# EVALUATION OF THE BALADI INDIRECT TENSILE TEST APPARATUS

## FINAL REPORT

**Report Number FHWA-OR-MA-92-07**
**Contract Number DTFH 61-89-C-00019**

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Prepared for

Federal Highway Administration
Washington, D.C. 20590

December 1991

Technical Report Documentation Page

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
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|---|---|
| 4. Title and Subtitle<br>EVALUATION OF THE INDIRECT TENSILE TEST FOR DETERMINING THE STRUCTURAL PROPERTIES OF ASPHALT MIX | 5. Report Date<br>JANUARY 1992 |
| | 6. Performing Organization Code |
| 7. Author(s)<br>WILBUR D. LARSON AND ANTHONY J. GEORGE, P.E. | 8. Performing Organization Report No.<br>FHWA-OR-MA-92-07 |
| 9. Performing Organization Name and Address<br>OREGON DEPARTMENT OF TRANSPORTATION<br>MATERIALS AND RESEARCH SECTION<br>800 AIRPORT ROAD SE<br>SALEM, OREGON 97310 | 10. Work Unit No. (TRAIS) |
| | 11. Contract or Grant No.<br>DTFH61-89-C-0019 |
| 12. Sponsoring Agency Name and Address<br>DEPARTMENT OF TRANSPORTATION<br>FEDERAL HIGHWAY ADMINISTRATION<br>OFFICE OF CONTRACTS AND PROCUREMENT<br>400 SEVENTH STREET, S.W., ROOM 4410 WASHINGTON, D.C. 20590 | 13. Type of Report and Period Covered<br>FINAL REPORT 3-27-89 to 12-31-91 |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract


DR. GILBERT Y. BALADI, OF MICHIGAN STATE UNIVERSITY, HAS DESIGNED AN INDIRECT TENSILE TEST DEVICE TO MEASURE CERTAIN CHARACTERISTICS OF ASPHALTIC CONCRETE. THE OREGON DEPARTMENT OF TRANSPORTATION CURRENTLY USES THE RETSINA MARK VI DEVICE TO MEASURE THE MODULUS OF RESILIENCY OF A/C, AND IS PARTICIPATING IN A STUDY THAT COMPARES THE $M_R$ TEST RESULTS OF THE TWO DEVICES. THIS REPORT GIVES A BRIEF DESCRIPTION OF THE TWO SYSTEMS, THE TEST PROCEDURE, THE RESULTS OBTAINED BY EACH, AND A STATISTICAL ANALYSIS OF THOSE RESULTS.

ELEVEN CALIBRATION SPECIMENS AND OVER THIRTY ASPHALT BRIQUET SPECIMENS WERE TESTED WITH VARYING DEGREES OF SUCCESS AND FAILURE. REPRESENTATIVE RESULTS ARE PRESENTED IN TABLES ONE THROUGH THREE, WHICH ALSO SHOW THE VARIANCE FROM THE MEAN $M_R$, PRINTS DEPICTING THE HORIZONTAL DEFORMATION OF SOME SPECIMENS (RECORDED WITH THE ATS SCOPE PROGRAM) ARE INCLUDED (FIGURES 1 - 16). THESE SHOW THE UNEVEN HORIZONTAL DEFORMATION EXPERIENCED IN DR. BALADI'S DEVICE. TABLES A - D PRESENT THE STATISTICAL ANALYSES.

IN CONCLUSION, THE RETSINA MARK VI SYSTEM IS THE EASIER TO OPERATE OF THE TWO; BUT THE BALADI DEVICE (RUN BY THE ATS SOFTWARE) IS SUPERIOR IN DATA COLLECTION, STORAGE, AND RETRIEVAL. THE BALADI DEVICE OPERATED ERRATICALLY AND NEEDS IMPROVEMENT BEFORE FURTHER COMPARISON TESTING CAN BE DONE.


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|---|---|
| 17. Key Words INDEX OF RETAINED MODULUS, RESILIENT MODULUS ($M_R$), INDIRECT TENSILE TEST (ITT), OPEN-LOOP PNEUMATIC LOADING SYSTEM, HORIZONTAL DIAMETRAL AXIS, LINEAR VARIABLE DISPLACEMENT TRANSDUCERS, ATS SOFTWARE, CYCLIC LOAD, STRAIN, REST PERIOD, TOTAL RECOVERABLE DEFORMATION | 18. Distribution Statement<br>UNRESTRICTED |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | 40 | |

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## DISCLAIMER

## TECHNICAL SUMMARY

## EVALUATION OF THE BALADI INDIRECT TENSILE TEST APPARATUS

This technical summary discusses the findings of a Federal Highway Administration (FHWA) study intended to compare a new indirect tensile test device alongside a device that is currently in use.

### PURPOSE

The Oregon Department of Transportation uses the Retsina Mark VI indirect tensile test device (ITT) to determine the modulus of resiliency (MR) of dense-graded asphaltic concrete. Dr. Gilbert Y. Baladi, of Michigan State University, has developed an ITT purported to achieve superior results. The purpose of this study is to compare the results derived from these two systems, and determine the efficacy and cost-effectiveness of the new device.

### APPROACH

Testing of asphalt briquets was done according to Oregon State Highway Division (OSHD) test method TM-315-91. Total recoverable deformation was used to calculate the $M_R$ for both systems. The Retsina Mark VI system uses an internal micro-processor to control the ITT and record the data, which is then used to manually calculate the $M_R$. Dr. Baladi's device is controlled by a separate pc-286 computer and the ATS testing program, which was developed by Digital Control Systems. The ATS program records and stores the data, and also calculates the $M_R$.

## FINDINGS AND RECOMMENDATIONS

Dr. Baladi's ITT device was not able to reproduce the results obtained by the Retsina Mark VI device. The reason for this is that specimen movement affected the horizontal deformation measurements to a significantly greater degree in the Baladi device than in the Retsina. There are two possible causes of this:

1) two different methods of holding the linear variable displacement transducers in contact with the specimen were used. The Retsina Mark VI has lvdt's mounted in a rectangular yoke, which is clamped to the specimen; while the Baladi device holds the lvdt's in fixed posts.

2) both systems have an open-loop pneumatic loading system. The Baladi device, with its fixed lvdt's, would probably benefit from a closed-loop loading system.

A "paired t" statistical analysis was used to compare samples tested in each system. The results indicate that the systems do not operate equally, and that there is greater variation in test results with the Baladi device. Further study of this new ITT device might include employing a better method of holding the lvdt's, similar to the yoke used by the Retsina. Also, due to the fact that our device employed an open-loop pnuematic system, the specimens didn't have a static seating load applied to them. A closed-loop system (one that can apply a static seating load) might reduce specimen movement.

## ABSTRACT

Dr. Gilbert Y. Baladi, of Michigan State University, has designed an indirect tensile test device to measure certain characteristics of asphaltic concrete. The Oregon Department of Transportation currently uses the Retsina Mark VI device to measure the modulus of resiliency of a/c, and is participating in a study that compares the $M_R$ test results of the two devices. This report gives a brief description of the two systems, the test procedure, the results obtained by each, and a statistical analysis of those results.

Eleven calibration specimens, and over thirty asphalt briquet specimens were tested, with varying degrees of success and failure. Representative results are presented in tables one through three, which also show the variance from the mean $M_R$. Prints depicting the horizontal deformation of some specimens (recorded with the ATS Scope program) are included (Figures 1 - 16). These show the uneven horizontal deformation experienced in Dr. Baladi's device. Tables A - D present the statistical analyses.

In conclusion, the Retsina Mark VI system is the easier to operate of the two; but the Baladi device (run by the ATS software) is superior in data collection, storage, and retrieval. The Baladi device operated erratically, and needs improvement before further comparison testing can be done.

# INTRODUCTION

Since 1980 the Oregon Department of Transportation has determined the effect of water saturation and freeze-thaw cycle on dense-graded asphaltic concrete by calculating an index of retained modulus. This method is intended to predict loss of resilient modulus of compacted, dense-graded asphalt due to field conditions of moisture and freezing. In addition, current and predicted future modulus values are generated for pavement design purposes.

Because ODOT seeks innovative and more efficient methods to determine the physical characteristics of its roadway materials, they decided to participate in a FHWA study entitled "Evaluation of Indirect Tensile Test for Determining the Structural Properties of Asphalt Mix." The main objective is to test a new indirect tensile test device alongside the device currently used, and evaluate its performance. The new device is based on a design by Dr. Gilbert Y. Baladi, of Michigan State University.
A secondary objective is to evaluate a new software package from Digital Control Systems of Berkeley, Ca. This software is designed to conduct modulus of resiliency ($M_R$) testing on both asphaltic concrete and soils.

## EQUIPMENT

### CURRENT

Currently, ODOT tests asphalt briquets for modulus of resiliency ($M_R$) in the Retsina Mark VI device. This indirect tensile test device consists of a bottom platen attached to a top piston guide platen by two heavy posts. The loading system is open-loop pneumatic consisting of a surge tank, pressure regulator, SMC solenoid air valve, and connectors. The pneumatic force is applied to the specimen through a single-action "Bellofram" air cylinder. At the bottom of the loading shaft is a 1000 lb. load transducer, mated to the top load strip with a 3/4 inch steel ball bearing. Both top and bottom load strips are 1/2 inch square by three inches long, with one face each milled out to a four inch radius to accomodate the specimens. Two linear variable displacement transducers (lvdt) are mounted in a yoke that clamps on to the specimen by means of four thumbscrews. A differential translator micrometer is used to calibrate the lvdt's. The load transducer is calibrated by the electronics package, which consists of a microprocessor, firmware, paper printer, digital readout, timing mechanism, control switches, a/d convertor, signal processing hardware, and a power supply.

### NEW

The new equipment was acquired from several sources. The indirect tensile test device and related frame was engineered and built by Sierra Microsystems of Auburn, Ca. The original Baladi design was modified slightly to improve its performance. Instead of bronze bushings to guide the loading shaft through the top platen, double, linear ball bearings with a split housing was used. A steel collar was attached to the load shaft to prevent the shaft and load strip from falling completely through the top platen. Also, attached to the load shaft is a horizontal arm. At one end is a second shaft that passes through bearings in the top platen for added stability, and at the other end is a shorter shaft that is used to measure vertical deformation by contacting a lvdt that is mounted in the top platen. Another modification was made to the four posts that join the upper and lower platens. Two were placed in the horizontal diametral axis, and two were placed in the perpendicular horizontal axis. One of these last two is removable to aid in the placement of the specimen. The other three are permanently mounted. Each post is designed to hold a lvdt, mounted in an adjustable collar, in the precise horizontal and vertical position required to measure the deformation of a four inch diameter specimen. The loading strips are similar to the Retsina's, but are four inches in length. Parts subject to wear were specially hardened.

Additional hardware includes: five Schaevitz lvdt's from Brett Associates of Seattle, Wa.; air supply components from SAS Fluid Power of Portland, Or., and Retsina of Oakland, Ca. (Identical to those used by the Retsina device). A pc-286 computer is used to control and monitor the test, via the Windows 2.11 format. Controlling the tests is the ATS 2.43 software from Digital Control Systems of Berkeley, Ca. Also, from DCS are the electronic signal conditioner and load controller. Technicians from Oregon State University, and Dr. Jorge Sousa of DCS, assisted ODOT materials personnel with assembling and calibrating the new system. The ATS package is successfuly being used at this time to perform soil modulus of resiliency tests.

# TEST PROCEDURE

## GENERAL

Before actual comparison testing was to commence, verification that the new device would operate satisfactorily was needed. Each specimen was first tested in the Retsina, following OSHD (Oregon State Highway Division) test method TM 315-91, and subsequently tested in the Baladi device. The corresponding results were compared. The OSHD TM 315-91 criteria calls for controlling the cyclic load force so that the resultant horizontal deformation is between 96 and 106 micro-inches. This was possible with the Retsina because, after each load pulse, the total horizontal deformation was displayed on a digital readout. With the Baladi, and specifically the ATS software, it was not possible to use strain control because the actual measurements were not available until after the test had finished and the $M_R$ results had been calculated. Even by displaying on screen the deformation waveforms with the ATS Scope program, it was impossible to accurately determine the actual displacements. Since strain control was out with the Baladi/ATS system, load control was the only other alternative. The cyclic load applied to the Baladi was manually adjusted in an attempt to match the corresponding load of the Retsina. Although it was somewhat easier to read the load forces on the scope, it was not always possible to exactly match the Retsina load force. Therefore, not all tests run on the Baladi were performed at the same loads as applied by the Retsina.

All specimens were tested in a room where the temperature was maintained at a constant 77 to 78 degrees farenheit. They were oriented in the same direction and the same axes were tested in both devices.

