CR 179519

MASS FLOW MEASUREMENT OF LIQUID CRYOGENS USING THE TRIBOELECTRIC EFFECT

NASA Contract NAS3-24873

Final Report
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I) ABSTRACT

A cross correlator technique using triboelectric technology has been shown to be a feasible method to measure liquid flow rate for liquid Nitrogen and JP4 jet fuel. This technology, invented and pioneered by Auburn International Incorporated, is also expected to be suitable for use with all other insulating liquids and cryogens.

The technology described in this report is particularly well suited for cryogenic use, since the sensor is non contacting and non intrusive, and therefore causes no additional pressure drop within the flow stream.

Further mechanical development of the in-line sensor is required to produce a prototypical version for test purposes under SSME fuel flow conditions. However, with the knowledge gained from this feasibility study, it is very likely that an acceptable sensor design for a full test bed evaluation could be produced.

II) SUMMARY

Contract NAS3-24873 was performed to investigate the feasibility of using a cross correlator technique, based upon triboelectric technology, to determine the flow rate of liquid nitrogen.

The project was divided into two major tasks. First, to modify the Auburn International cross correlator for suitability in this application; secondly, to investigate the suitability of four different sensor designs. Both tasks were performed and completed within the scope of the contract. After encountering several operational difficulties, successful cross correlations were performed to determine liquid nitrogen velocity at an on-site nitrogen test site, using a non-intrusive, in-line sensor configuration.

As an addendum to the project and in an attempt to compare cross correlation technique with an independent flow measuring system, further successful tests took place using JP4 jet fuel. The flow rate determined by the cross correlator compared favorably with the flow rate determined by a ball meter.

III) INTRODUCTION

The flow velocity of a liquid can be derived directly from the transit time of natural turbulence signals between two transducers spaced along the direction of flow. Cross correlation is a technique that lends itself to determining this transit time for fluctuating turbulence signals derived from multiple sources.

When an insulating liquid flows within pipework, it is now well known that it is possible for the liquid to accumulate charge due to a multitude of charge transfer mechanisms (the triboelectric effect [Ref. 1] and charge absorption at the pipe wall interface being just two). This phenomenon of the charge being carried within the stream is referred to as a "streaming current".

What is far less recognized is that superimposed upon this uniformly charged fluid are charge distributions which result from turbulence and non-homogeneity of the flow regime. These random charge distributions are the source of natural turbulence signals which can be harnessed in a microprocessor based cross correlation technique to determine the liquid velocity. Subsequently, the mass flow of the liquid may be derived with knowledge of the flow area and liquid density.

This discovery and concept was conceived by Auburn scientists in 1983.

IV) EXPLANATION OF CROSS CORRELATION

1. The Technique:

Cross correlation is a technique which is used to determine the time lag between two similar, but time displaced signals (Ref. 2). In this investigation, "flow" signals are generated by the random fluctuations of the charge distribution which are present within flowing liquid nitrogen.

A certain charge distribution induces a certain flow signal at an upstream sensor. The same charge distribution will induce a similar flow signal at a downstream sensor, but since this charge distribution has taken a finite time to travel between the two sensors, there will, therefore, be a time displacement. The charge distribution is constantly changing, but the sensor spacing is chosen so that in the transit time, the pattern is still recognizable by cross correlation.

The cross correlation function is defined by the convolution type integral.

$$R(x,y) = \int_0^{\infty} x(t).y(t-\tau)dt$$

The peak of the cross correlation as a function of τ occurs at $\tau = \Delta T$, corresponding to the transit time of the flow (ΔT).

It is possible to make an extremely good estimate of R(x,y) for sampled data using a summation function.

$$R^*xy_j = 1/N_i \sum_{i=1}^{n} (x_i \ \ y_{i-j} \ \ ).$$

This digital computation lends itself particularly well to microprocessor based hardware. The Auburn Model 3000 cross correlator was designed to perform this summation function and hence determine flow velocity.

The following calculations are typical to calculating Rxy_j:

$Rxy_1 = x_1y_1 + x_2y_2 + \dots x_ny_n$

$Rxy_2 = x_1y_2 + x_2y_3 + x_ny_{n+1}$

$Rxy_3 = x_1y_3 + x_2y_4 + \dots x_ny_{n+2}$

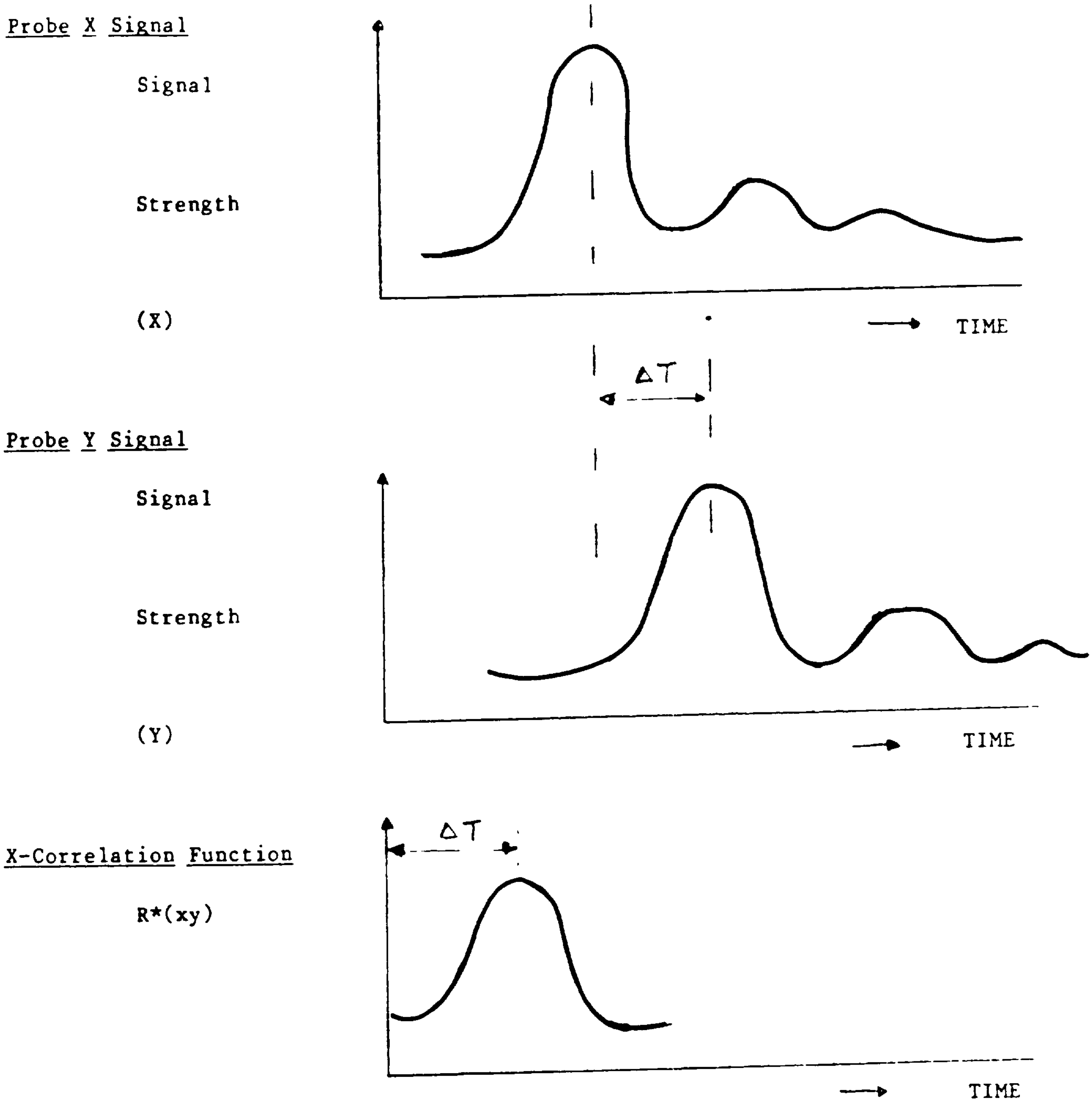
$Rxy_4 = \dots\dots$

$$\text{Flow Velocity} = \frac{S}{\Delta T}$$

Where S = Sensor plate spacing

ΔT = Cross correlation peak.

(transit time of flow).



2. <u>Constraints on Correlation Measurements</u>

A) <u>Resolution:</u> The resolution or accuracy of a cross correlator is dependent on the rate at which data is stored. The resolution depends on the number of samples collected in the transit time of the flow between the sensors - since it is only possible to shift the data relative to each other by finite amounts of time to calculate the cross correlation function (equal to multiples of the A/D conversion time).

Resolution = 1/n

Where n = number of data points stored in time ΔT, the transit time.

B) Time of Response:

The processing time of the correlator is limited by the time to perform the multiplications and accumulations. It is not necessary to use all the data points for multiplication purposes. If only certain data points are used, the multiplication time can be dramatically reduced, (the waveform shape can be well defined with fewer data points than are needed for the resolution criteria).

A correlator should be designed to track on the correlator maximum - from data resulting from previous correlations (indicating the probable range of the expected time shift), and also should have the flexibility to use a different number of points in the multiplication process. This will considerably reduce the processing time.

V) TEST APPARATUS FOR LIQUID NITROGEN

Investigation before the project indicated that the charge activity within the flowing liquid nitrogen would increase substantially with Reynolds No. greater than 40,000 (Ref. 3).

The initial project was to build a suitable loop for testing the different sensor configurations.

A 1/2 inch I.D. test loop was designed with a layout as shown in Diagram A (Test Apparatus for Liquid Nitrogen). A turbine meter (supplied by NASA) was incorporated into the loop as an independent measure of the liquid flow rate.

An Auburn 1090 void fraction monitor was incorporated into the flow loop to measure the liquid/gas phase content within the pipe section. (Appendix C)

The electrical connections from the sensor plates were connected to the front end amplifiers and then the output from these to an oscilloscope and/or cross correlator.

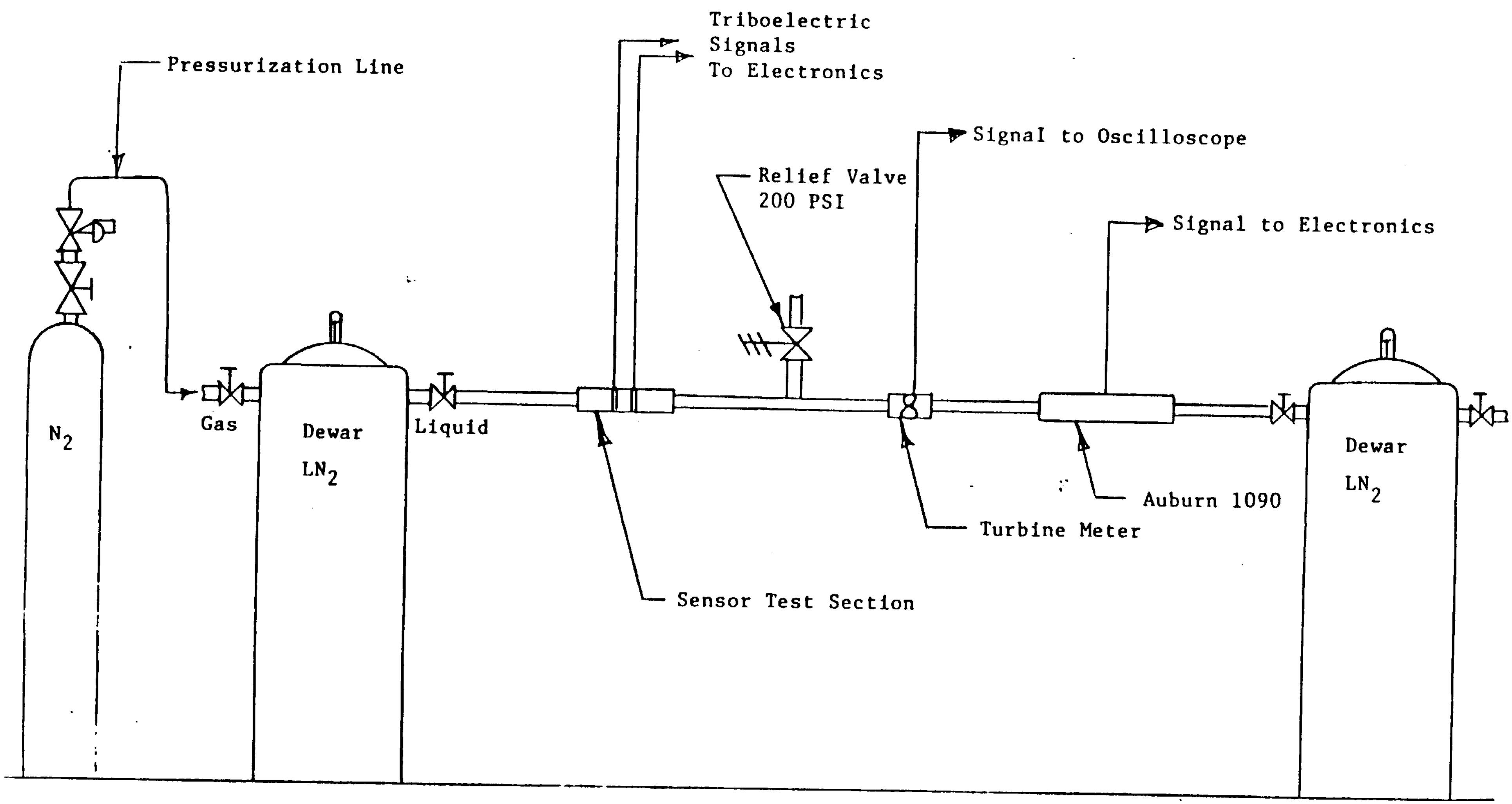


Diagram A: Test Apparatus for Liquid Nitrogen

VI) CROSS CORRELATOR SYSTEM DESIGN

1. Sensor Design:

A) Background

Sensor Design Criteria: The sensor design criteria are such that the sensor plates can be used to induce a usable signal from the variation in the charge distribution within the flowing liquid. Repeatability of induced signals from an upstream to a downstream sensor plate should be as great as possible for cross correlation purposes and, therefore, an idealized sensor design would disturb the flow as little as possible so that the flow regime remains constant. The sensor should therefore be non-intrusive.

Principle of Operation of Sensor: An electric field exists for all charged bodies. The variation of an E field will result in electron flow within an uncharged body placed within this field. The fluctuating E field, due to the flowing charge distributions, will induce an oscillating current in a metallic sensor. This oscillating current can be amplified and can be used as a flow signal.

B) Sensors Tested During Contract

a) Non-Contacting Circumferential Sensor: Referring to the principle of operation of an E field inducing sensor, the sensor (Drawing A, Appendix A) should be separated from the flow stream by an electrically insulating material. This is so that the sensor does not monitor direct electrical activity (such signals would be unrepeatable from one sensor to another). It was decided to make the sensor section using an electrically insulating pipe with the sensor plates mounted on the outside surface of the pipe. Material chosen for the pipework was a CTFE (Kel-F®), which is rated for cryogenic use.

