fully agree among ourselves as to the merits, or otherwise, of this proposition. Some of us disagree with it, saying that:

(a) as far as the general public is concerned, rope removal on the basis of LBS is a more straightforward, and easily understood, concept than on the basis of LMA;

(b) we have ample documentation relating "true" LBS data to estimated values. We are unaware of any comparable data-bank for "true" vs chart-reading based LMA values. Some such data have been published, but most of them are based on laboratory situations, rather than operational ones. To build up such a data-bank would, of course, be prohibitively expensive. It is much simpler to obtain the destructive vs non-destructive LBS test results, and even these data-banks are very expensive and difficult to maintain at the necessary level of accuracy;

(c) our present contracted test series provides ample evidence that reported LMA results too are prone to serious mistakes of a human nature. Some of the original reports contain mistakes due, primarily, to: (1) misplaced 100% reference levels in their LMA charts, (2) to ignored instrument related phenomena — which will require further investigation — such as droop, zero drift, and quantitative resolution and (3) to erroneous instrument calibration and gain-settings.

Others among us are of the opinion that, in view of the fact that even the measured LMA data are prone to human error, one should not further compound the problem by trying to convert from actual instrument data (LMA and LF chart traces) to uncertain LBS estimates.

Results of our present test series might assist the regulatory authorities in weighing the pros and cons of the two viewpoints.

In Tables 2, 3, 4, and 5 we list examples of mistaken LMA chart-readings. The first two tables cover the shop-floor tests of our $1\frac{3}{4}$ in. stranded ropes with artificial defects, described in detail in ref. 5. Even though, as far as possible, the tabulated results have been corrected, the spread between the various chart-readings, and between some of these and the "true" %LMA values, is "unacceptable", insofar as it is more than the limit of ±2.0% which we, as well as others (5, 7) would expect, considering the capabilities of present day EM instruments.

Tables 4 and 5 cover the in situ and shop-floor results obtained with a $1\frac{1}{4}$ in. FLC operational rope, described in detail in ref. 6. Here again human errors resulted in "unacceptable" spreads between the different %LMA chart-readings, even after we reviewed and corrected the mistakenly reported ones, as far as we could. In fact we accepted, without major adjustments, only one of the three in situ test reports, and only one of the four shop-floor reports. In our opinion the problems arose, at least in part, from a mistaken recording of the actually used LMA sensitivity, and from problems with proper chart splicing. The former error, for one, could have been discovered, had a calibration wire been taped to the rope. Such a device could also have helped with the proper splicing of charts, and in clarifying just exactly where along the rope the test runs were initiated.

Suggested remedies

The aforementioned, and similar, mistakes could, probably, be avoided, by providing better, and more uniform, training and certification procedures.

In our view it would also be very helpful if: (1) absolute, rather than relative, %LMA chart-readings were to be obtained — at least at the "best" and "worst" rope sections, and (2) if the LF chart traces were rendered more meaningful by some means of proper calibration process. We plan to discuss these two suggestions in more detail in future publications.

In addition it would be useful to consider the possibility of assisting human involvement in the measuring process by computerization of some procedures, e.g., of data-analysis and pattern recognition, and perhaps even of instrument calibration and gain-setting.

Other points of special interest

In addition to the foregoing, test results of special interest also include those that elucidate: (1) the repeatability aspect of the chart-readings, (2) the comparability aspect of the in situ and reel-to-reel measurements, (3) the effect of trapped debris upon the %LMA chart readings, and (4) quantitative resolution.

— Repeatability and Comparability aspects —

We found that results were repeatable to a remarkable degree, and consistently so. As an example, we reproduce in Figures 6 to 13 some of the relevant results, discussed in detail in references 5 and 6. The repeatablility of the characteristic %LMA traces, generated by the artificial defects designated in ref. 5 by the symbols: A6; A9 and A10; A13 and A14; B13 and B12; as well as B15 (Figures 6 to 10), is quite remarkable, especially in view of the fact that these were obtained quite independently of each other, with different instruments, at different times, and with different operators. These figures also illustrate the great advantage in having both LMA and LF chart-traces. The two together make it, inter alia, easier to pin-point the exact location of rope defects, and to say whether these are of a positive or negative %LMA nature.

We also found that results were repeatable and comparable, consistently and to a remarkable degree, between in situ and reel-to-reel tests. As discussed in ref. 6, this was so even if testing occurred at different locations, with different instruments and operators, more than six months apart, and with rough rope handling inbetween (dismantling, transportation). Figures 11, 12, and 13 illustrate this point. Note the similarity between the in situ and shop-floor Rotesco AC charts in Fig. 11, and the near identity of the Magnograph charts in Fig. 12, although here too one was obtained in situ and the other reel-to-reel. Also note the unmistakable fingerprinting of the characteristic rope anomaly in Fig. 13, obtained months apart, once in situ and once reel-to-reel, with different operators and different EM instruments. The dimensions (see Fig. 13a) 'L' (ft), and 'X' (%LMA) are also very similar: 43.6–50.4 ft for 'L', and 2.2–3.5 (at most) %LMA for 'X'.

It would appear, therefore, that even quantitatively the in situ and reel-to-reel test results are comparable. In fact, the in situ and shop-floor test results at the South skip end of our rope #4 are almost identical when obtained with the Rotesco AC and the LMA-250 testers (Table 4). We suspect a human error prevented this to be so in case of the Magnograph tests as well, especially with these two charts being almost identical otherwise (Fig. 12).

The foregoing conclusion on comparability might be contrary to what, on occasion, has been published elsewhere. It will, however, be less surprising on considering the following: (1) the %LMA chart readings are not absolute but relative values, taken, say, at the "worst" in relation to the "best" rope section; but (2) how much does this ratio between the "best" and "worst" change from when the rope is in situ to when it is on the shop-floor?

— Effect of trapped debris —

The artificial defects built into our $1\frac{3}{4}$ in. stranded test-ropes included sections where the fibre-core had been replaced by debris filled plastic tubes (5). This "trapped debris" consisted of: (a) pure iron-filings, (b) magnetite, and (c) actual corrosion products, scraped off our project's operational rope #7. The inside area of the plastic tubes amounted to almost 22% of the test rope's total metallic cross-sectional area.

The filling factor for the loose fillings was in the order of 55%. Even so, the effect of the corrosion products on the LMA signals was nil, or next to nil, while even the maximum effect (i.e., that of the pure iron-filings) was no more than 1.6% LMA, instead of the theoretical 11.0% LMA. This is shown in Table 6.

A detailed discussion of this phenomenon is presented elsewhere (4). These results agree with those published by others (8). Even so, though, one often hears contrary opinions, namely that the effect of trapped debris on the LMA charts is the same as that of a solid rope.

— Quantitative resolution —

In this report we base our comparisons on direct readings of the respective LMA instrument-charts. In case of the $1\frac{3}{4}$ in. stranded test-ropes with artificial defects (Tables 2 and 3) this procedure cannot be faulted, because all of the defects are much longer than the averaging lengths of the individual test-instruments used. In case of real life operational ropes, though — such as the $1\frac{1}{4}$ in. FLC rope (Tables 4 and 5) — we do not know the true extent of the rope defects. We must, however, assume that they cover a considerable range, including short anomalies where the quantitative resolution of the different EM instruments needs to be considered. The sensor head lengths of the instruments used in our test series were some 8-11 in. (the German WBK and the LMA-250) and 14-16 in. (the Rotescograph and Magnograph).

While we are unable to extract relevant information from our own $1\frac{3}{4}$ in. stranded test-rope tests, we referred to this problem on hand of results achieved with the LMA-250 and the Magnograph by others (5). For the step-responses of these instruments we noted a ratio of some 1:1.9, respectively. Moreover, we noted that the Magnograph measures LMA with a 100% efficiency for rope defects that are 11-13 in. long, or longer. Additional investigations will have to be undertaken to further elucidate questions of quantitative resolution.

Additional 'Code of Practice' requirements

We suggest that some of our conclusions might, perhaps, be usefully incorporated in the relevant 'Codes of Practice'. These include: (a) that EM test reports list, and clearly differentiate, between LF and LMA chart readings, and the LBS estimates, (b) that these reports always contain all relevant test- and rope-related data, including the reel number of the ropes. Other suggestions, that might be so incorporated, are listed elsewhere (3).

Suggested follow-on work-phases

While we do not consider any hardware related follow-on work to be of immediate concern, we do suggest that future computerization of data-analysis and of pattern-recognition should be considered. Our immediate concern, however, is with the need to set up facilities for operator training, and for both operator and instrument certification. We are also concerned about the paucity of independent expertise — such as exists, for example, at MSHA — for undertaking EM measurements and chart-evaluations in case of dubious results, or for speeding up action whenever necessary.

SUMMARY

In this report we summarize the conclusions arrived at as a result of a major CANMET project, involving close cooperation between Canadian and US organizations. We note that our principal concern is with mistakes that are of human origin, and not with the quality of the commercially available EM instruments. An overview of the test-results, which led us to this conclusion, is provided. So is a brief discussion of a series of technical details which are of special interest. Full details are available in the referenced publications. Additional papers are in the process of preparation.