RETSINA MARK VI

Per OSHD TM 315-91, the Retsina is set to run a series of ten cycles/test, with a load pulse of 0.25 sec., and a cycle duration of three (3) seconds. The diameter of the specimen is sensed prior to the applied load and stored. 0.1 sec. after the beginning of the load increase is sensed, the diameter is sensed again and compared to the stored value. This procedure effectively gives the total deformation after a 0.1 sec. load pulse. This value is displayed on the digital readout immediatley following the load pulse. Each specimen is conditioned for a minimum of 20 cycles. If cycles 21 to 30 meet the deformation criterion the test results may be recorded. If not, the test is repeated until satisfactory results are obtained. It is sometimes necessary to perform an additional 50-70 cycles before the horizontal deformations stabilize.

BALADI

The Baladi/ATS system was set to run a series of 100 cycles/test, and record the last ten cycles (this is preset by the operator in a test schedule file). An applied load duration of 0.1 sec. was used to match the recording time of the Retsina, with a cycle duration of one sec. The ATS program senses the deformation for the entire period and uses this information to compute the total recoverable deformation. Both systems measure the diameter of the specimen at the end of the rest period and again after loading for 0.1 second.

## TEST RESULTS

### SPECIMENS

All specimens are four (4) inches in diameter, and have a nominal thickness of two and one-half (2.5) inches. Seven (7) OSHD calibration specimens, four (4) calibration specimens from Steele Engineering, Inc., (used in the SHRP P-07 program), nine (9) asphalt briquets from Kansas DOT, and over twenty (20) asphalt briquets from ODOT projects were tested.

### INITIAL TESTING

To "shakedown" the new system, two sets of three asphalt briquets were tested, first in the Retsina and then in the Baladi. These specimens experienced severe rocking action in the Baladi device. Even with careful alignment and realignment, the rocking persisted. The resultant $M_R$'s from the Baladi device were higher than the Retsina due to offsetting horizontal deformations (one positive, the other negative) summing up to a low total deformation. The results were so erratic in the Baladi that a true comparison was not possible.

It was evident that great care had to be exercised in placing the specimen between the load strips of the Baladi device to eliminate the rocking action. After further inspection of the new device it was found that the top load strip moved sideways on its mounting pin, and had a slight wobble. Stainless steel feeler guages were used to shim the load strip, which eliminated the play and made it secure. The top and bottom load strips were determined to be in good vertical alignment.

Additional measures were taken to assure proper specimen alignment. One was to replace the bullet nose tips on the horizontal lvdt's with flat nose tips. It was possible that the small, pointed tips were hanging up in the small depressions in the irregular surface of the asphalt specimens. Flat nosed tips provided a smooth surface for the specimen to ride against and caused the lvdt's to measure only horizontal movement. But, after close examination, this change did not appear to affect either the displacement or the rocking motion. Another measure taken was to create a template from a piece of 4" abs plastic pipe the same length as the specimen thickness. Two perpendicular diameters were marked on each side of the template, and by placing this around the specimen coincident perpendicular axes were marked on each face. This procedure was very successful in aligning the specimen in the Retsina device, but did not prove helpful in the Baladi. Another device was made from three 1/4 inch metal strips welded together in a channel configuration. When held against the upper and lower load strips the vertical side of the jig contacted the specimen tangent to its circumference, thereby assuring that the specimen was parallel with the load strips, and centered in the vertical plane. Although correct in theory, it did not eliminate the rocking encountered in the Baladi device.

## CALIBRATION SPECIMENS

Next tested were the seven OSHD calibration specimens. Three are made of acetal copolymer, which is a very hard, slick material (680K psi). These specimens continually rocked in the Baladi device. The oscilloscope waveforms show deformation in positive and negative directions, when both should be positive. Three other specimens are made of abs plastic and are also very hard, but not as slick (403K psi). They also rocked in the Baladi device. Repeated repositioning of the specimens did not eliminate the problem. Use of the template and jig did not help, either (see figures #1 & 2 for specimen movement. As the specimens expand, the lvdt's contract, their signal output is positive and the waveforms rise in a positive direction). The seventh specimen is made of hard rubber. Being much softer (8K psi) than the other calibration specimens, it did not rock or hop at all and the horizontal deformations were well balanced (see figure #3). Test results on this specimen compared well with the Retsina. All the Retsina test results were stable and conformed with earlier tests. The variance from their mean does not exceed two percent. The Baladi test results, on the other hand, were erratic and varied from their mean by up to 87 percent. The hard rubber specimen was an exception. (See table #1 for the results).

Four (4) other calibration specimens from SHRP were also tested. One is made of lucite, one of teflon, one of polypropylene, and one of hard rubber. The first three are very hard and slick, and also exhibited excessive rocking. A good test was unobtainable from either of these three. The fourth tested favorably, similar to the OSHD rubber specimen. The Retsina showed the $M_R$ to be 5647 psi, and the Baladi came in at 5775 psi. Kansas DOT Baladi results came in at 5700 to 6000 psi, and Steele Engineering reports a mean of 6300 psi.

Even by exercizing extreme care in aligning the specimens in the vertical and horizontal axes, the rocking action could not be eliminated. Some reduction was possible, but only after repeated, and time consuming, repositioning of the specimen and lvdt's. Because consistent results were unobtainable with these calibration specimens, more asphalt specimens were tested in an attempt to determine the problems with the Baladi device, and document the results and differences of the two systems.

## ASPHALT SPECIMENS

Over 30 asphalt specimens were tested with mixed results. Using careful alignment procedures was no guarantee that the specimen would not rock. The only way found to correct the rocking action was to manually run several cycles and watch the deformations on the scope. If rocking was evident, the specimen was manually repositioned, the lvdt's reset, and the cycles repeated. This was very time consuming, as some samples required up to six setups, or more, and still the problem was not always rectified. Some asphalt specimens did not rock, and the test results were acceptable. Well-shaped, even deformations occured with some, while on others the deformations were uneven enough to warrant repositioning (see figures # 4 - 12 for deformation waveforms).

The results of five ODOT asphalt specimens are presented in table #2. Nearly every asphalt specimen tested in the Baladi yielded significantly lower $M_R$ results than in the Retsina. Results of the Retsina are all within eight percent of their mean. The Baladi results varied up to 13 percent from their mean, and there was greater dispersion.

Finally, a set of eight asphalt specimens from Kansas Department of

Transportation was tested. Everything that had been done to eliminate rocking in the Baladi still did not completely eliminate the problem. Even if the rocking was eliminated, there was still the problem of uneven deformation. There was as much difficulty encountered with the Kansas specimens as with the ODOT ones (see figures # 13-16). The results of the Retsina are consistent, with a variance from their mean of no more than eight percent. The Baladi results are erratic, and vary from their mean by up to 25 percent. The Baladi results are also significantly lower than the Retsina. Results obtained one year earlier by Kansas DOT with their Baladi type device, are included in table three for comparison. Note that the ODOT Retsina results are higher, possibly due in part to asphalt aging, but the ODOT Baladi results are generally lower (see table #3 for the results).

## SUMMARY OF RESULTS

Because of rocking and uneven deformation, six of the calibration specimens gave results either higher or lower when tested in the Baladi than when in the Retsina. Three of the SHRP calibration specimens performed the same, or worse, and no results were obtainable. The two rubber specimens performed exceptionaly well, matching the results of both the Retsina Mark VI and the KDOT Baladi (SHRP specimen only).

Rocking was not as pronounced with the asphalt specimens, although it was still a problem, and uneven deformation was as great a problem as the rocking. Most of the Baladi's results were significantly lower than the Retsina's, although some were close.

For the calibration (hard) specimens, the variance from the mean $M_R$ for each group ranged up to 87 percent in the Baladi, while in the Retsina it never exceeded two percent. The variance from the mean $M_R$ for all asphalt samples reached 15 percent, with most below eight percent in the Retsina. In the Baladi the variance ranged up to 25 percent with more dispersion.

There are some similarities between the Oregon DOT briquets and those from Kansas DOT. Tested in the Retsina, the average $M_R$ of the Oregon specimens is 210K psi, vs 236K psi for those from Kansas. Oregon specimens tested in the Baladi averaged 148K psi, 62K psi lower than the Retsina; while Kansas specimens averaged 166K psi in the Baladi, 70K psi lower than the Retsina. The average variance from the mean $M_R$ of all asphalt specimens is shown below.

VARIANCE FROM MEAN $M_R$ OF ASPHALT SPECIMENS

| | RETSINA | BALADI |
|---|---|---|
| OREGON | 3.8% | 4.7% |
| KANSAS | 5.6% | 10.3% |

## STATISTICAL EVALUATION

A "two-tailed paired t" test was performed to determine if there was a significant difference between the means of the $M_R$'s obtained by each device. The null hypothesis for this test is:

$$Ho: \mu_d = \text{hypothesized value}$$

The test statistic is:

$$t = \frac{\bar{X}_d - \text{HYPOTHESIZED VALUE}}{S_d / \sqrt{n}}$$

The purpose of the statistical evaluation is to show that there is, or is not, a difference between the two devices. The hypothesized value is 0, and the null hypothesis becomes:

$$Ho: \mu_d = \mu_1 - \mu_2 = 0;$$

$$Ho: \mu_d = 0$$

The alternative hypothesis is:

$$Ha: \mu_a \neq 0$$

And the test statistic becomes:

$$t = \frac{\bar{X}_d - 0}{Sd/\sqrt{n}}$$

Three groups of specimens were analyzed:

1) six ODOT calibration specimens,
2) five ODOT asphalt specimens, and
3) nine KDOT asphalt specimens.

The KDOT specimens were also analyzed to show the difference between the ODOT Baladi device and the KDOT Baladi device.

The nature of Ha implies that a two-tailed rejection region should be used. Using a level of significance of .001, all the t values exceeded the critical t value for the corresponding degrees of freedom. This leads to the probability that there is less than 0.1% chance that, if the two devices are equal, these results would be obtainable.

$.001>p>0$ Is cause to reject Ho and accept Ha, because p is less than 0.5.

## ADVANTAGES/DISADVANTAGES OF THE TWO SYSTEMS

### RETSINA MARK VI

The Retsina Mark VI is easier to operate than the Baladi/ATS system. Specimen placement is easy, and by clamping the lvdt's to the specimen with a yoke, the effect of sideways movement is virtually negated. Control of the $M_R$ test can be by either strain control or load control. Although it is possible to monitor undesired specimen movement (with the led's that indicate displacement), it is not possible to visually see the horizontal deformations. After each test, the Retsina delivers a printed tape that shows sample information, average load, total horizontal deformation for each cycle, and the average total deformation for each test. It will also calculate the average $M_R$ from the ten repetitions of each test. The Retsina does not record horizontal deformation for each side, but rather, the total recoverable deformation. When a new test is started, any old data is lost, and cannot be analyzed further. A tape must be printed to save any data.

### BALADI/ATS

The Baladi device is extremely difficult to use. Specimen alignment is the major drawback. Repositioning of the specimen and lvdt's to achieve balanced deformation and eliminate rocking is very laborious and time consuming. Sometimes improvement is made, sometimes the effort proves futile. The major advantage the Baladi/ATS system has over the Retsina is the ATS software. Data collection, storage, and $M_R$ reporting are highly superior to the Retsina. Besides allowing for visual monitoring of sample deformation and the applied cyclic load, it has an excellent and precise calibration program. Test control is very good, with provisions for storing individual sample data, test parameters, and recording data. Data can be analyzed and customized reports printed. Sample information, raw data, and finished reports can be saved for further evaluation.

The ATS Scope program is useful in monitoring deformation and load waveforms. It is reasonably easy to monitor the applied load, however, the deformation values are very difficult to visually determine. Some bugs in the ATS Scope program were encountered. Some scope files would not print, and for those that did print the x axis (duration) was lost, and the y axis (displacement) shifted downward on the grid.

This software is currently being used to control equipment used to determine the $M_R$ of soils. This equipment utilizes a closed-loop pneumatic system, and precise load control is possible. The results from this system have been very good, and we are quite pleased with its operation.

## CONCLUSION

The indirect tensile test device designed by Dr. Baladi did not operate satisfactorily, and did not compare well with the Retsina Mark VI system. Because of problems encountered with specimen movement in the Baladi device, displacement measurements were subject to question, and modulus of resiliency values were not repeatable nor congruent with those of the Retsina Mark VI. To eliminate unwanted movement, placing the specimen in the Baladi device became so laborious and time consuming that it made the test procedure burdensome. This study is being concluded because the Baladi indirect tensile test device would not operate satisfactorily. The extra time and expense required to determine, and correct, the causes for its poor performance exceed our present responsibilities.

