R-95-08

EVALUATION OF STATOR COILS REMOVED FROM HEADGATE ROCK GENERATING UNIT 3

July 1995

U.S. DEPARTMENT OF THE INTERIOR
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During commisioning tests on Headgate Rock Generating Unit 3, two turn-to-turn insulation failures developed in the stator coils. This report describes the results of the evaluation of stator coils removed from Headgate Rock Generating Unit 3 following the turn-to-turn insulation failures. The evaluation was performed in the Bureau of Reclamation's Hydroelectric Research and Technical Services Laboratory in Denver, Colorado.

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by

Lori Rux

Hydroelectric Research and Technical Services Group
Infrastructure Services
Technical Service Center
Denver, Colorado

July 1995

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

U.S. Department of the Interior
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INTRODUCTION

Background

Unit 3 is one of three generators at the Headgate Rock Powerplant, located on the Colorado River in southwestern Arizona. The stator windings for the three identical generating units were manufactured by Villares, Inc., of Brazil, under subcontract to the Hydraulic Turbine/Governors/Generators supply contract let to Voith Hydro. The three-phase stator windings are rated 4160 V rms line-to-line, 7.222 kVA, at 0.9 power factor.

During commissioning tests on unit 3, two turn-to-turn insulation failures developed in the stator coils. The first failure occurred during initial voltage buildup of the stator winding. The terminal voltage was about 99 percent when the failure occurred. The second turn failure developed on the fully loaded unit after 2 to 3 minutes of operation. A subsequent surge test was performed on each pair of coils in the stator. The 10 coils sent to the Electric Power Branch laboratory for analysis, as well as many others, failed the field surge test at a voltage below 700 V/turn. According to the manufacturer, all Headgate Rock coils successfully withstood a 700-V/turn factory surge test.

Purpose

Electrical tests, dissection, and visual analyses were performed on 10 stator coils removed from Headgate Rock Unit 3. The following were performed:

1. Strand-to-strand insulation resistance measurements.
2. Circulating current tests.
3. Turn-to-turn insulation (surge) tests.
4. Strand-to-strand insulation a-c withstand voltage tests.
5. Coil dissection and analysis
6. Turn insulation thickness measurements

Evaluation of the unit 3 stator coils was conducted to investigate turn-to-turn insulation failures observed during generator commissioning tests. Laboratory tests and analyses of the stator coils were performed to determine the location and cause of the failures, as well as to evaluate the entire insulation system for application technique, bonding, and impurities.

The results of the stator coil evaluation will be used to assess the manufacturer's proposal to rewind unit 3 with new coils having dedicated mica-tape turn insulation. Headgate Rock units 1 and 2 have the original turn insulation system. The subject analysis will also enable Reclamation to assess the likelihood that units 1 and 2 will experience similar premature turn-to-turn insulation failures after a short time in service.

CONCLUSIONS

Details of the coil tests and results are given in the following **Test Procedures and Results** section. Nine of the ten coils sent to the Electric Power Branch for analysis had turn insulation failures. The tenth coil failed during laboratory surge tests.

A method was devised to pinpoint the location of the turn insulation failures. Using this technique, the failures were located and five coils were selected for dissection and visual analysis. No gross defects, such as voids or impurities, were found at the site of the failures. However, measurements of the turn insulation thickness revealed that the actual thickness of the turn insulation was about one-half the thickness specified in the coil design (0.15 mm [6 mils] versus 0.33 mm [13 mils]).

Results of the stator coil tests and dissection analyses indicate the unit 3 turn insulation failures are a consequence of inadequate turn insulation thickness. The discrepancy between the design specifications and the actual insulation thickness can probably be attributed to substandard process control during manufacture of the coils. Based on discussions with the manufacturer, uncertainty exists regarding the amount of compression applied during formation of the coils. Use of excessive pressure could explain why the actual turn insulation thickness is about one-half the thickness specified in the coil design.

The stator coils used in this evaluation will be retained in the event that future testing is required.

TEST PROCEDURES AND RESULTS

Winding Construction and Insulation of Coils

The stator core has a total of 540 slots (180 slots/phase). Each phase of the stator winding consists of four parallel circuits, with 45 four-turn coils connected in series per parallel circuit. The three phases are wye-connected.

The following description of the stator coil insulation system is primarily taken from *Headgate Rock Stator Winding Description* (Villares, Inc.), which is part of the specification. However, discrepancies exist among various documents provided by the manufacturer, as well as between design information and laboratory observations of the stator coils. Significant differences will be shown in brackets.

The stator coils are made up of four strands of rectangular tough pitch copper conductors separated into two tiers of four-turns. The strand insulation of each conductor is made of continuous glass and polyester fibers, thermally fused during manufacture of the insulated wire.

The conductor bundles are compacted and the slot portion is molded into a solid section. A vertical glass cloth separator provides for bonding between the two tiers of conductors. One inverted turn, located near the knuckle opposite from the coil leads, provides for compensation of differences in induced voltage between individual strands.

The groundwall insulation was produced with high-grade "resin-rich" mica paper tapes. Backing and facing layers of thin glass cloth and polyester mat provide mechanical resistance to the tapes. The tapes in the slot portion are applied half-lapped in a continuous taping process. (In some of the documents describing the winding design, the manufacturer asserts the existence of dedicated mica-tape turn insulation [similar to the groundwall insulation]. The subject coils do not have dedicated turn insulation. Two adjacent layers of strand insulation serve as the turn insulation.)

Insulated coils are grouped in batches and undergo a two-step drying and curing process, where vacuum, temperature, and pressure are sequentially combined to obtain a compact and solid groundwall insulation without voids or delaminations. No impregnating treatment with a liquid resin is required because the "resin-rich" tapes contain the necessary amount of synthetic resin.

The coils are finished with a slot discharge suppression system, consisting of a low-resistivity, semiconducting resin coat painted over the slot portion of the coil. The effect of this system is to bring the ground potential directly to the surface of the groundwall insulation, electrically short-circuiting possible air spaces between the coil surface and the slot wall. (In addition, one layer of semiconducting glass armor tape is butt-wrapped over the groundwall insulation in the painted slot portion of the coil.)

Tests and Results

Strand-to-strand insulation resistance measurements.—Interstrand resistance measurements were made on all 10 coils. The individual strands were carefully spread apart at both ends of the coil leads. A Keithley 139A DMM (Digital Multimeter) was connected between each and every strand and the resistance value was recorded. Out of ten coils, nine exhibited low resistance measurements between two or more strands. Typically, low interstrand insulation values indicate strand-to-strand shorts. However, because the Headgate Rock coils do not have dedicated turn insulation, low interstrand resistance values may also indicate turn-to-turn failures. Only coil No. 162 appeared to be a good coil. The interstrand resistance measurements of the coils are given in table 1.

Table 1. — Strand-to-strand insulation resistance measurements (ohms).

Coil No.	1-2	1-3	1-4	2-3	2-4	3-4
18	∞	∞	∞	∞	∞	0
19	∞	∞	∞	∞	∞	0
59	∞	1.06k	∞	∞	∞	∞
60	∞	1.19k	∞	∞	∞	∞
162	∞	∞	∞	∞	∞	0
163	∞	∞	∞	∞	∞	0.38k
498	∞	3.0M	1.8	∞	∞	1.8M
499	∞	∞	∞	0.32	0.32M	2.6k
500	∞	∞	∞	∞	3.66k	
501	3.21M	200	11.0	3.21M	3.21M	10.8k

<u>Legend:</u>
∞ - Measured resistance is greater than 999 MΩ.
0 - Zero resistance on DMM MΩ scale.

Circulating current tests.—To confirm the existence of the suspected turn-to-turn insulation failures, a Sorensen DCS 20- to 50-amp d-c supply was connected between strands with low interstrand resistance values. A d-c voltage was applied between the strands and was increased until the interstrand insulation failed, as evidenced by the rapid onset of current from the supply. The current was allowed to circulate through the low strand-to-strand resistance for several minutes. Typical values of interstrand breakdown voltage were between 3 and 10 V, well below the normal 18.9-V peak turn-to-turn operating voltage. The circulating current ranged from 3 to 10 amps. Coils No. 18, 19, 59, 60, 163, and 501 were tested in this manner.

As current passed through the resistance of the interstrand insulation failure, the dissipated energy (I^2R losses) produced a "hot spot," which was easily detected by the touch of a passing hand. The location of the hot spot was marked and later dissection proved the circulating current technique was successful in locating the position of the turn-to-turn short to within a few centimeters.

All turn-to-turn insulation failures were located within the slot portion of the coils. This result was somewhat unexpected; the turn insulation in the bend area of a multi-turn coil is usually weaker than the insulation in the slot because of mechanical damage resulting from coil formation and winding installation processes (Gupta et al., 1987). Numerous turn insulation failures in the slot region of the winding, with no failures in the end-turns, suggest the failures may be related to compression of the slot area insulation during manufacture of the coils.

Turn-to-turn insulation (surge) tests.—During generator commissioning tests, the initial voltage build-up on the stator winding resulted in two damaging turn-to-turn insulation failures. As a result, the manufacturer decided to surge test all coils in the unit 3 stator core. Holes were drilled through the coil-to-coil jumper insulation to access the coil conductors. The coils were tested in pairs, to a maximum test voltage of 5600 V/two coils, or 700 V/turn. The field surge test did not discern which of the two coils tested bad. If either or both of the coils exhibited a turn-to-turn insulation failure, the pair of coils was rejected. The subject ten coils, among many others, failed the field surge test at a voltage below 700 V/turn. The five pairs of coils were removed from different phases and parallel circuits. The position of the coils within the parallels was near the neutral connection end.

(According to information supplied by the manufacturer, the unit 3 stator coils passed a factory surge test to 5600 V/two series-connected coils [700 V peak/turn] prior to shipment and installation in the core.)