Our principal recommendation is to provide better facilities for uniform operator training, and for uniform operator and instrument certification. Here again, as has been the case with the cooperative work described in this report, Canada/US cooperation might be beneficial in achieving the desired training and certification standards speedily, and at mutually acceptable levels.

We believe that there is also a need for more independent experts in the field of EM testing and chart-evaluation, possibly on the staff of mining companies, of research organizations, and of the regulatory authorities.

Moreover, we suggest that the relevant Codes of Practice be expanded with additional recommendations, that would make the test reports more helpful.

Finally, we include a few suggestions as to future development work. We think that computerization of certain techniques might be helpful, e.g., of data-analysis, pattern recognition and even of instrument calibration. As well we suggest the development of novel procedures, such as obtaining absolute, rather than relative, %LMA values, and the use of calibrated LF signals.

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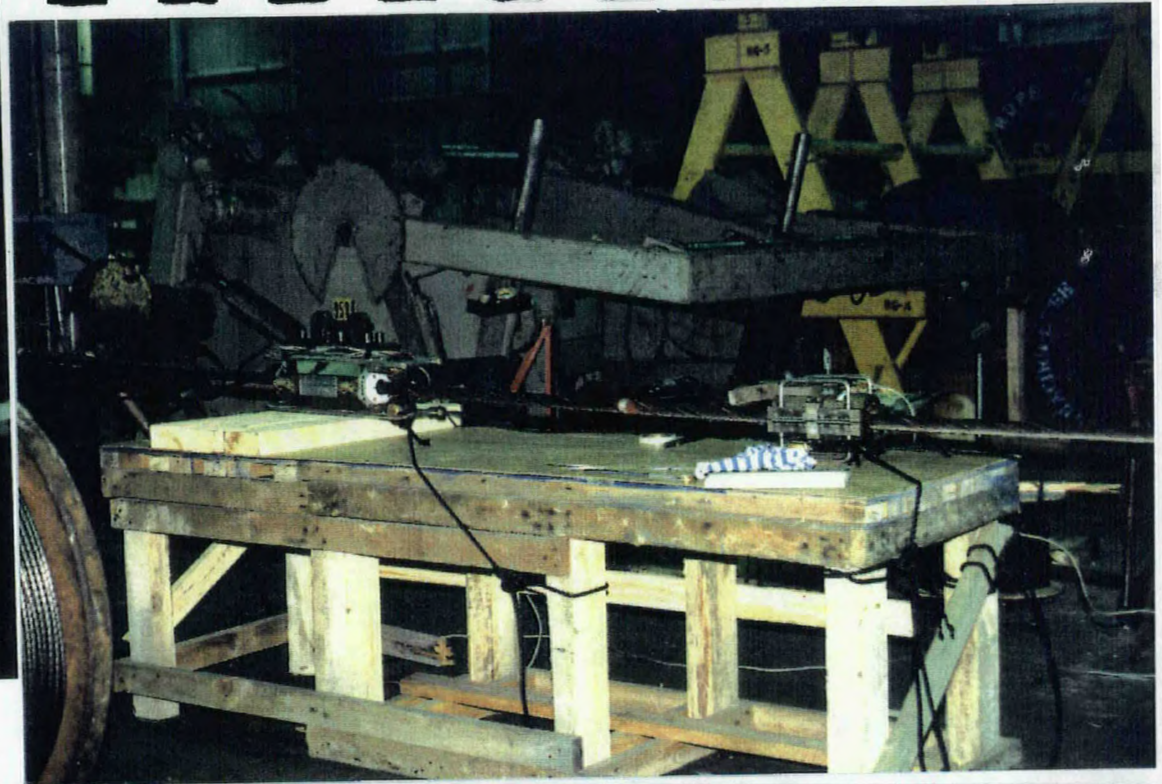
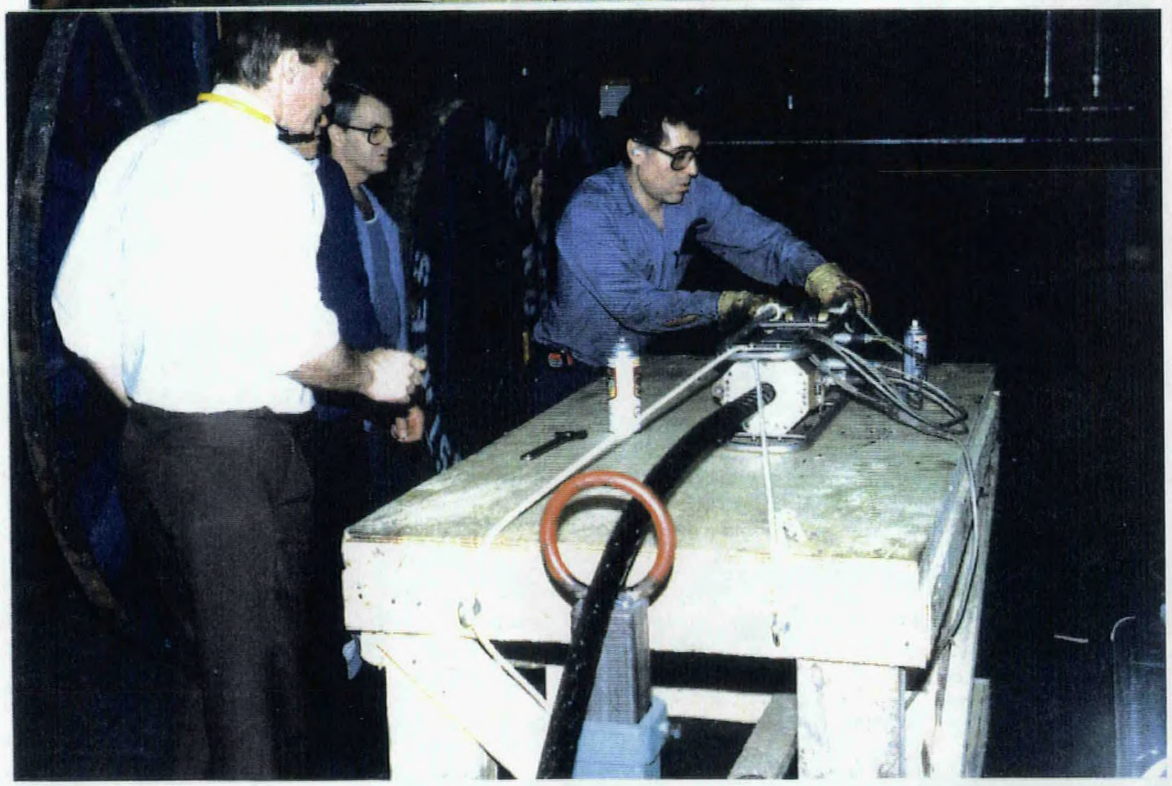
APPENDIX

Figures 1 to 13, as well as Tables 1 to 6, inclusive

(a) view from rope inlet-end



(b) side view: LMA-250 at right, Magnograph at left of picture; rope moving from right to left



(c) view from rope outlet-end

Fig. 1 — General views of test-procedure

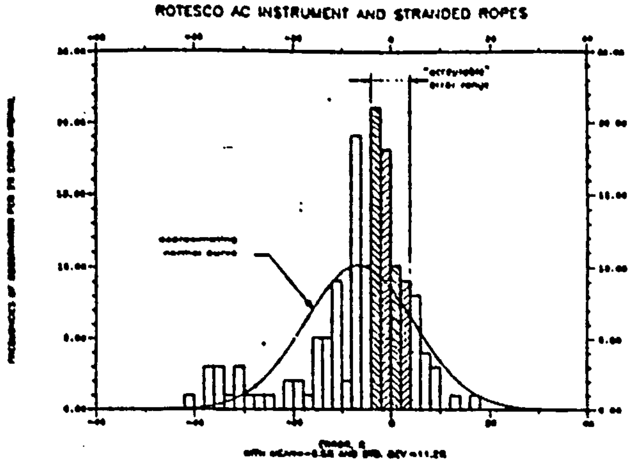


Fig. 2a — Error% vs frequencies of observation (144 altogether), and the approximating normal curve — stranded ropes and Rotesco AC instrument

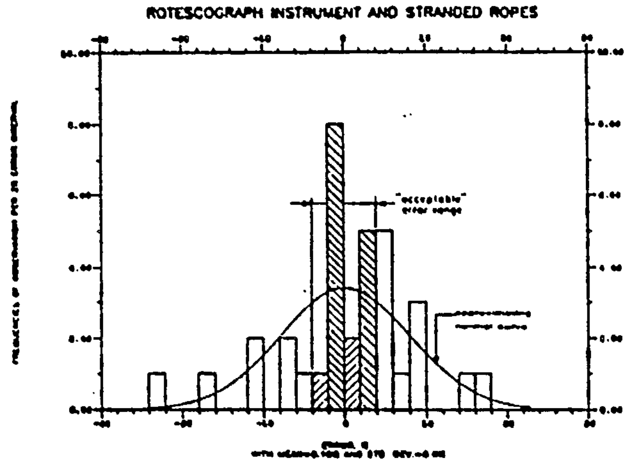


Fig. 2b — Error% vs frequencies of observation (34 altogether), and the approximating normal curve — stranded ropes and Rotescograph instrument

