SQUARE ROOT ERROR AND IMPULSE LINE PULSATION AT CATS. TERMINAL MIDDLESBROUGH, UK

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1. Introduction

The Central Area Transmission System (CATS) is a natural gas gathering system based in the central area of the North Sea. A riser platform and 255 miles of pipeline, including six subsea tie-in points, supplies gas to the Teesside based terminal that is situated on the North East coast of the United Kingdom. BP Amoco operates the system on behalf of CATS co-venturers which consists of the following companies BG International, BP Amoco, Amerada Hess, Phillips, TotalFina, and Agip

Current fields which flow gas through the CATS system include both BP Amoco operated and third party operated fields and are as follows:.

Everest	BP Amoco Operated
Lomond	BP Amoco Operated
J-Block	Phillips Operated
Armada	BG Operated
Erskine	Texaco operated
ETAP	BP Amoco Operated
Banff	Conoco Operated
Andrew	BP Amoco Operated

CATS Pipeline Schematic

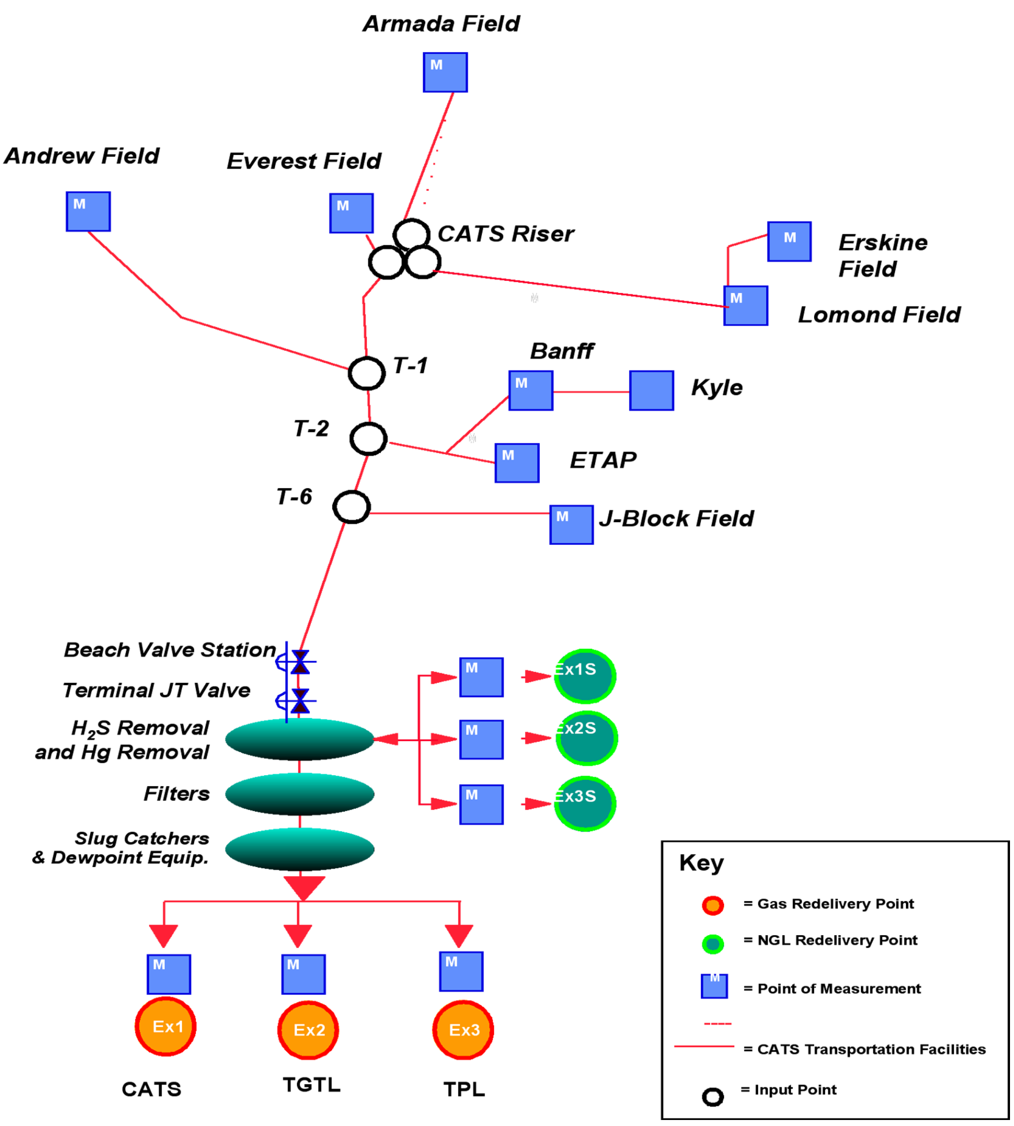


Fig 1

During 1996 the CATS terminal was expanded in order to transport gas from the ETAP, Armada and Erskine fields and redelivery this gas into Transco's National Transmission System (NTS). This expansion included the installation of Hydrogen Sulphide treatment vessels, a new re-delivery metering facility (EX1) for the pipeline, two 600mmsfc/day gas processing trains and an export metering facility (P1NTS) in order to measurement the inputs into the NTS. This expansion took the throughput of the CATS system from 0.65 BCF/day to 1.6 BCF/day

Each of the CATS gas processing trains is a typical fractional unit with depropanisation, debutioniastion and C5+ liquid streams. A schematic for these trains as been provided in Fig 2 After the initial low temperature separation and stabilisation Nuovo Pignone reciprocating compressors are used to compress the stabilised gas off take back up to the required export pressure.