The sensor plate material is a copper backed polyamide strip which was glued to the external surface of the CTFE. A soldered connection was used to electrically connect the sensor plates to the low noise cable which conducts the induced signal to the front-end amplifier.

Sensor spacing was initially chosen to be approx. 1cm (1 pipe diameter) and the sensor plate width is 3 mm. Investigation showed that the sensor width made little difference to the strength of the signal and better resolution was possible with a thinner sensor.

The sensors must be electrically shielded with a Faraday shield to reduce signal pickup from background noise (predominantly 60 Hz). This shield must be grounded and should be separated from the flow stream by at least 1 cm, to reduce the effective sensor capacitance to ground, which would reduce the gain of the amplifiers. After trying different shielding configurations, aluminum mesh was chosen.

b) <u>Turbulent Sensor:</u>

A 1mm pin was mounted in the flowstream 5-10mm upstream of the sensor plates to cause increased turbulence and eddies within the flow streams. The configuration of the sensor plates remained the same as before (Drawing B, Appendix A).

c) <u>Venturi Sensor:</u>

The same original concept was used in this design relating to the electrical configuration. The difference was in the physical construction of the Kel-F pipework. The Kel-F was manufactured as a converging - diverging nozzle (Drawing C, Appendix A). But the throat area was kept constant for a 10 cm length so that the sensor plates could again be mounted on the exterior of the pipe section.

d) <u>Non-Intrusive Sensor - with icing protection:</u>

This was the sensor configuration that proved to be the optimum design and which produced excellent results near the end of the project (Drawing D, Appendix A).

A problem with icing taking place over the sensor plate surfaces had been noticed during all nitrogen testing. This was thought to lead to sensor shorting, and also capacitive coupling across the front end amplifier, resulting in signal attenuation. Therefore, we provided a sealed enclosure around the sensor section into which silica gel was poured to absorb the atmospheric water vapor. This proved to eliminate all icing problems.

2) Cross Correlator Design:

A. Modification to Auburn Cross Correlator

The original Auburn Model 3000 cross correlator had to be modified for use with liquid nitrogen. The main reason for this was that the frequency of the signal generated by liquid nitrogen is typically 5-10 times greater than that with a flowing dry solid. Therefore, the digitizing and processing rate had to be increased.

There are two main functions of the cross correlator: 1) analogue to digital conversion and; 2) multiplication/accumulation. The rate at which data needs to be digitized is governed by resolution criteria (see section IV,2,A) and also Nyquist criteria governed by the frequency of the signals.

It was decided that a maximum data accumulation rate of 1 point per 8μs was acceptable. Since the digitizing rate is controlled by a programmable clock, this 125khz rate can be reduced if necessary.

Not knowing what the likely magnitude range of the nitrogen flow signals would be, a 12 bit A/D converter was used to assure that adequate digital processing range was available. In retrospect, it would have been possible to use an 8 bit A/D converter. The calculation function of the correlation requires many multiplications, to determine the R_{xy} maximum (see section 4) typically about 100,000. Therefore, it is of utmost importance to minimize the time for each multiplication. The calculation period of a cross correlation must be carefully controlled so that the processing time of the cross correlator can be reduced. Therefore, taking into account these timing considerations, we decided to design the multiplier as a separate piece of hardware. Using this design, a multiplier/accumulate time of 400ns was accomplished.

B. <u>Hardware Design of Correlator</u> (See Diagram B)

The cross correlator has been designed around the advanced CMOS Hitachi 64180 enhanced Z80 microprocessor, because the processor can address 512 k bytes memory locations and also has added commands for programming over the Z80 microprocessor. The original Auburn correlator was Z80 based and,

FUNCTIONAL DIAGRAM OF CROSS CORRELATOR

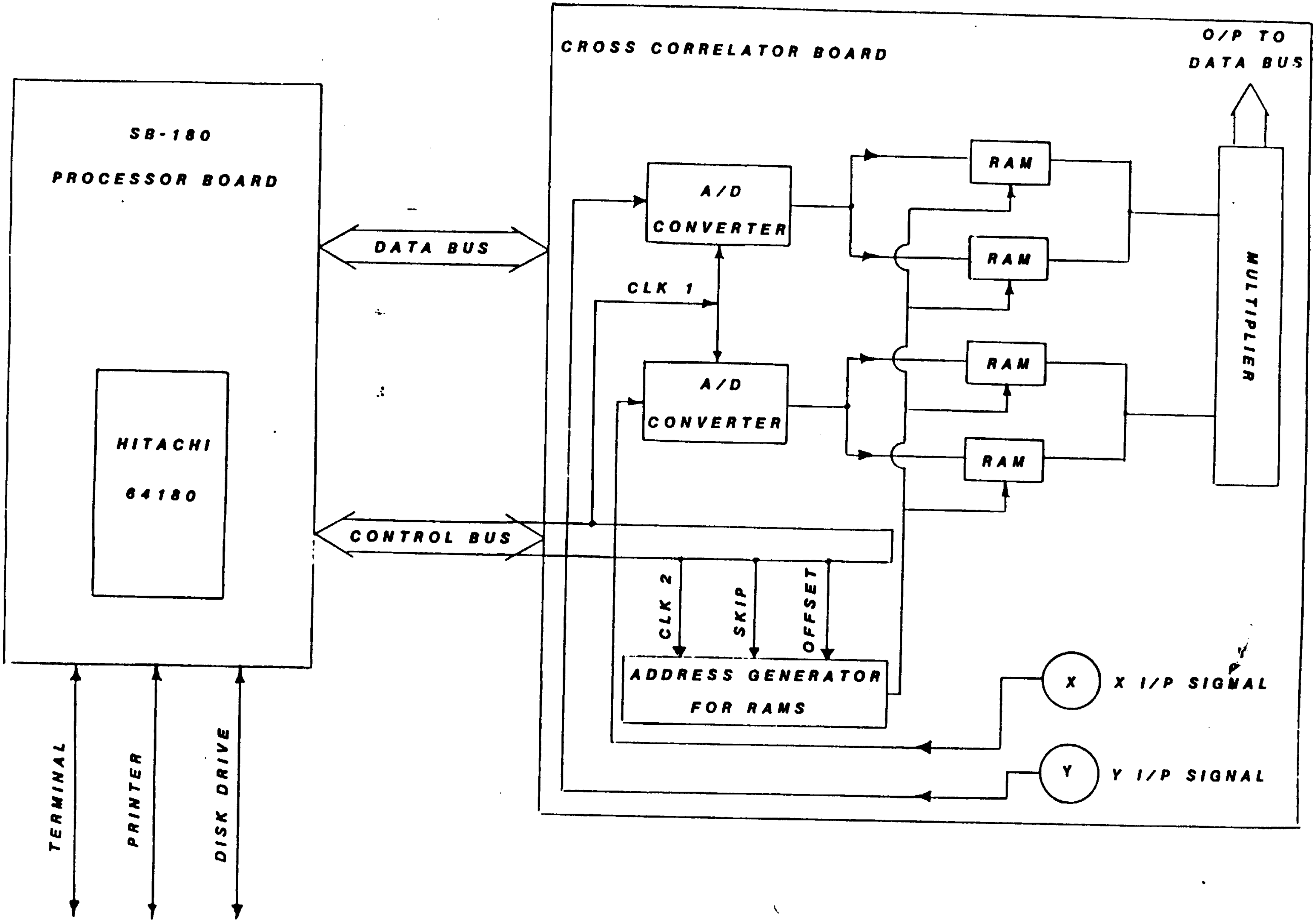


Diagram B: Functional Diagram of Cross Correlator therefore, it was possible to reuse much of the software. The SB180 developmental board manufactured by Micromint was chosen as a means for easily incorporating the microprocessor into the system. The fundamental layout of the cross correlator board was a 2-channel A-D converter with the sampling rate controlled by a clock. The digitized 12 bit signal is stored in remote RAM with the address being controlled by a series of other clocks and latches. The multiplier accumulator (TRW 2110) is fed data from the RAM memory whose address is programmable from the microprocessor. One multiplication/accumulation loop which might involve 1,000 or so multiplications is controlled by the hardware, the counters adjusting the RAM addresses and clocks controlling the process. The multiply/accumulation output is then returned to the microprocessor for analysis.

C. Other Design Features of the Cross Correlator

Since the cross correlator is principally a hardware based system, the microprocessor, as well as acting as a controller, is also used for data analysis and interpretation. It is possible to program the correlator to "home-in" on the cross correlation maximum using the following variables which are controlled by the microprocessor.

a) Data Sampling Rate: The A/D converter can be programmed to sample data with a period as shoft as 8μs. The sampling rate is programmable through the A/D controlling clock (1024 data points per channel are stored in the correlator RAM).

b) No. of Multiplications per multiply/accumulate cycle: - MULTH/4

The no. of points to be used in one multiply/accumulate cycle is programmable through the "Multiply Controlling Clock". The accuracy of the instrument increases with no. of multiplications performed per accumulation. However, so does the processing time of the instrument. There is, therefore, some compromise to be made between processing time and accuracy.

c) SKIP: The number of data points skipped between each point used for multiplication. This allows only certain data points to be used for multiplication rather than necessarily every one. If the frequency of the stored wave form is small enough, Nyquist criteria may determine that the flow signal wave can be defined well enough with fewer points.

d) OFFSET: The number of data points that the downstream waveform is time displaced relative to the upstream waveform. This variable is increased as each cross/correlation point is calculated.

e) ACCUM: The number of cross correlation points to be calculated.

f) LOCATION: The value of OFFSET which produces the cross correlation maximum value.

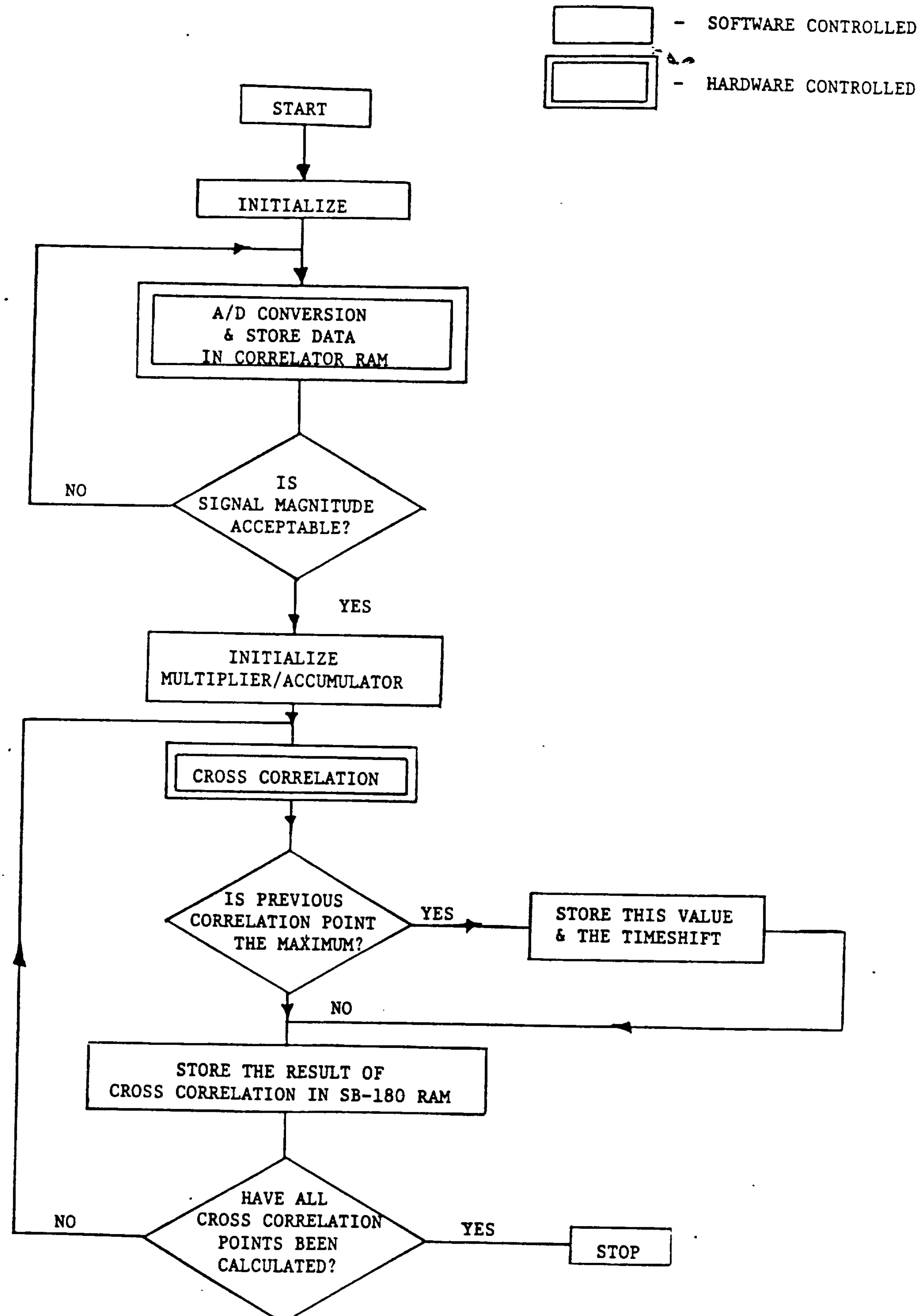
With the ability to change these variables, the Auburn cross correlator is able to "home-in" on the cross correlation maximum. (i.e. perform an approximate correlation in flow data points, and then perform an accurate cross correlation in the determined time range of interest).

D. Software Design: (See Diagram C)

The Z80 software used on the modified cross correlator is fundamentally the same as used on the original Auburn cross correlator. A flow diagram of the logic of the software is shown in diagram C.

FLOW DIAGRAM FOR CROSS CORRELATOR SOFTWARE

DIAGRAM C



3. Front End Design: (See Diagram D)

A low noise high gain amplification circuit is used to amplify the sensor signal to a flow signal acceptable in magnitude (Maximum 10V) for the cross correlator. The current to voltage gain is 10^{12}. This is attained using the circuit drawn in Diagram D. The band width of the amplifier was tested and found to be in the range of 300 khz. An amplifier circuit is required for each of the sensors. Since the amplification characteristics of each front end are the same, each wave form is subjected to the same gain. The circuits were built in a symmetric fashion along side each other and then enclosed in a single aluminum enclosure.