## RECOMMENDATIONS

Further development of this study can be aided by answering the following questions:

1) Is specimen movement inherent in this type of test?
2) If so, how much, and can it be controlled?
3) Are fixed lvdt's a good idea for an ITT device, or is clamping them to the specimen with a yoke better?
4) Does a closed-loop loading system (whether pneumatic or hydraulic) make a difference in specimen behavior?

The principle problem encountered was the inability to determine a viable $M_R$ because of excessive movement of the specimen in Dr. Baladi's device. Because of the complex nature of this problem, further investigation is beyond the scope of this report.

TABLE #1

| CALIB. SAMPLE # | | RETSINA Mr | VAR | BALADI Mr | VAR | BALADI COMMENTS |
|---|---|---|---|---|---|---|
| #2 | 0* | 7564 | ±0.7% | 6930 | ±0.8% | good deformation |
| | 90 | 7464 | | 6820 | | |
| #3 | 0 | 687309 | + 1% | 290210 | -42% | #3, 4 & 5 are made of acetal copolymer. The mean for the Retsina is 679,990 psi, for the Baladi it is 503,180 psi. |
| | 90 | 677615 | -0.3% | 378850 | -25% | |
| #4 | 0 | 674128 | -1% | 503060 | -0.2% | |
| | 90 | 675301 | -1% | 342940 | -32% | |
| #5 | 0 | 684943 | +1% | 564570 | +12% | |
| | 90 | 680673 | +0.1% | 939470 | +87% | |
| #6 | 0 | 400906 | -1% | 49930 | -49% | #6, 7 & 8 are made of abs plastic. The mean for the Retsina is 403,470 psi, for the Baladi it is 97,580 psi. |
| | 90 | 395761 | -2% | 38990 | -60% | |
| #7 | 0 | 406484 | +1% | 179480 | +84% | |
| | 90 | 410493 | +2% | 108980 | +12% | |
| #8 | 0 | 393976 | -2% | 138810 | +42% | |
| | 90 | 413184 | +2% | 69300 | -29% | |

*denotes axis orientation

## TABLE #2

| PROJ. NAME SAMPLE # | | RETSINA $M_R$ | VAR | BALADI $M_R$ | VAR | BALADI COMMENTS |
|---|---|---|---|---|---|---|
| Ashland POE-Truck Inspection Station | | | | | | |
| #6 | 0* | 203290 | ±6% | 155700 | ±0.9% | fair deformation |
| | 90 | 180260 | | 158550 | | uneven deformation |
| #8 | 0 | 195680 | ±6% | 144780 | ±2% | good deformation |
| | 90 | 174910 | | 138840 | | slight rocking |
| District 12 Oiling | | | | | | |
| #13 | 0 | 132950 | ±3% | 120210 | ±10% | good deformation |
| | 90 | 141090 | | 99250 | | fair deformation |
| #13** | 0 | 159020 | ±0.3% | 100810 | ±2% | rocking |
| | 90 | 159890 | | 97340 | | rocking |
| Brookman Road-Garland Road | | | | | | |
| #7115 | 0 | 260390 | ±2% | 169150 | ±0.6% | fair deformation |
| | 90 | 248930 | | 171350 | | " " |
| #7115** | 0 | 286090 | ±0.4% | 152860 | ±4% | uneven deformation |
| | 90 | 283810 | | 165270 | | " " |
| Spring Creek-Lostine | | | | | | |
| #2t | 0 | 264650 | ±8% | 221810 | ±13% | uneven deformation |
| | 90 | 226060 | | 172380 | | slight rocking |
| #2t** | 0 | 237360 | ±5% | 172160 | ±5% | rocking, uneven |
| | 90 | 213430 | | 155910 | | fair deformation |

**after a freeze-thaw cycle

*denotes axis orientation

TABLE #3

| KANSAS DOT ASPHALTBRIQUETS | | RETSINA Mr | VAR | BALADI Mr | VAR | KANSAS BALADI | VAR |
|---|---|---|---|---|---|---|---|
| 148#9 | 0* | 255140 | ±5% | 179810 | ±2% | 229000 | ±18% |
| | 90 | 231000 | | 174320 | | 224000 | |
| 144#10 | 0 | 247400 | ±4% | 178850 | ±11% | 239000 | ±15% |
| | 90 | 228890 | | 142250 | | 184000 | |
| 148#5 | 0 | 353200 | ±7% | 211390 | ±3% | 295000 | ±13% |
| | 90 | 304490 | | 199480 | | 233000 | |
| 144#5 | 0 | 262350 | ±5% | 131400 | ±8% | 226000 | ±8% |
| | 90 | 236620 | | 112210 | | 194000 | |
| 140#2 | 0 | 189940 | ±2% | 235480 | ±25% | 199000 | ±1% |
| | 90 | 181770 | | 140290 | | 196000 | |
| 140#6 | 0 | 198420 | ±7% | 160980 | ±2% | 189000 | ±.03% |
| | 90 | 173320 | | 156000 | | 190000 | |
| 140#12 | 0 | 207850 | ±8% | 132280 | ±10% | 201000 | ±8% |
| | 90 | 177780 | | 160590 | | 172000 | |
| 148#15 | 0 | 281290 | ±4% | 135990 | ±17% | 262000 | ±16% |
| | 90 | 258930 | | 192310 | | 198000 | |
| 144#17 | 0 | 255690 | ±8% | 209570 | ±15% | 199000 | ±4% |
| | 90 | 216850 | | 156150 | | 185000 | |

*denotes axis orientation

TABLE A
ODOT Calibration Specimens, paired t analysis
RETSINA VS. BALADI
X1 = Retsina, X2 = Baladi
NOTE: d=X1-X2; D=avg d; Sd=std.dev.; SD=Sd/sg rt(N); t=D/SD

| Sample # | N | X1 | X2 | d | D | (d-D) | (d-D)^2 | Sd | SD | t |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 687309 | 290210 | 397099 | 241349 | 1.56E+05 | 2.43E+10 | 177208 | 5.12E+04 | 4.7179 |
| " | 2 | 677615 | 378850 | 298765 | | 5.74E+04 | 3.30E+09 | | | |
| 4 | 3 | 674128 | 503060 | 171068 | | -7.03E+04 | 4.94E+09 | | | |
| " | 4 | 675301 | 342940 | 332361 | | 9.10E+04 | 8.28E+09 | | | |
| 5 | 5 | 684943 | 564570 | 120373 | | -1.21E+05 | 1.46E+10 | | | |
| " | 6 | 680673 | 939470 | -258797 | | -5.00E+05 | 2.50E+11 | | | |
| 6 | 7 | 400906 | 49930 | 350976 | | 1.10E+05 | 1.20E+10 | | | |
| " | 8 | 395761 | 38990 | 356771 | | 1.15E+05 | 1.33E+10 | | | |
| 7 | 9 | 406484 | 179480 | 227004 | | -1.43E+04 | 2.06E+08 | | | |
| " | 10 | 410493 | 108980 | 301513 | | 6.02E+04 | 3.62E+09 | | | |
| 8 | 11 | 393976 | 138810 | 255166 | | 1.38E+04 | 1.91E+08 | | | |
| " | 12 | 413184 | 69300 | 343884 | | 1.03E+05 | 1.05E+10 | | | |

Degrees of Freedom = 11

Critical t = 4.44
t = 4.7179
Confidence level = 99.9%

Probability = .001 > p > 0

TABLE B
ODOT asphalt specimens, paired t analysis
RETSINA VS. BALADI
X1 = Retsina, X2 = Baladi
NOTE: d=X1-X2; D=avg d; Sd=std.dev.; SD=Sd/sg rt(N); t=D/SD

| Sample # | N | X1 | X2 | d | D | (d-D) | (d-D)^2 | Sd | SD | t |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 1 | 203290 | 155700 | 47590 | 60715 | -13125 | 172265625 | 31919 | 7979.81 | 7.6086 |
| " | 2 | 180260 | 158550 | 21710 | | -39005 | 1521390025 | | | |
| 8 | 3 | 195680 | 144780 | 50900 | | -9815 | 96334225 | | | |
| " | 4 | 174910 | 138840 | 36070 | | -24645 | 607376025 | | | |
| 13 | 5 | 132950 | 120210 | 12740 | | -47975 | 2301600625 | | | |
| " | 6 | 141090 | 99250 | 41840 | | -18875 | 356265625 | | | |
| 13 | 7 | 159020 | 100810 | 58210 | | -2505 | 6275025 | | | |
| " | 8 | 159890 | 97340 | 62550 | | 1835 | 3367225 | | | |
| 7115 | 9 | 260390 | 169150 | 91240 | | 30525 | 931775625 | | | |
| " | 10 | 248930 | 171350 | 77580 | | 16865 | 284428225 | | | |
| 7115 | 11 | 286090 | 152860 | 133230 | | 72515 | 5258425225 | | | |
| " | 12 | 283810 | 165270 | 118540 | | 57825 | 3343730625 | | | |
| 2T | 13 | 264650 | 221810 | 42840 | | -17875 | 319515625 | | | |
| " | 14 | 226060 | 172380 | 53680 | | -7035 | 49491225 | | | |
| 2T | 15 | 237360 | 172160 | 65200 | | 4485 | 20115225 | | | |
| " | 16 | 213430 | 155910 | 57520 | | -3195 | 10208025 | | | |

Degrees of freedom = 15

Critical t = 4.073
t = 7.6086
Confidence level = 99.9%

Probability = .001 > p > 0

TABLE C

Kansas specimens, paired t analysis

RETSINA vs. BALADI

X1 = Baladi, X2 = Retsina

NOTE: d=X2-X1; D=avg d; Sd=std.dev.; SD=Sd/sg rt(N); t=D/SD

| KDOT# | N | X1 | X2 | d | D | (d-D) | (d-D)^2 | Sd | SD | t |
|---|---|---|---|---|---|---|---|---|---|---|
| 148#9 | 1 | 179810 | 255140 | 75330 | 69532 | 5798 | 33614227 | 48927 | 11532.14 | 6.0294 |
| " | 2 | 174320 | 231000 | 56680 | | -12852 | 165179616 | | | |
| 144#10 | 3 | 178850 | 247400 | 68550 | | -982 | 964760 | | | |
| " | 4 | 142250 | 228890 | 86640 | | 17108 | 292676060 | | | |
| 148#5 | 5 | 211390 | 353200 | 141810 | | 72278 | 5224077160 | | | |
| " | 6 | 199480 | 304490 | 105010 | | 35478 | 1258672716 | | | |
| 144#5 | 7 | 131400 | 262350 | 130950 | | 61418 | 3772143427 | | | |
| " | 8 | 112210 | 236620 | 124410 | | 54878 | 3011570494 | | | |
| 140#2 | 9 | 235480 | 189940 | -45540 | | -115072 | 13241616327 | | | |
| " | 10 | 140290 | 181770 | 41480 | | -28052 | 786927172 | | | |
| 140#6 | 11 | 160980 | 198420 | 37440 | | -32092 | 1029910727 | | | |
| " | 12 | 156000 | 173320 | 17320 | | -52212 | 2726116149 | | | |
| 140#12 | 13 | 132280 | 207850 | 75570 | | 6038 | 36454760 | | | |
| " | 14 | 160590 | 177780 | 17190 | | -52342 | 2739708227 | | | |
| 148#15 | 15 | 135990 | 281290 | 145300 | | 75768 | 5740756149 | | | |
| " | 16 | 192310 | 258930 | 66620 | | -2912 | 8481038 | | | |
| 144#17 | 17 | 209570 | 255690 | 46120 | | -23412 | 548132149 | | | |
| " | 18 | 156150 | 216850 | 60700 | | -8832 | 78008149 | | | |