The new EX1 and PINTS metering system were designed in accordance with current established metering standards and comprise of five 16in orifice plate runs for both systems as shown in FIG3. Each metering stream has both upstream and downstream isolation valves and a stream switching value situated downstream of the orifice plate carrier. In operation it is this switching valve which is opened or closed in order to bring the associated stream on or off-line.

The metering header design and pipework immediately upstream from the metering system had been considered, in terms of flow profile and characteristics, in order to deliver the required accuracy and uncertainty performance. However no detailed modelling was deemed necessary in order to ascertain the effects of possible pulsation caused through the configuration of pipework or the reciprocating compressors.

In the final commissioning phase of both EX1 and PINTS, very small fluctuating differential pressure measurements (DP's) were noticed on metering runs that were off-line. Concerns were raised with regard to these low differential pressures and the effect they may be having on flow measurement.

Fluctuating DP's caused by pulsation are know to cause errors associated with the square root error (SRE) of differential transmitters and through this then affect the overall uncertainty of the measurement system. CATS decided that the effect of the above factors needed to be evaluated in order to demonstrate the measurement system met its design parameters.

It is this investigation into the cause of these small DP's that this paper outlines both in terms of the methodology and techniques used to ascertain the possible effect of pulsation on flow measurement with particular reference to (SRE).

The investigation would eventually prove that no effects on the measurement values were being recorded, on any of the measurement systems at the CATS terminal. Both the newly installed skids, being EX1 and P1NTS as well as the original EX2 and EX3 skids were covered by the testing program and shown to be accurate at all rates in accordance with both the standard industry guidance and the CATS Measurement Manual (CMM).