High-voltage surge tests were conducted in the Electric Power Branch laboratory on the failed coils to demonstrate the effects of turn insulation failures. Coil No. 162 was also tested to provide a benchmark surge test waveform and to establish the level of interturn dielectric strength present in a good coil. A Baker DT260 surge tester and a Hitachi VC-6025A digital storage oscilloscope were used to perform the tests. The rise-time of the surge pulse was 0.5 µs. The coils were tested to about 750 V/turn.

Surge test data exhibit pronounced differences between waveforms of coils with turn failures and the waveform of the good coil. The failed coils display a lower initial voltage peak (for the identical output setting of the surge tester) as well as a higher frequency of oscillation, evidenced by a zero-crossing shift to the left. Such differences in surge test waveforms are typical and are attributed to the lower series inductance of coils with turn insulation failures. A complete record of all surge test results is provided in appendix A.

Coil No. 498 was surge tested before and after the circulating current test. No difference in the surge test waveform was observed. Coil No. 162 (the good coil) initially passed the surge test at about 1050 V/turn. The test voltage was gradually increased and, after several repetitions, the coil experienced a turn-to-turn failure at about 1200 V/turn. An audible "snap" could be heard as the turn insulation failed. Strand-to-strand resistance measurements were repeated on coil No. 162. A low resistance value of 1.7 kΩ was measured between strands 1 and 3, indicating that a permanent fault remained between the strands.

The normal turn-to-turn operating voltage and typical surge test voltage (line-to-ground) specified by Reclamation are determined as follows:

$$\text{Turn-to-turn operating voltage (peak)} = \frac{\sqrt{2}\,U_n}{\sqrt{3}\,N_1\,K_p\,K_d} = \underline{\underline{18.9\text{ V}}}$$

where U_n = line-to-line voltage (4160 V)
N_1 = number of turns in a series path (180)
K_p = pitch factor (assume 1.0)
K_d = distribution factor (assume 1.0)

$$\text{Reclamation Surge Test Voltage (peak)} = 21 \times V_{TT} \times N_{eff} = \underline{\underline{1190\text{ V}}}$$

where V_{TT} = turn-to-turn operating voltage (18.9 V)
N_{eff} = effective turns/coil = turns/coil minus one (Gupta et al., 1987)

The minimum turn insulation surge withstand voltage specified by Reclamation is very lenient when compared to recent IEEE (Institute of Electrical and Electronics Engineers) recommendations. IEEE Standard 522-1992 (*IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines*) recommends new coils withstand a test voltage of 4.2 pu for a 0.5-µs impulse. One pu is defined as the rated peak line-to-neutral operating voltage ($(\sqrt{2}/\sqrt{3})V_{LL}$) and is 3400 V for the Headgate Rock stator coils. According to the IEEE standard, the coils for the Headgate Rock generators should be designed to withstand a test voltage of about 14,300 V conductor-to-ground, which is equivalent to 3560 V/turn (14,300 V/coil ÷ 4 turns/coil). As reported above, the field tested coils failed at or below 2800 V (0.79 pu), and coil No. 162 failed in the laboratory around 4800 V (1.34 pu).

Strand-to-strand insulation a-c withstand voltage test.—Coil No. 500 was randomly chosen for a-c withstand tests on the strand-to-strand insulation. The individual strands were separated at both ends of the coil leads. A test voltage of 110 V rms (the factory strand test level) was applied between each and every strand. No strand insulation failures occurred, except between strands 2 and 4, which had a known low interstrand resistance value. The voltage was then increased to 500 V rms and the strand test was repeated between all strands except 2 and 4. No strand insulation failures occurred.

Coil dissection and analysis. — One inverted turn, located in the arm of each coil, provides for compensation of differences in induced voltage between individual strands. (The explicit location of the turn transposition was not given on the coil drawings supplied by the manufacturer.) Laboratory dissection revealed that the transposition starts about 4 cm from the coil knuckle opposite from the coil leads and is completed over a distance of about 6 cm. Refer to appendix B for a diagram illustrating the location of the turn transposition and a photograph of a cross sectional view of the transposition.

The groundwall insulation of several coils was visually inspected for abnormalities. The insulation in the slot area appeared free of voids and/or delaminations. However, numerous tiny contaminants were imbedded within the insulation. Several distinctly different kinds of impurities were found. None seem to be metallic in nature, nor do they appear to be associated with the turn insulation failures. Photographs C1 and C2, located in appendix C, provide examples of the contaminants. Although presumably not related to the turn-to-turn failures, the number and variety of impurities in the insulation system tend to indicate a lack of manufacturing cleanliness and quality standards.

Five stator coils were randomly selected for detailed visual analysis of the turn insulation failures. A 12- to 18-cm length of coil, identified during the circulating current test described above, was sectionalized from the rest of the coil. The groundwall insulation was removed and the strands were examined for evidence of burned insulation between turns. In cases where no signs of the failure were immediately obvious, the coil turns were separated until the site of the failure was found. This simple procedure enabled verification of the turn-to-turn failures on all five of the dissected coils. Photographs D1, D2, and D3 in appendix D illustrate typical turn-to-turn failures.

To identify the cause of the turn failures, the insulation and conductors around the faulted area were carefully examined for manufacturing defects, impurities, mechanical damage, etc. No obvious defects in the insulation system were found. However, an abundance of voids in the epoxy resin between strands and between turns was observed. Apparently, the epoxy resin binder from the groundwall tapes was not adequately impregnated and/or retained between strands during manufacture of the coils. Refer to photographs E1 and E2 in appendix E.

Turn insulation thickness measurements. — The stator coil conductor strands are insulated with thermally fused glass and polyester fibers. The turn insulation is comprised of two adjacent layers of strand insulation.

The glass and polyester fibers provide both electrical insulation and physical separation between strands. The dielectric material(s) between adjacent conductor strands determine the impulse strength of the machine turn insulation. In the absence of solid insulation, air between the strands serves as the dielectric. The typical dielectric strength of polyester-reinforced glass is 15.7 kV/mm (400 V/mil). The breakdown strength of air is about 3.0 kV/mm (75 V/mil) (Fink and Beaty, 1978). Rough, defective, or contaminated conductor surfaces could result in even lower breakdown voltages.

Turn insulation thickness measurements were made using a 10X magnifying lens with a 1/20-mm photo-printed straight line scale. In the slot area of the stator coils, the turn insulation thickness ranged from 0.15 to 0.20 mm (6 to 8 mils). The minimum turn insulation thickness in the area of the turn transposition was about 0.15 mm (6 mils). According to the manufacturer's design criteria, the thickness of the turn insulation should be 0.30 to 0.36 mm (13 mils ± 1 mil). The measured thickness of the turn insulation is about one-half the design value.

Ignoring possible insulation defects, the dielectric breakdown strength of 0.15 mm (6 mils) of polyester glass is theoretically around 2400 V. The actual breakdown strength will vary based on the manufacturer's unique polyester glass formula.

The theoretical dielectric strength does not allow for voids or impurities between layers of the polyester glass insulation. Nor does it account for any mechanical, thermal, or environmental stresses suffered by the insulation during manufacture, installation, or operation of the stator winding. Therefore, the actual withstand voltage of the stator coils is likely to be substantially lower (as supported by the numerous failures of unit 3 coils). Of the ten unit 3 stator coils sent to the Electric Power Branch for analysis, only coil No. 162 (a survivor that passed all previous tests) was surge tested to failure. Coil No. 162 failed the laboratory test at about 1200 V/turn. The other nine coils failed in the field at or below 700 V/turn.

The evidence and test data cited above indicate the turn-to-turn insulation failures of the Headgate Rock stator coils are the result of 1) inadequate turn insulation thickness and 2) voids within and/or between the two layers of strand insulation.

Summary of Results

Results of laboratory tests and analysis of the Headgate Rock unit 3 stator coils are summarized below:

1) A reliable technique for locating the site of the turn insulation failure has been demonstrated.

2) All turn failures occurred in the slot portion of the coils.

3) The turn insulation failures developed along the flat interfaces between turns, rather than at the convex curved interfaces.

4) There is no dominant preferred turn-pair for the failures of the turn insulation.

5) Discrepancies between actual turn insulation thickness and design specification suggest the cause of the unit 3 turn insulation failures is likely related to substandard manufacturing process control.

RECOMMENDATIONS

Rewinding unit 3 using coils with dedicated mica-tape turn insulation, as the manufacturer proposes, will likely eliminate the turn-to-turn insulation failures seen with the old design. The proposed insulation system appears to have sufficient turn insulation to withstand the specified surge tests. Nevertheless, a complete laboratory analysis of the new coils is highly desirable.

According to the winding manufacturer, the turn insulation of units 1 and 2 is identical to that of unit 3. There is no reason to believe the materials and/or processes used during manufacture of the unit 3 coils are different from those of the units 1 and 2 coils. We can only assume that the actual turn insulation thickness of all three generators is less than the value specified in the design.

In light of the multiple failures of unit 3, the long-term serviceability of units 1 and 2 is a serious concern. We suspect units 1 and 2 would not withstand a 700-V/turn field surge test. Furthermore, the ability of units 1 and 2 to withstand normal system surges, thermal cycling, and mechanical vibration after 5 to 10 years of aging is questionable.

Given the history of the unit 3 turn insulation failures and the results of the laboratory evaluation, we strongly recommend, that along with unit 3, the stator windings of units 1 and 2 also be rewound with coils having dedicated turn insulation.

EPILOGUE

A recent study of the turn insulation capability of large a-c motors, sponsored by EPRI (1988), demonstrated that turn insulation without mica has a relatively low impulse strength and is subject to deterioration caused by partial discharges.

> "A stator insulation design which includes both strand and turn insulation, applied in separate processes, may be more forgiving to variations in manufacturing processes than a design without dedicated turn insulation. Thus if a minor manufacturing problem occurs in making the turn insulation, it is less likely to result in coil failure since there is a measure of insurance from the strand insulation.
>
> One approach to reducing motor costs has led to designs using upgraded strand insulation without dedicated turn insulation. Although this may save some initial costs, premature winding failure in service could result since there is no fallback if minor taping or impregnation flaws occur normally."