Degrees of Freedom= 17

Critical t= 3.97
t = 6.0294
Confidence level= 99.9%

Probability = .001 > p > 0

TABLE D

Kansas specimens, paired t analysis

OR BALADI vs. KA BALADI

X1 = Oregon Baladi X2 = Kansas Baladi

NOTE: d=X2-X1; D=avg d; Sd=std.dev.; SD=Sd/sg rt(N); t=D/SD

| KDOT# | N | X1 | X2 | d | D | (d-D) | (d-D)^2 | Sd | SD | t |
|---|---|---|---|---|---|---|---|---|---|---|
| 148#9 | 1 | 179810 | 229000 | 49190 | 44758 | 4432 | 19639669 | 39127 | 9222.27 | 4.8533 |
| " | 2 | 174320 | 224000 | 49680 | | 4922 | 24222803 | | | |
| 144#10 | 3 | 178850 | 239000 | 60150 | | 15392 | 236903403 | | | |
| " | 4 | 142250 | 184000 | 41750 | | -3008 | 9050069 | | | |
| 148#5 | 5 | 211390 | 295000 | 83610 | | 38852 | 1509452003 | | | |
| " | 6 | 199480 | 233000 | 33520 | | -11238 | 126300136 | | | |
| 144#5 | 7 | 131400 | 226000 | 94600 | | 49842 | 2484191736 | | | |
| " | 8 | 112210 | 194000 | 81790 | | 37032 | 1371344336 | | | |
| 140#2 | 9 | 235480 | 199000 | -36480 | | -81238 | 6599666803 | | | |
| " | 10 | 140290 | 196000 | 55710 | | 10952 | 119939003 | | | |
| 140#6 | 11 | 160980 | 189000 | 28020 | | -16738 | 280171803 | | | |
| " | 12 | 156000 | 190000 | 34000 | | -10758 | 115741736 | | | |
| 140#12 | 13 | 132280 | 201000 | 68720 | | 23962 | 574161469 | | | |
| " | 14 | 160590 | 172000 | 11410 | | -33348 | 1112111336 | | | |
| 148#15 | 15 | 135990 | 262000 | 126010 | | 81252 | 6601833336 | | | |
| " | 16 | 192310 | 198000 | 5690 | | -39068 | 1526334669 | | | |
| 144#17 | 17 | 209570 | 199000 | -10570 | | -55328 | 3061224469 | | | |
| " | 18 | 156150 | 185000 | 28850 | | -15908 | 253075069 | | | |