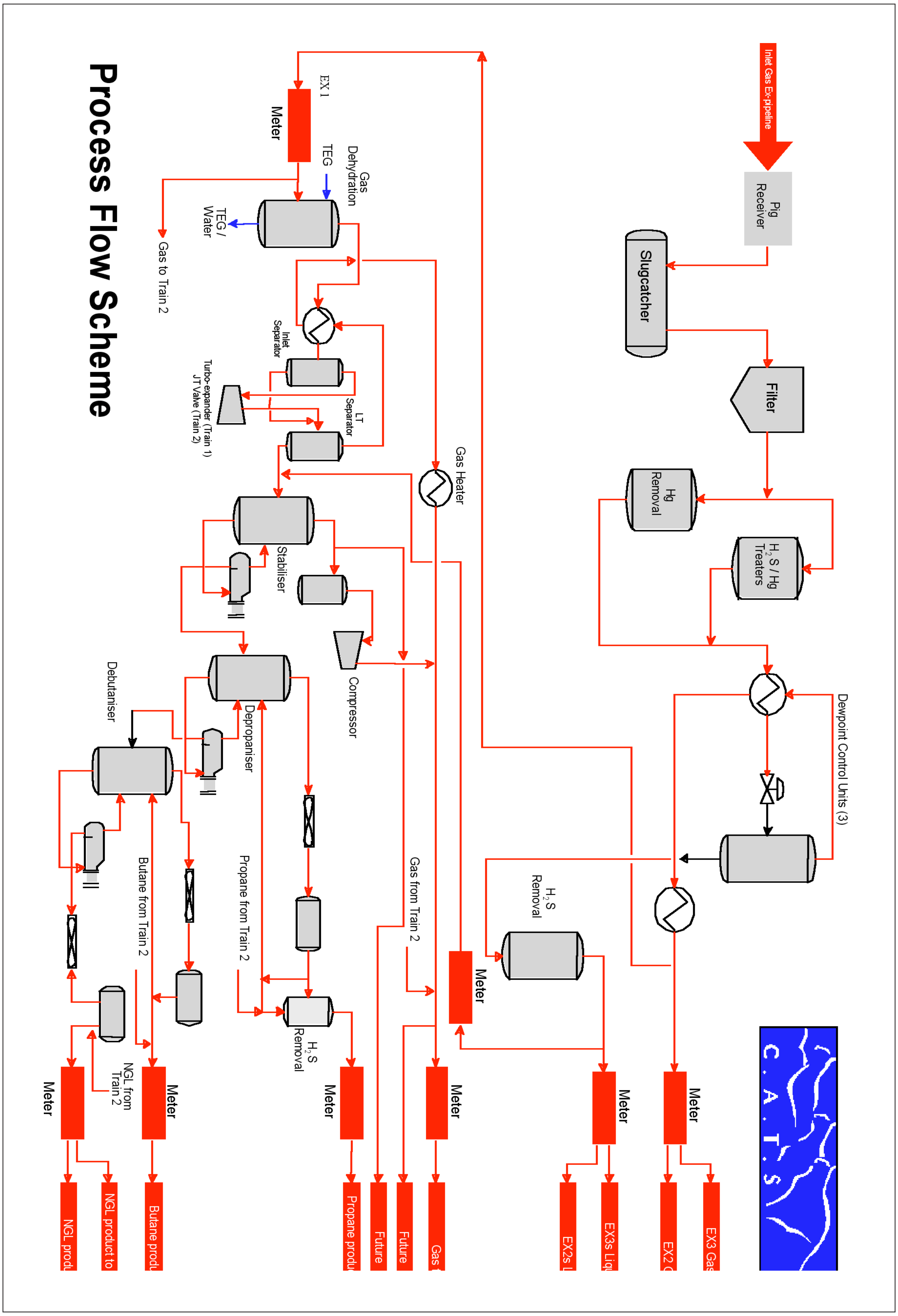