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Gupta, B.K., B.A. Lloyd, G.C. Stone, D.K. Sharma, and J.P. Fitzgerald, "Turn Insulation Capability of Large AC Motors, Part 2 - Impulse Strength," *IEEE Transactions on Energy Conversion*, Vol. EC-2, No. 4, pp. 666-673, December 1987.

Villares, Inc., *Headgate Rock Stator Winding Description*, E-11526.

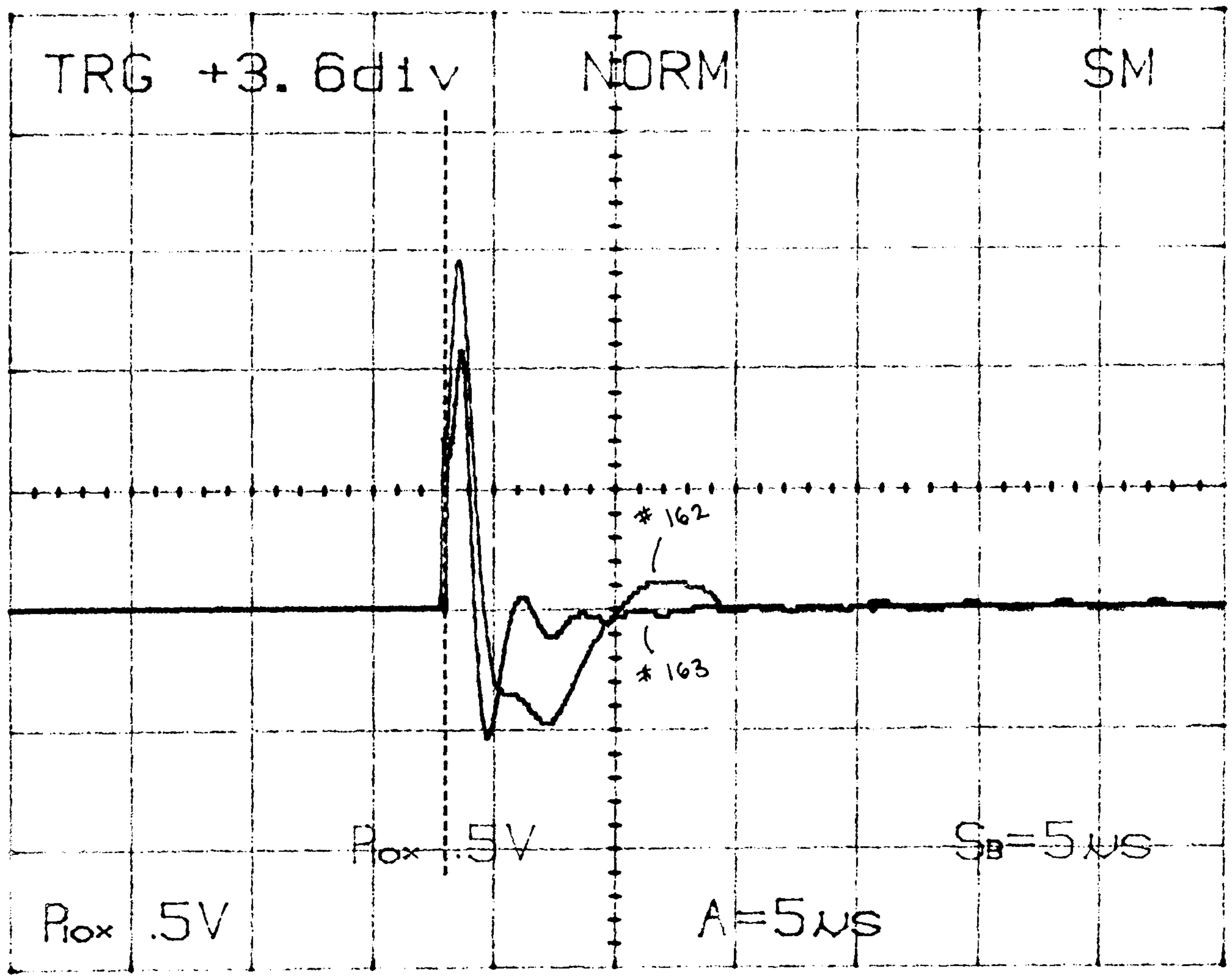
APPENDIX A

Turn-to-Turn Insulation (Surge) Test Results

Headgate Rock
Coils #162 & 163

Surge Test

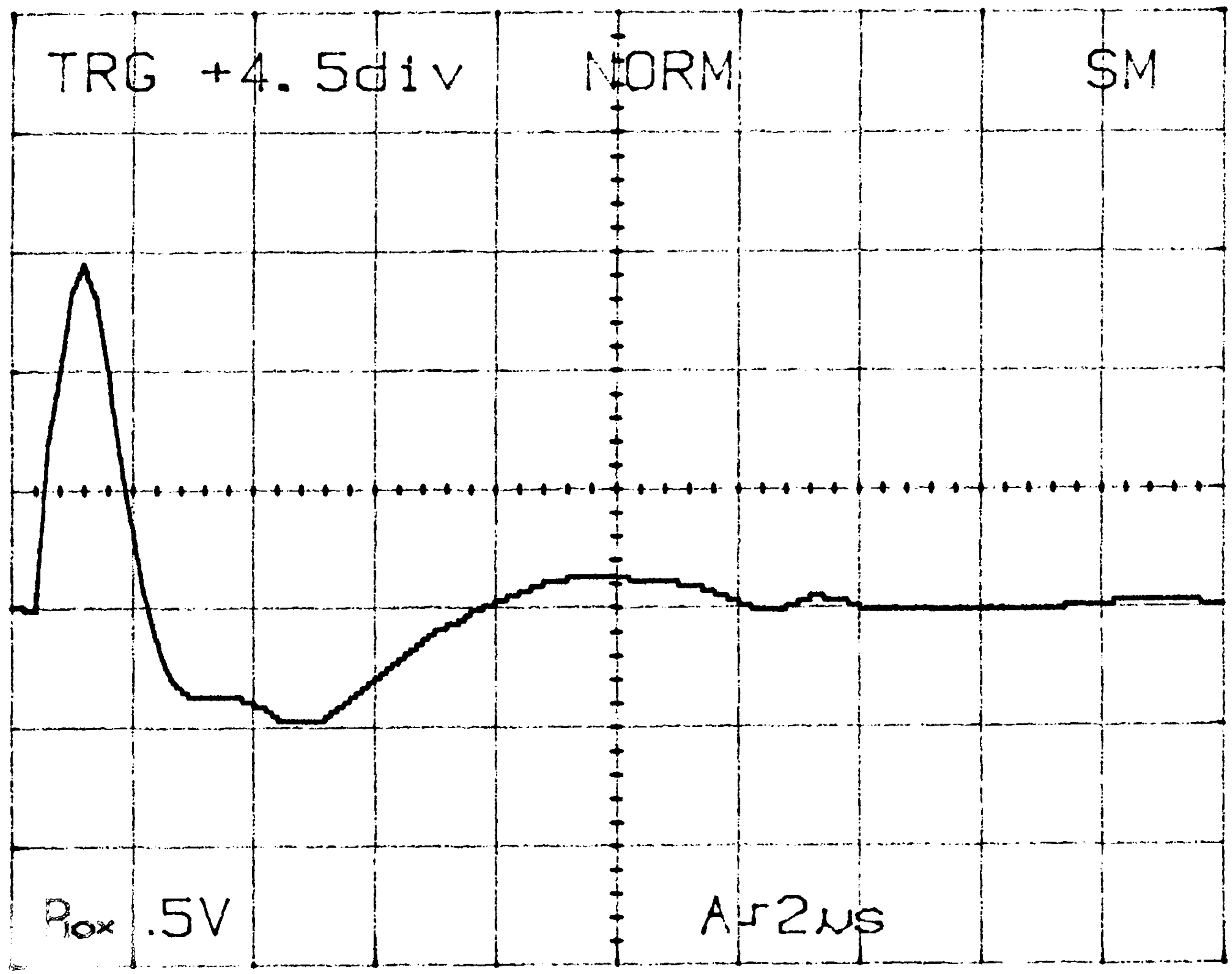
Surge test comparing coil w/ turn insulation failure (#163) and coil w/o turn insulation failure (#162).



Headgate Rock
Coil #162

Before turn failure.