Degrees of Freedom = 17

Critical t = 3.97
t = 4.853
Confidence level = 99.9%

Probability = .001 > p > 0

OSHD CALIBRATION SPECIMEN #3

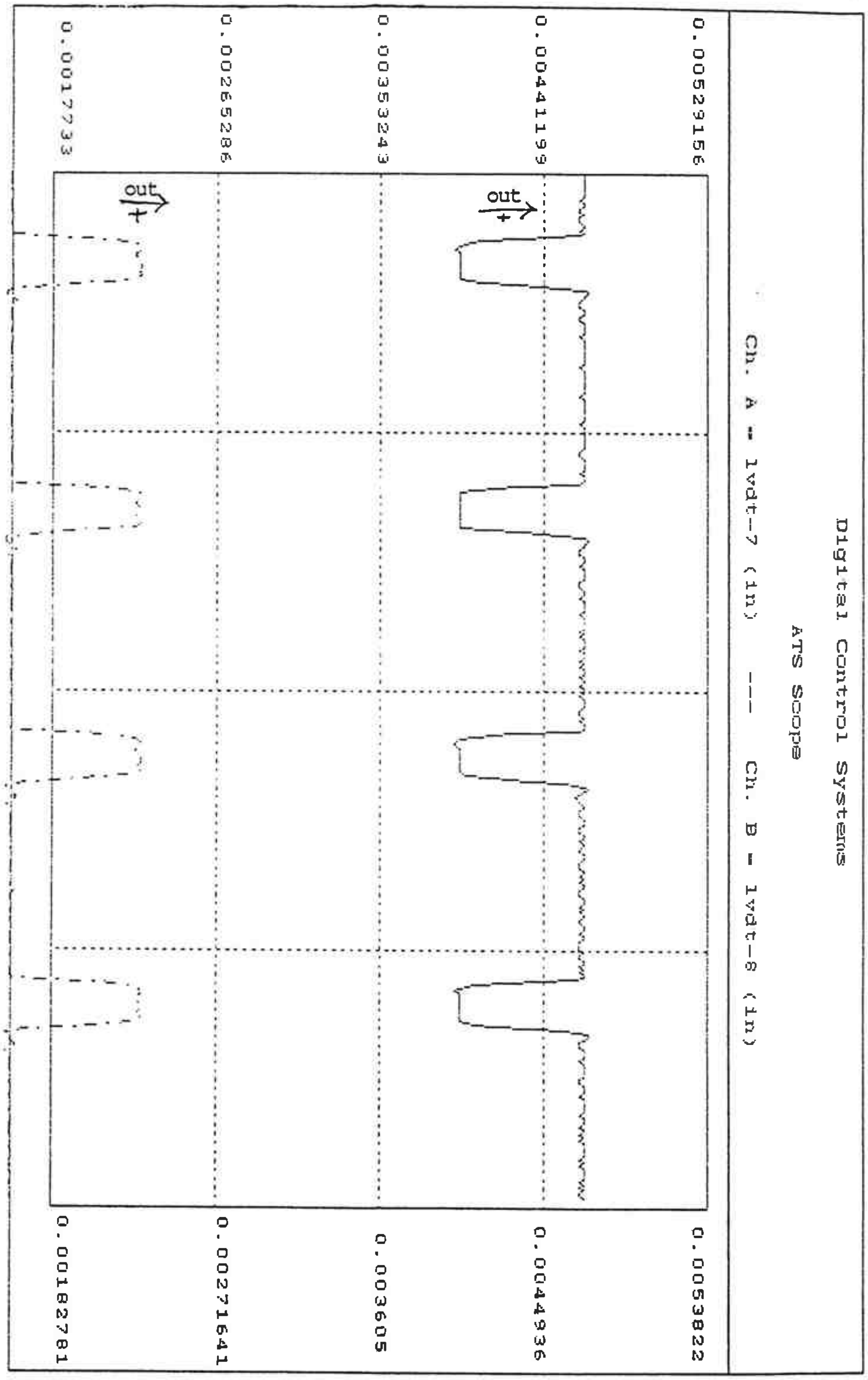


Figure #1

OSHD CALIBRATION SPECIMEN #5

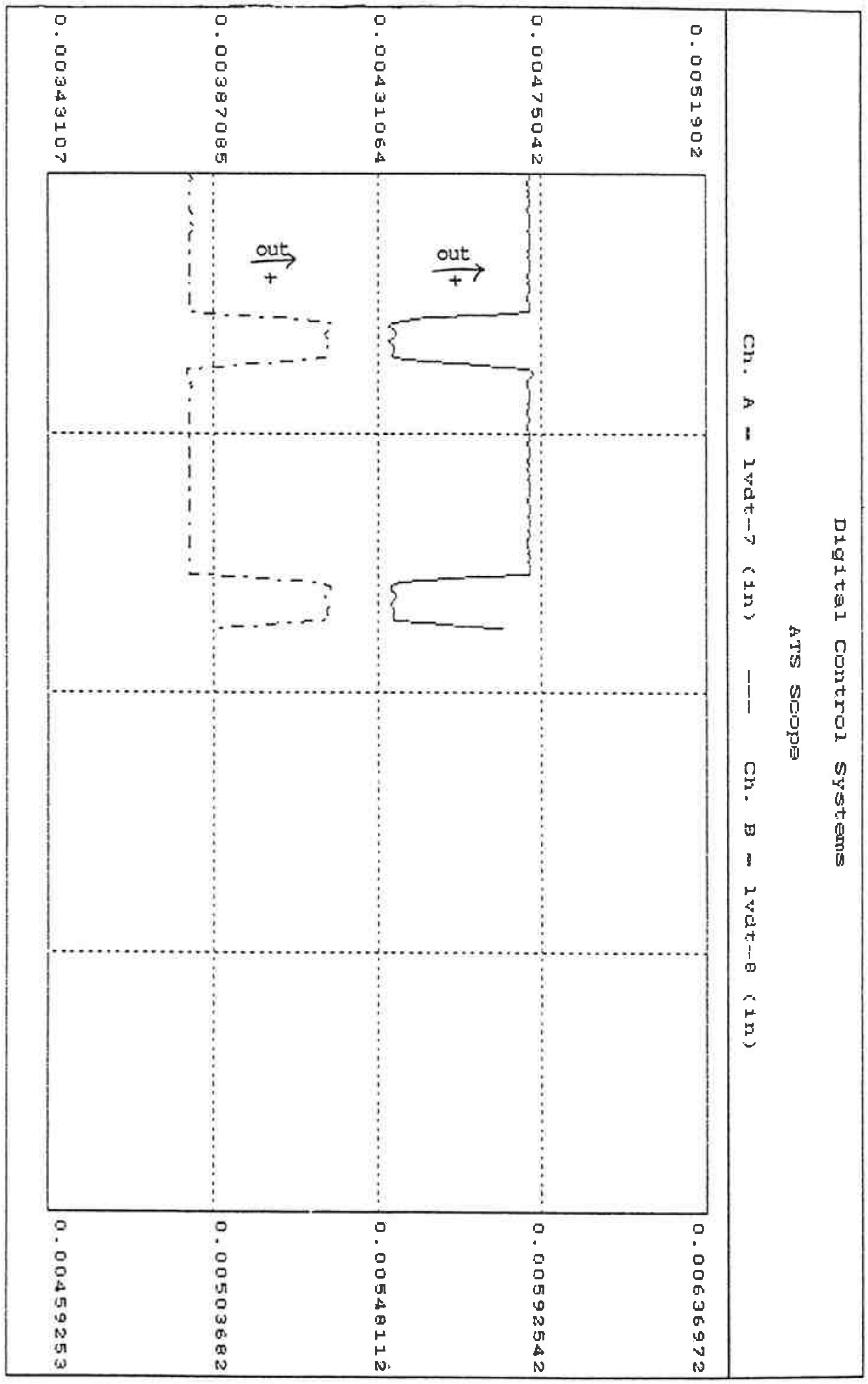


Figure #2

SHRP CALIBRATION SPECIMEN #R-4

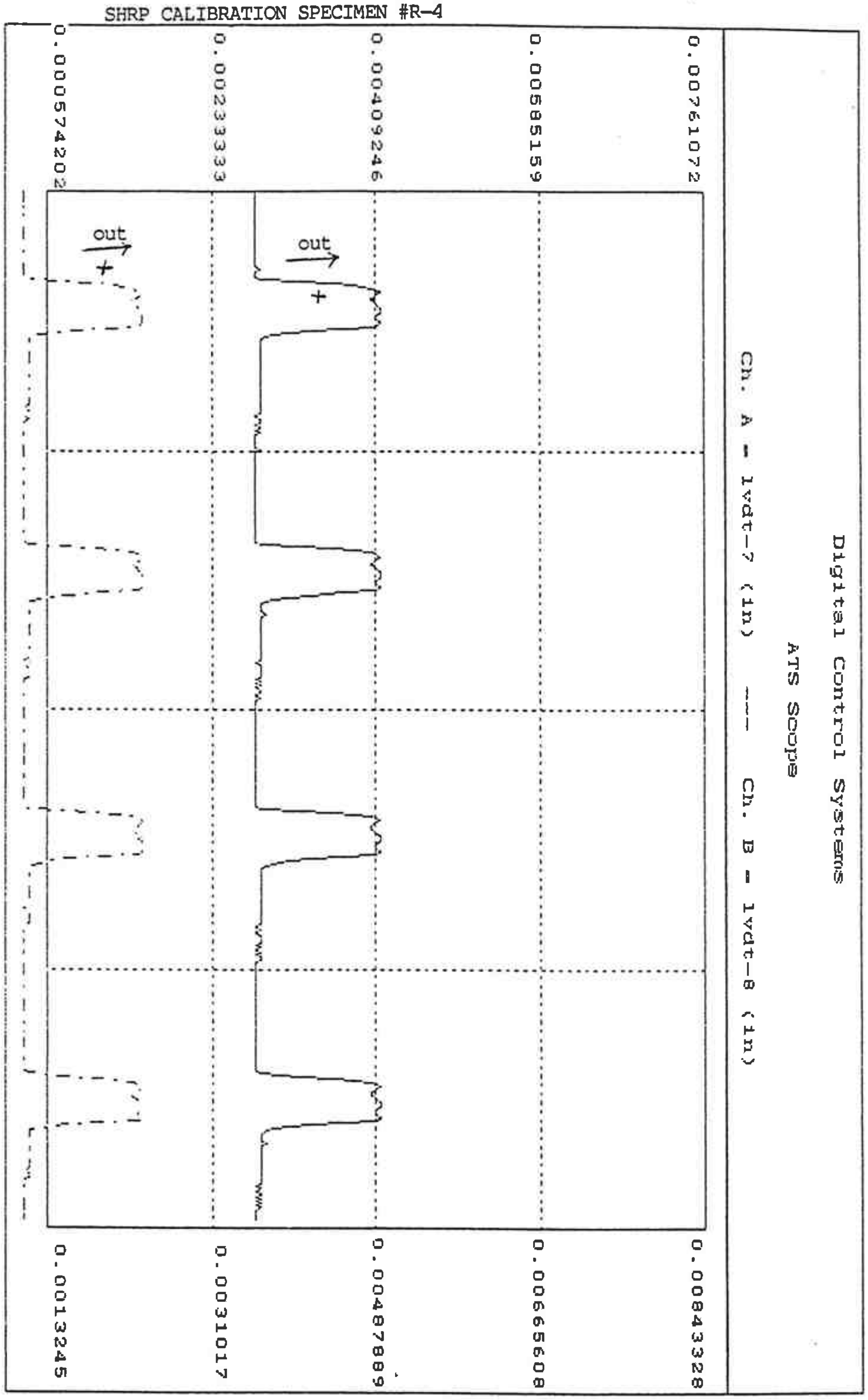