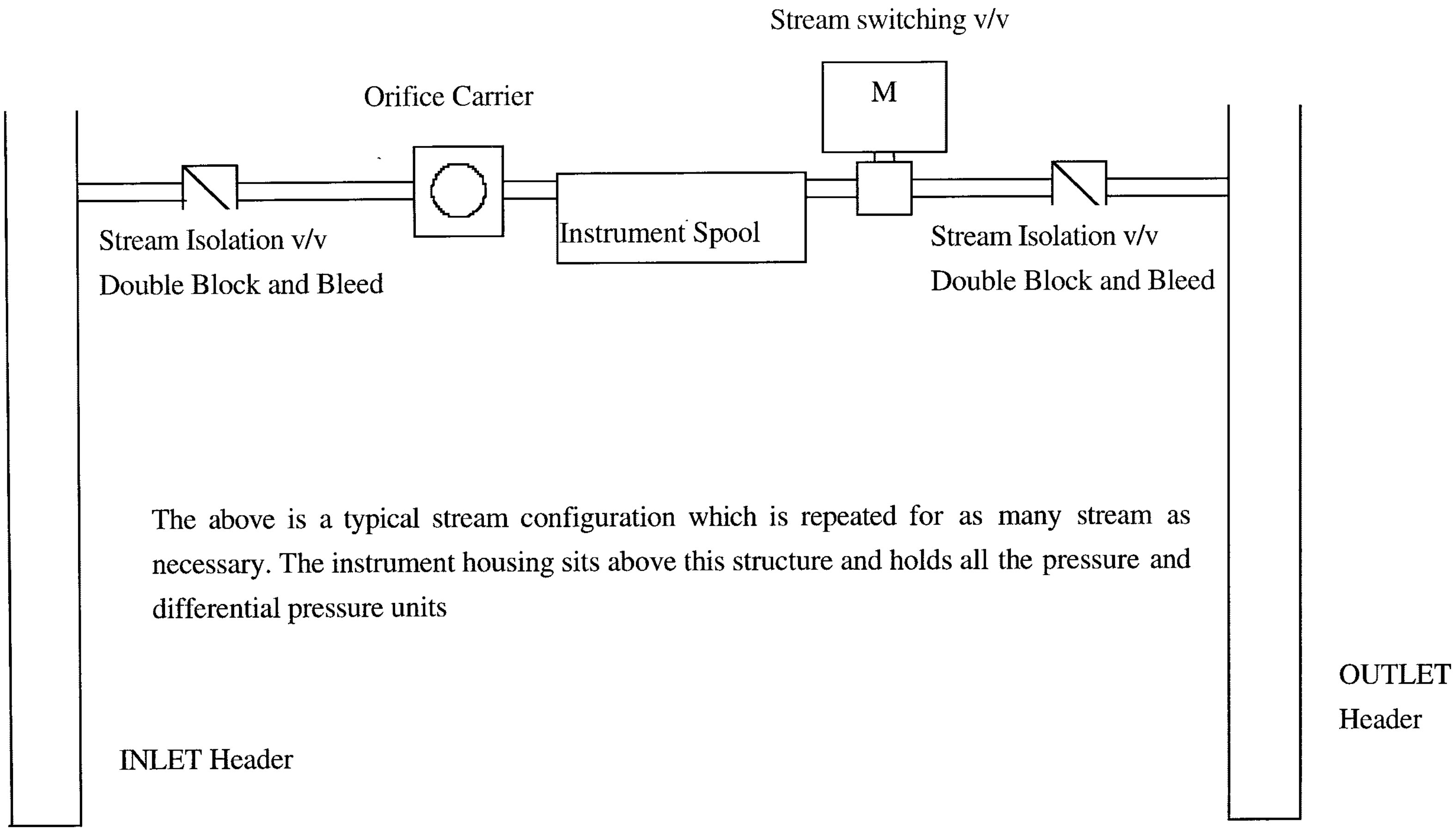