4. Auburn Model 1090: Liquid/Vapor Fraction Monitor - See Appendix C

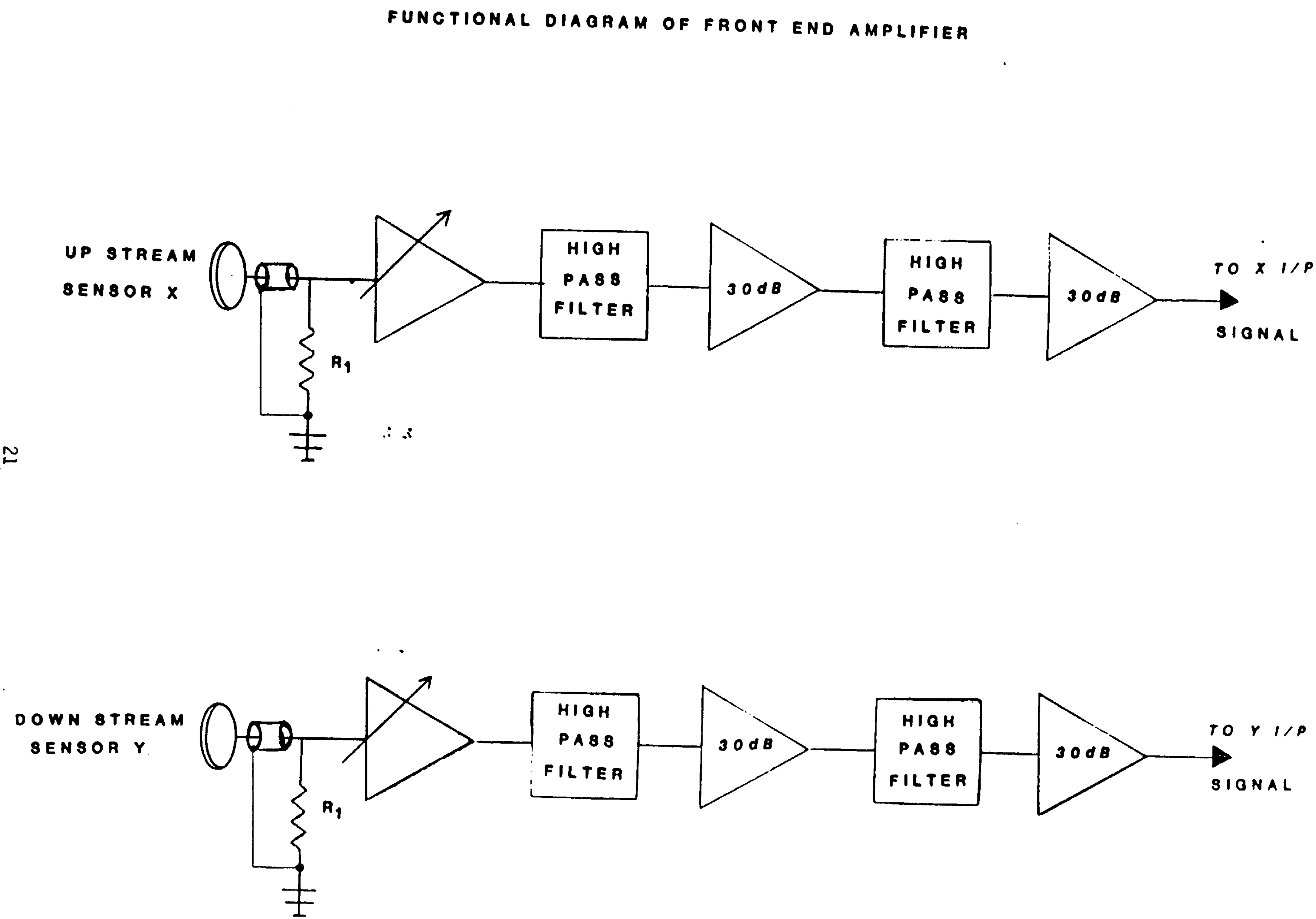


Diagram D: Functional Diagram of Front End Amplifier

VII) SUMMARY OF WORK PERFORMED

1.A. Test Procedure

The following test procedure was performed during the investigation of the different sensor configurations:

A) Insert and connect sensor in nitrogen loop.

B) Connect output of front end amplifiers to storage oscilloscope.

C) Make ground connections to Faraday shield and all loop pipework.

D) Switch on power to front end amplifiers and make sure noise levels measured on oscilloscope are approximately zero.

E) Open valves in nitrogen loop and allow nitrogen to flow - make sure loop is properly vented.

F) Wait approx. 3-4 min. for steady state liquid flow to take place (monitor output of Auburn 1090 which directly measures phase content of liquid nitrogen). This allows the loop to come to thermal equilibrium.

G) Store the flow signals from upstream and downstream sensor in oscilloscope memory.

H) Note all relevant flow parameters being investigated.

I) Transfer stored oscilloscope signals to IBM compatible PC via RS232 for data storage purposes as required.

1. B. <u>Additional test procedure performed when using cross correlator to determine liquid nitrogen flow rate.</u>

During set-up:

A) Connect front end output to cross correlator in addition to oscilloscope.

B) Connect oscilloscope external trigger to cross correlator.

C) Connect up cross correlator to terminal.

D) Initiate cross correlator.

After the 3-4 minute timespan for steady state nitrogen flow conditions to become settled:

A) Start cross correlator.

B) Store the oscilloscope data (triggered by the cross correlator).

C) Transfer to disc for storage, data in cross correlator RAM. This includes digitized flow signals and cross correlator results.

D) Transfer oscilloscope memory to PC disc drive.

2. <u>Nitrogen Testing:</u>

A) <u>Testing Non-Contacting Circumferential Sensor Section</u>

Flow signals produced at the sensor were amplified by the front end amplifier and monitored with a storage oscilloscope. Initial results were extremely positive (i.e. the signals were repeatable and a definite time lag between them was apparent). During this test, the liquid phase content as measured by the Auburn 1090 was 60 to 80%, indicating the need to increase the phase content to near 100%.

B) Loop Modification

To additionally pressurize and supercool the liquid nitrogen, the test loop was modified to permit pressurization of the liquid nitrogen Dewar as much as possible using a remote nitrogen gas source. (Due to stratification effects, it is possible to sustain a temperature differential in the Dewar and, therefore, produce supercooled liquid.) This, combined with increased pressure differential, enabled the loop to be run at 100% liquid flow.

C) Re-test of Non-Contacting Sensor.

Several tests were performed to evaluate the effects of the sensor performance tested as before, but with liquid phase content near 100% liquid. The signal strength decreased dramatically to the magnitude comparable with the noise levels of the front end amplifiers. At this stage the "Turbine Meter" supplied by NASA became inoperative, probably due to an interference problem between turbine blade and casing.

D) Investigations to Increase Signal Strength

Investigation took place to increase gain/noise ratio of the front end amplifier, but it was determined that the design of the front end was nearly as optimized as possible for frequency response requirements. Additional tests were performed involving cooling the front end amplifier with cryogen, but it was concluded that this alone would not result in enough of an increase in gain/noise ratio to make flow signals usable.

A program was initiated to try and induce increased charge distribution within the flowing nitrogen. We investigated the use of E field and magnetic field induced charge distributions. Little success was realized and we forthwith abandoned this line of investigation.

E) Testing Turbulent Sensor:

Increased turbulence in the flow stream was completed by placing 1mm intrusive pins into the flow upstream of the sensors. Sensor signal increased substantially, but signal strength decayed rapidly further down stream indicating we were monitoring evaporation effects which tend to be unrepeatable and unsuitable for cross correlation.

F) Need for High Velocity Testing

Evaluation of the 3-4m/s flow velocity in Auburn's loop reveals that the

Reynolds number may be too small for substantial streaming currents, and therefore, a Venturi was introduced in which flow velocity increases within the converging section. Some improvement was noted as signal strength increased and the flow signals showed signs of repeatability. However, evaporation within the venturi results in the superposition of signals which makes the use of streaming current signals difficult.

It was decided to continue the investigation at an off site location with higher flow rate to determine if increased velocity would indeed produce suitable correlation signals.

Auburn's nitrogen supplier (Northeast Cryogens) permitted tests to be performed at their installation. A sensor test (sensor A) section was inserted into the nitrogen pipe work and an analysis of the resultant flow signal was performed. Usable flow signals were indeed obtained, but after a period of time, when substantial icing of the sensor plates occurred, attenuation of the flow signals was observed (this phenomenon was also previously noticed with some Venturi sensor tests, and was independently confirmed by testing the circuit in a dry solids test loop).

G) Successful - Non-Contacting Sensor Testing - on Nitrogen

A re-test was accomplished at Auburn's nitrogen suppliers site using non contacting, non intrusive sensor configuration and a "silica gel" enclosure around the sensor to reduce the icing effect. The magnitude of flow signals with 100% liquid proved to be excellent for cross correlation and flow signals showed good repeatability with time shift between them. Cross correlation was performed on the flow signals indicating excellent correlation with the nitrogen suppliers estimation of the nitrogen flow rate.

3. Cross Correlator - Modification:

Initial work involved modifying the Auburn cross correlator (see section VI.2.A.) for test suitability with liquid nitrogen. A major portion of time was consumed debugging the software designed for the hardware of the modified cross correlator. A few delays were encountered at the initial stage of the project while reworking the PC board for these purposes.

The correlator is an extremely hardware based piece of equipment and, therefore, the debugging process involved writing many software programs to prove the different functionalities of the board (testing, A/D conversion, storing of data, testing RAMS, testing the ability to shift RAM address and increment these, test multiply/accumulation and the ability of the instrument to meet the high speed characteristics required).

Once the correlator had been debugged its' functionality was checked using waveforms from a signal generator and from a dry solids flow loop (this was an application where Auburn already had much working experience and subsequently required comparatively little time to accomplish).

VIII) RESULTS

1. Analysis of Results of Sensor Testing:

A) Non-Contacting Circumferential Sensor:

Testing of this sensor design (Drawing A) with 60% liquid flow at a velocity of 4m/s yielded flow signals with distinct repeatability and time lag between them (see Plot A). These signals are of excellent profile for cross correlation. An approximate calculation of the expected time shift of the waveforms from knowledge of the flow rate - compared very favorably with the time difference between the two flow signals.

On increasing the percent liquid content to near 100%, the magnitude of the flow signal decreased to a level at which it was not possible to observe them above the background noise. This test showed that the substantial charge distribution which had yielded the flow signal had been partially the result of a gas/liquid interface within the flow stream. A separate test using nitrogen gas (no liquid present) showed no sign of flow signal generation. It is thought that this electrical activity within the liquid/gas is due to severe disruption of the polarized surface which is taking place as the liquid evaporates. However, the flow signals obtained provided a good example of the efficacy of the cross correlation technique.

B) <u>Turbulence Inducing Sensor:</u>

This sensor design (Drawing B, Appendix A) was used to investigate the effect of increasing flow stream turbulence upon the magnitude of the signal strength. The pin inserted in the flow stream was used to create turbulent eddies. Typical flow signals are found in Plot B, Appendix A. The effect of creating such turbulence is two fold:

1) The magnitude of signal at the upstream sensor (x) is increased to an acceptable level (i.e. it can be differentiated above the background noise).

2) The magnitude of the signal at the downstream sensor (y) is much less than the upstream signal - minimal repeatability was observed.

Therefore, it would seem that in this particular test most of the signals being generated are related to the evaporation which takes place due to the pressure drop behind the pin rather than an increase in the streaming current effects. The charging activity is so short lived between the two sensors that evaporation would seem to be the major cause of charge generation in this instance.

In any case - the use of the "turbulence sensor" would not be applicable for cross correlation, due to the unsuitability and unrepeatability of the wave forms. This sensor design is also undesirable since it is intrusive.

C) <u>Venturi</u> <u>Sensor</u>:

This sensor design (Drawing C, Appendix A) was investigated to increase the flow velocity past the sensor and therefore increase the magnitude of the streaming currents within the flow stream. A typical flow signal is shown in Plot C, Appendix A.

Visual analysis of this signal showed there to be present two fundamental frequencies. The 1khz signal showed good signs of cross correlatability (i.e. there was good repeatability and apparent time shift). When using this sensor configuration we were concerned that evaporation taking place in the Venturi due to the pressure drop might be the source of some electrical activity. It was, therefore, uncertain whether the 10khz signal is related to evaporation effects or streaming currents.

The problem with the venturi sensor is that the Reynolds number which governs the amount of charging within the liquid is not substantially increased. Also the distance over which charging of the liquid takes place at the higher velocity is extremely small (5cm). At this stage, due to uncertainty, it was decided to try and perform a test at a location with an increased flow rate at full bore and to abandon the Venturi testing.

D) Non-Intrusive sensor with icing protection

This non-contacting sensor (Drawing D, Appendix A) was especially designed to eliminate icing effects. This phenomenon was noticed and resolved when calibrating the cross correlator on a dry solids loop to measure the particle velocity.
Using this sensor resulted in particularly successful test results at a remote site with the nitrogen velocity of 5m/s in a 1 inch line (see Plot D, Appendix A). The two flow signals showed good repeatability with distinct time shift and the cross correlator calculated the flow velocity in a series of 10 tests.

Cross-correlations were performed during these 10 tests and flow signal data, results and flow signals were stored on hard disc memory for later analysis. A typical cross correlation has been plotted in Graph A, and the readings taken in these tests in Table A and Table B (to interpret results in Tables A and B see following section).

In reference to the results shown in Table A, the calculated time shift from the cross correlator varied from test to test indicating a pulsating flow. This was confirmed by visual and audio observation. For a particular test, the time shift determined by the cross correlator correspond to the time shift determined by visual analysis of the flow signals (Plot D, Appendix A).

2. <u>Interpreting The Cross Correlator Results</u>

To interpret the cross correlator results, as shown in Table B, Appendix A, the following facts about the system should be noted.

A) <u>Cross Correlation Function:</u>

The calculated cross correlation function is transferred to the Hitachi RAM and stored in memory location 5000 Hex and upwards. Each Rxy point is a 4 byte (4 x 2 digit) hexadecimal number and therefore, every 4 memory locations is a sequential point of the function. The timeshift between each point is governed by the data accumulation rate (set at 32.55μs per point for this testing - clock frequency/200).

Two's compliment arithmetic is used and since the high byte of the accumulation is only 3 bits long, a negative number begins with a high two bytes of 07FF.

One of the cross correlation functions has been plotted out. (Graph A)

B) Cross Correlation Maximum:

The maximum value of the calcualted cross correlation function is stored in memory address 1000, 1001 and 1002 (MSB, 2nd byte, LSB, respectively). LOCATION (VI.2.C) of the cross correlation value is stored in the memory address 1003 and 1004 (LSB and MSB, respectively). The LOCATION is a function of the time displacement between the two signals.

And the time shift between the waveforms may be calculated from:

T = LOCATION x Period of stored data

For all this testing: Period of stored data = 32.55μs

T = OFFSET x 32.55μs.

C) Cross Correlation Parameters:

The values of the pre-programmable variables of the cross correlator are displayed in the following memory locations:

ACCUM - the number of correlation points calculated (100A, 100B)

MULTH/4 - the number of multiply points used to produce each correlation point (1007, 1008)

SKIP - the number of data points skipped between each multiply point (1009)

These parameters are explained in VI.2.C.

IX. RECOMMENDATIONS

1. Sensor Design:

The non-contacting, non-intrusive sensor configuration has proved successful during the final test series of this project. We would recommend further development of this configuration for suitability in actual test conditions.

Further modifications are recommended for two reasons:

A) The present sensor design is rated to 200 psi and SSME test bed evaluation will require an increase in this pressure rating. Several design possibilities are available for this purpose, and:

B) The method used to reduce ice formation over the sensor surface (silica gel) is not to be recommended for long term use, due to the experimental nature of the technique.