11

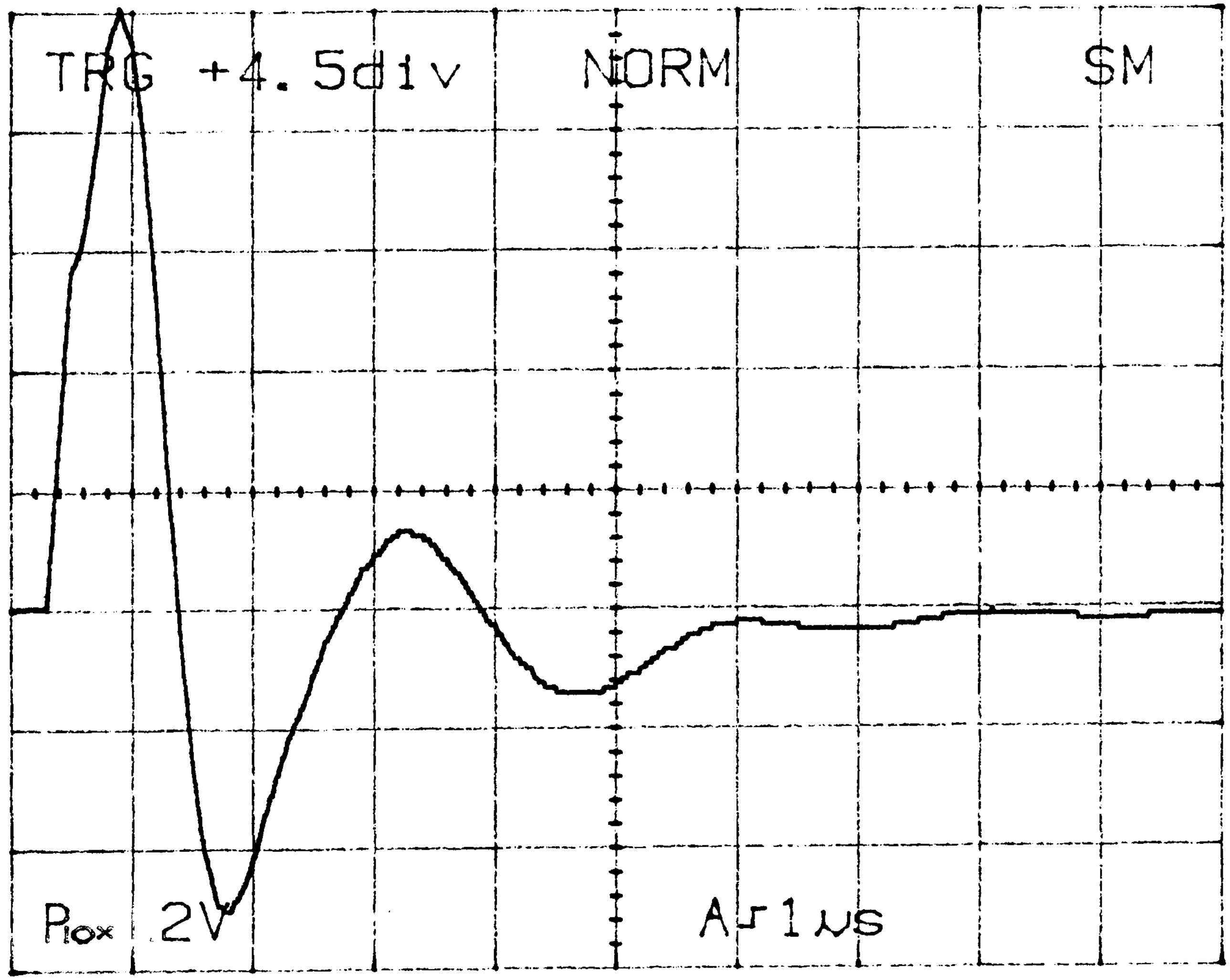


Headgate Rock
Coil #162

Surge Test
3/1/93

After turn failure.

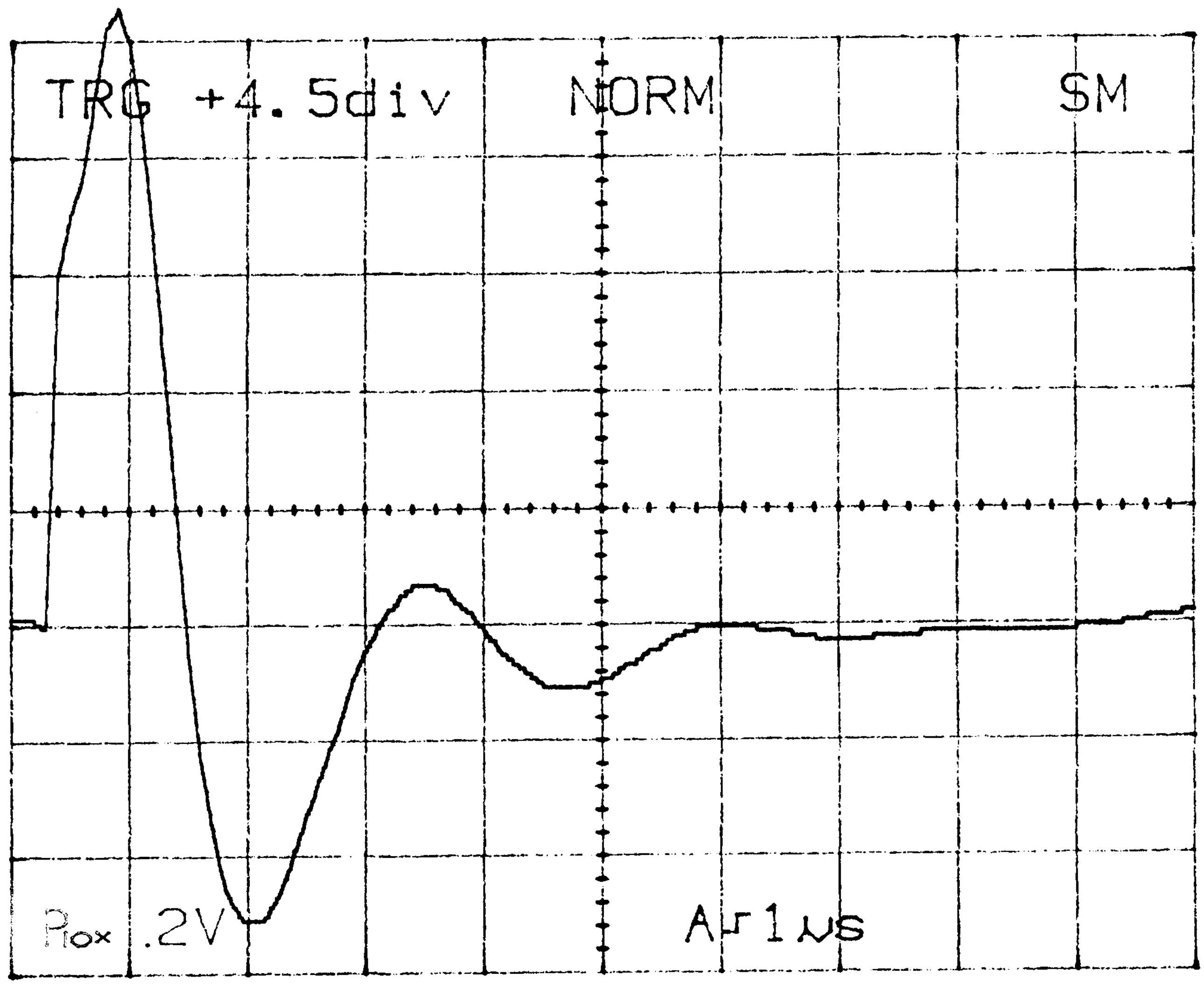
Note: Different time scale.