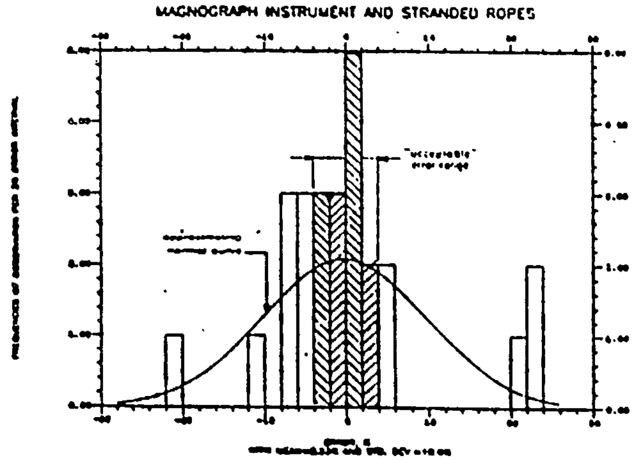


Fig. 2c — Error% vs frequencies of observation (26 altogether), and the approximating normal curve — stranded ropes and Magnograph instrument

Fig. 2 (after ref. 2) — Error% vs frequencies of observation and the approximating normal curve — stranded ropes

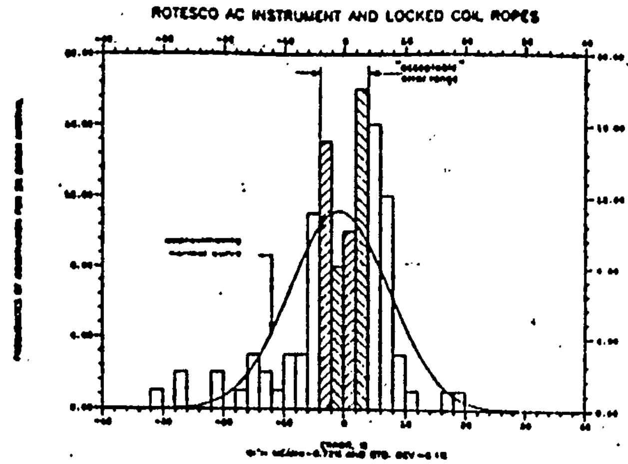


Fig. 3a — Error% vs frequencies of observation (113 altogether), and the approximating normal curve — locked coil ropes and Rotesco AC instrument

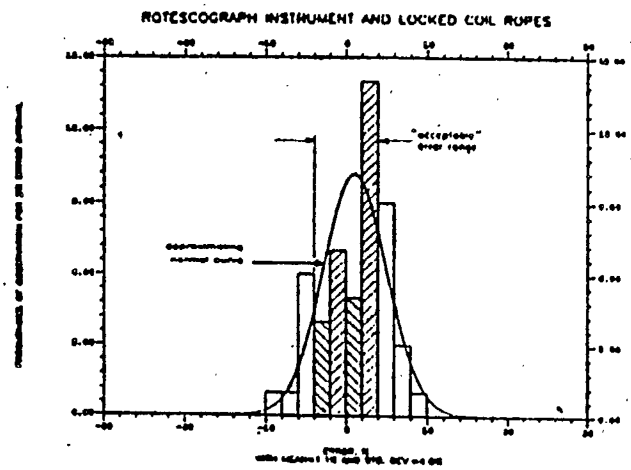


Fig. 3b — Error% vs frequencies of observation (51 altogether), and the approximating normal curve — locked coil ropes and Rotescograph instrument

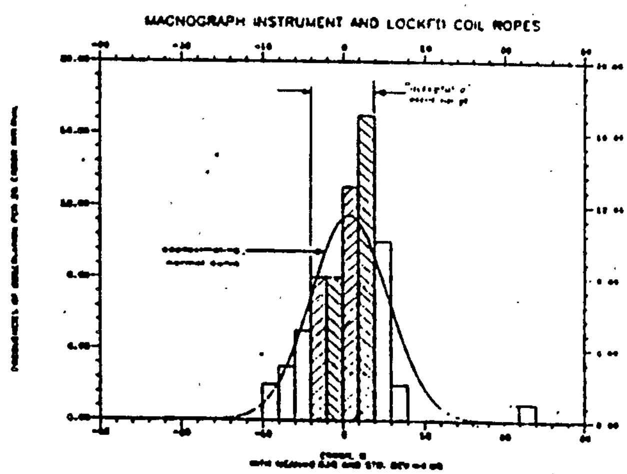


Fig. 3c — Error% vs frequencies of observation (69 altogether), and the approximating normal curve — locked coil ropes and Magnograph instrument

Fig. 3 (after ref. 2) — Error% vs frequencies of observation and the approximating normal curve — locked-coil ropes

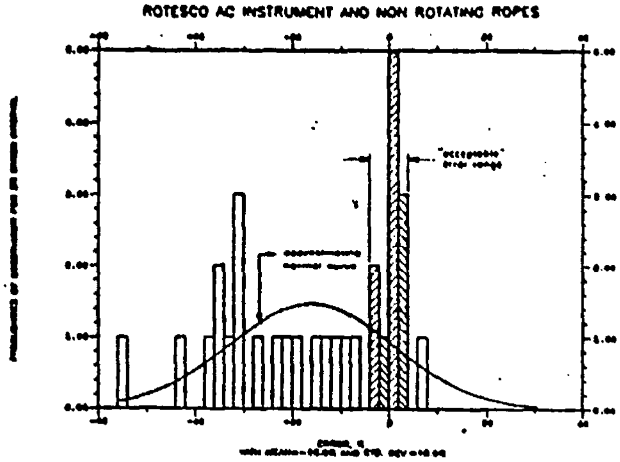


Fig. 4 (after ref. 2) — Error% vs frequencies of observation (31 altogether), and the approximating normal curve — non-rotating ropes and Rotesco AC instrument