Work has been performed to investigate the design changes that would be required. A suitable design might involve using a composite of a kevlar matrix and CTFE filler as the sensor section. The necessary sensor plates could be incorporated or imbedded into the sensor section during the manufacture which involves building up a series of layers. Such a design would eliminate the problem of icing since the sensor plates would be captured within the sensor section.

2. <u>Sensor Testing</u>:

Now that a satisfactory sensor concept exists; and the feasibility of this cross correlator technique has been proven, further testing should take place to optimize this technique for SSME suitability.

A) <u>Sensor Magnitude</u> - A new test program should incorporate a study to investigate the exact relationship of the magnitude of the flow signal to: flow velocity; length of pipe; and pipe material.

B) <u>Correlation Parameters:</u> It would be interesting to further investigate how the cross correlator parameters (i.e. data sampling rate, number of data points, sampling rate) effect the resolution of the cross correlator. Though published data does exist on this subject, further investigation is warranted.

C) Calibration: Further comparison of the cross correlator against alternative flow meters should be made. The subject of the ability to measure true average velocity not significantly being effected by flow profile variation, should be similarly evaluated. However, the evidence suggests that this condition will not occur due to the fact that this technique measures turbulence effects generated throughout the flow stream.

X) CONCLUSION

It has been proven feasable during this test program to employ a cross correlation technique based upon triboelectric technology to determine the flow rate of liquid nitrogen. It is expected that this technology could also be used for other liquid cryogens as well as many other insulating liquids. In fact, recently, this technology was also proven feasible as a flow measurement method for JP4, jet fuel. There are still unanswered questions relating to the exact magnitude of the flow signals and its relationship with the flow conditions. Further testing should take place to investigate such effects.

Having proved that the cross correlator technique is both feasible and possible using liquid nitrogen, and that the technique indicates realistic flow rates as calibrated with an independent flow meter using JP4 - we feel justified to state that the technique can be used to measure flow rate of liquid nitrogen and probably all other liquid cryogens and insulating fluids with high repeatability and accuracy. With the knowledge derived from this project, a suitable non-intrusive sensor could be built for a test on a site more realistically simulating SSME flow conditions.

XI) **REFERENCES**

1. R. L. Dechene and W. J. Averdieck, "Triboelectricity - A New Fine Particle Measurement Parameter", 17th Annual Meeting of the FINE PARTICLE SOCIETY, SAN FRANCISCO, CA July 29th, 1986.

2. M. S. Beck, "Correlation in instruments: Cross Correlation Flowmeters", Instrument Science and Technology, 1981.

3. Luisana Marcona and Gerard Touchard, "Courants D'ecoulement dans les Liquides Cryogeniques", Journal of Electrostatics, Vol. 15, 1984.

APPENDIX A

Drawings, Plots, Graphs & Tables

1) Drawings

A - Non contacting, circumferential sensor

B - Turbulence Sensor

C - Venturi Sensor

D - Non intrusive, ice protected sensor

2) Plots

A - Flow signals from 60% liquid nitrogen using non contacting circumferential sensor.

B - Flow signals with liquid nitrogen using turbulence sensor.

C - Flow signals from liquid nitrogen using Venturi sensor.

D - Flow signals from liquid nitrogen using non intrusive; ice protected sensor.

3) Graphs

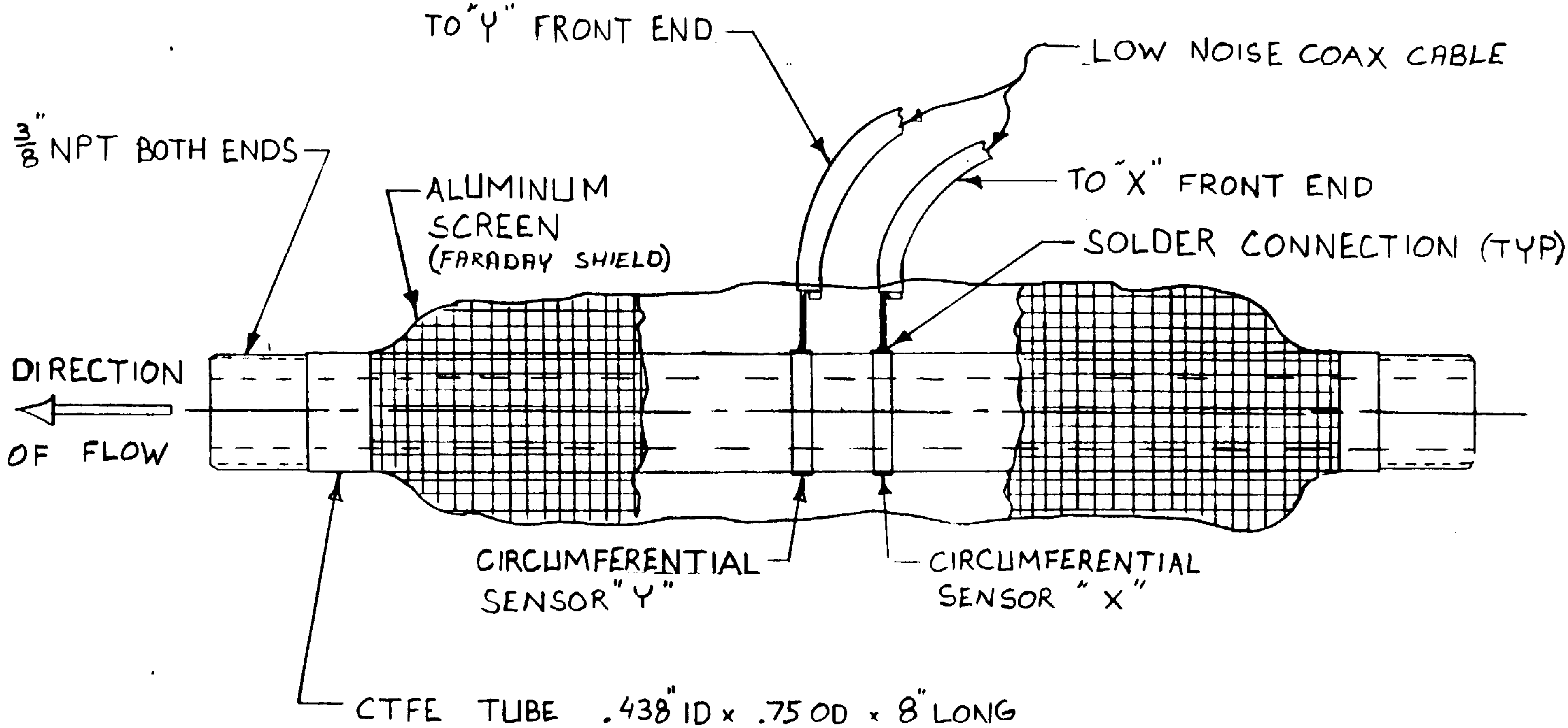
A - Cross correlation curve (Rxy) for a liquid Nitrogen test.

4) Tables

A - Cross correlation results

B- Print out of cross correlation memory contents,showing a typical result.

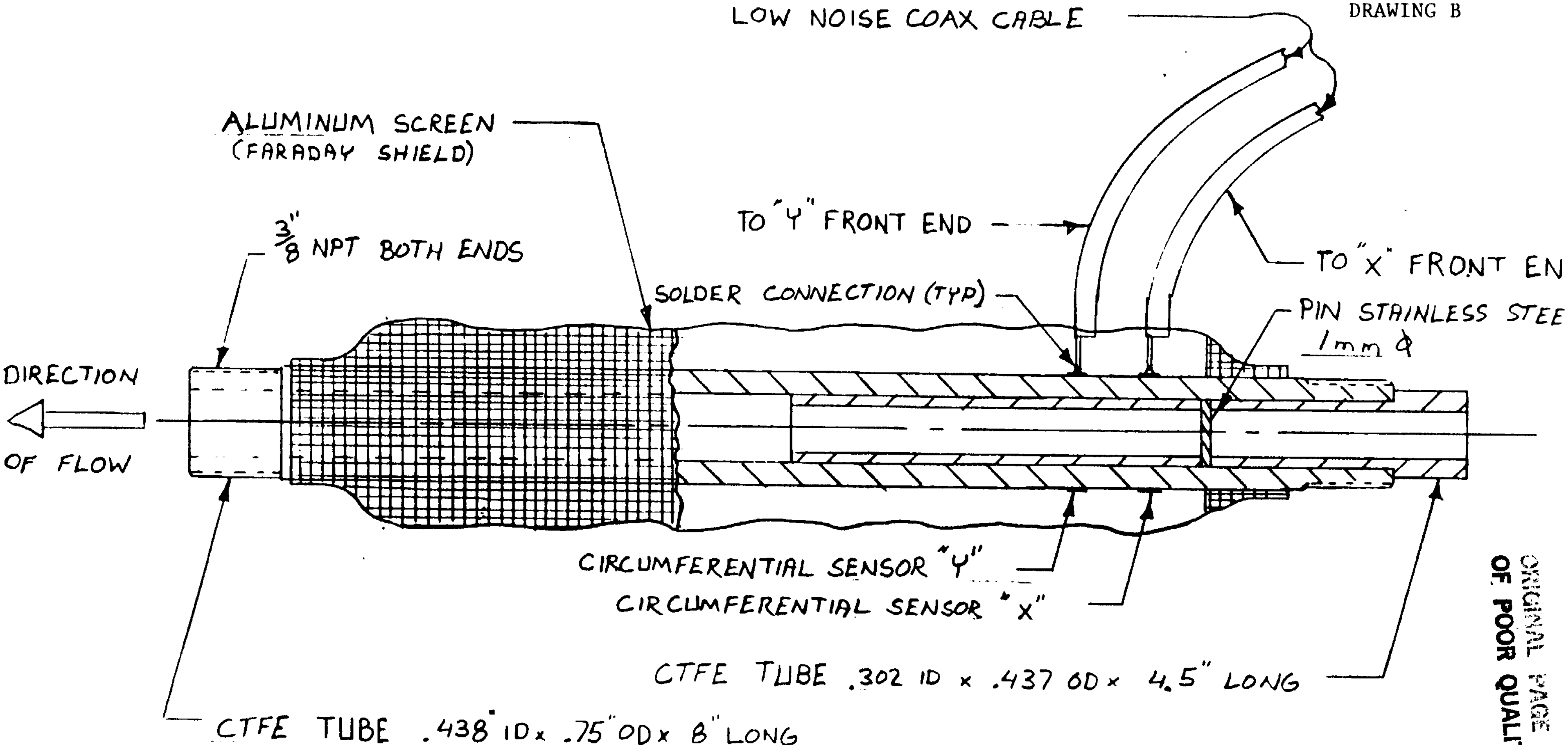
DRAWING A



DRAWING A

NASA: NITROGEN SENSOR		
SCALE: FULL DATE: 7-24-86	APPROVED BY	DRAWN BY J. CAMPBELL
NON-CONTACTING CIRCUMFERENTIAL SENSOR		
auburn Danvers, Massachusetts		DRAWING NUMBER 3000A0705

DRAWING B



DRAWING B

NASA: NITROGEN SENSOR

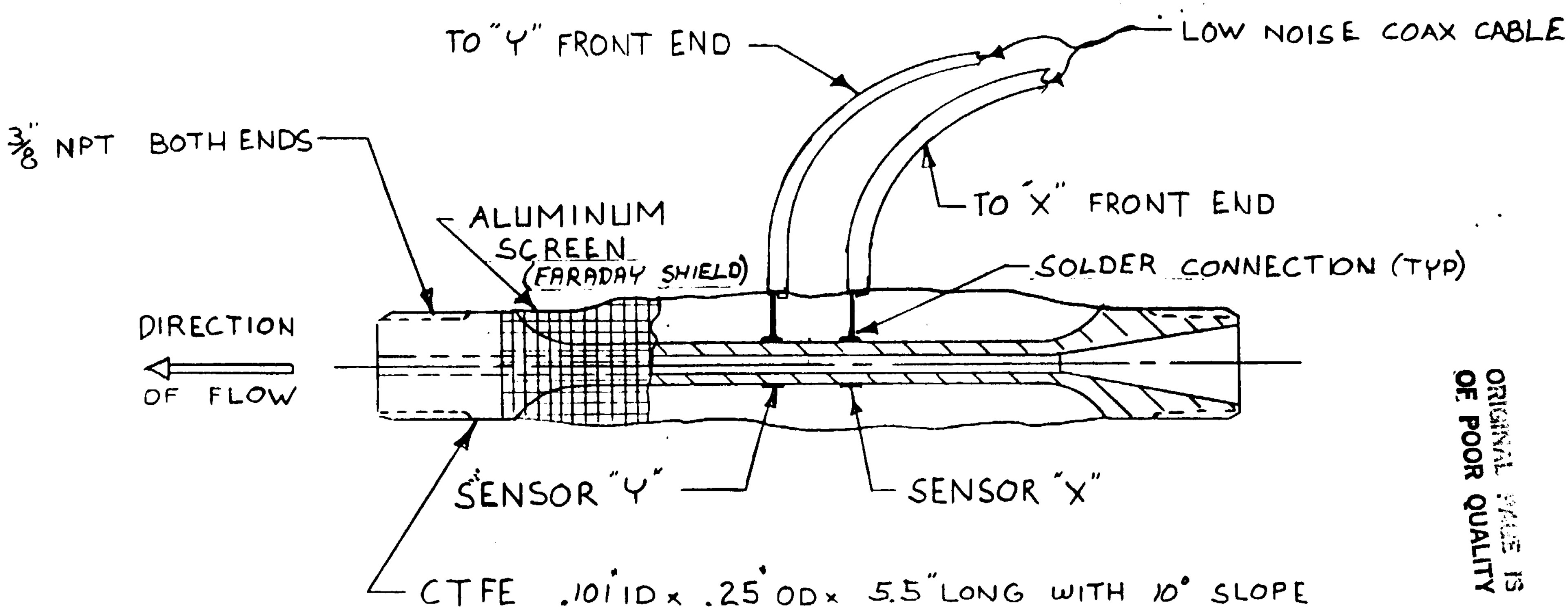
SCALE: FULL	APPROVED BY	DRAWN BY
DATE: 7-24-86		J. CAMPBELL