12

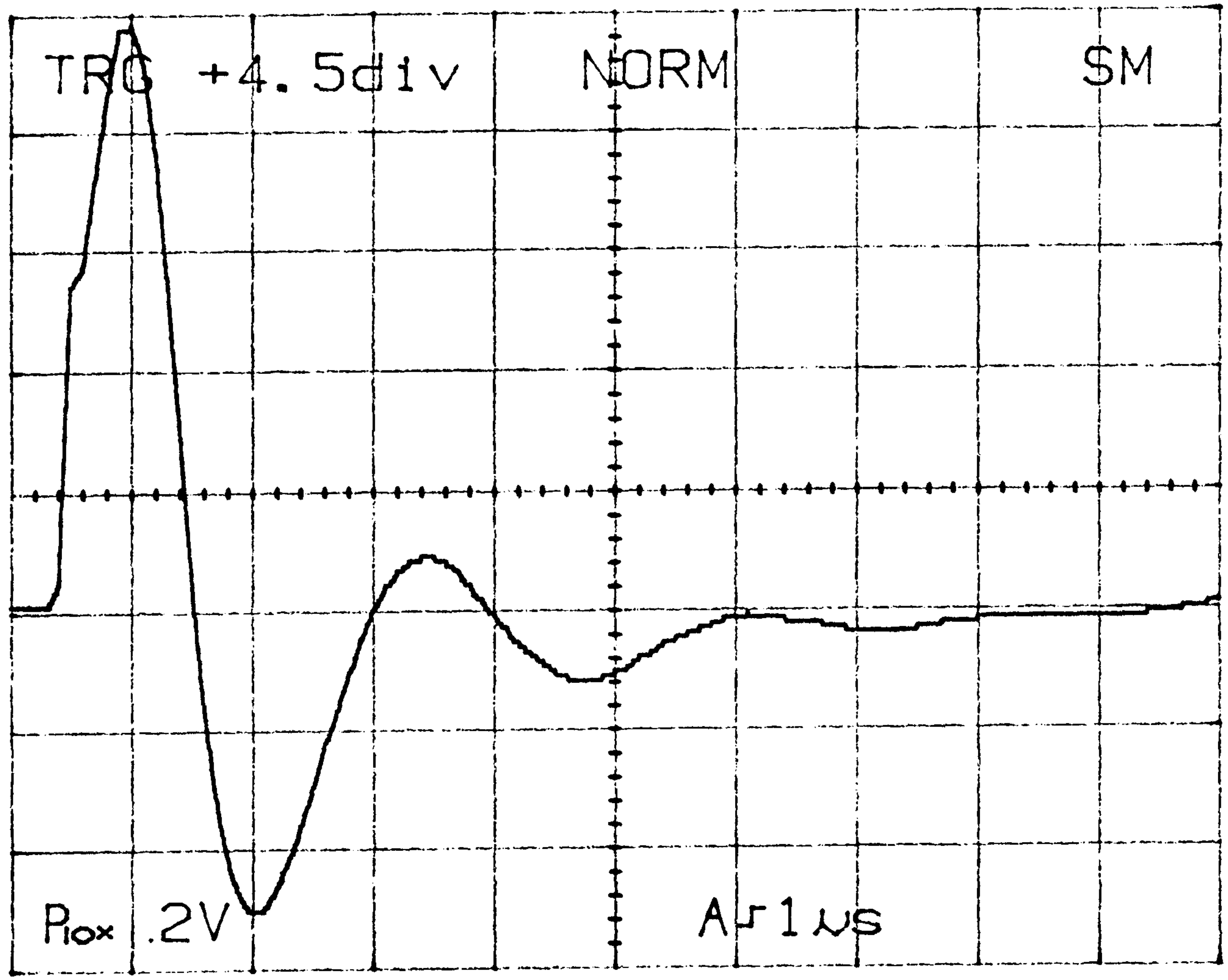
Headgate Rock
Coil #163

Surge Test
3/1/93



Headgate Rock
Coil # 498

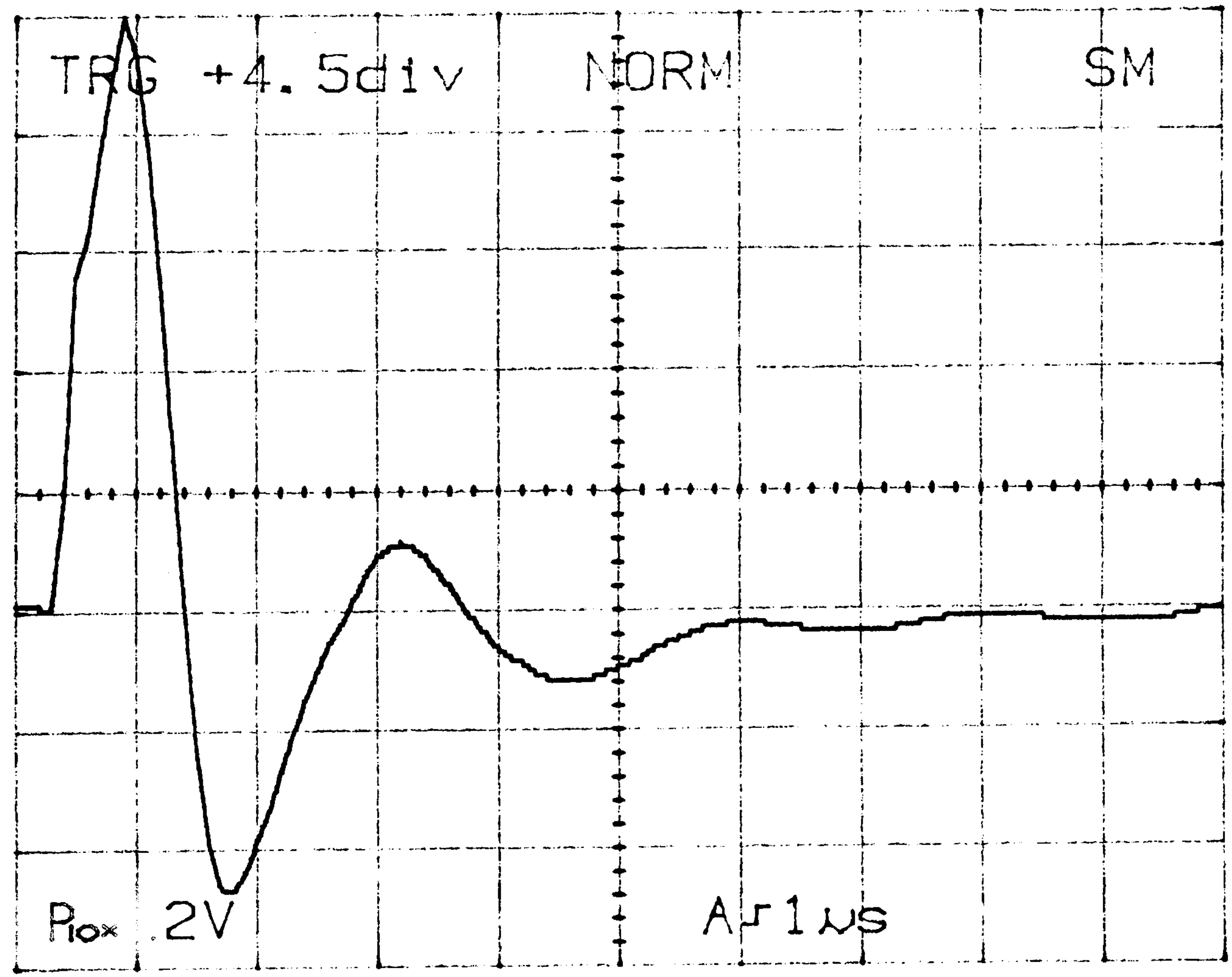
Surge Test
3/1/93



14

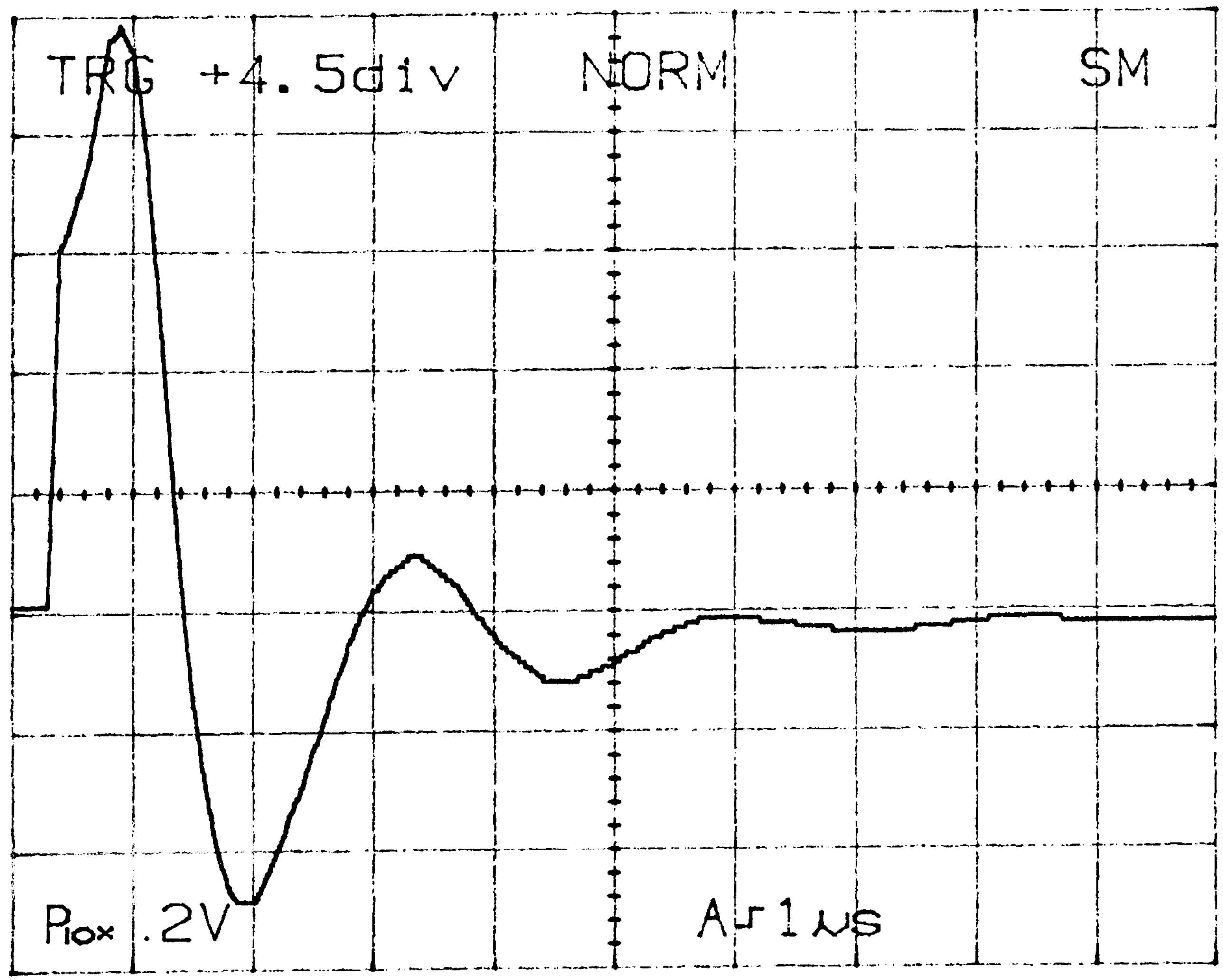
Headgate Rock
Coil # 499

Surge tester
3/1/93



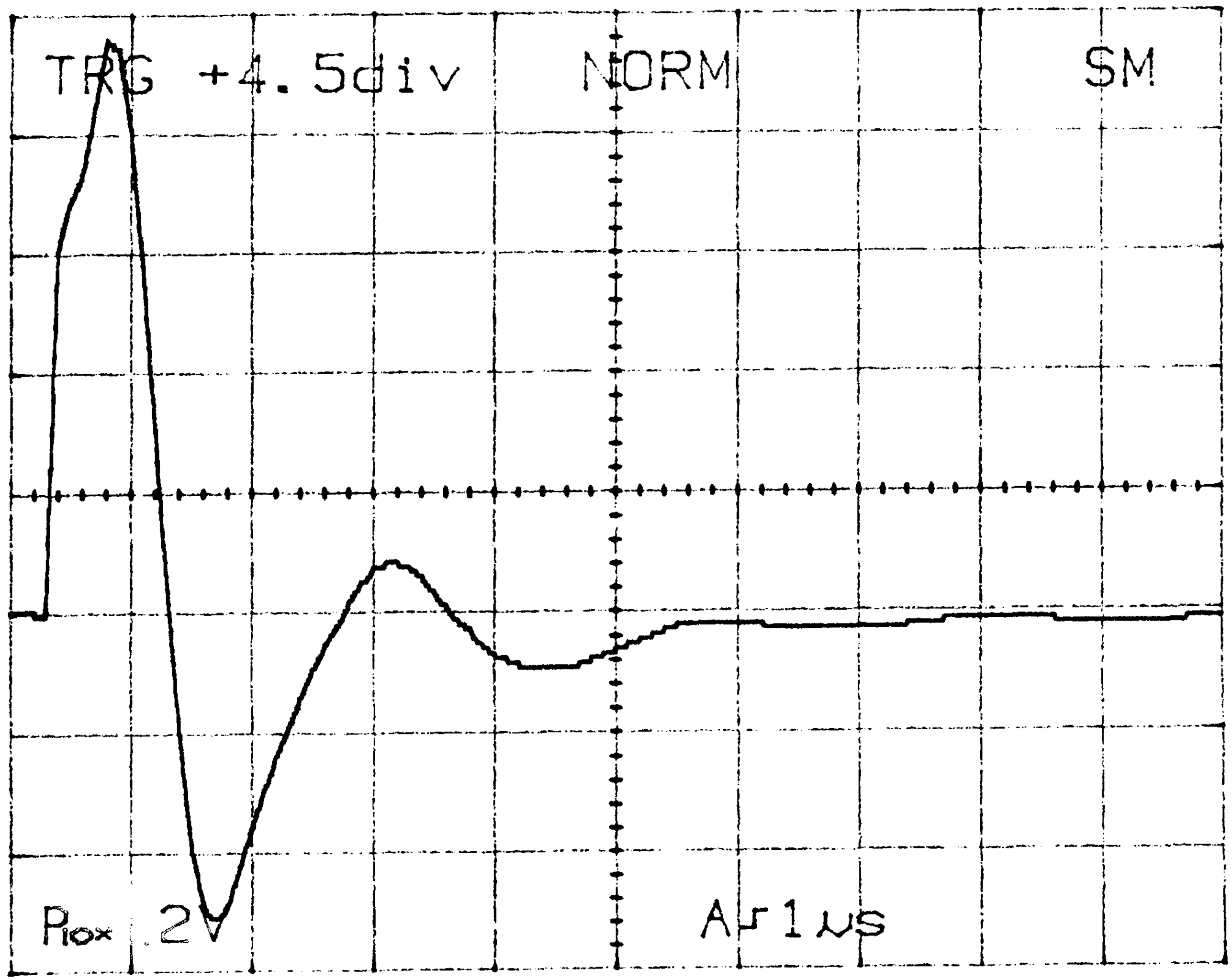