Figure #3

SAMPLE #136-6 0° DRY

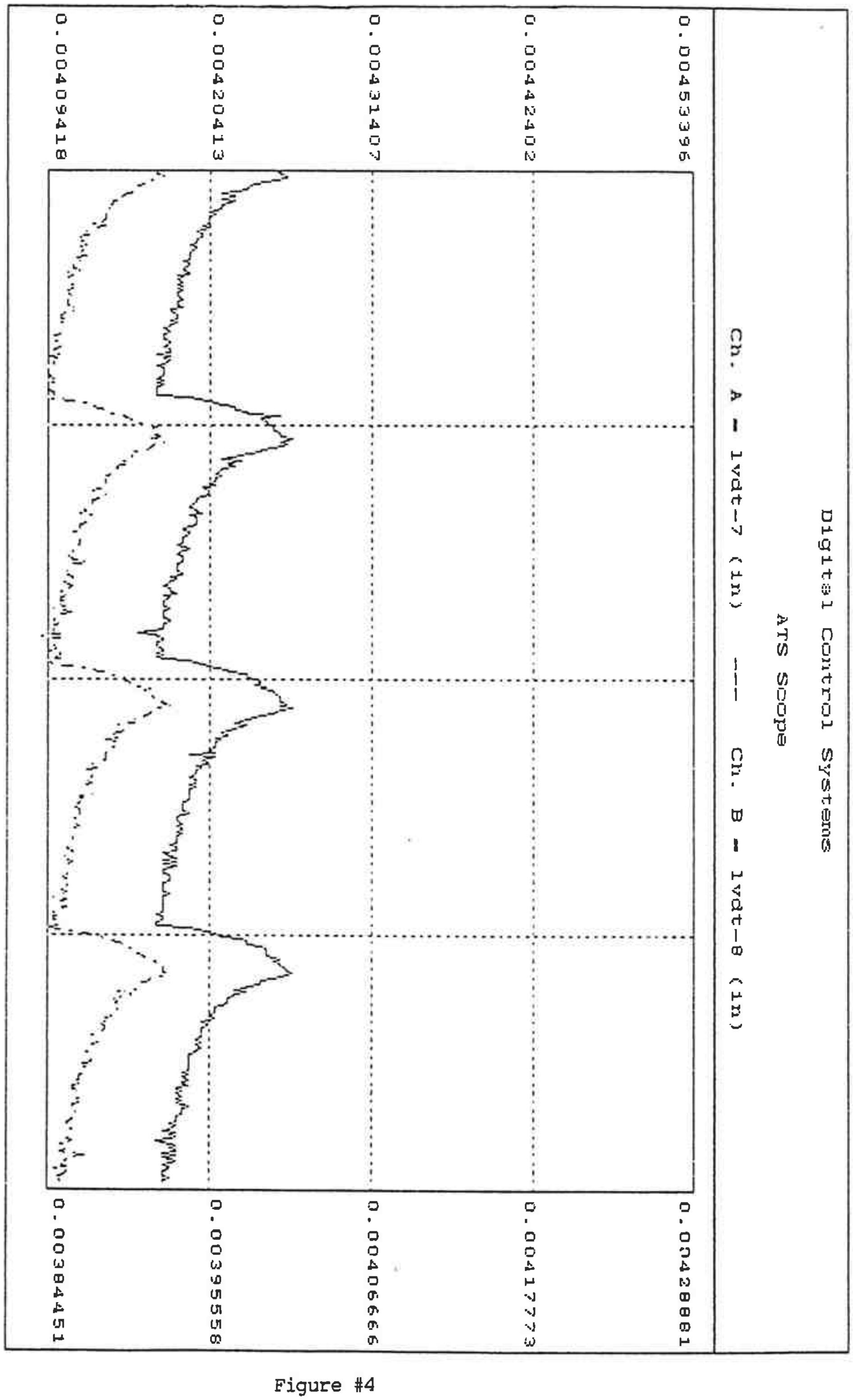


Figure #4

SAMPLE #136-6 90° DRY

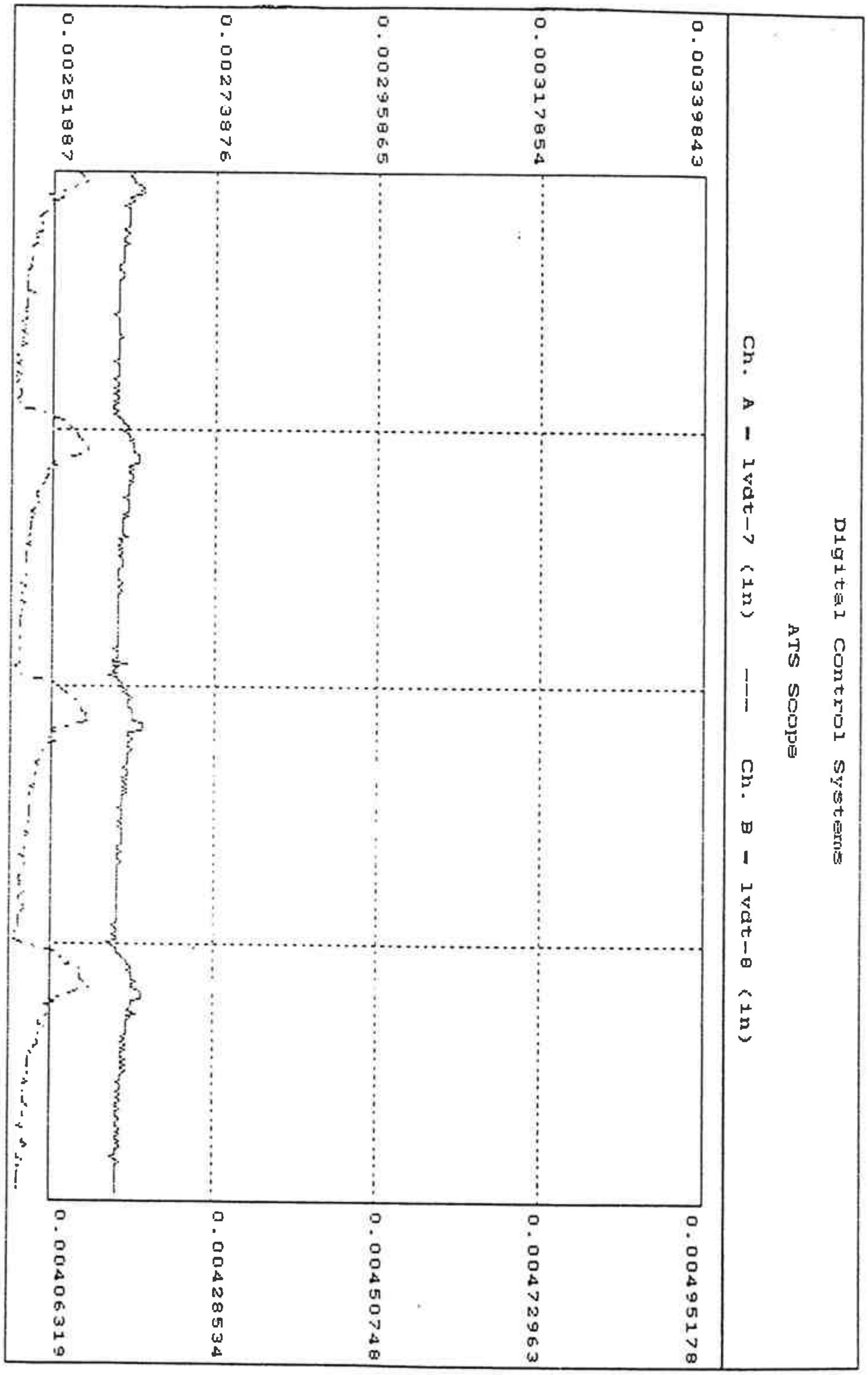


Figure #5

LAB #91-138 #13 0° DRY

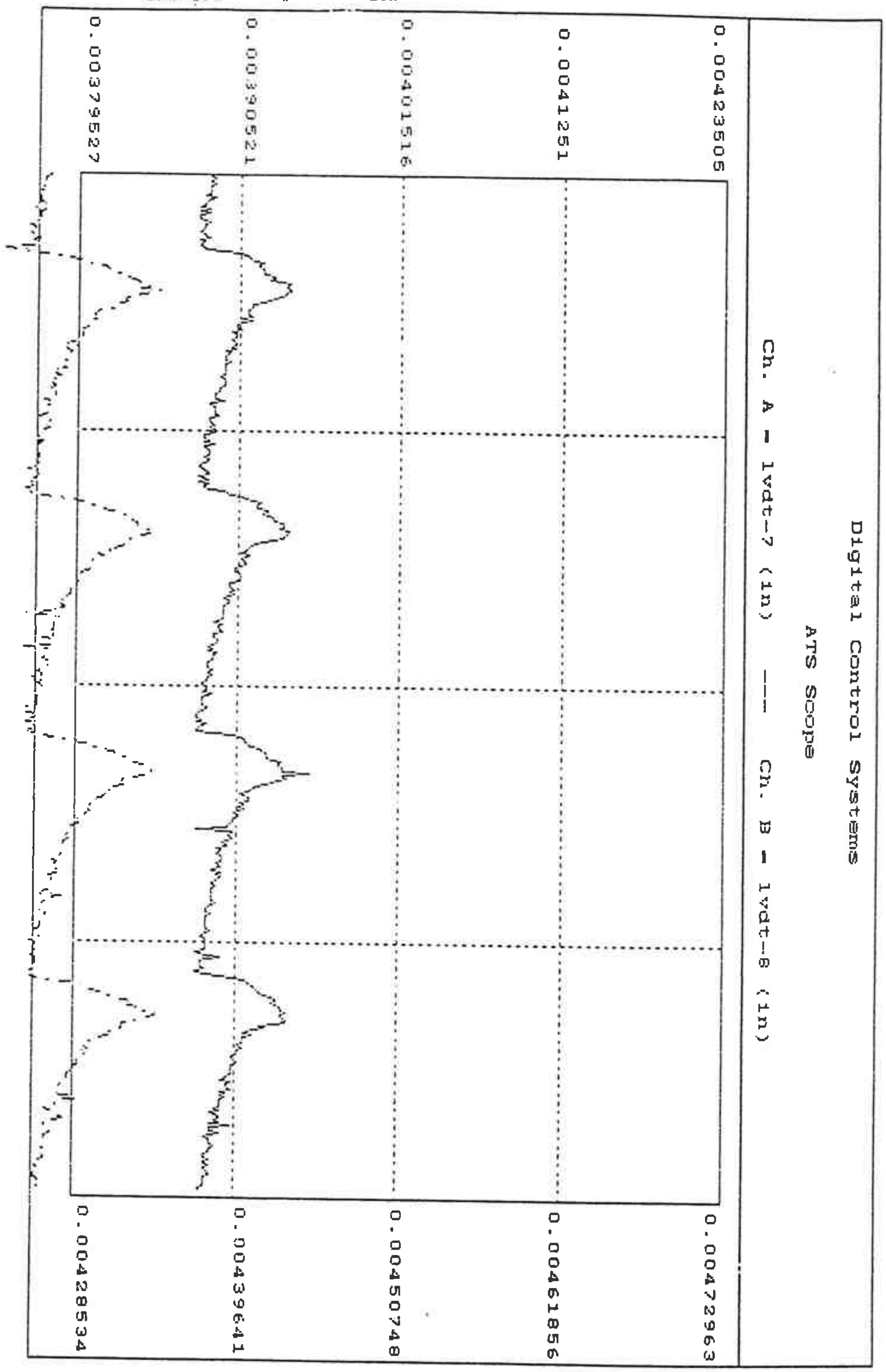


Figure #6

LAB #91-138 #13 0° FREEZE-THAW

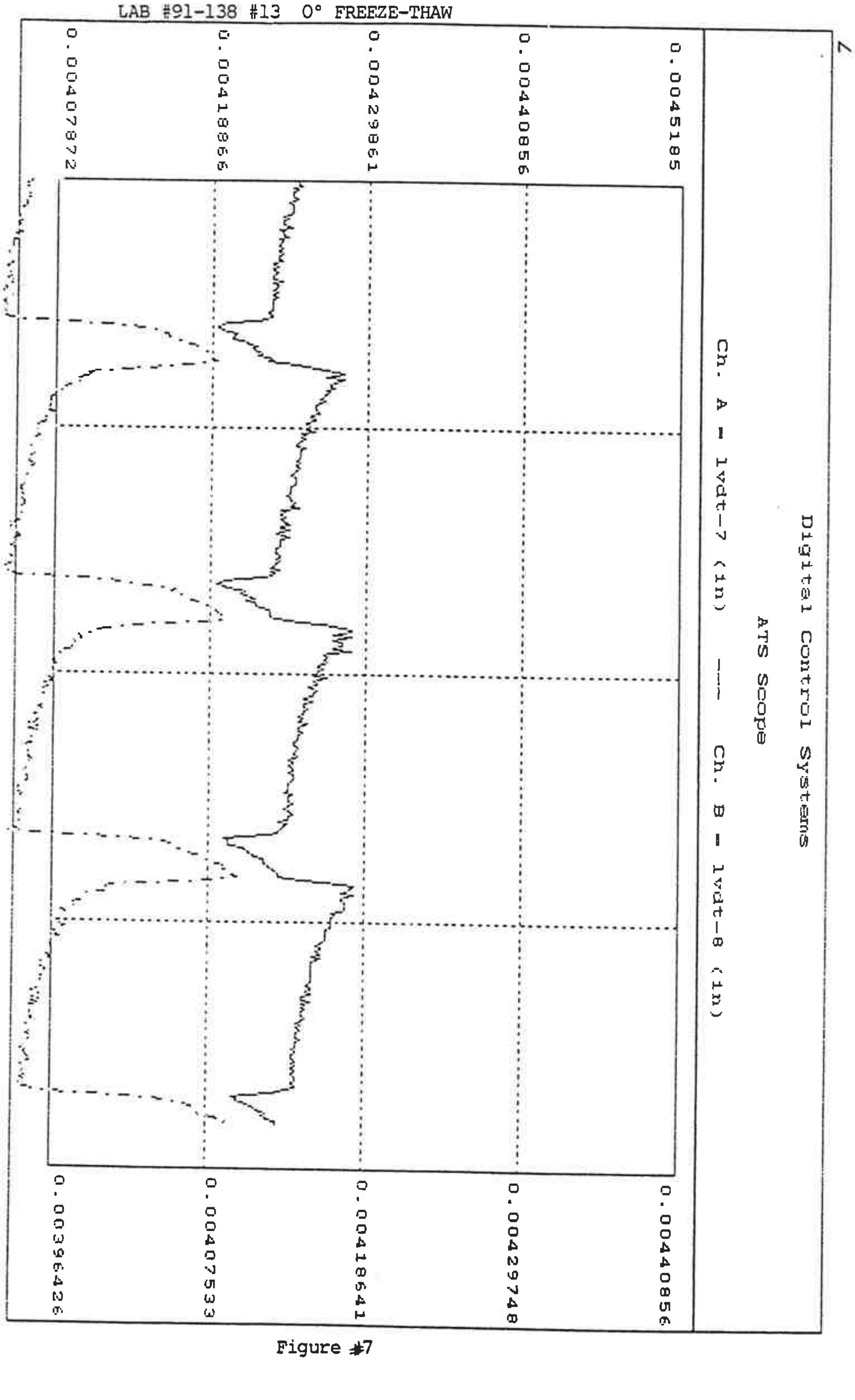


Figure #7