NON-CONTACTING TURBULENCE SENSOR

auburn Danvers, Massachusetts

DRAWING NUMBER 3000 A0706

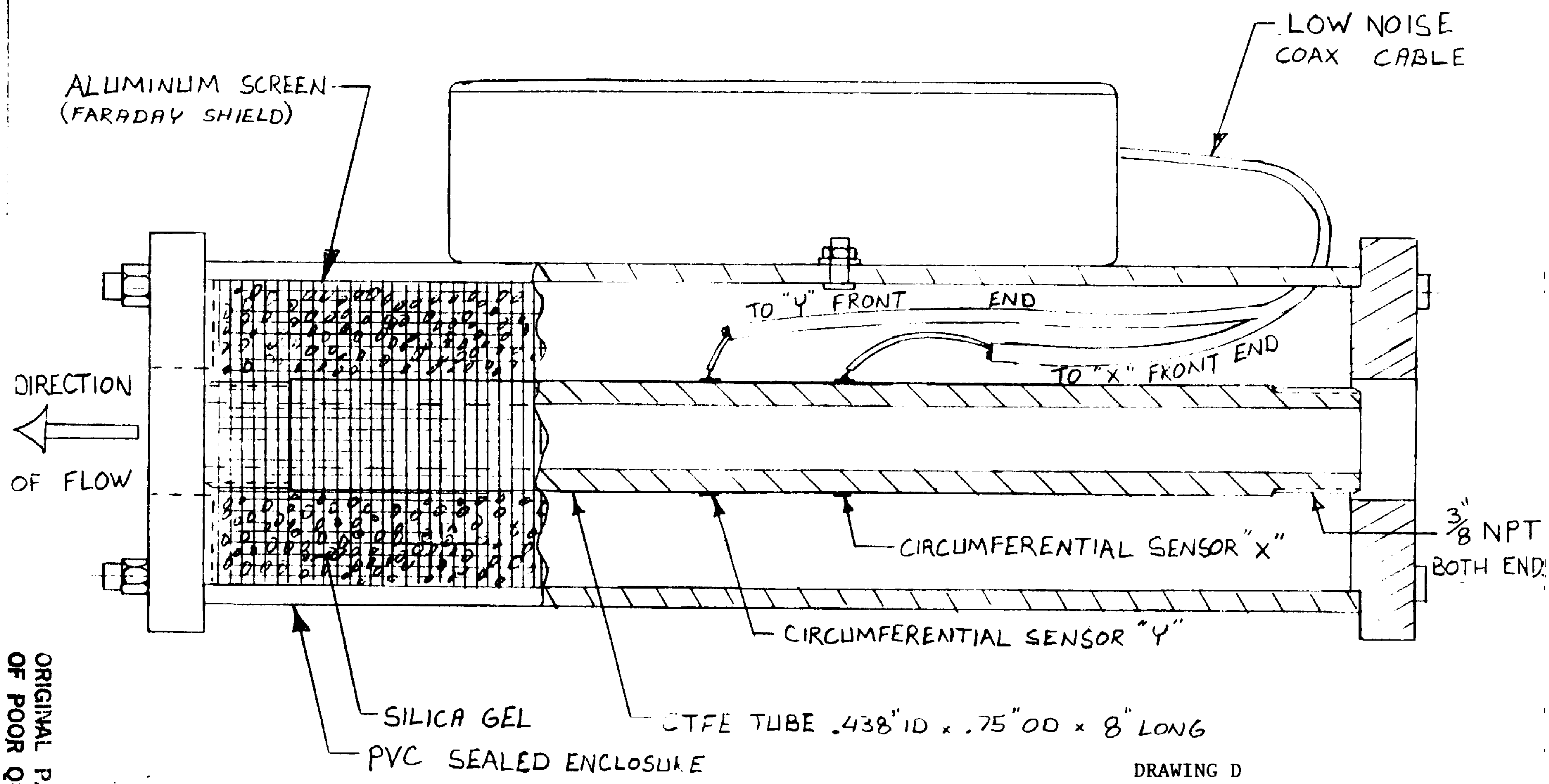
DRAWING C



DRAWING C

NASA: NITROGEN SENSOR		
SCALE: FULL DATE: 7-24-86	APPROVED BY	DRAWN BY J. CAMPBELL
VENTURI SENSOR		
auburn Danvers, Massachusetts		DRAWING NUMBER 3000A0704

DRAWING D



NOTE: ALL CONNECTIONS ARE SOLDERED

DRAWING D

NASA: NITROGEN SENSOR

SCALE: FULL DATE: 7-24-86	APPROVED BY	DRAWN BY J. CAMPBELL
NON-CONTACTING ICE PROTECTED SENSOR		
auburn Danvers, Massachusetts		DRAWING NUMBER 3000A0707

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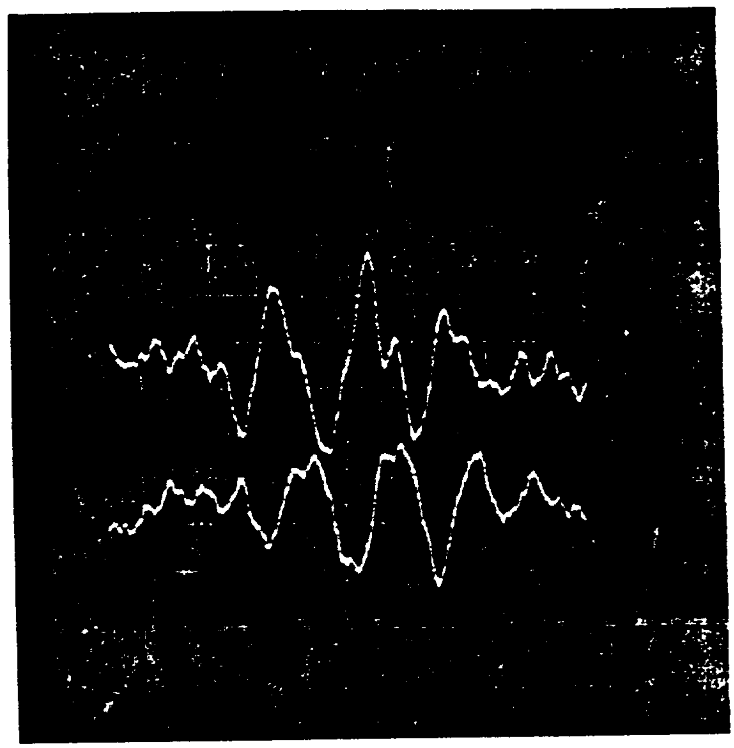
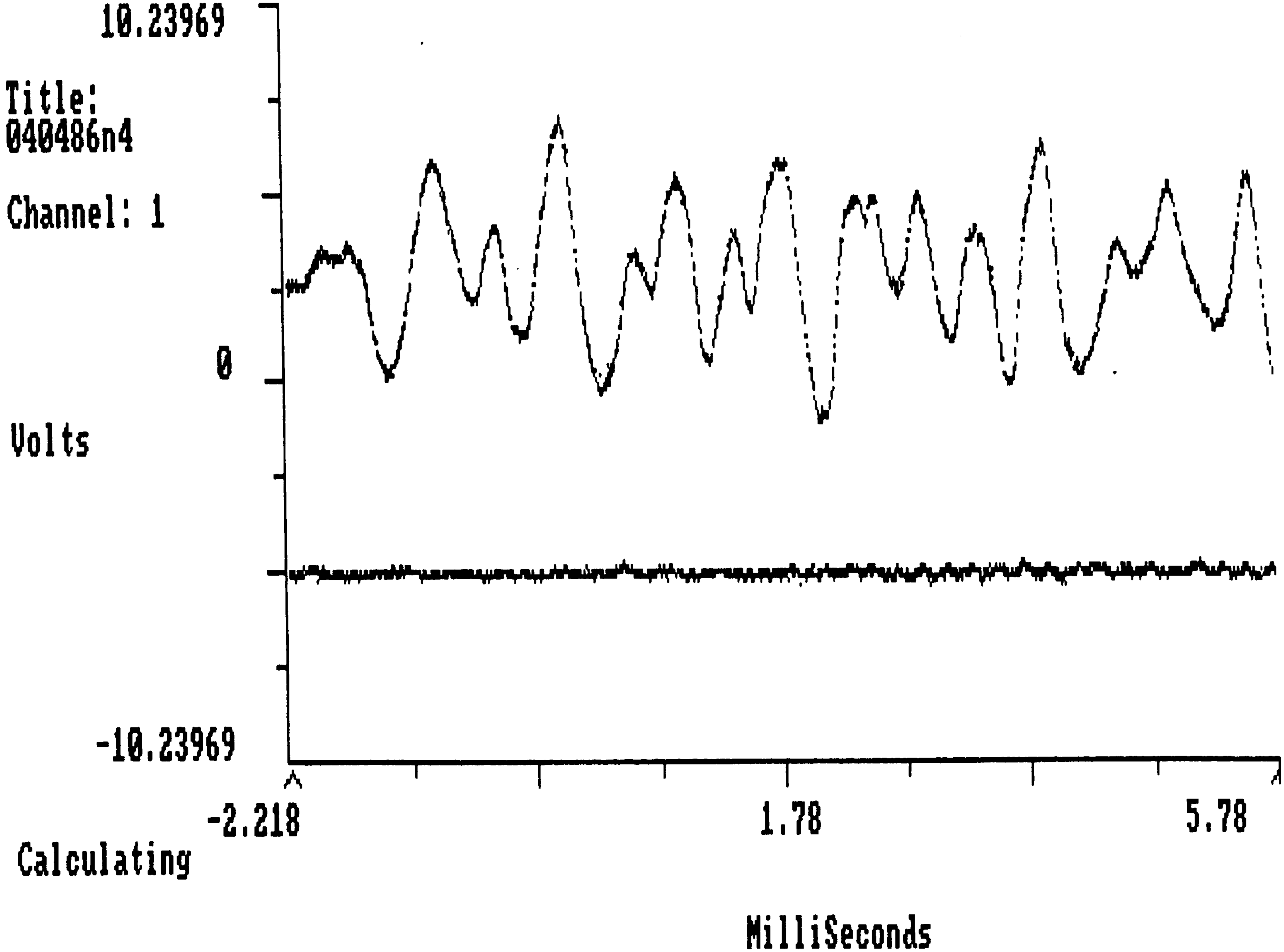
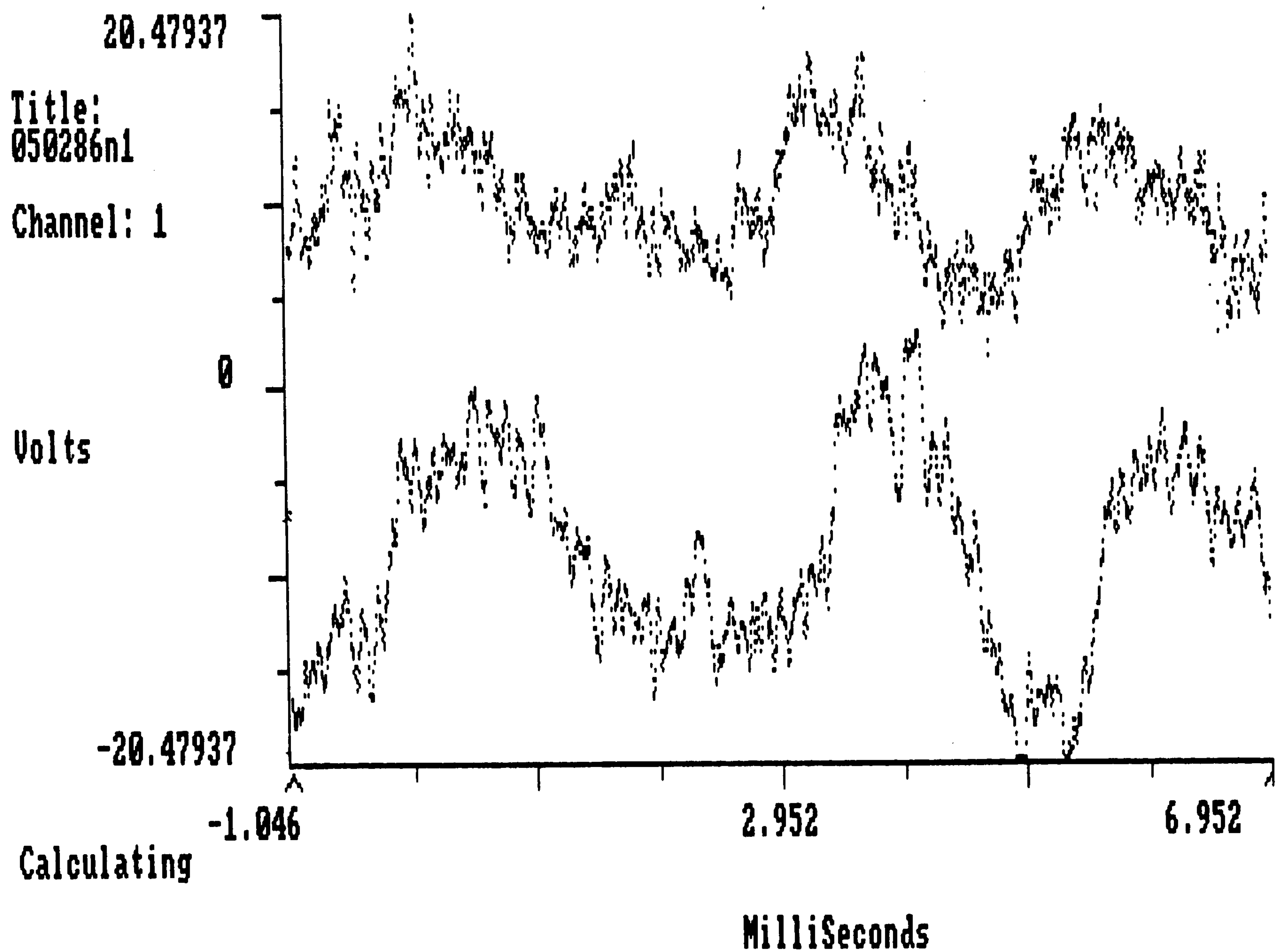


Test 6
2.28.86

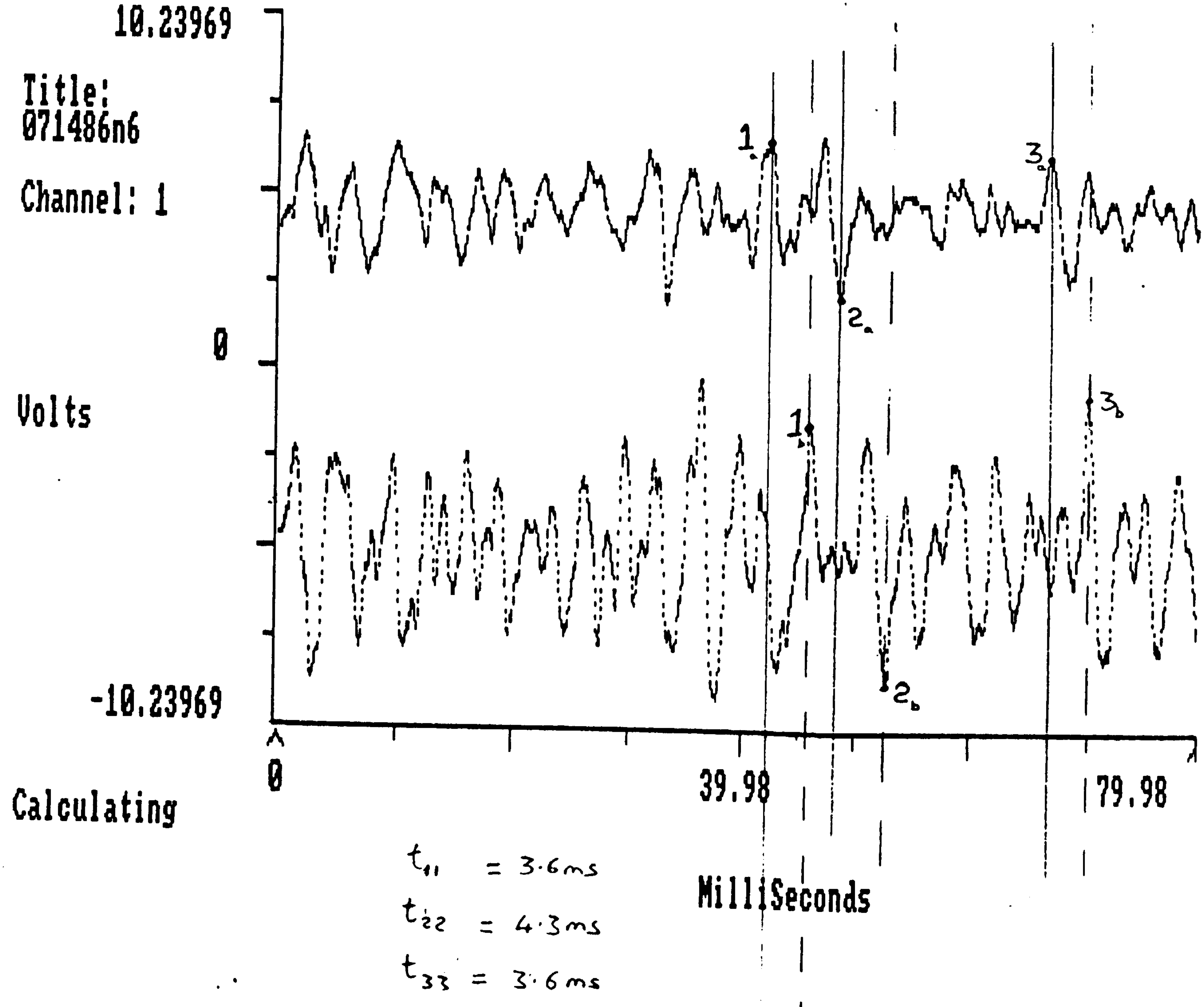
PLOT A: Flow signals from 60% Liquid Nitrogen using non contacting circumferential sensor.