Headgate Rock
Coil #500

Surge Tester
3/1/93



Headgate Rock
Coil #501

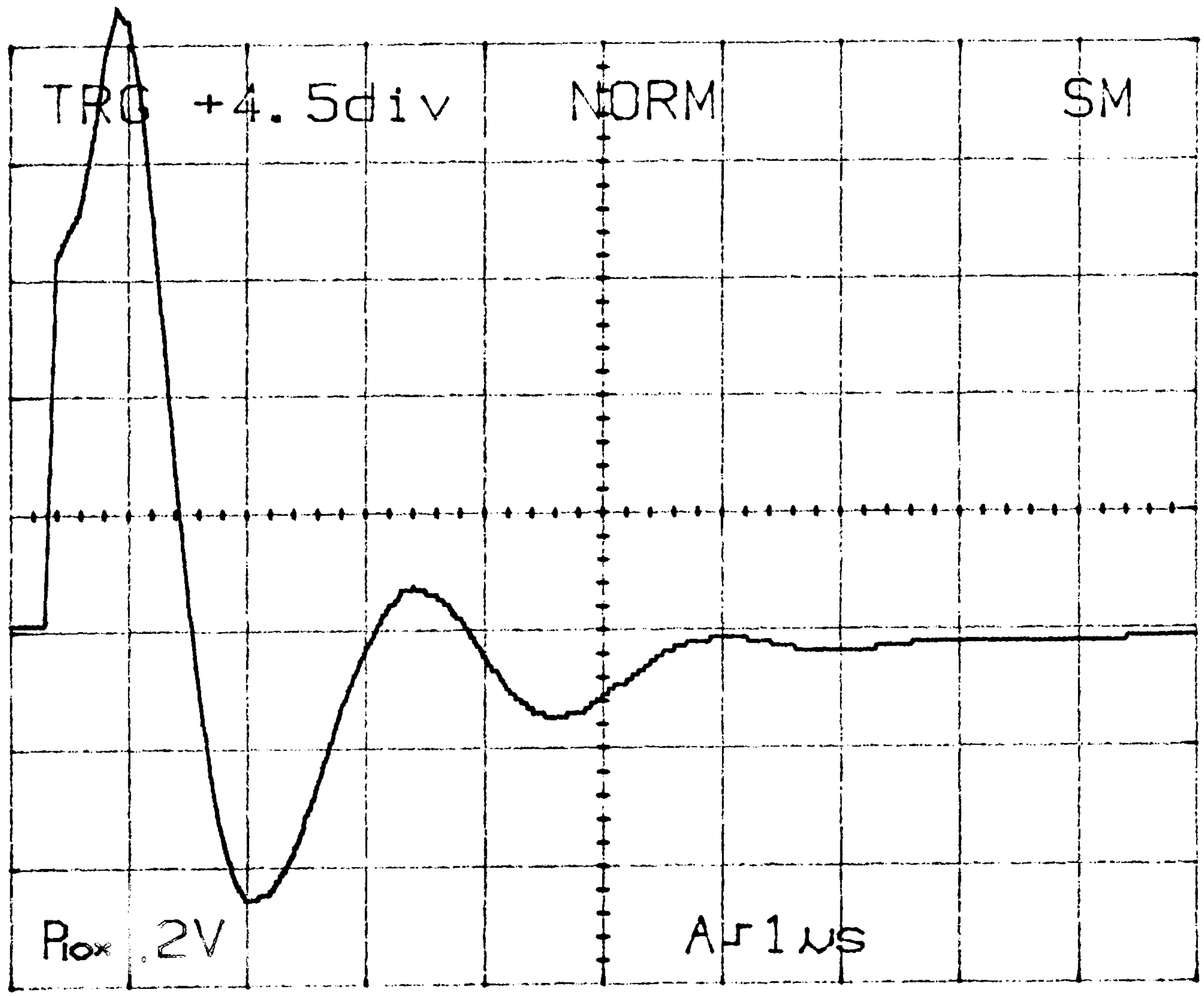
Surge Test
3/1/93



17

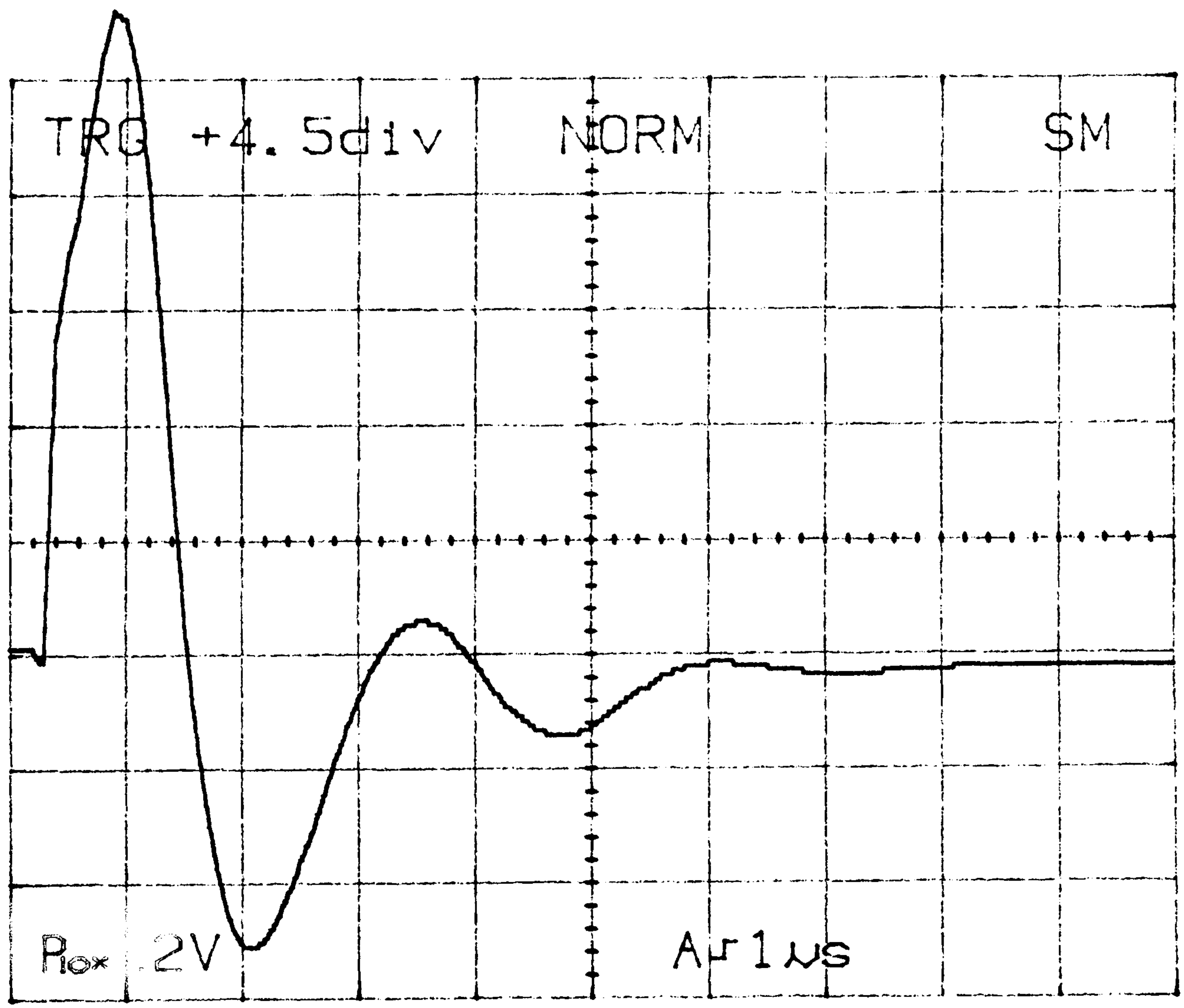
Headgate Rock
Coil #59

Surge Test
3/1/93



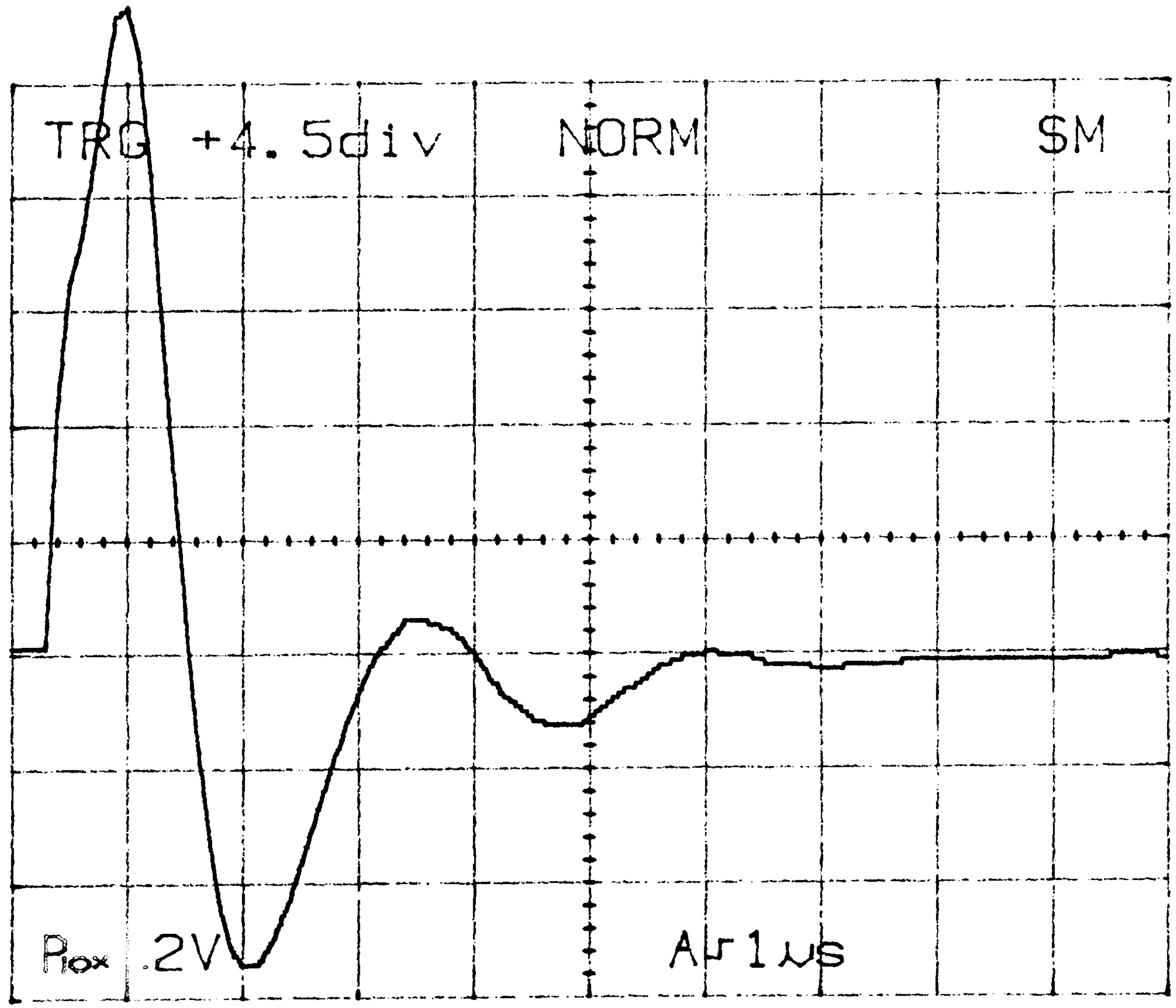
Headgate Rock
Coil #19

Surge Test
3/1/93