SAMPLE #7115 DRY 90°

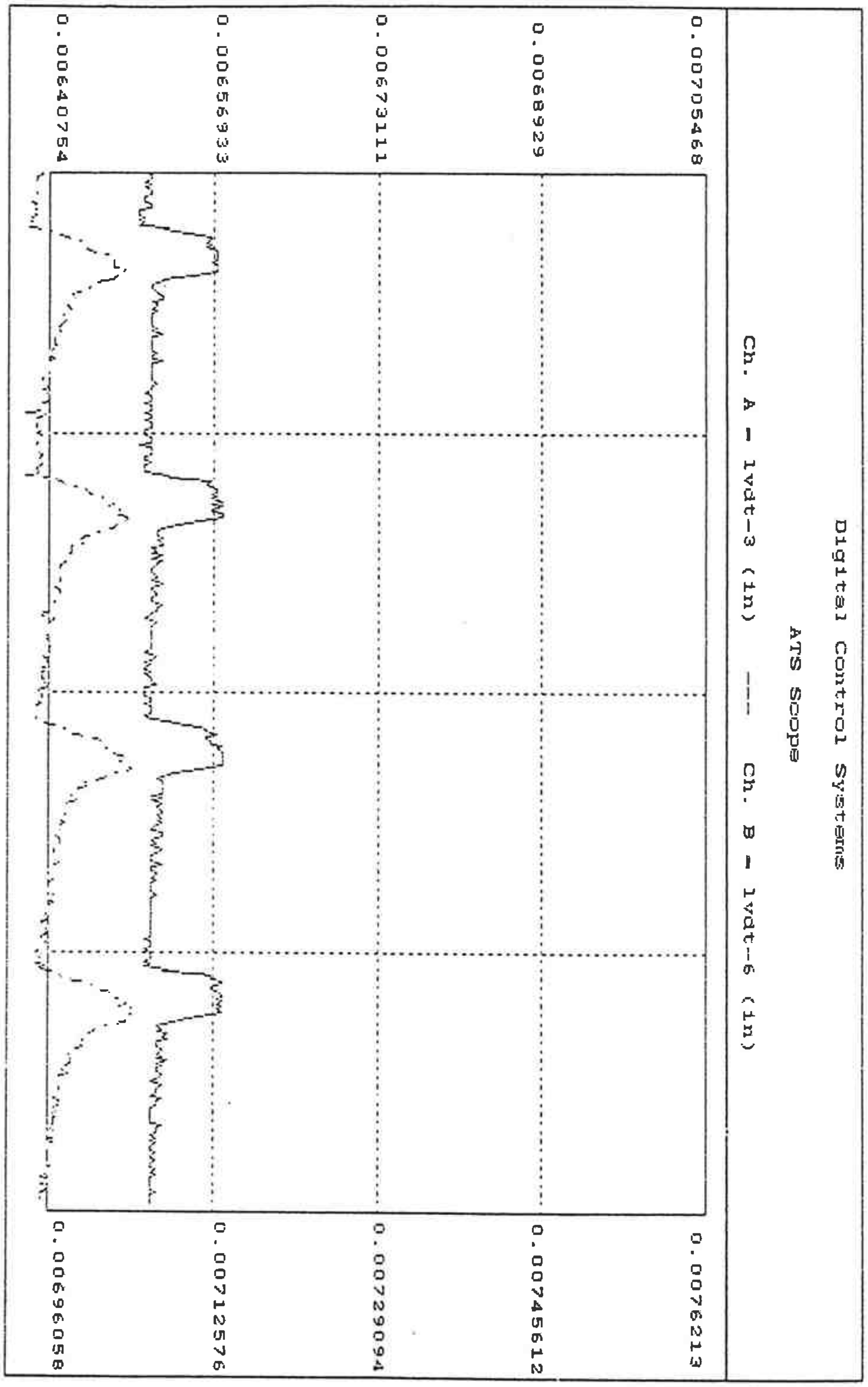


Figure #8

SAMPLE #2T 0° DRY

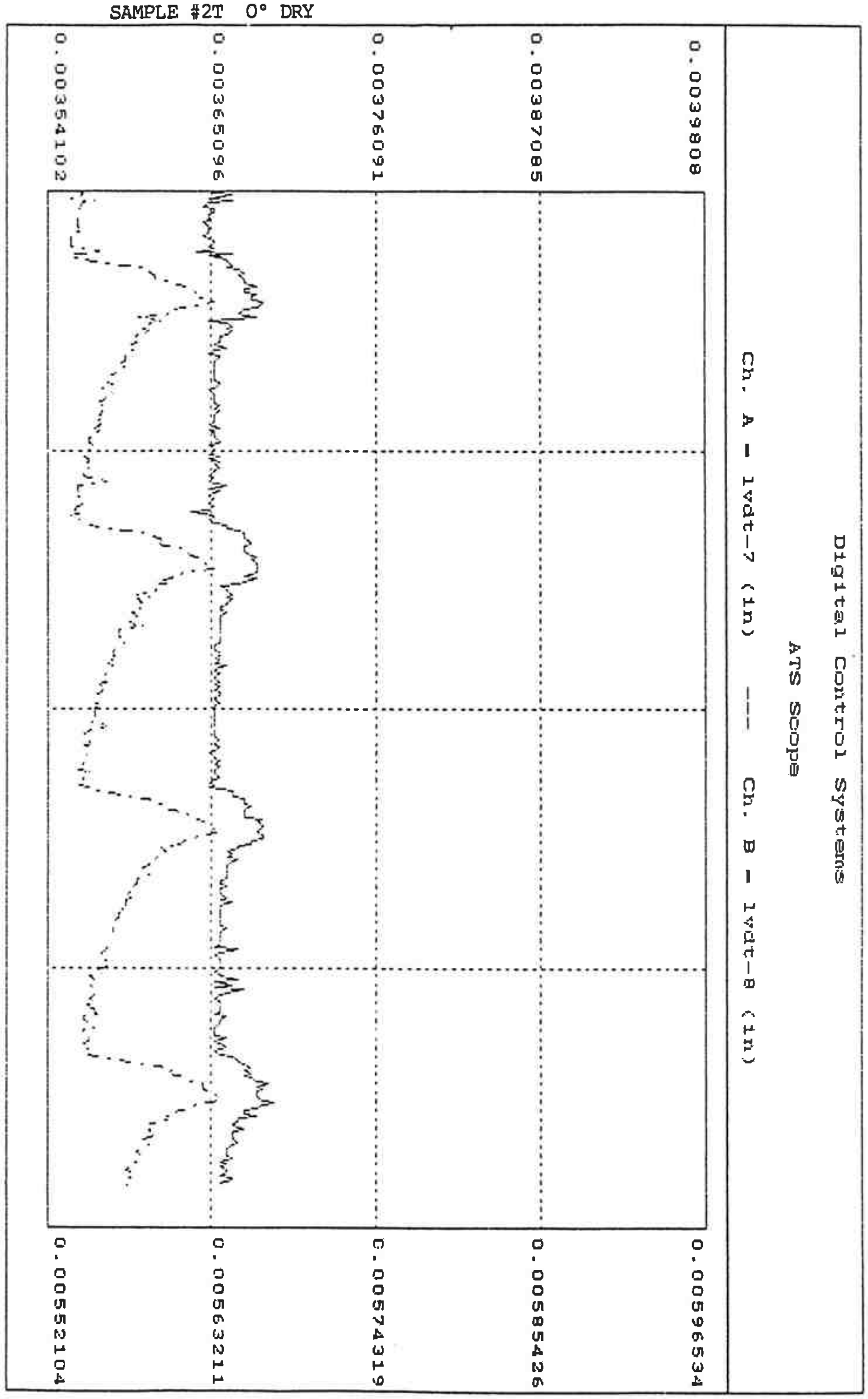


Figure #9

SAMPLE #2T 90° DRY

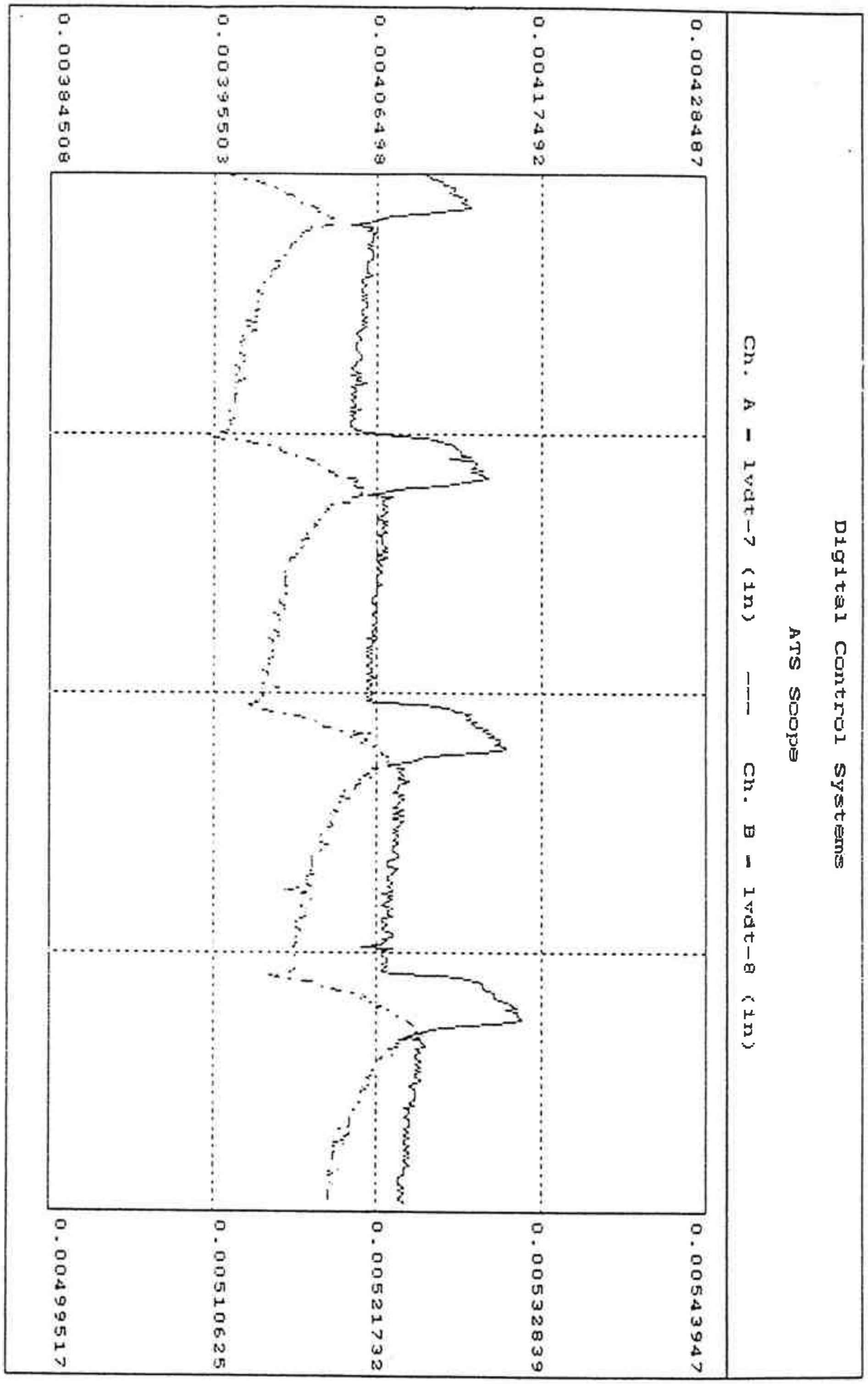


Figure #10

SAMPLE #2T 0° FREEZE-THAW

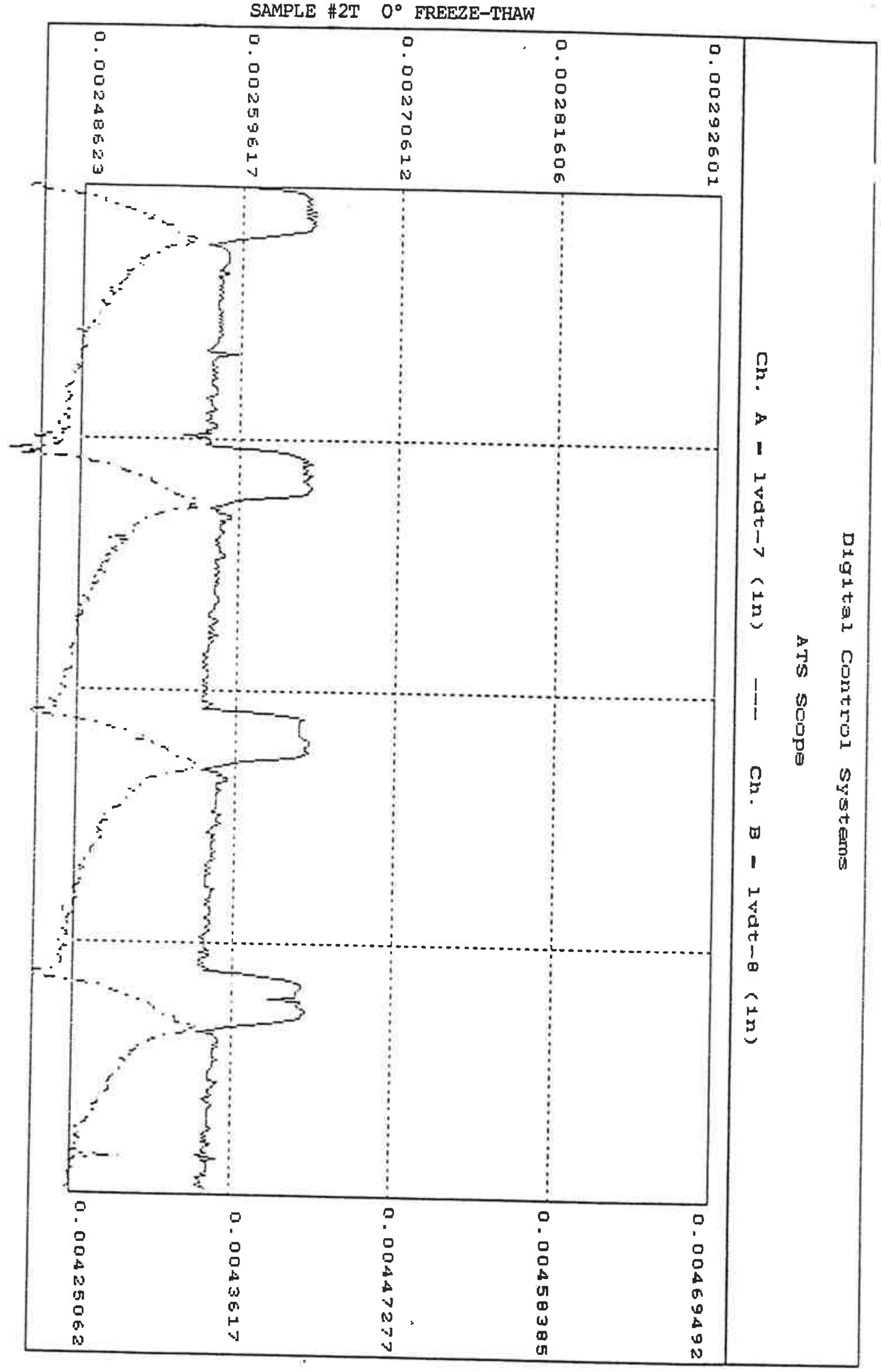


Figure #11

SAMPLE #2T 90° FREEZE-THAW