Plot B: Flow signals with liquid nitrogen using Turbulence Sensor

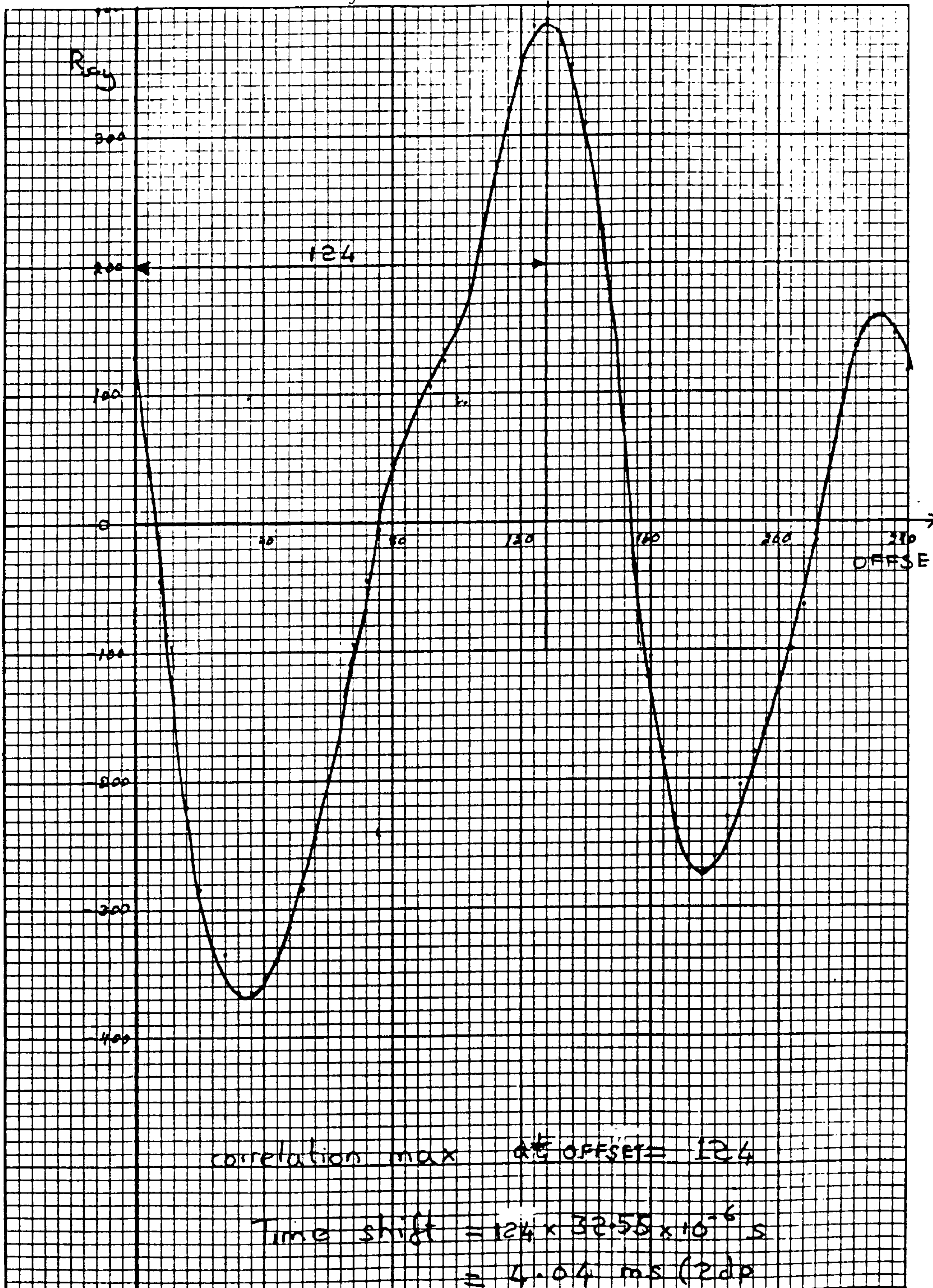


Plot C: Flow Signals from liquid nitrogen using Venturi Sensor



Plot D: Flow signals from liquid nitrogen using non-intrusive, ice protected sensor.

Graph A: Cross correlation curve (R_{xy}) plotted for liquid nitrogen test.



DATE 07/14/86 LIQUID TESTED N_2

TABLE Ai

SENSOR SEPARATION 2.54 cm

SENSOR WIDTH 0.135 cm

INNER PIPE DIAMETER 1.519 cm

TEST	CORRELATOR READING							OSCILLOSCOPE READING	
	# MULTH. (HEX)	# SKIP (HEX)	# ACCUM (HEX)	LOCATION (HEX)	ΔT (msec)	VELOCITY (ms^{-1})		TIME	VELOCITY
071486N1	1000	1	100	006A	3.45	7.36			
	1C00	1	100	006B	3.48	7.30			
	200	5	100	006E	3.58	7.09			
	400	5	100	0069	3.42	7.43			
	500	5	100	0069	3.42	7.43			
071486N3	800	1	100	008C	4.56	5.57			
	1000	1	100	0082	4.23	6.00			
	1C00	1	100	0084	4.30	5.91			
	400	2	100	008A	4.49	5.66			
	600	2	100	0086	4.36	5.83			
	800	2	100	0082	4.23	6.00			
071486N4	800	1	100	0051	2.64	9.62			
	1000	1	100	0057	2.83	8.98			
	1C00	1	100	0060	3.12	8.14			

Table Ai: Cross Correlator Results

DATE 07/14/86

LIQUID TESTED N_2

TABLE Aii

SENSOR SEPARATION 2.54 cm

SENSOR WIDTH 0.135 cm

INNER PIPE DIAMETER 1.519 cm

TEST	CORRELATOR READING						OSCILLOSCOPE READING	
	# MULTN. (HEX)	# SKIP (HEX)	# ACCUM (HEX)	LOCATION (HEX)	ΔT (msec)	VELOCITY (ms^{-1})	TIME	VELOCITY
071486N8	800	1	100	007B	3.91	6.50		
	1000	1	100	007C	4.04	6.29		
	1C00	1	100	007A	3.47	6.40		
	200	5	100	0073	3.74	6.79		
	400	5	100	007D	4.07	6.24		
	500	5	100	007D	4.07	6.24		
071486NA	800	1	100	009B	5.06	5.03		
	1000	1	100	0094	4.82	5.27		
	1C00	1	100	0095	4.85	5.24		
	200	5	100	00A0	5.21	4.88		
	400	5	100	0096	4.88	5.20		
	500	5	100	0096	4.88	5.20		

ΔT = LOCATION # 32.55 μSec

VELOCITY = $\frac{\text{SENSOR SEPARATION}}{\Delta T}$

Table Aii: Cross Correlation Results

TABLE B: Print out of cross correlation memory showing a typical result (see interpreting results)

```
        /1000      /1003               /1007     /100A
          ↓          ↓                   ↓         ↓
1000    01 B5 70 7E 00 00 00 00 10 01 00 02 C3 37 10 C5      ..p.............
```

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OF POOR QUALITY

```
5000 00 00 B2 B4 00 00 6F 17 00 00 6F 17 00 00 45 39      ......o...o...E9
5010 00 00 2F A2 00 00 19 3A 00 00 02 8D 07 FF EB 5D      ../.....:.......
5020 07 FF D4 36 07 FF BC B1 07 FF A5 5C 07 FF 3E 07      ...6.......\....
5030 07 FF 77 2A 07 FF 60 C8 07 FF 4B 2F 07 FF 36 9F      ..w*..`...K/..6.
5040 07 FF 23 41 07 FF 11 11 07 FE FF F8 07 FE F0 5D      ..#A...........]
5050 07 FE E1 FB 07 FE D5 0C 07 FE C9 31 07 FE BE B8      ...........1....
5060 07 FE B5 67 07 FE AD 8A 07 FE A6 E7 07 FE A1 B7      ...g............
5070 07 FE 9D 05 07 FE 99 B0 07 FE 96 C7 07 FE 95 00      ................
5080 07 FE 93 7C 07 FE 92 D0 07 FE 92 4A 07 FE 92 E7      ...........J....
5090 07 FE 93 93 07 FE 95 2F 07 FE 96 E2 07 FE 99 46      ......./.......F
50A0 07 FE 9B F3 07 FE 9F 11 07 FE A2 60 07 FE A6 6D      ...........`...m
50B0 07 FE AA FE 07 FE B0 37 07 FE B5 E6 07 FE BC 5A      .......7.......Z
50C0 07 FE C3 34 07 FE CA BB 07 FE D2 C0 07 FE DB 0F      ...4............
50D0 07 FE E3 FC 07 FE ED 3B 07 FE F6 A3 07 FF 00 4A      .......;.......J
50E0 07 FF 0A 6D 07 FF 15 16 07 FF 20 4F 07 FF 2B C9      ...m.......O..+.
50F0 07 FF 38 19 07 FF 44 57 07 FF 51 0D 07 FF 5D B9      ..8...DW..Q...].
5100 07 FF 6A C7 07 FF 77 B1 07 FF 85 3F 07 FF 92 96      ..j...w....?....
5110 07 FF A0 3B 07 FF AD A3 07 FF BB 3E 07 FF C8 83      ...;.......>....
5120 07 FF D5 B5 07 FF E2 74 07 FF EF 0D 07 FF FA FA      .......t........
5130 00 00 06 52 00 00 11 17 00 00 1A F3 00 00 23 E2      ...R..........#.
5140 00 00 2C 36 00 00 33 F2 00 00 3A CA 00 00 40 FC      ..,6..3...:...@.

5150 00 00 46 7A 00 00 4B A0 00 00 50 4C 00 00 54 E9      ..Fz..K...PL..T.
5160 00 00 59 12 00 00 5D 64 00 00 61 8A 00 00 65 F2      ..Y...]d..a...e.
5170 00 00 6A 5D 00 00 6F 0E 00 00 73 B2 00 00 78 AC      ..j]..o...s...x.
5180 00 00 7D 8F 00 00 83 0E 00 00 86 4B 00 00 88 4B      ...........K...K
5190 00 00 98 4B 00 00 9B C9 00 00 A3 49 00 00 A3 49      ...K.......I...I
51A0 00 00 A3 49 00 00 BD F1 00 00 C7 EF 00 00 C7 EF      ...I............
51B0 00 00 C7 EF 00 00 EA 0F 00 00 F6 5F 00 00 F6 5F      ..............._
51C0 00 00 F6 5F 00 01 1B 50 00 01 27 A5 00 01 27 A5      ..._...P..'...'.
51D0 00 01 27 A5 00 01 49 F6 00 01 54 40 00 01 54 40      ..'...I...T@..T@
51E0 00 01 54 40 00 01 6E 8D 00 01 75 74 00 01 75 74      ..T@..n...ut..ut
51F0 00 01 75 74 00 01 83 24 00 01 85 70 00 01 85 70      ..ut...$...p...p
5200 00 01 85 70 00 01 84 EB 00 01 83 26 00 01 80 1A      ...p.......&....
5210 00 01 7C 60 00 01 77 29 00 01 71 59 00 01 6A 2A      ...`..w)..qY..j*
5220 00 01 61 F9 00 01 58 78 00 01 4E 29 00 01 42 6B      ..a...Xx..N)..Bk
5230 00 01 35 55 00 01 27 18 00 01 17 AB 00 01 07 04      ..5U..'.........
5240 00 00 F5 6D 00 00 E2 A9 00 00 CE F6 00 00 BA 96      ...m............
5250 00 00 A5 85 00 00 8F CD 00 00 79 7F 00 00 62 FA      ..........y...b.
5260 00 00 4C 15 00 00 35 4D 00 00 1E 43 00 00 07 2E      ..L...5M...C....
5270 07 FF F0 2A 07 FF D9 9A 07 FF C2 F1 07 FF AD 28      ...*...........(
5280 07 FF 97 66 07 FF 82 90 07 FF 6E 52 07 FF 5B 55      ...f......nR..[U
5290 07 FF 49 1C 07 FF 38 E1 07 FF 29 BA 07 FF 1C 9B      ..I...8...).....

52A0 07 FF 10 39 07 FF 06 CC 07 FE FD 2A 07 FE F7 13      ...9.......*....
52B0 07 FE F1 AD 07 FE EE 4F 07 FE EC 67 07 FE EC 75      .......O...g...u
52C0 07 FE ED C6 07 FE F0 61 07 FE F4 24 07 FE F9 36      .......a...$...6
52D0 07 FE FE C6 07 FF 05 24 07 FF 0B C9 07 FF 12 6D      .......$.......m
52E0 07 FF 19 3E 07 FF 1F E6 07 FF 26 B1 07 FF 2D 27      ...>......&...-'
52F0 07 FF 33 EC 07 FF 3A 56 07 FF 41 00 07 FF 47 4B      ..3...:V..A...GK
5300 07 FF 4D C0 07 FF 53 E8 07 FF 5A 50 07 FF 60 19      ..M...S...ZP..`.
5310 07 FF 66 00 07 FF 6B 39 07 FF 71 0D 07 FF 76 AC      ..f...k9..q...v.
```

APPENDIX B

JP4 Testing

Contents

APPENDIX B

JP4 TESTING

1. Background:

NASA had expressed particular interest in whether triboelectric technology combined with a cross correlator could be made applicable for the measurement of JP4 jet fuel. Therefore, Auburn decided to perform a feasibility study on JP4 and proved that such technology could be used for monitoring its' flow rate. There was also concern that little independent comparison of the correlator results had been performed with liquid nitrogen due to the late development of successful results. Since we lost the use of the NASA supplied "Turbine Meter", it was decided that the additive of a JP4 test program would serve to: 1) evaluate the technology for another liquid, and 2) to permit comparison of the computed cross correlation with an independent flow metering device (a ball meter).