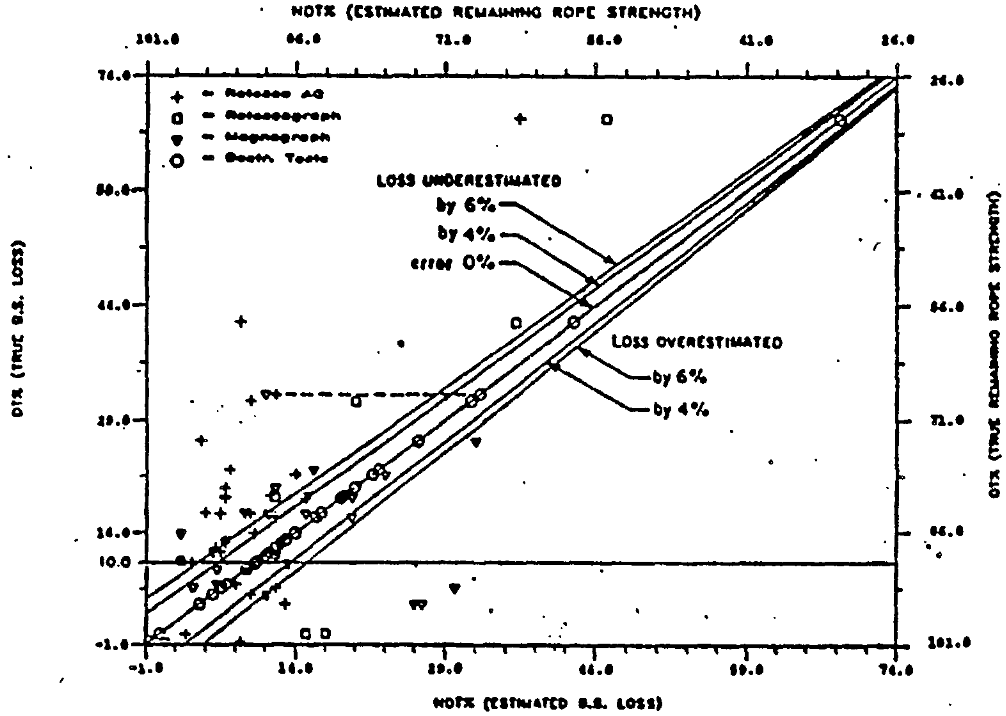


Fig. 5a (after ref. 3) — Stranded ropes; all comparative test data

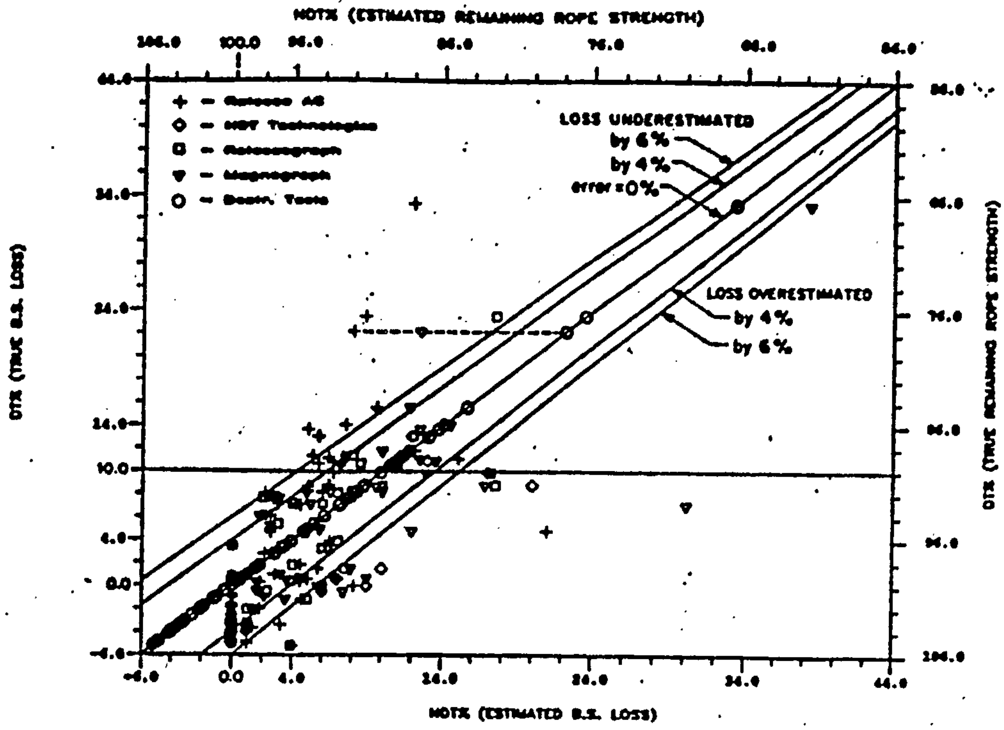


Fig. 5b (after ref. 3) — Locked-coil ropes: all comparative test data

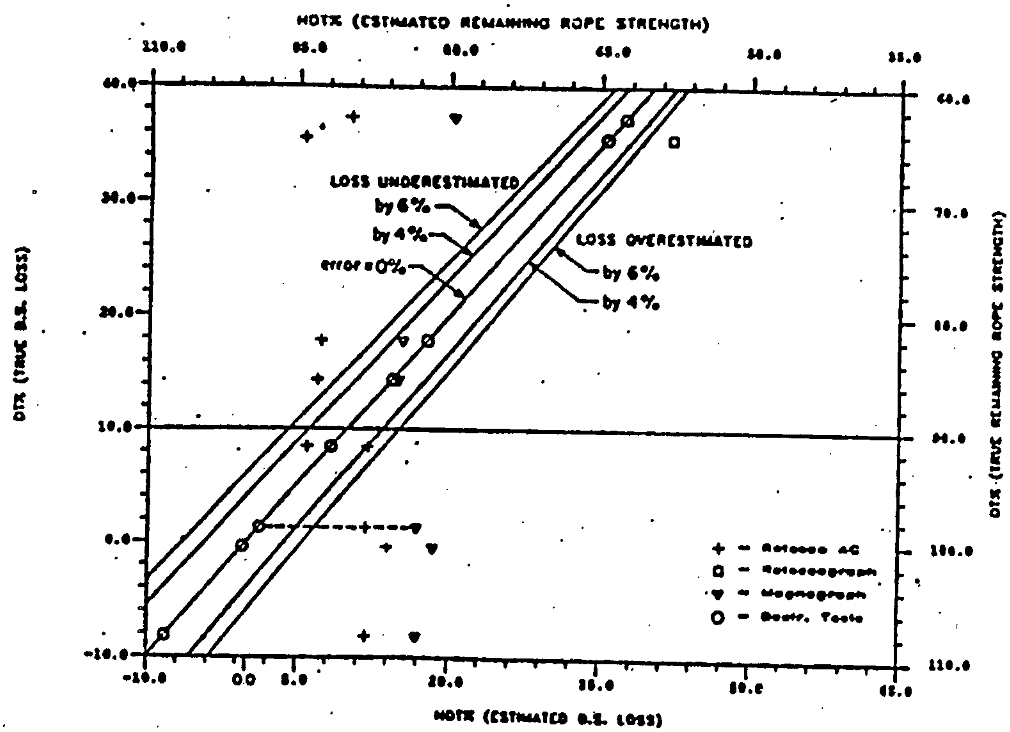


Fig. 5c (after ref. 3) — Non-rotating ropes; all comparative test data

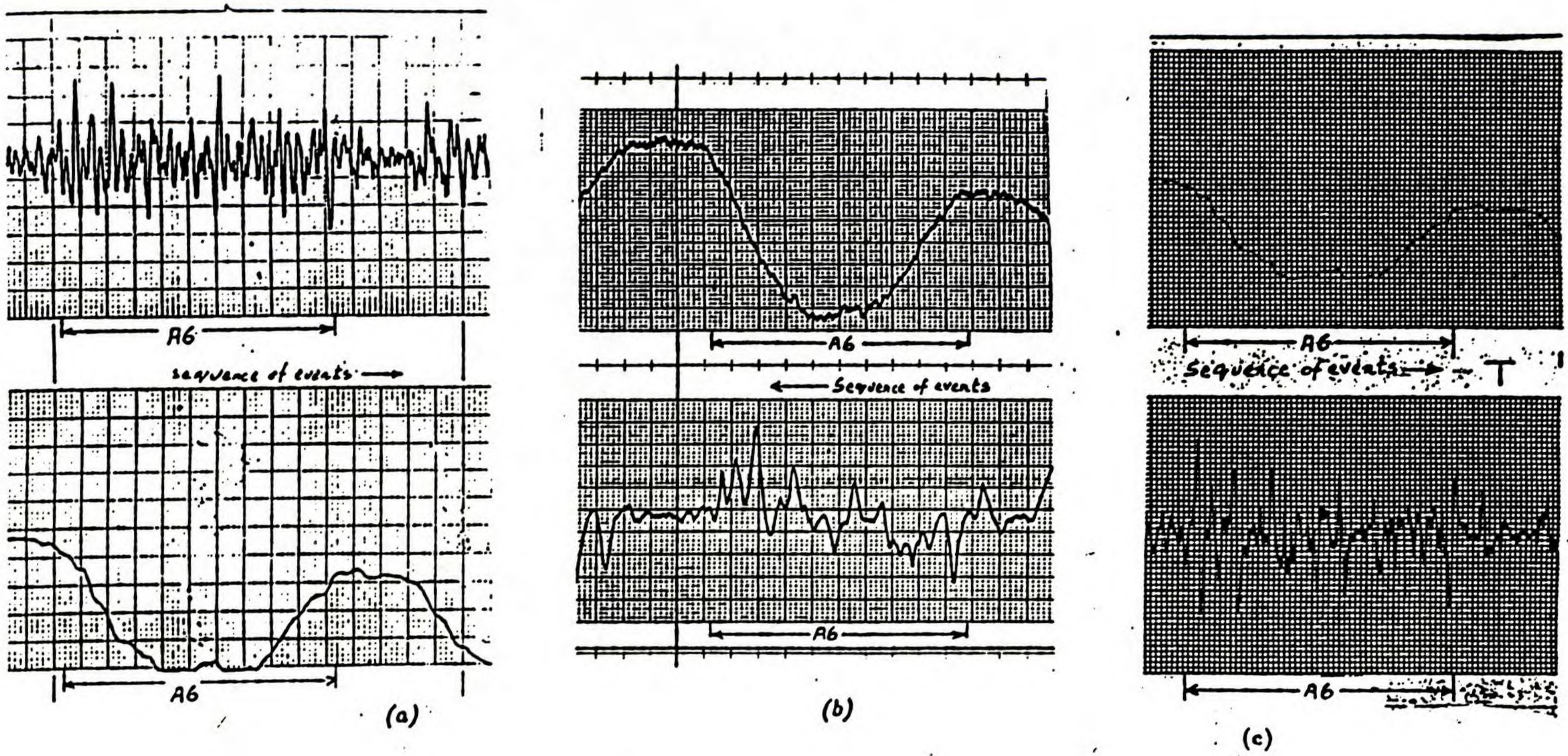


Fig. 6 (after ref. 5) — Rope 'A', April, 1989, testing with (a) Rotescograph, (b) Magno-graph, and (c) LMA-250 instruments; defect A6