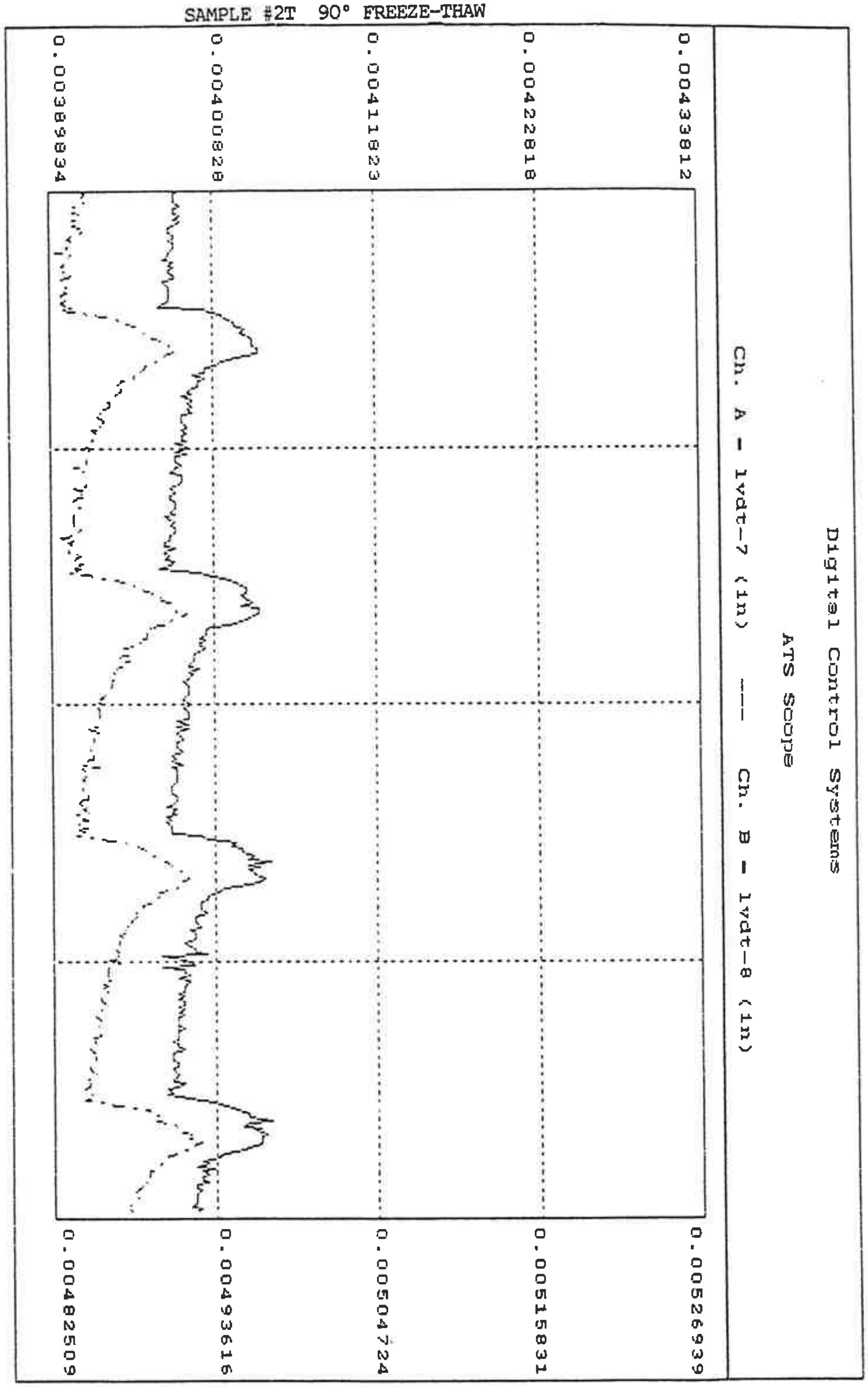


Figure #12

K-DOT 148#9 0°

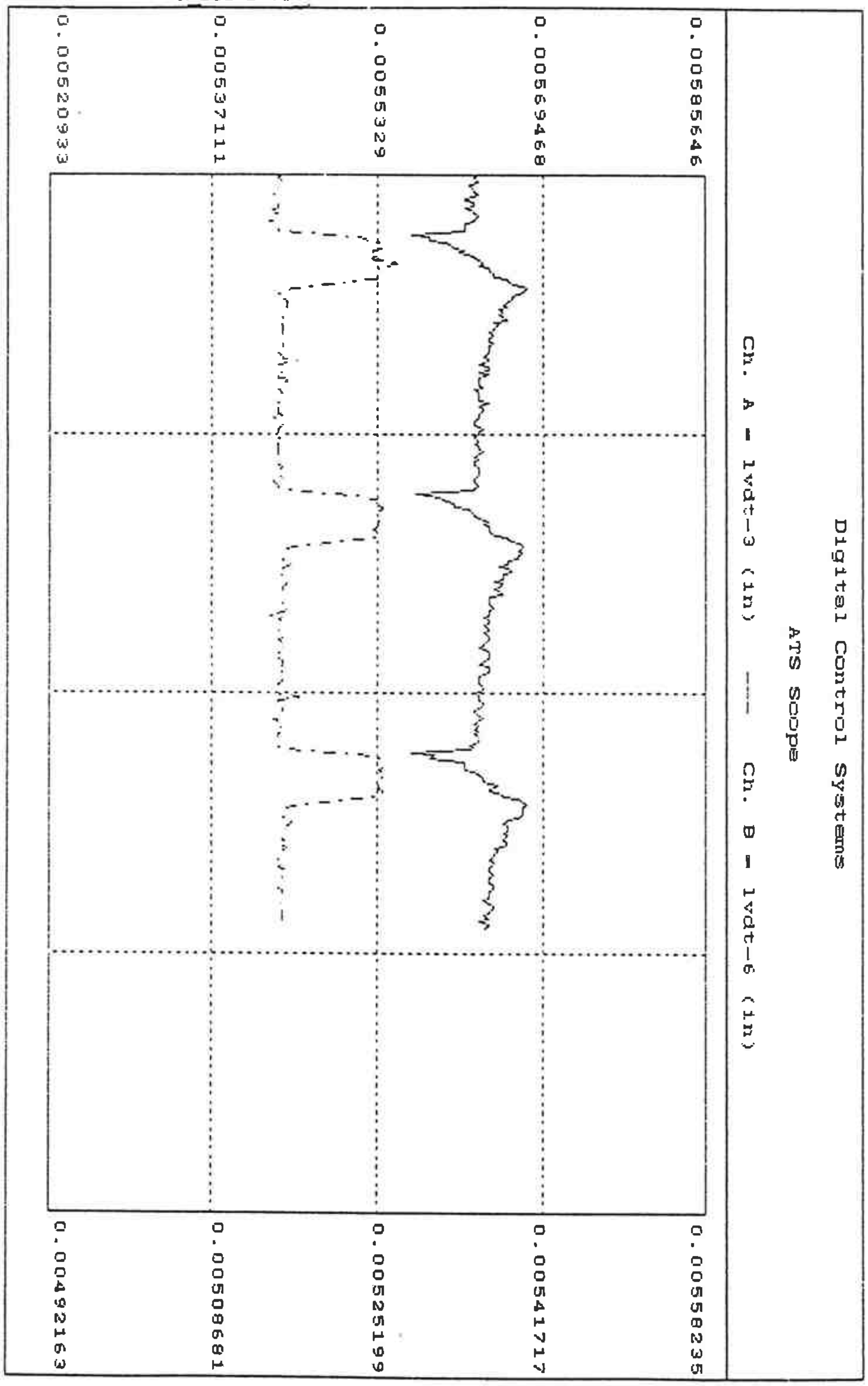


Figure #13

K-DOT 148#9 90°

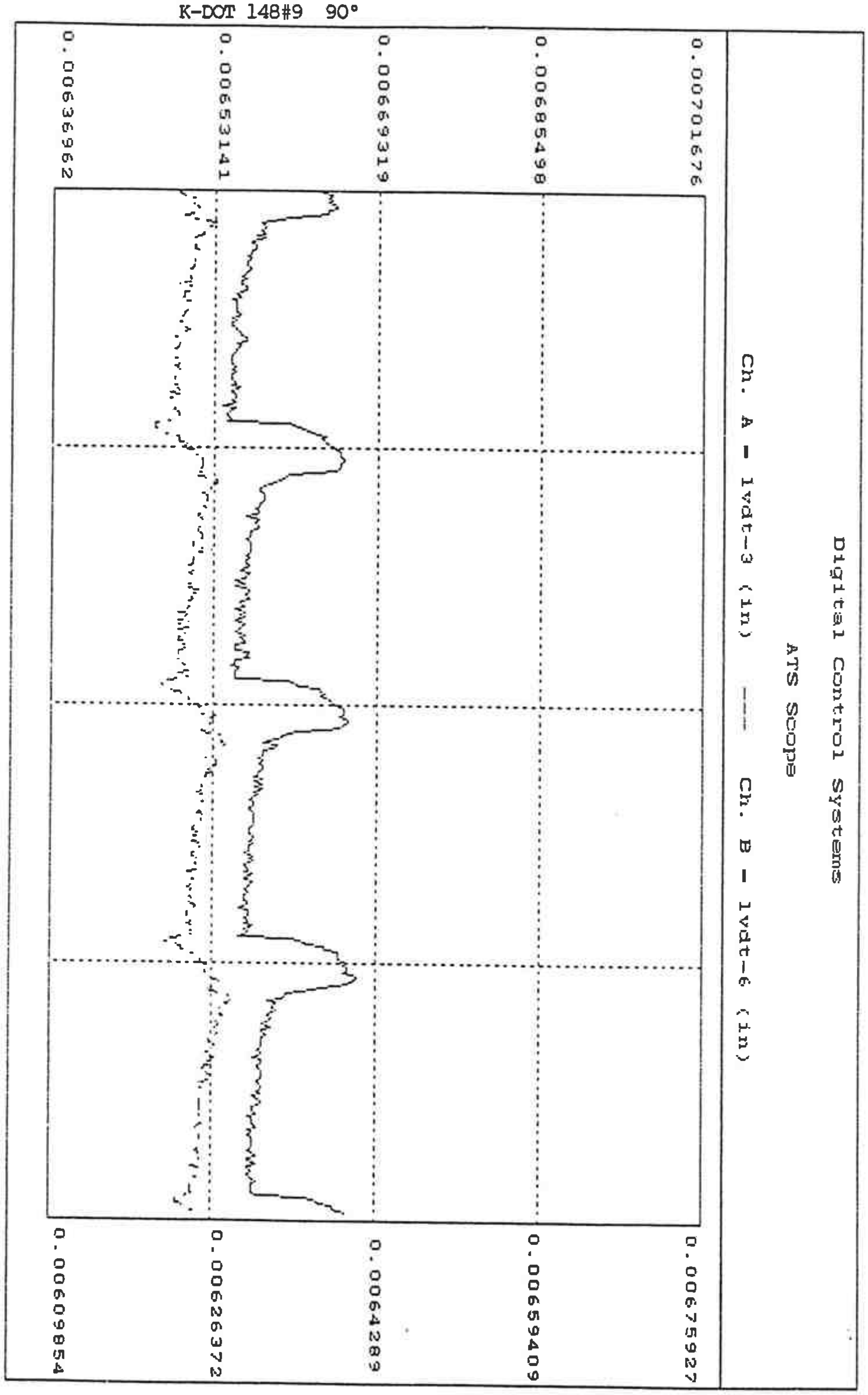


Figure #14

K-DOT 148#5 0°

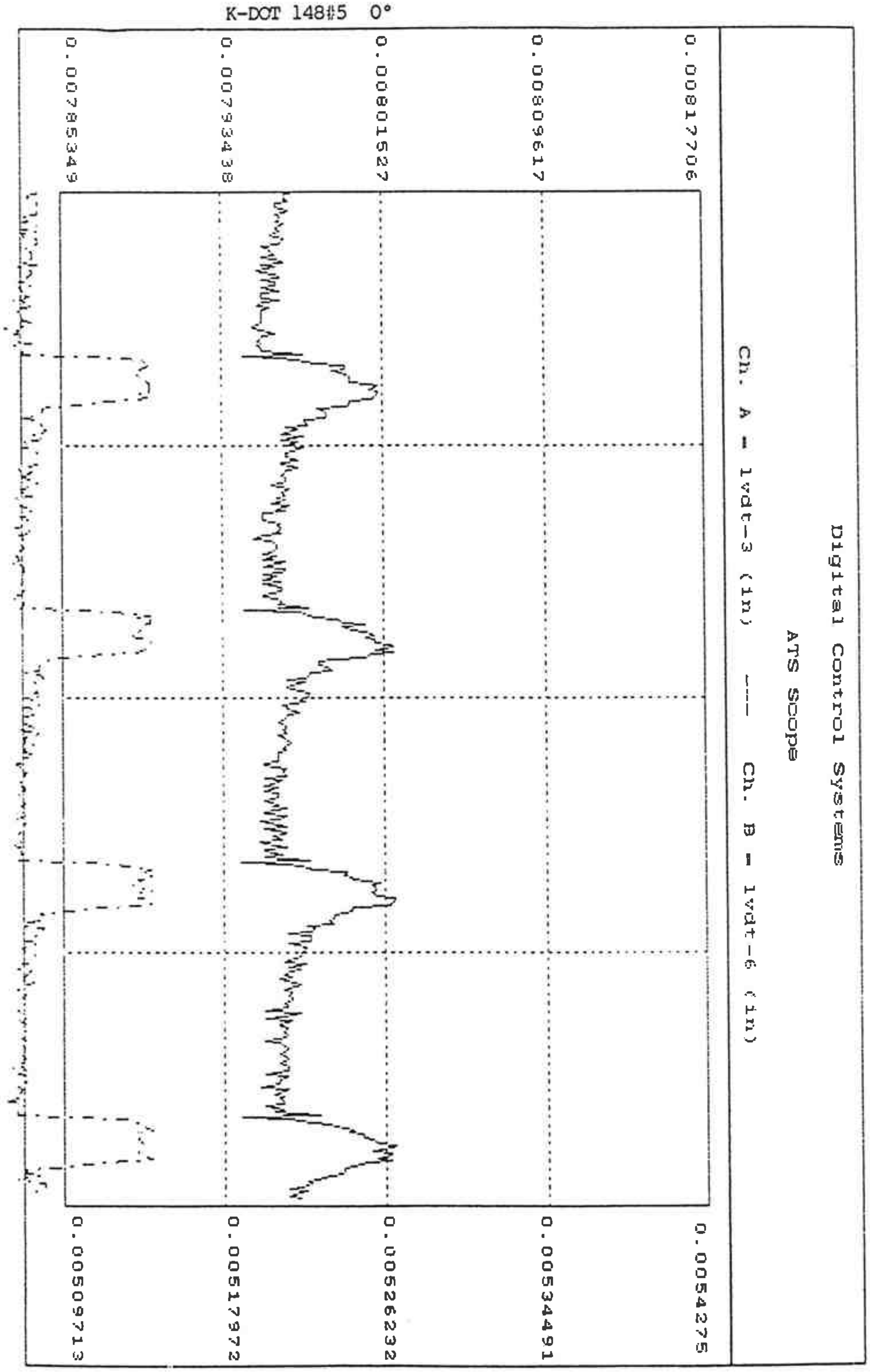


Figure #15

K-DOT 148#5 90°

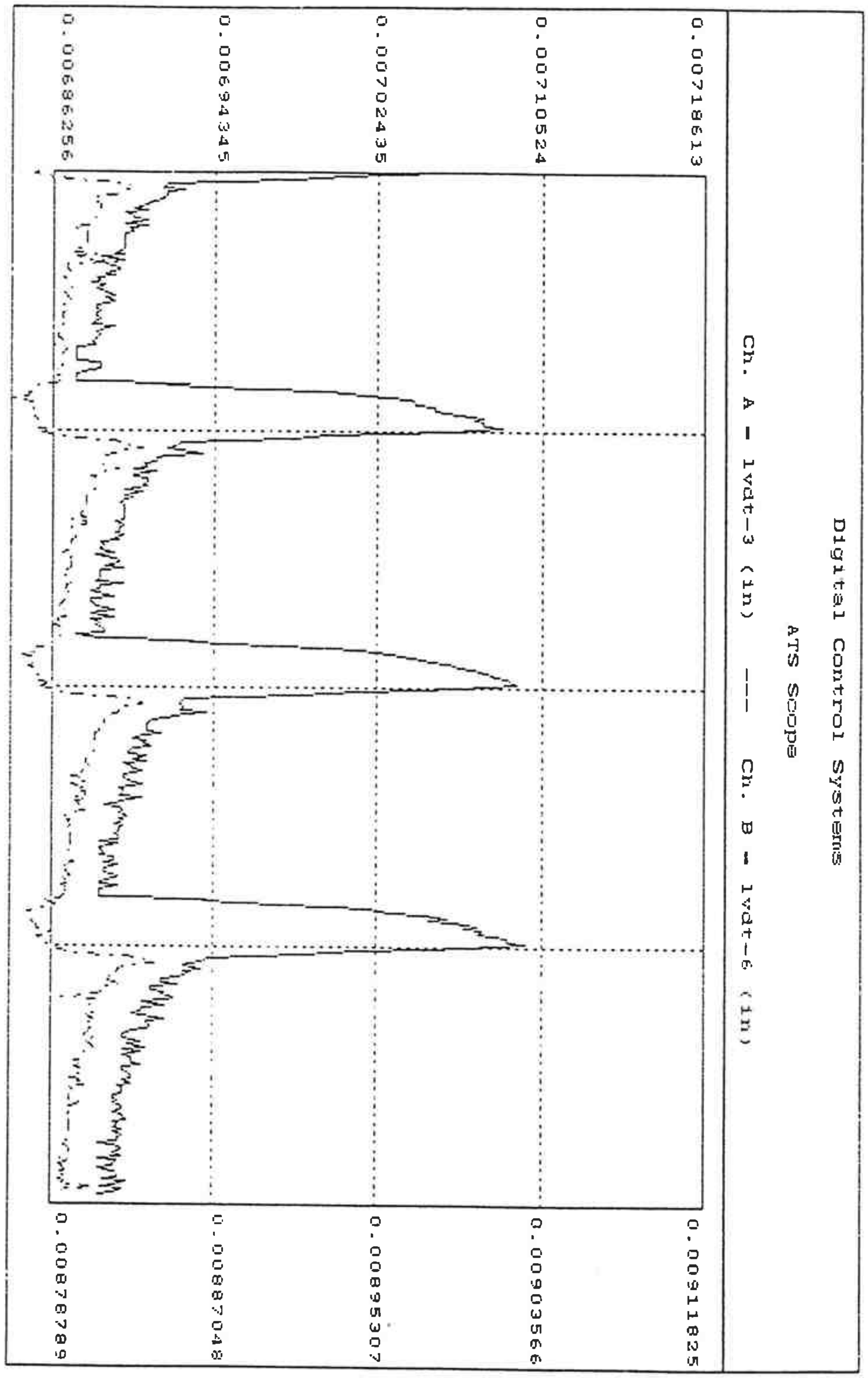


Figure #16