2. JP4 Test Procedure: A test loop was built (Drawing 1) to directly compare the output of the cross correlator against a ball meter. Using this loop it was possible to vary the JP4 flow velocity from 0-5ms^{-1} through the test section.

The sensor section was exactly the same non-contacting, non-intrusive sensor section as used in the successful liquid nitrogen test series. The test procedure was executed exactly as performed in the nitrogen testing series. Ten test points were taken with velocities varying over the 0-3m/s range and the cross correlator OFFSET (function of velocity) and ball meter reading were recorded. (Table 1)

3. <u>Test Results</u>: The velocity of the flow stream was calculated from the time shift between waveforms derived by the correlator and the separation of the sensor plates (Plot 1).

The cross correlator velocity was plotted against the ball meter reading (Graph 1). No attempt was made to calibrate the ball meter for JP4, since this experimentation was performed solely to prove the linearity of cross correlator output with flow velocity.

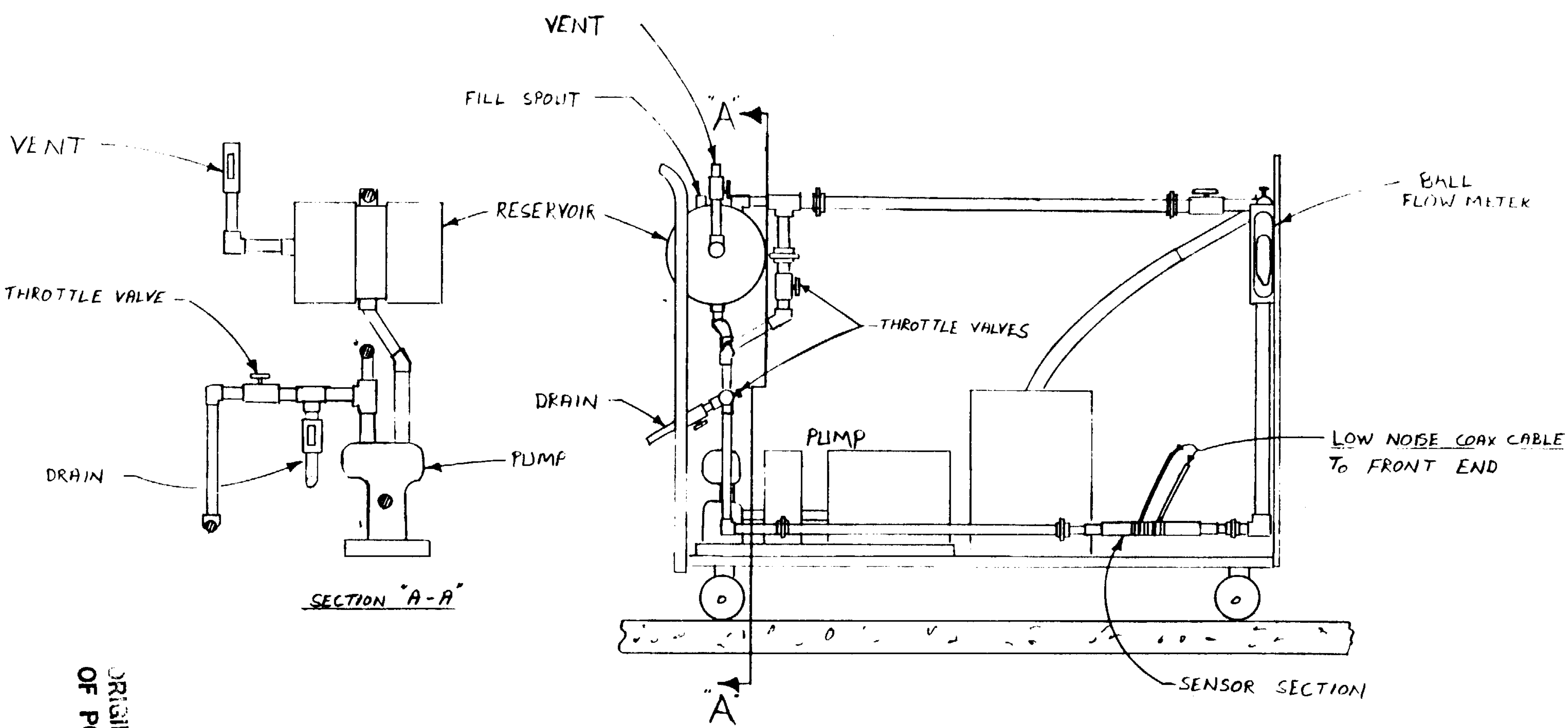
Gradient of best line fit: 0.571

Gradient of error line: 0.521

Percent error in line fit: = 8.7%

(Reference Graph 1)

4. <u>Conclusion</u>: The ball meter is rated for 10% accuracy and, therefore, this test proved that with the limitations of the experiment, the cross correlator can be used to measure liquid flow rate and that its' output is proportional to increase in velocity.



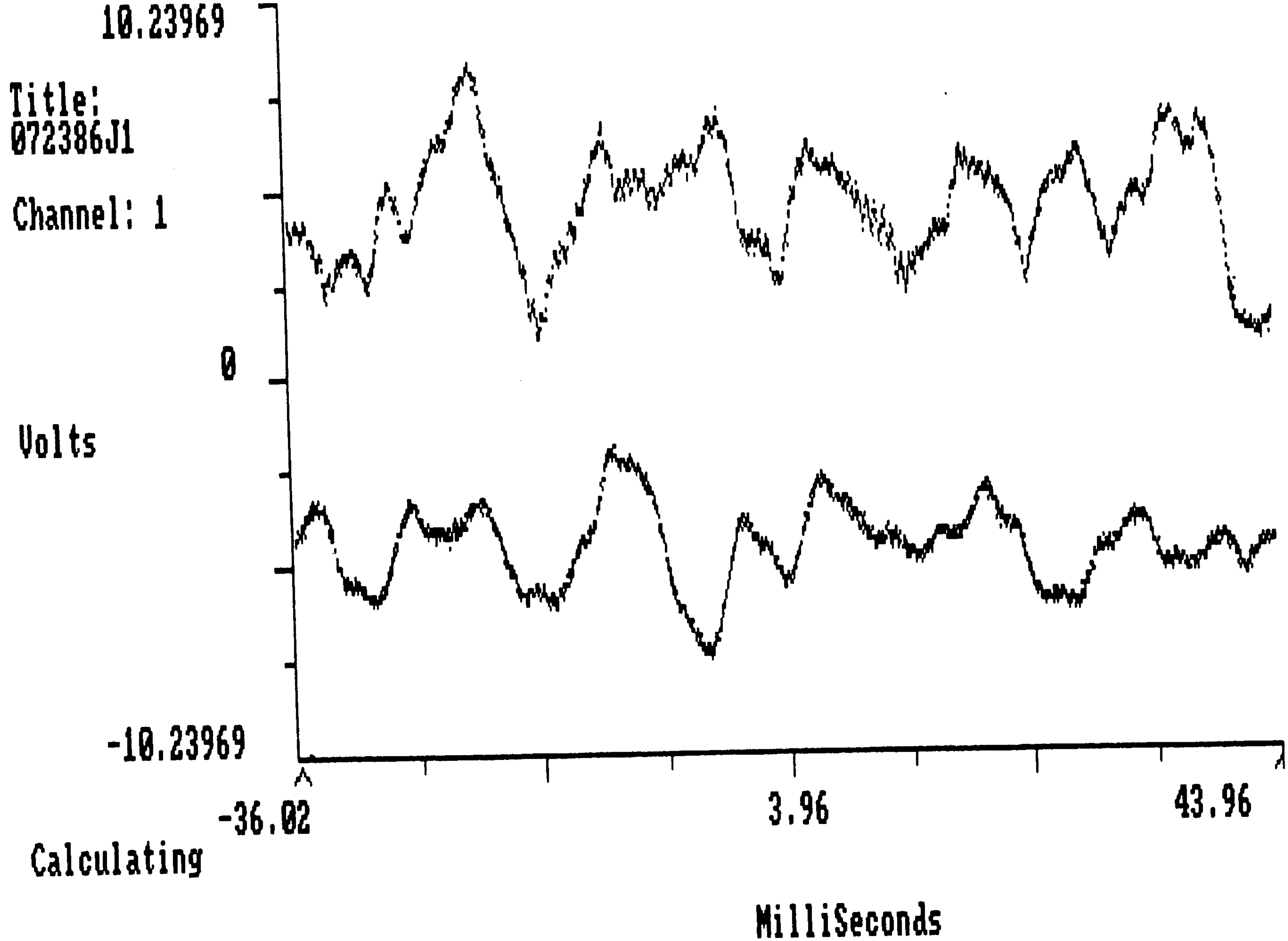
DRAWING 1

NASA: SENSOR

SCALE: 1½" = 1'
DATE: 7/25/86
APPROVED BY
DRAWN BY J. CAMPBELL

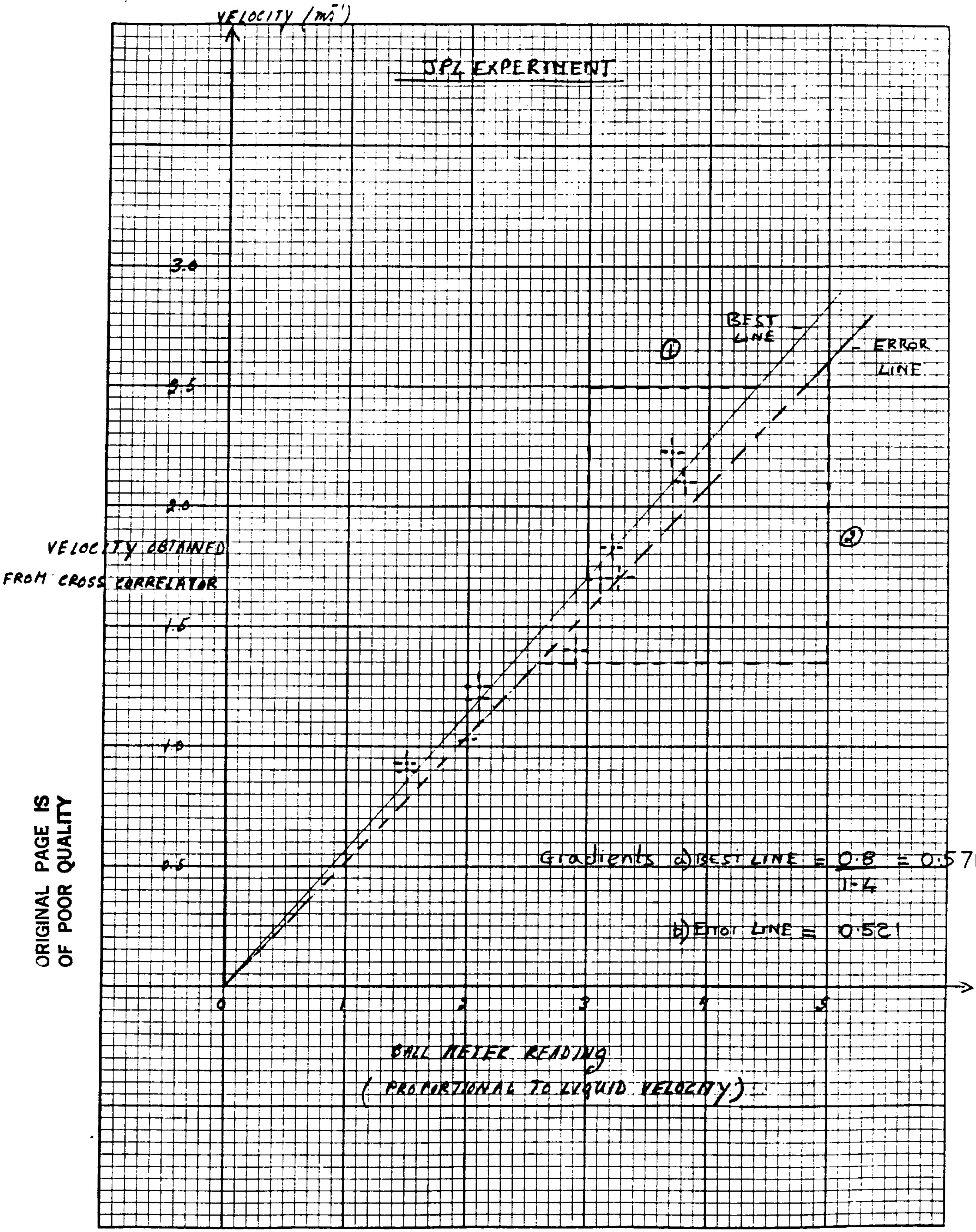
TEST LOOP FOR JP4 FUEL

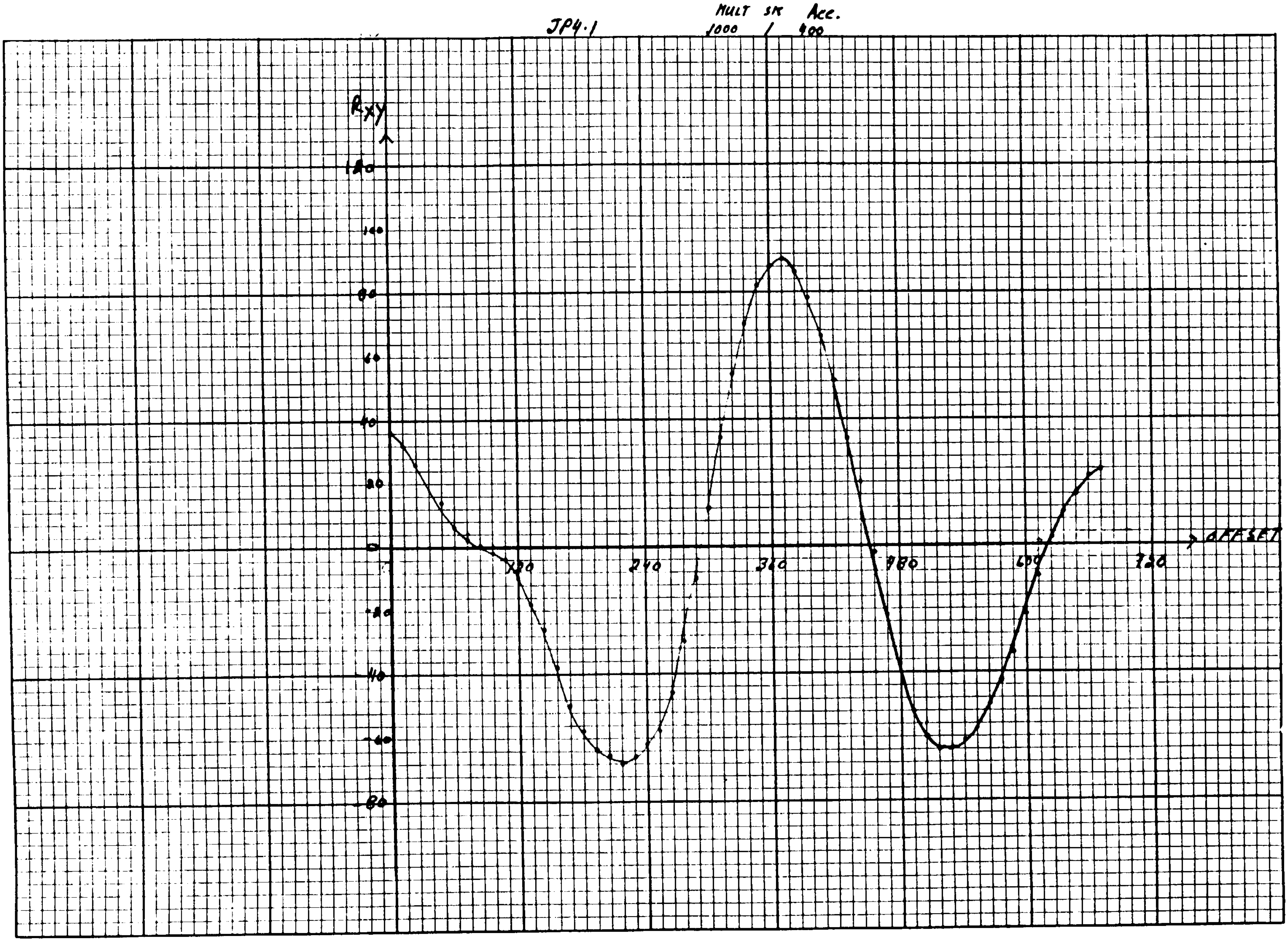
auburn Danvers, Massachusetts
DRAWING NUMBER 300080708



Plot 1: Flow Signals from JP4

Graph 1: Velocity from Cross Correlator against Ball Meter Reading for JP4 flow.