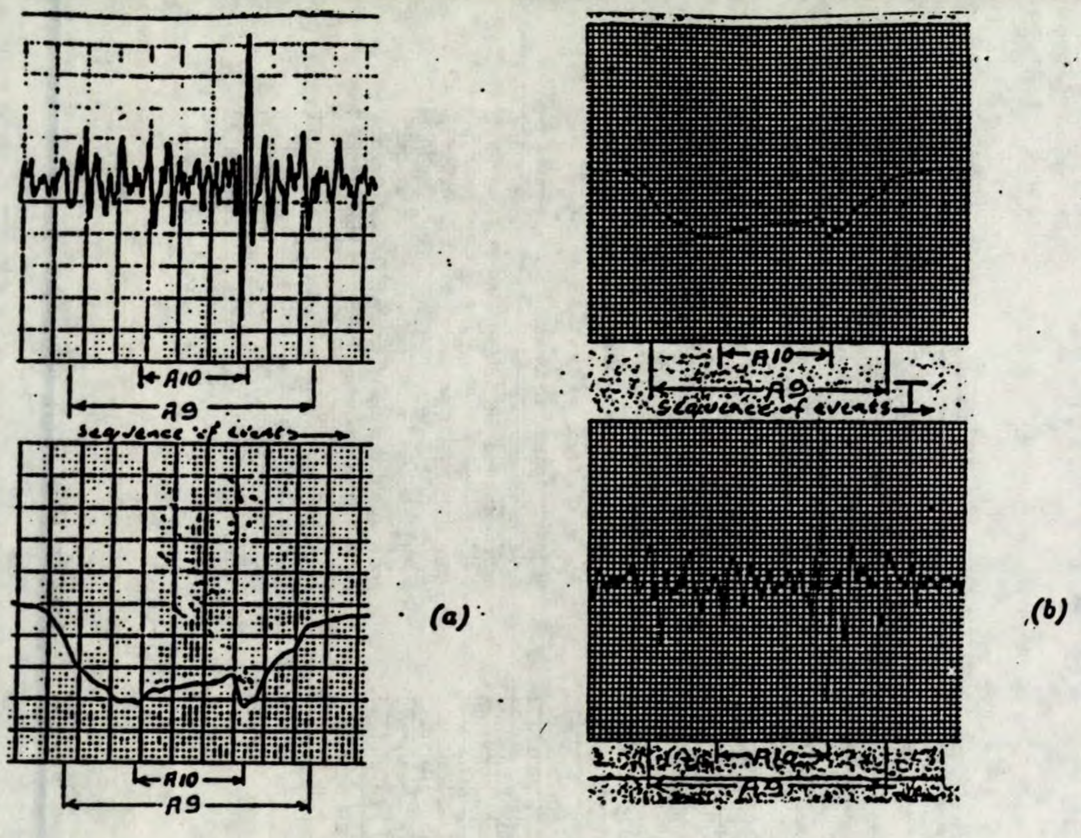


Fig. 7 (after ref. 5) — Rope 'A', April, 1989, testing with (a) Rotescograph, and (b) LMA-250 instruments; defects A10 and A9

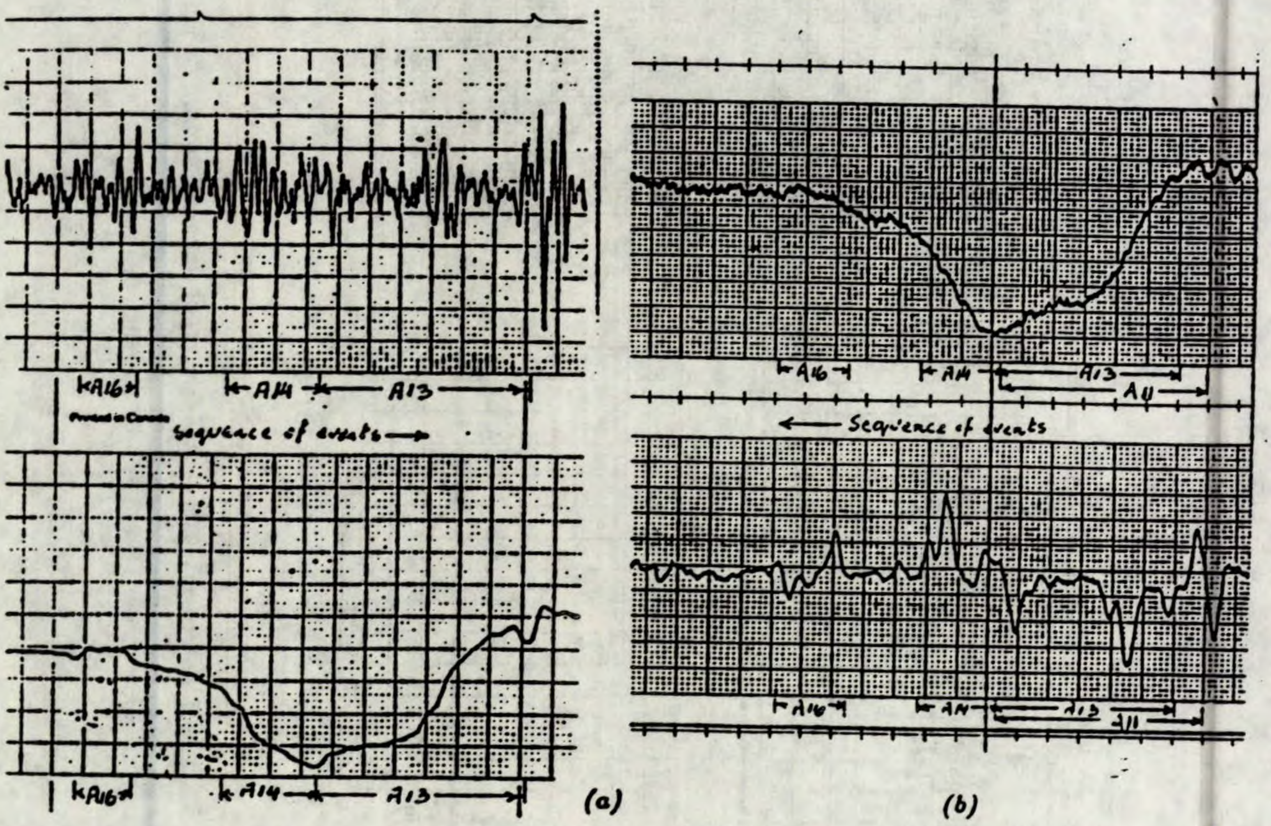


Fig. 8 (after ref. 5) — Rope 'A', April, 1989, testing with (a) Rotescograph, and (b) Magnograph instruments; defects A16, A14 and A13

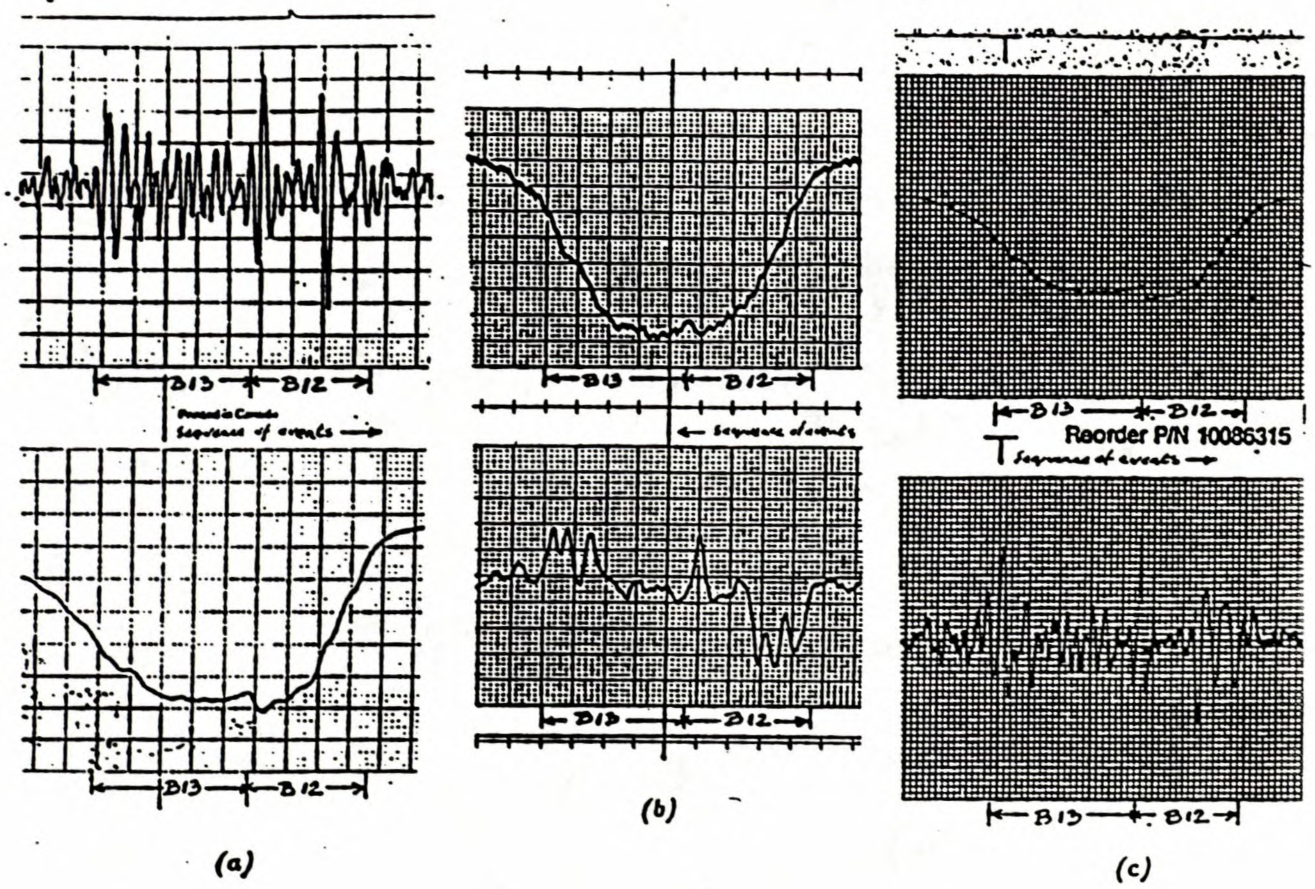


Fig. 9 (after ref. 5) — Rope 'B', April, 1989, testing with (a) Rotescograph, (b) Magnograph, and (c) LMA-250 instruments; defects B13 and B12