Process Flow Scheme
Inlet Gas Ex-pipeline
Pig Receiver
Slugcatcher
Filter
Hg Removal
H_2S / Hg Treaters
Dewpoint Control Units (3)
H_2S Removal
Meter
Gas Heater
Gas Dehydration
TEG
EX 1
TEG / Water
Gas to Train 2
Inlet Separator
LT Separator
Turbo-expander (Train 1)
JT Valve (Train 2)
Stabiliser
Compressor
Depropaniser
Debutaniser
Gas from Train 2
Propane from Train 2
Butane from Train 2
NGL from Train 2
Future
Future
Gas
C.A.T.S

Fig 2



The above is a typical stream configuration which is repeated for as many stream as necessary. The instrument housing sits above this structure and holds all the pressure and differential pressure units

Fig 2

2. Initial Symptoms

During the early stages of start-up both the EX1 and P1NTS metering systems were flowing at low rates of approx. 70 mmscf/day. At these conditions no symptoms were evident which would suggest possible future measurement problems. However on increasing flow rates fluctuating DP's were observed, in the range of 0.5 to 0.8 KPa, on meter tubes which were selected to standby mode (i.e. the stream switching valve closed, upstream and downstream isolation valves opened).

Initial thoughts were that there was a problem with achieving valve integrity on stream switching valves. Venting the body cavity on the stream switching valves to flare and monitoring for any pressure increase quickly disproved this.

Flowing several periods of monitoring and trending these low DP's against plant operations, thoughts turned to the belief that a possible cause could be pulsation generated by the reciprocating compressors. CATS were aware through Amoco's measurement network that work had been completed in the USA on this issue and decided to ask for assistance from the measurement network. From these discussions concerns were raised with reference to the level of Square Root Error (SRE). It was important to prove that any such error induced into the SRE caused by any pulsation was below the 0.5 limit set out in the CMM, with reference to the potential affect on the performance of measurement systems at the CATS Terminal.

In conclusion to the above observations and discussions it was decided that three elements would require to be determined, pulsation, the differential pressure readings observed on the closed in meter tubes and ultimately the effect on the SRE.

At this point CATS requested the mechanical and fluids engineering division of Southwest Research Institute (SwRI) to investigate pulsation effects and fluctuating differential pressure readings on off line meter tubes.

3. Procedure

Detailed tests were conducted on the first three streams of the CATS plant sales gas meters, P1NTS, and the pipeline redelivery meters, EX1. The remaining streams were not commissioned at the time of the tests due to the low throughput requirement of the system and consequently they did not form part of the testing program

The original re-delivery meters were also tested although no symptoms of the fluctuating differential pressure readings seen on EX1 and P1NTS had been observed at these stations.

The purpose of the tests was to evaluate whether the DP's seen at the measurement stations were a direct result of pulsation effects and attempt to locate the source of any such pulsation. In order to achieve this accurate measurement of the fluctuating DP's would be required. The frequency and amplitude of pulsation in the meter runs and the instrumentation impulse lines were also evaluated in order that the full effect on SRE could be determined.

A total of 16 tests were performed in the field investigation and the test configurations are outlined in Appendix 1 Table of Results.

The investigation was conducted by obtaining two types of measurements: differential pressure and pulsation (dynamic pressure). Two differential pressure measurements were made one with the measurement units mounted as close to the orifice as practical and then secondly at the far end of the instrument impulse lines. The first measurements allowing the SRE level to be determined from the dynamic variations (fluctuations) close to the orifice fitting. The dynamic amplification and distortion of the orifice signal, caused by the impulse line length and configuration, were then determined from the second measurements taken at the location of the system DP transmitters.

Pulsation data was collected using high frequency piezoelectric dynamic pressure transducers. These were connected to pressure tappings in the meter tube piping in a few cases and on the ends of the impulse lines during other tests. The pulsation measurements provide additional information about the conditions at the end of the impulse lines and are used to confirm the differential pressure measurements.

A number of the tests were designed specifically to prove or disprove particular aspects of the pulsation behaviour.

Test 1	Base line readings taken for each stream.
Test 2	The meter tube on which differential pressure was being measured was shut down to determine the effect of eliminating flow on the differential pulsation.
Test 3	Base line readings taken for the next set of tests.
Test 4	The flow rate on the meters being tested was reduced by opening the previously shut off stream. The impulse line pulsation on the shut off run increased when the upstream manual valve was opened prior to the downstream automatic valve being opened.
Test 5	Base line readings taken for the next set of tests.
Test 6	A different meter run was shut off to confirm the effect of eliminating the flow rate on pulsation.
Tests 7-10	Conducted at the higher pressure inlet gas, EX1, meters.
Test 9	Flow rate in the monitored stream was increased, by closing the valves on one of the other steams.
Test 10	The previously closed meter run was opened and the monitored stream was closed and data was measured with no flow.
Test 11	A brief test conducted on two of the impulse lines on the EX2/3 meters and no changes in operating conditions were made.
Tests 12-16	Conducted on NTS Sales Gas Meters to determine the effect of the over head (OH) compressors and other changes. During the first 4 of these tests, 12 through 15, the flow was through meter runs 1 and 2 only. During Test 13 the OH compressors were shut off and it was determined that the low level, approximately 6 Hertz (Hz) pulsation was present even when the compressors were not operating. Tests 14 and 15 involved an exchange of transducer locations to measure any impulse line shift or change in the average differential pressure. During the final test, No. 16, the third meter run was opened to flow to confirm the effect of reducing flow rate in the monitored stream.