Graph 2: Cross Correlator curve (R_{xy}) plotted for a JP4 Test.

DATE 07/23/86 LIQUID TESTED JP4

SENSOR SEPARATION 1.0" (2.54 cm)
SENSOR WIDTH 0.25" (0.635 cm)
INNER PIPE DIAMETER 0.598" (1.5189 cm)

TIME OF TESTING	BALL METER READING: METER READING	FLOW RATE	VELOCITY	CORELATOR READING: # MULT	# SKIP	# ACCUM.	OFFSET LOCATION	TIME	VELOCITY
72386JP4.1	3.8			1000	1	400	(370) 0172H	12.04 mA	2.11 mA^{-1}
72386JP4.2	3.20			1000	1	400	(455) 01C7H	14.81 mA	1.72 mA^{-1}
72386JP4.3	2.9			1000	1	400	(555) 022BH	18.07 mA	1.41 mA^{-1}
72386JP4.4	2.1			1000	1	400	(624) 0279 H	20.31 mA	1.25 mA^{-1}
72386JP4.5	2.1			100	1	400	(648) 0288H	21.09 mA	1.20 mA^{-1}
72386JP4.6	1.5			100	1	400	(855) 0357 H	27.83 mA	0.91 mA^{-1}
	1.5			100	1	400	(853) 0355 H	27.77 mA	0.91 mA^{-1}
	1.5			100	1	400	(852) 0354 H	27.73 mA	0.92 mA^{-1}
72386JP4.7	1.6			100	1	400	(852) 0354 H	27.73 mA	0.92 mA^{-1}
	2.0			100	1	400	(549) 0225 H	17.87 mA	1.42 mA^{-1}
72386JP4.8	2.0			100	1	400	(759) 02F7 H	24.71 mA	1.03 mA^{-1}
	2.0			100	1	400	(767) 02FF H	24.97 mA	1.02 mA^{-1}
	3.1			100	1	400	(462) 01CE H	15.07 mA	1.69 mA^{-1}
	3.25			100	1	400	(456) 01C8 H	14.84 mA	1.71 mA^{-1}
	3.25			100	1	400	(456) 01C8 H	14.84 mA	1.71 mA^{-1}
72386JP4.9	3.70			100	1	400	(352) 0160 H	11.46 mA	2.22 mA^{-1}
	3.70			100	1	400	(350) 015E H	11.39 mA	2.23 mA^{-1}

TABLE 1
J P4 Test Results

APPENDIX C

Auburn 1090

Product Description:

The Auburn Model 1090 is an instrument designed to measure the gas/liquid phase content as insulating liquid by means of an electrically rotating, six part, capacitance field. Electrical field rotation (EFR) eliminates errors caused by flow regimine non-homgenety, commonly associated with two-plate capacitance devices. This "EFR" technology was invented by Auburn International, Inc. and is patented in the U.S. and other major countries.

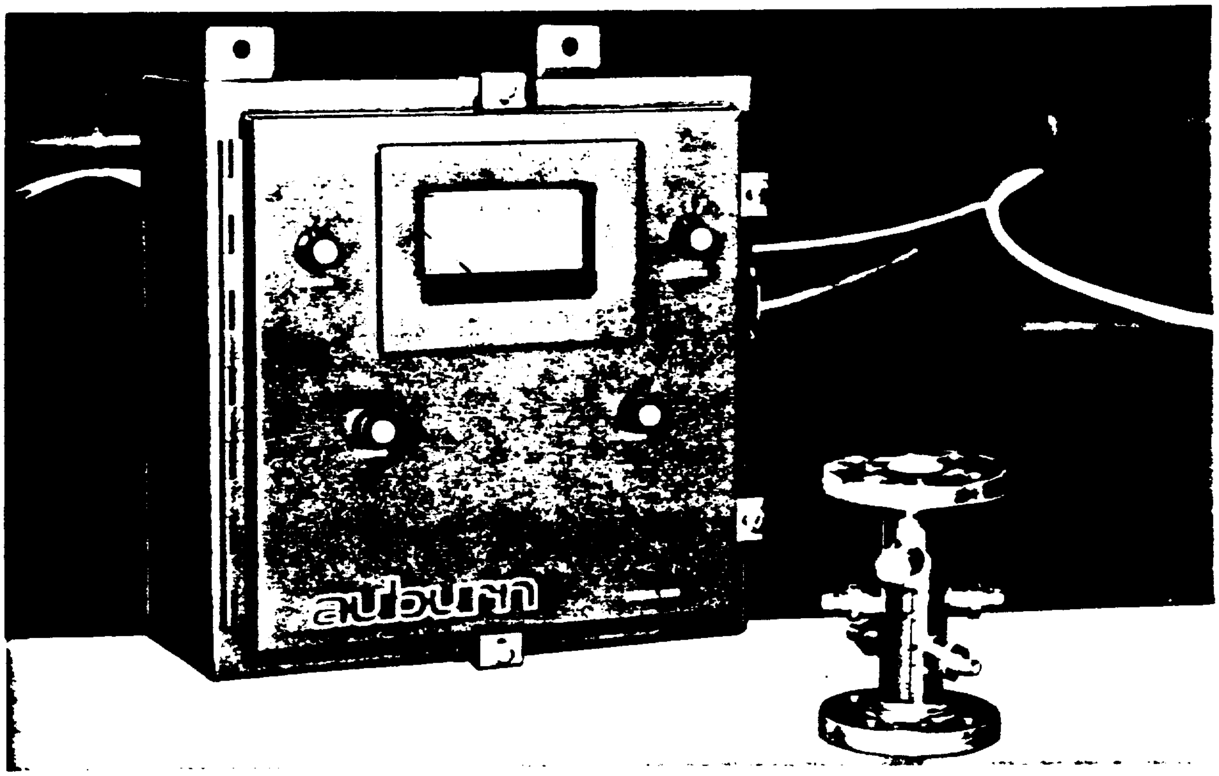
Attachment:

1. Data Sheet

auburn INTERNATIONAL

Two-Phase Flow Monitor

Model 1090*



The Auburn Model 1090 is a process control instrument designed to measure the solid, liquid, or gas content of a two-phase flow. The unique, patented rotating-field method employed in this instrument assures accurate measurement. This measurement can be made for any solid/liquid, solid/gas, liquid/gas, or liquid/liquid flow where both media are non-conductive.

APPLICATIONS

- **Polymer pellets/Air**
- **Polymer/Hexane**
- **Coal/Air**
- **Coal/Oil**
- **Coal Gasification**
- **MHD Boiler Feed Control**
- **Catalyst/Air**
- **Solid/Gas**
- **Liquid/Gas**
- **Solid/Liquid**

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FEATURES

- **Patented Field-Rotation Technique** ..... **assures accurate measurement in horizontal and vertical pipes**
- **Real-Time Measurement** .... **provides continuous on-line measurement**
- **Non-Intrusive Sensor** .... **No pressure drop or flow disturbance**
- **Mass Flow Measurement Capability** .... **by incorporating a velocity measurement, mass flow measurement can be obtained**

*Patented

Auburn International, Inc., One Southside Road, Danvers, Massachusetts 01923 (617) 777-2460 TWX: 710-347-1770

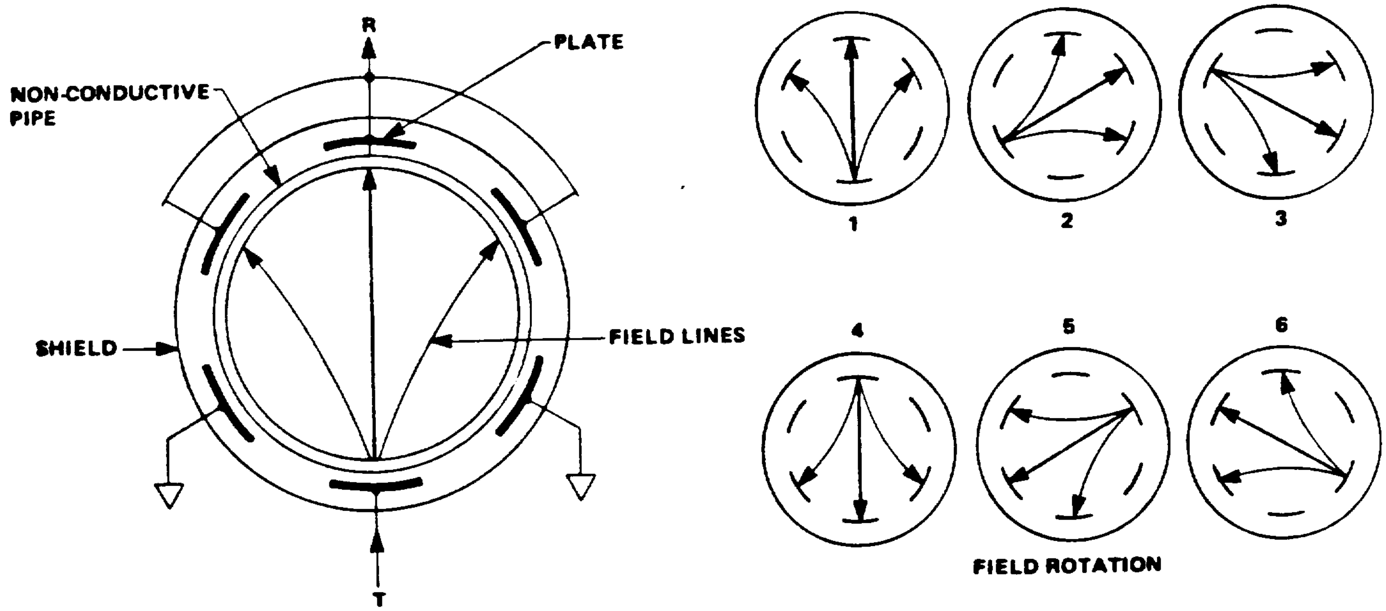
auburn INTERNATIONAL

General Description

The Auburn Model 1090 employs an in-line sensor to measure the relative volume fractions of a two-component flowing mixture. The device can be used for solid/gas, solid/liquid, liquid/gas, or liquid/liquid applications where, the flowing media are non-conductive. The sensor is non-intrusive and causes no flow disturbance or pressure drop. The instrument provides continuous real-time measurement with a response time of approximately 5 ms.

Electrical Field-Rotation Principle

The Model 1090 employs a patented electrical field-rotation technique for uniform, accurate measurement within the sensor cross-section. The instrument measures the average dielectric constant of a flowing mixture, which is related to the relative amounts of the two flow components within the sensor volume. This technique renders the measurement independent of pipeline attitude and mixture distribution within the pipeline. The sensor utilizes six electrodes placed around the inner circumference of the sensor.



As shown above, an electric field is induced across the sensor by transmitting a signal from one plate and receiving on the opposite three plates. A capacitance measurement is thereby achieved. The field is rotated at a rate of 208 rps by sequentially shifting the electrical connections to the plates. No mechanical rotation occurs. This technique assures uniform measurement in the entire sensor volume.

Options:

- Mass Flow Measurement .... utilizing a velocity measurement, the mass flow can be determined
- Signal Averaging .... averages fluctuations in the measurement over time
- Hazardous Environment Protection ..... explosion-proof enclosures available

Specifications:

Power	120V, 60 Hz
Electrode Excitation	0-20 VPP, 30 KHz
Field Rotation Rate	208 rps
Signal output	0-10 VDC (4-20mA optional)
Sensor: Pressure max.	1500 psig
Sensor: Temperature max.	350°C
Enclosures	Rack Mountable, or NEMA 4 (hazardous environment enclosures optional)

1. Report No.
CR 179519

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Mass Flow Measurement of Liquid Cryogens Using the Triboelectric Effect

5. Report Date

6. Performing Organization Code

7. Author(s)
Ronald L. Dechene

8. Performing Organization Report No.

9. Performing Organization Name and Address
Auburn International, Incorporated
One Southside Road
Danvers, MA 01923

10. Work Unit No.

11. Contract or Grant No.
NAS3-24873

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Final - 9-12-86

14. Sponsoring Agency Code

15. Supplementary Notes
Project Manager, R. M. Masters
NASA Lewis Research Center
Cleveland, OH 44135

16. Abstract
A cross correlator technique using triboelectric technology has been shown to be a feasible method to measure liquid flow rate for liquid Nitrogen and JP4 jet fuel. This technology, invented and pioneered by Auburn International, Incorporated, is also expected to be suitable for use with all other insulating liquids and cryogens.

The technology described in this report is particularly well-suited for cryogenic use, since the sensor is non-contacting and non-intrusive, and therefore, causes no additional pressure drop within the flow stream.

Further development of the in-line sensor is required to produce a prototypical version for test purposes under SSME fuel flow conditions. However, with the knowledge gained from this feasibility study, it is very likely that an acceptable sensor design for a full test bed evaluation could be produced.

17. Key Words (Suggested by Author(s))
Transducer - Flow - Cryogenic
Transducer - Triboelectric Effect
Transducer - Flow Non-intrusive

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price*

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