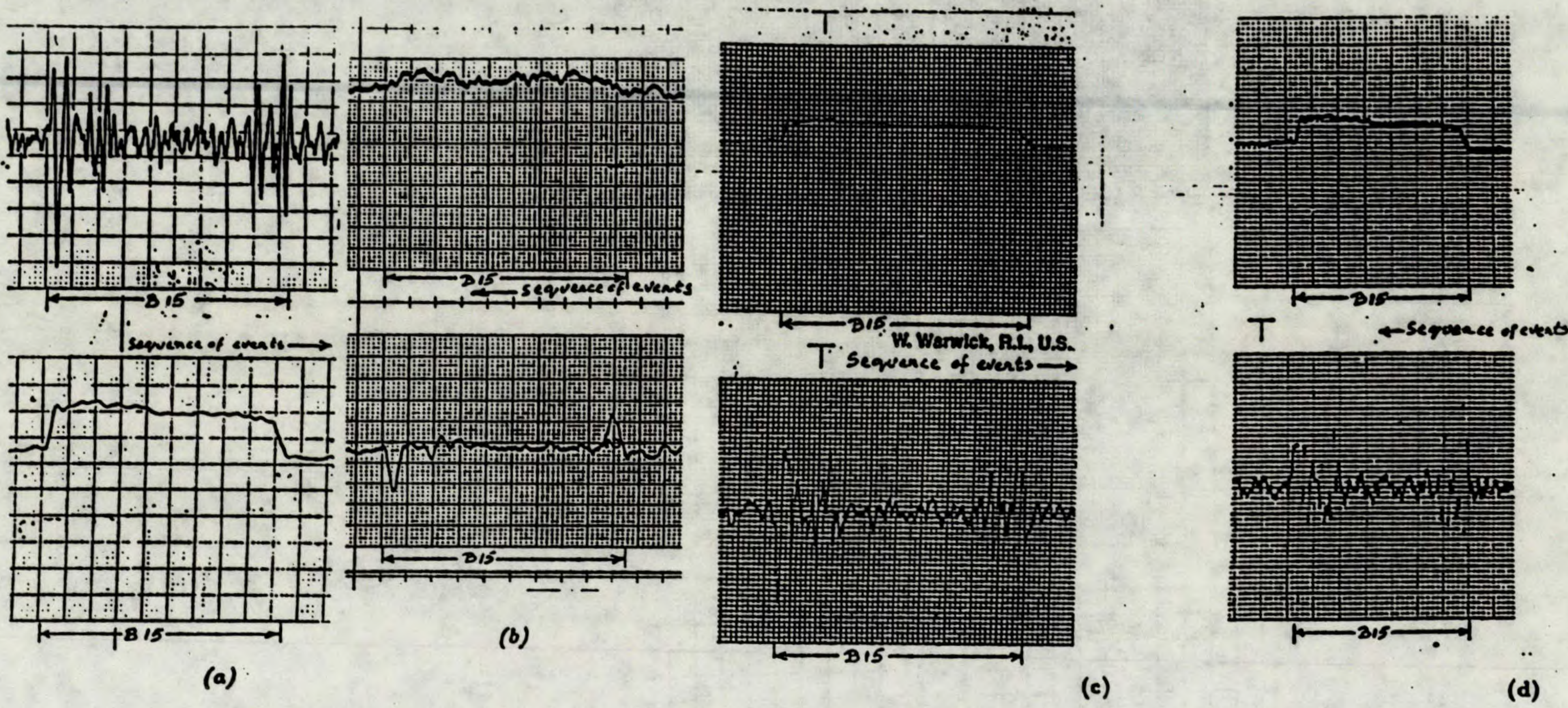


Fig. 10 (after ref. 5) — Rope 'B' testing with (a) Rotescograph, (b) Magnograph, and (c) LMA-250 instruments in April, 1989; also (d) in March, 1990, with LMA-250; defect B15

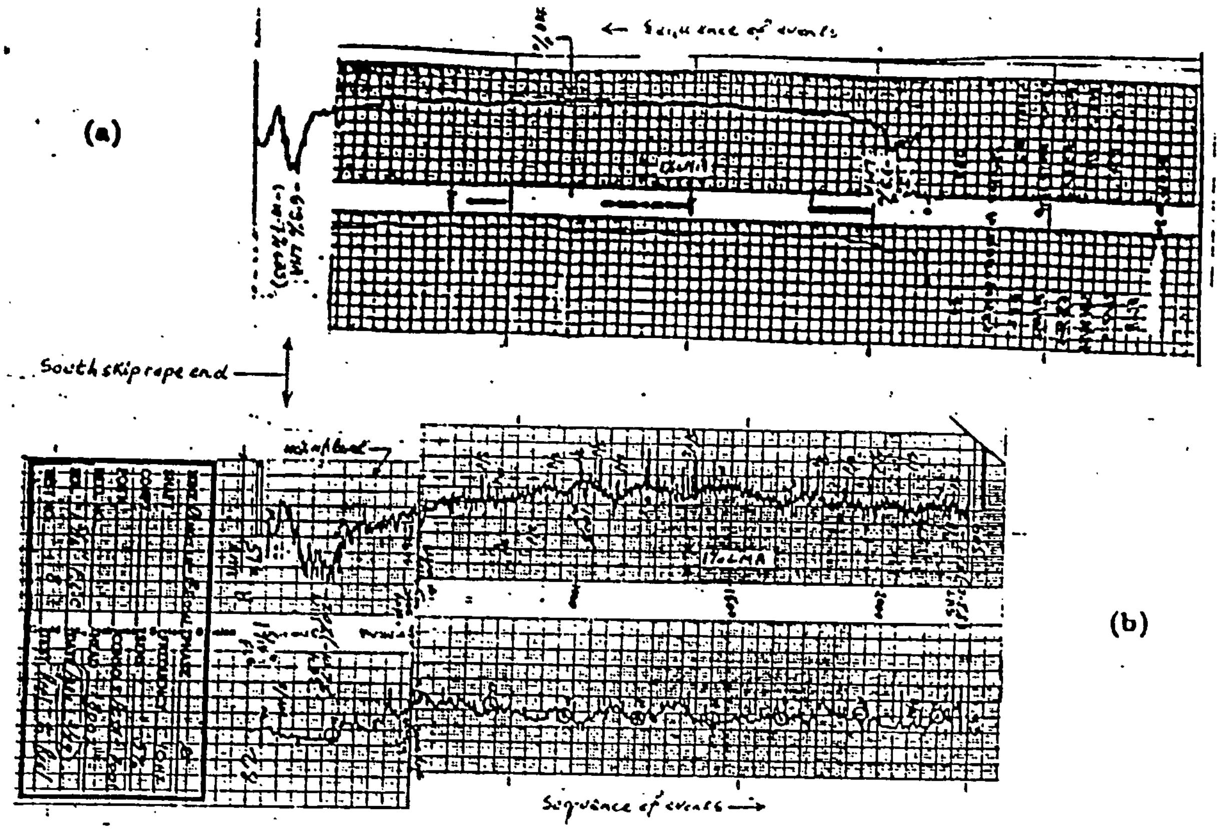


Fig. 11 (after ref. 6) — Rotesco AC tests, in situ, on 26.9.88, and on the shop-floor, on 3.4.89