Headgate Rock
Coil # 18

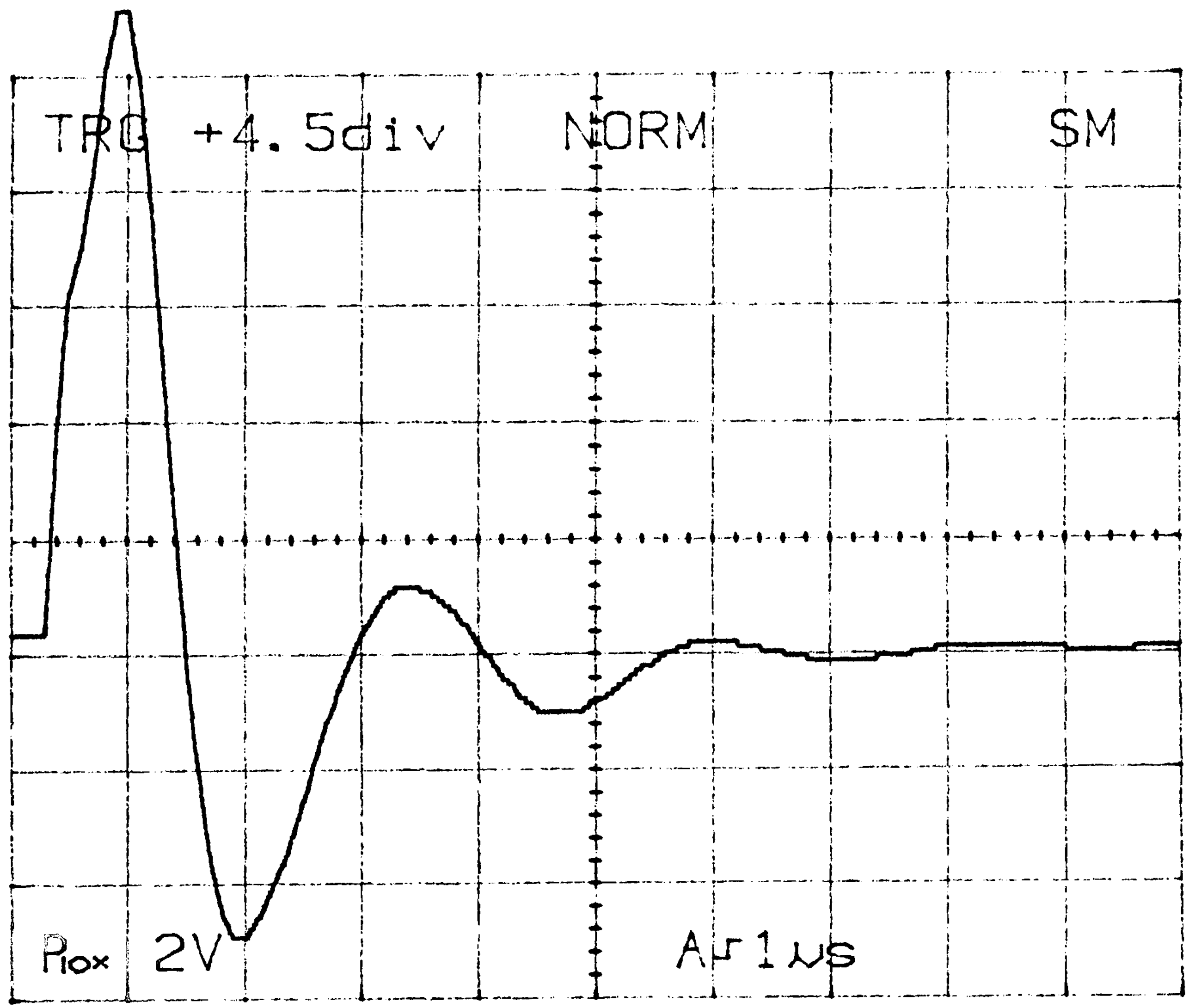
Surge Test
3/1/93



Headgate Rock
Coil # 498

Surge Test
3/1/93

Repeated Surge Test After Circulating
8Amps between Strands 1 and 3.
(No change.)



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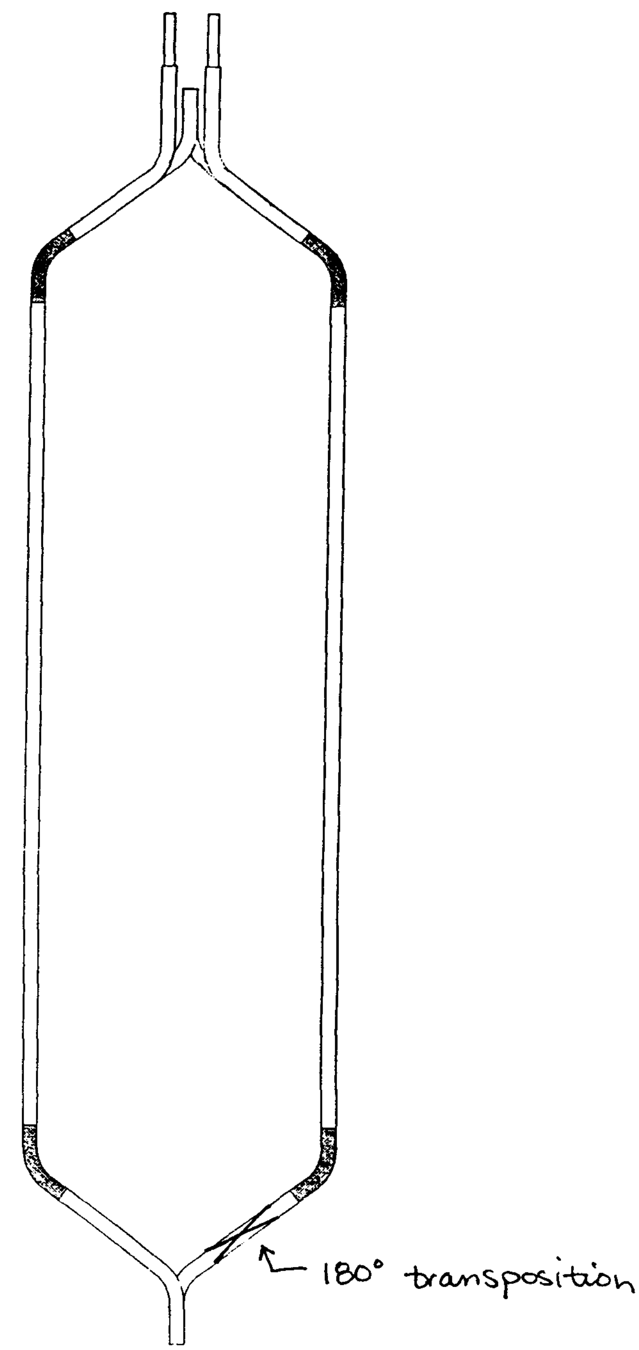
APPENDIX B