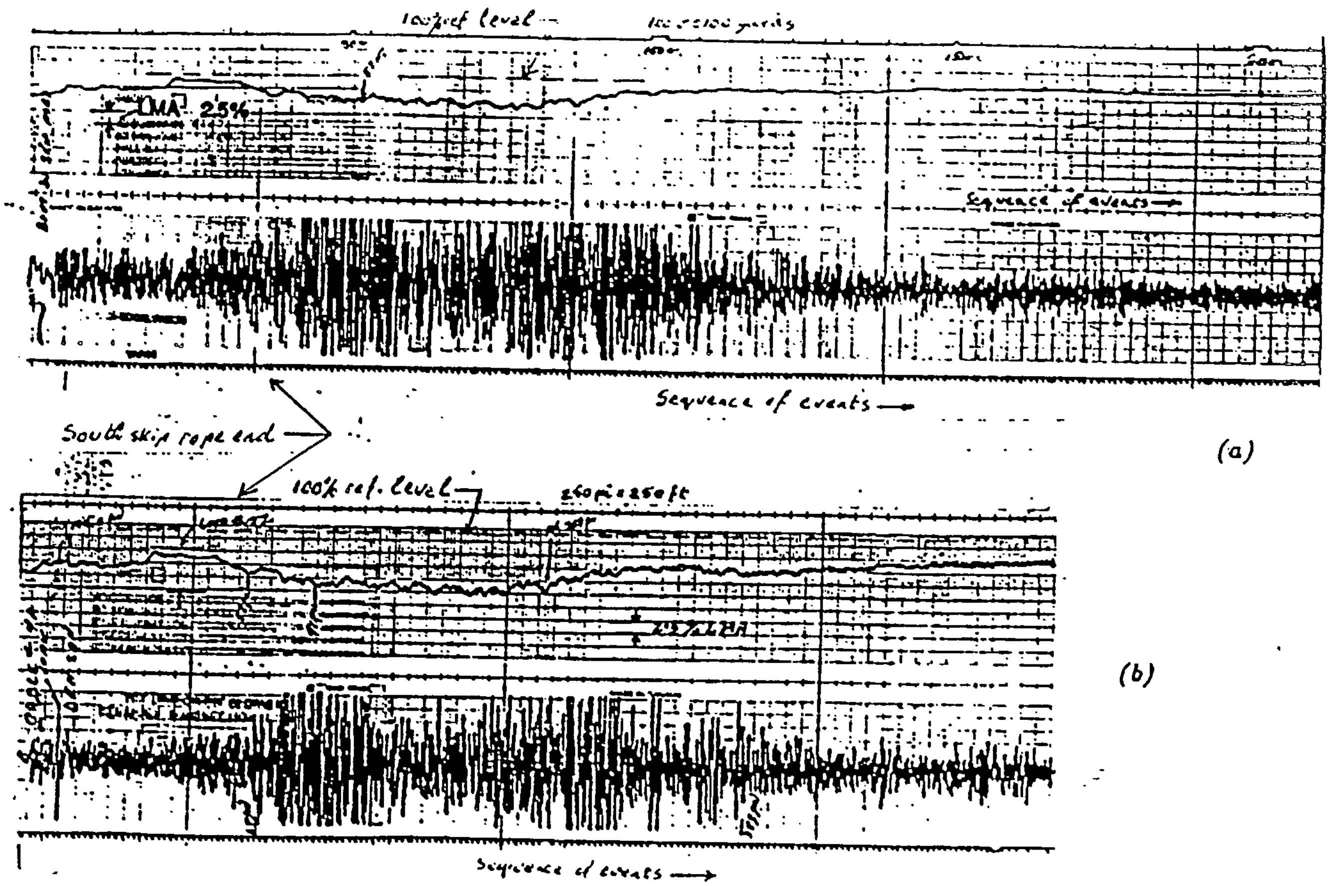


Fig. 12 (after ref. 6) — Magnograph tests of South skip rope end, in situ, on 19.10.88, and on the shop-floor, on 4.4.89

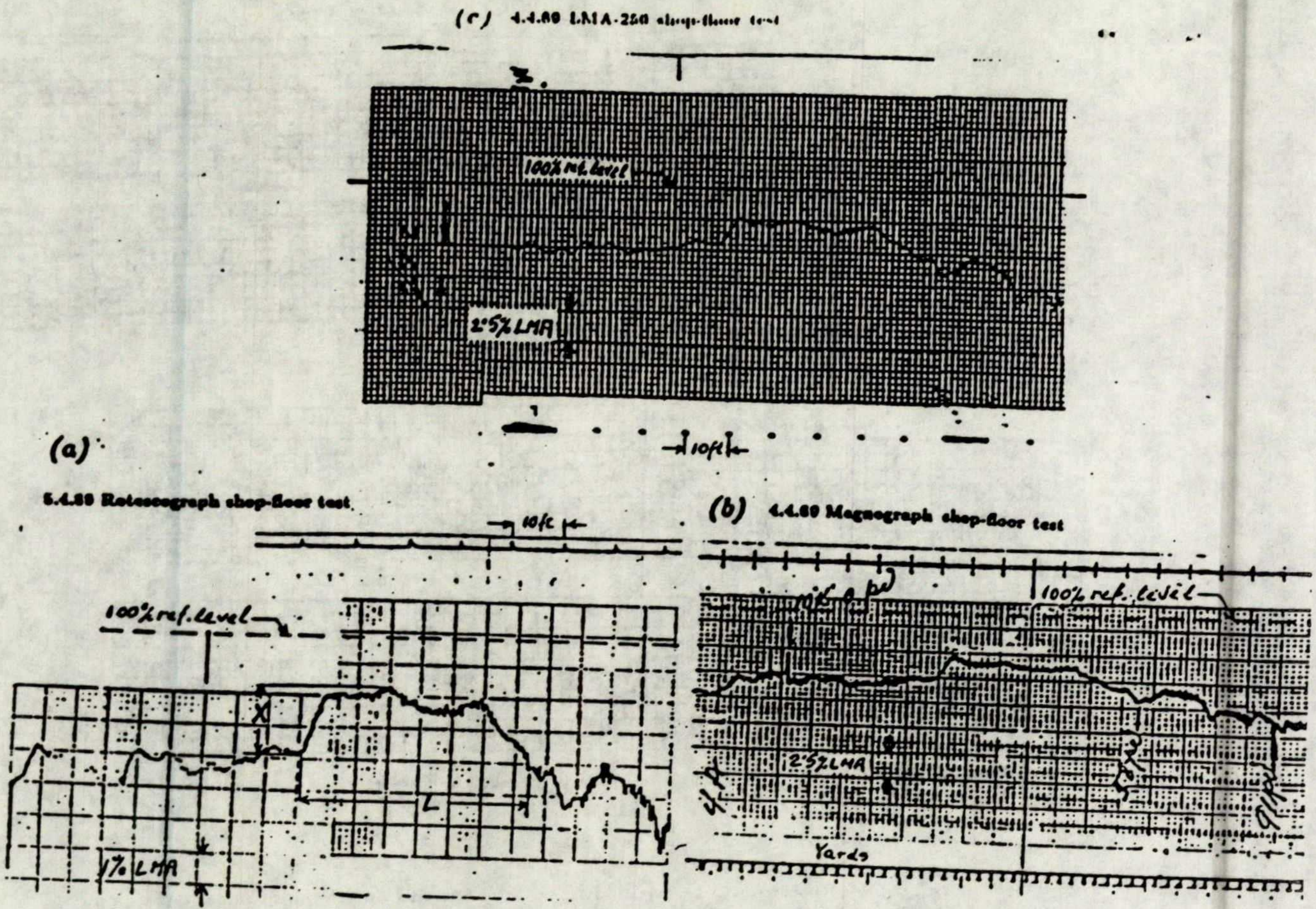


Fig. 13a (after ref. 6) — Rotescograph, LMA-250, and Magnograph shop-floor tests of characteristic feature in South skip rope end

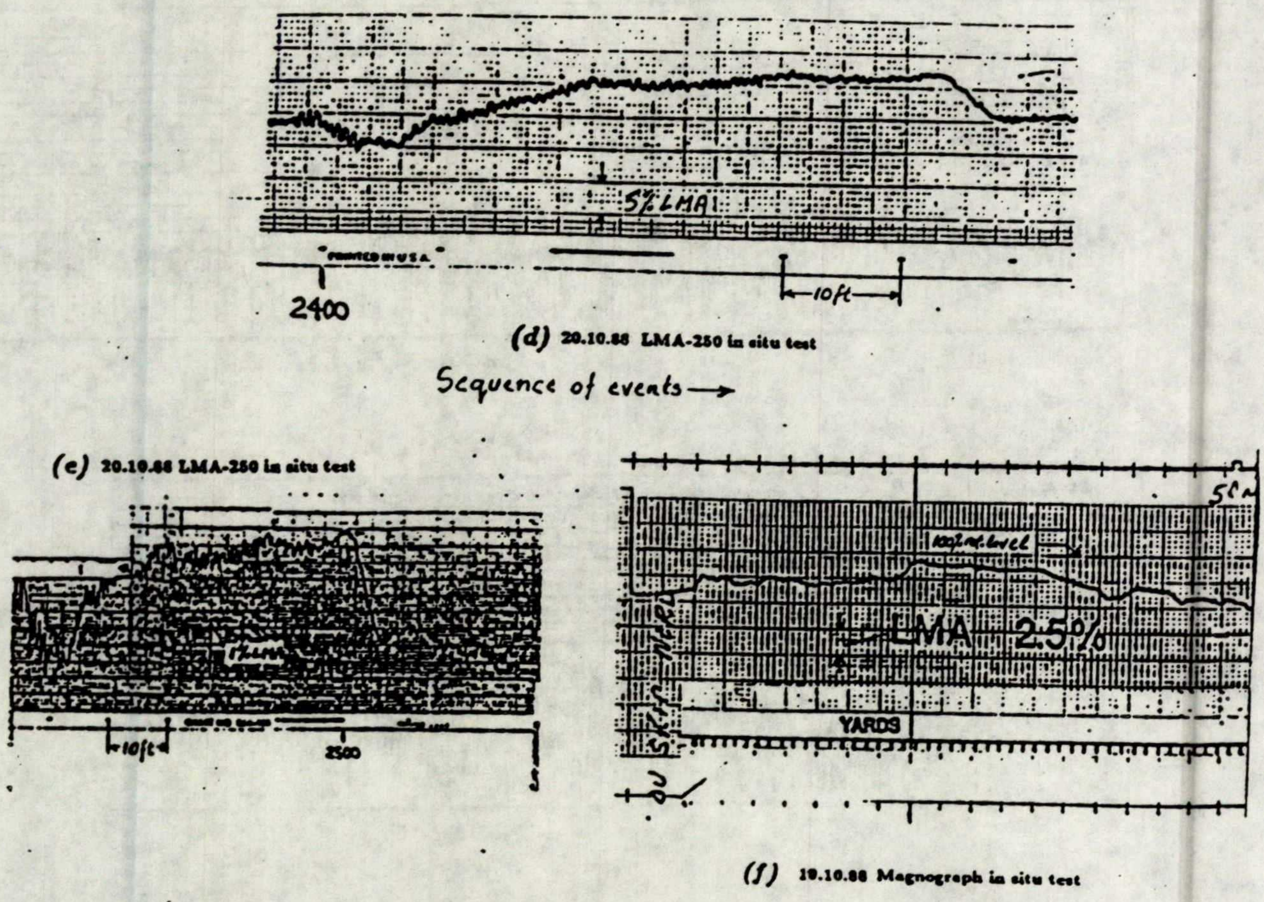


Fig. 13b (after ref. 6) — Rotescograph, LMA-250, and Magnograph in situ tests of char acteristic feature in South skip rope end