Turn Transposition

7-1654 (1-89)
Bureau of Reclamation

COMPUTATION SHEET

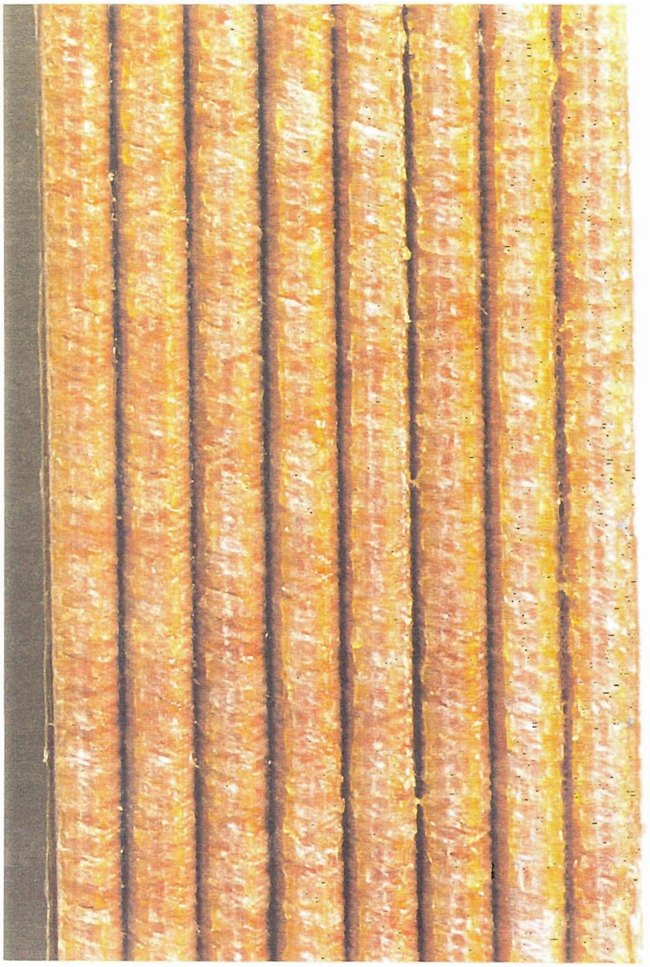
BY	DATE	PROJECT	SHEET ___ OF ___
L. Rux	5/93	Headgate Rock	
CHKD BY	DATE	FEATURE	
		Stator Coil	
DETAILS			
Location of of turn transposition			



Photograph B.1. - Turn transposition.

APPENDIX C

Contaminants in the Groundwall Insulation

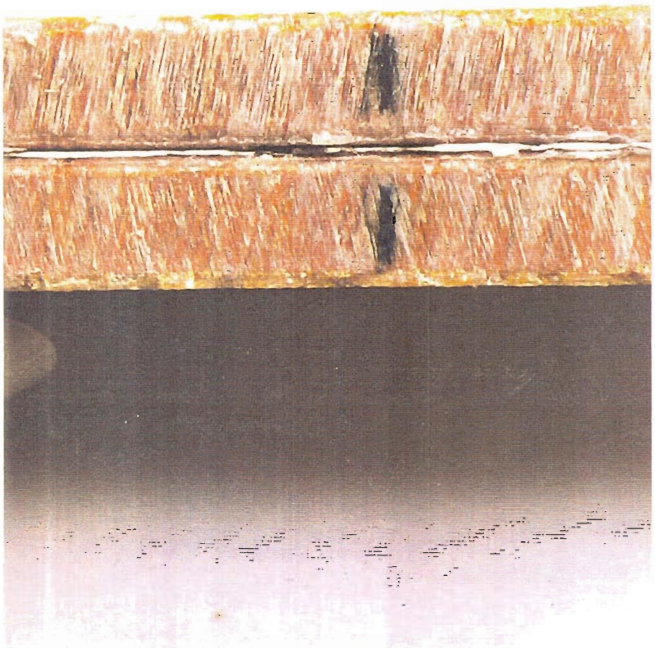


Photograph C.1. - Green, rubbery impurities in groundwall insulation.

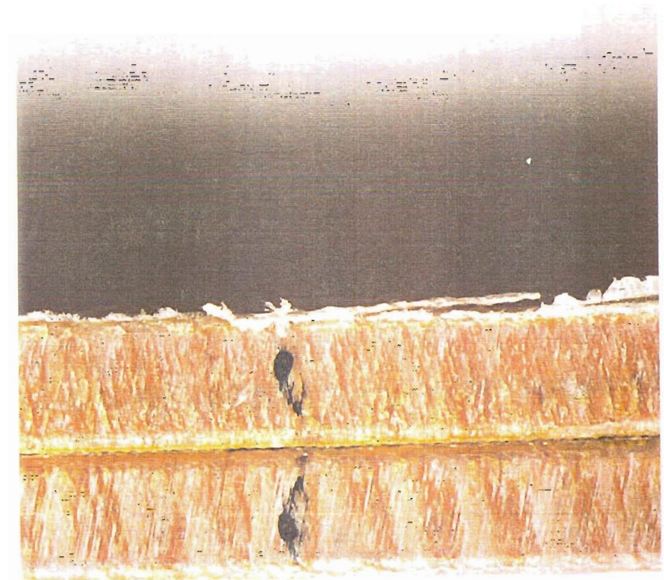
Photograph C.2. - Reddish-brown impurities in groundwall insulation.

APPENDIX D

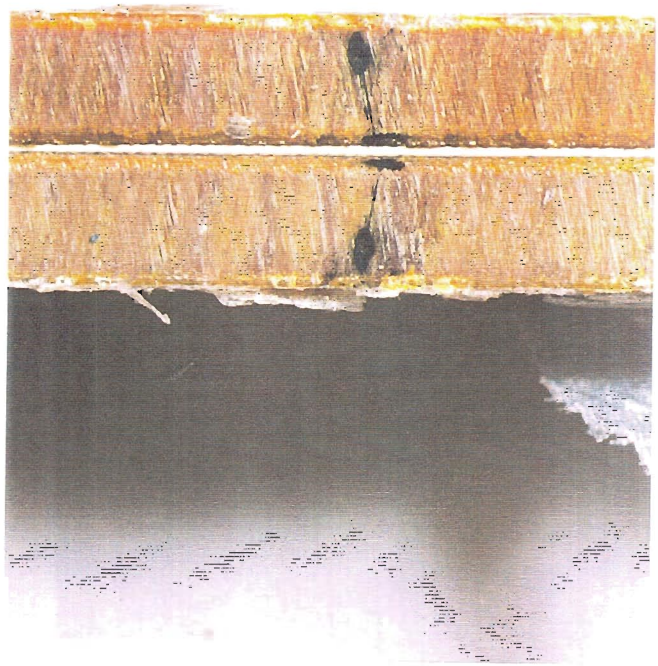
Turn-to-Turn Insulation Failures



Photograph D.1. - Turn-to-turn insulation failure.



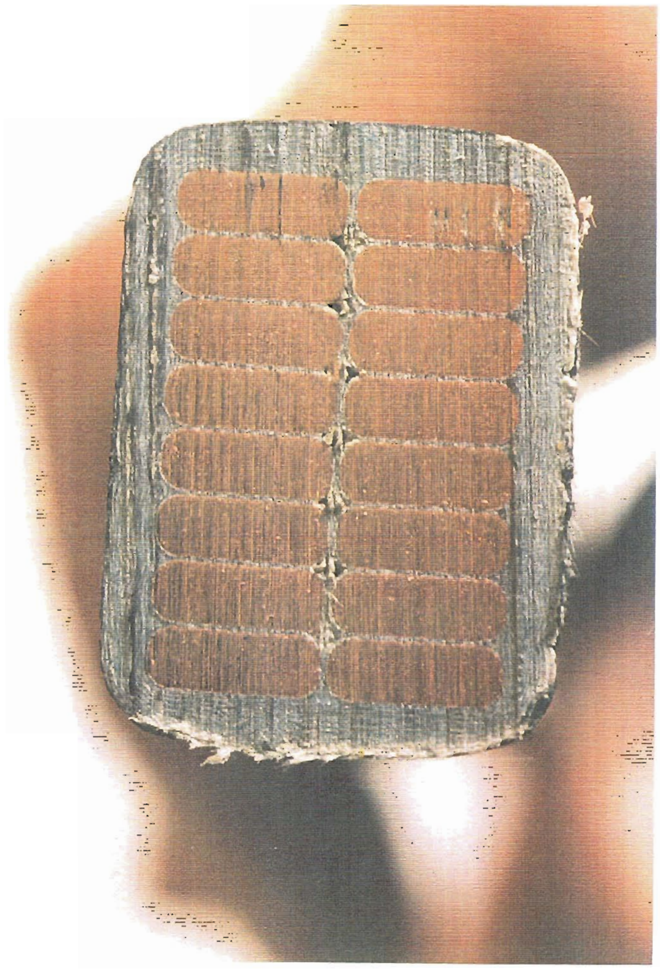
Photograph D.2. - Turn-to-turn insulation failure.



Photograph D.3. - Turn-to-turn insulation failure.

APPENDIX E

Voids Between Conductor Strands



Photograph E.1. - Cross section of coil in slot area; shows voids between conductor tiers.

Photograph E.2. - Side view of conductor tier; shows voids in strand insulation and between adjacent turns.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.