Table 1 (after ref. 2)

Analysis of test data — a summary

EM instr. used — results obtained	Rope construction		
	LC	NR	STR
Rotesco AC —			
total # of DT/NDT data-pairs, Σ	113	31	144
$\overline{X}$ of all errors, %	-0.72	-16.0	-6.5
S of all errors, %	8.1	16.9	11.2
"acceptable" data**, % of Σ	37	33	38
Rotescograph —			
total # of DT/NDT data-pairs, Σ	51	1	34
$\overline{X}$ of all errors, %	1.1	—	0.10
S of all errors, %	4.0	—	8.0
"acceptable" data**, % of Σ	65	0	56
Magnograph —			
total # of DT/NDT data-pairs, Σ	69	6	26
$\overline{X}$ of all errors, %	0.83	-3.3	0.23
S of all errors, %	4.8	6.9	10.0
"acceptable" data**, % of Σ	64	83	50

**: % of total NDT data — i.e., of "estimated" strength-losses — that are within the "permissible" (in the sense of Ontario's Performance Requirements) ±4% error range; the NDT=0 values are omitted here

Table 2 (after ref. 5)

Test rope A — Max. %LMA in the major LMA rope sections

Rope section symbol	A2	A3	A6	A9	(A13+A14)
True LMA	unknown	-7.0	-7.6	-7.2	-7.7
Rotescograph					
Tests of April 5, 10, and 15, 1989					
5 mm/sec chart speed	-1.4	-4.6 (-2.4)*	-4.8 (-2.8)	-2.9 (-4.3)	-4.1 (-3.6)
1 mm/sec chart speed	-1.6	-5.0 (-2.0)	-5.6 (-2.0)	-2.8 (-4.4)	-5.5 (-2.2)
0.5 mm/sec chart speed	-1.5	-4.5 (-2.5)	-4.9 (-2.7)	-2.8 (-4.4)	-3.8 (-3.9)
LMA-250					
5 mm/sec chart speed					
Tests of 5.4.89	-2.0	-7.6 (+0.6)	-8.0 (+0.4)	-4.5 (-2.7)	-7.5 (-0.2)
Tests of 6.3.90	-2.2	-7.8 (+0.8)	-8.6 (+1.0)	-4.8 (-2.4)	-7.6 (-0.1)
Magnograph					
Tests of 4.4.89					
2.5% LMA/major chart division	-2.0	-6.8 (-0.2)	-7.8 (+0.2)	-5.8 (-1.4)	-7.5 (-0.2)
1.0% LMA/major chart division	-1.8	-6.3 (-0.7)	-7.3 (-0.3)	-5.0 (-2.2)	-6.7 (-1.0)
Tests of 6.3.90					
2.5% LMA/major chart division	-1.9	-6.6 (-0.4)	-7.4 (-0.2)	-5.2 (-2.0)	-6.7 (-1.0)
1.0% LMA/major chart division	-1.4	-6.0 (-1.0)	-6.8 (-0.8)	-4.6 (-2.6)	-6.0 (-1.7)

*: bracketed values = accuracy = true %LMA – NDT %LMA

Table 3 (after ref. 5)

Test rope B — Max. %LMA in the major LMA rope sections

Rope section symbol	B2	B3	B6	B9	(B12+B13)
True LMA	unknown	-7.0	-7.6	-7.2	-7.7
Rotescograph					
Tests of April 5, 10, and 15, 1989					
5 mm/sec chart speed	-2.5	-6.2 (-0.8)*	-6.1 (-1.5)	-5.7 (-1.5)	-5.2 (-2.5)
1 mm/sec chart speed	-1.8	-4.6 (-2.4)	-4.6 (-3.0)	-4.5 (-2.7)	-4.0 (-3.7)
0.5 mm/sec chart speed	-1.8	-5.0 (-2.0)	-5.0 (-2.6)	-5.0 (-2.2)	-4.6 (-3.1)
LMA-250					
5 mm/sec chart speed					
Tests of 5.4.89	-3.3	-9.0 (+2.0)	-9.5 (+1.9)	-9.2 (+2.0)	-8.1 (+0.4)
Tests of 6.3.90	-3.2	-8.4 (+1.4)	-8.7 (+1.1)	-8.6 (+1.4)	-8.0 (+0.3)
Magnograph					
Tests of 4.4.89					
2.5% LMA/major chart division	-3.0	-7.5 (+0.5)	-8.0 (+0.4)	-8.0 (+0.8)	-7.5 (-0.2)
1.0% LMA/major chart division	-2.8	-7.2 (+0.2)	-7.6 (0.0)	-7.8 (+0.6)	-7.3 (-0.4)
Tests of 6.3.90					
2.5% LMA/major chart division	-2.6	-7.3 (+0.3)	-7.6 (0.0)	-7.8 (+0.6)	-7.0 (-0.7)
1.0% LMA/major chart division	-2.6	-6.8 (-0.2)	-6.8 (-0.8)	-7.1 (-0.1)	-6.7 (-1.0)

*: bracketed values = accuracy = true %LMA – NDT %LMA

Table 4a (after ref. 6)

LMA_{max} chart readings, and LBS_{max} estimates —
South skip rope end; in situ tests

Item No.	Test Instr.	As reported		As reviewed	
		LMA_{max}	LBS_{max}	LMA_{max}	LBS_{max}
1	Rotesco AC	0.9%	1.5%	0.9%	1.5%
2	Rotesco AC	2.5%	4.0%	2.6%	4.0%
3	Rotesco AC	6.3%	10.0%	6.9%	10.0%
4	Magnograph	8.0; 10.0% 10.5%		6.0; 6.5%	9.5; 24.0%
5	LMA-250	23.0%		11.5%	

Table 4b (after ref. 6)

LMA_{max} chart readings, and LBS_{max} estimates —
South skip rope end*; shop-floor tests

Item No.	Test Instr.	As reported		As reviewed	
		LMA_{max}	LBS_{max}	LMA_{max}	LBS_{max}
7	Rotesco AC	5.4%	8.6%	7.0%	10.7%
8	Magnograph	8.5%	22.5; 21.0%	11.5%**	27.8%
9	LMA-250	10.8%		10.8%	
10	Rotescograph	—	—	8.3%	16.6%
11	Rotescograph	9.0%	18.0%	4.9%	9.8%

*: rope #4A on shop-floor

**: at least

Table 5a (after ref. 6)

LMA_{max} chart readings, and LBS_{max} estimates —
North skip rope end; in situ tests

Item No.	Test Instr.	As reported		As reviewed	
		LMA_{max}	LBS_{max}	LMA_{max}	LBS_{max}
1	Rotesco AC	0.9%	1.5%	0.9%	1.5%
2	Rotesco AC	1.8%	3.0%	1.8%	3.0%
3	Rotesco AC	3.2%	5.0%	3.9%	5.0%
4	Magnograph	6.0; 6.5%	9.5; 24.0%	2.0%	
5	LMA-250	6.0%		3.0%	

Table 5b (after ref. 6)

LMA_{max} chart readings, and LBS_{max} estimates —
North skip rope end*; shop-floor tests

Item No.	Test Instr.	As reported		As reviewed	
		LMA_{max}	LBS_{max}	LMA_{max}	LBS_{max}
6	Rotesco AC	3.0%	4.6%	2.4%	3.7%
7	Rotesco AC	—	—	1.8%	2.8%
8	Magnograph	3.0%	13.5%	3.0%	13.5%
9	LMA-250	4.5%		4.5%	
10	Rotescograph	—	—	2.4%	4.8%
11	Rotescograph	1.4%	2.8%	2.7%	5.4%

*: rope #4B on shop-floor

Filler	%LMA
Iron	1.1
Magnetite	3
Rope debris	2

Table 6a (after ref. 4) — Theoretical %LMA values, due to powder-filled rope cores

Filler	rope A*	rope B
Iron	1,0	1,6
Magnetite	0,4	0,5
Rope debris	0,2	0,3

*: Location of core fillers is uncertain for rope A

Table 6b (after ref. 4) — Maximum Rotescograph %LMA values, due to powder-filled rope cores