4. Results

Square Root Error Results

Unfiltered SRE levels are the worst case scenario and often include pulsation frequency peaks. These were seen at the orifice, however, with the filtering mechanisms used both by the transmitters and flow computers these are not included in the actual SRE value recorded. The unfiltered SRE levels measured at orifices during each of the tests are shown in the Appendix 1 Table of Results.

Inappropriate pulsation peaks can be identified on a case by case basis and filtered where the difference is important. For example, as the meter run was being shut down during Test 2, an SRE of 1.05 percent was recorded. However, because of a local impulse line frequency, this unfiltered SRE is larger than the filtered or corrected SRE for Test 2, which was 0.26 percent. SRE levels are larger at low flow rates when the average differential pressure is low. The largest SRE seen during Test 2 occurred when the differential pressure was 10 KPa. The NTS meters at CATS are not operated at differential pressures below this level. At a normal flow rate of 25 KPa, the corresponding SRE would be approximately 0.25 percent unfiltered and less than 0.1 percent if properly filtered.

SRE levels at the NTS Sales Gas Meters and the other meters tested are also reported in Appendix 1 Table of Results. They are approximately 0.25 percent or less when filtered. At normal flow rates that result in differential pressures of 12.5 KPa or more, the worse case SRE is expected to be less than 0.25 percent in all cases and significantly less under most standard operating conditions.

Pulsation Frequency and Amplitude Results

In addition to the square root error levels, differential pressure amplitude and dynamic pressure data were recorded during each test to determine the frequencies and amplitude of the pulsation within the meter runs and the impulse lines. The significant pulsation frequency and amplitudes are presented in Appendix 1 Table of Results for each test. In addition a sample of frequency spectrum sheets for Tests 1 through 16 are presented in Appendix 2.

As shown in the results table, when differential pressure was measured close to the orifice, there was typically a low level pulsation of 1 KPa at a frequency of 6 to 9Hz with frequencies of 6.5 to 7.0 Hz being the most common centre frequency (see Tests 1 through 4). The orifice differential pressures close to the meter also contained larger amplitude, higher frequency component around 69 to 70 Hz. The amplitude of this differential pulsation ranged from 1KPa to over 15 KPa. The differential pulsation near the orifice also contained intermediate frequencies, such as 42 and 56Hz, at lower amplitudes, as shown in the Appendix 1 Table of Results.

The source of the 6 to 7 Hz pulsation’s were found to be in the meter run piping but at a low level less than 1.5 KPa, as shown by several measurements. The amplitude of the low frequency pulsation in the meter run piping and in the impulse line close to the orifice are essentially the same, less than1 KPa.

On the other hand, the amplitude of the 6 to 7Hz differential pressure measured at the transmitter end of the impulse lines is much larger, and ranged from 1 KPa to 20 KPa. The reason for the increase in amplitude of this low frequency pulsation is the fact that the impulse lines have an acoustic resonance at or near this approximate 7 Hz excitation. The resonance of the impulse line is produced by the tubing stub length, which connects the transmitters to the orifice. The source of the pulsation excitation is external to the impulse lines and is thought to be from some small disturbance in the gas plant piping.
The amplitude of the low frequency (approximately 6 to 7 Hz) pulsation at the transmitters is the cause of the fluctuating differential pressure readings in the metering system flow computer. From these measurements assurance was drawn that there was no dynamic variation in flow rate or a significant measurement error, which corresponds to the observed variation in differential pressure.

Early in the testing, the source of the low level 6 to 7 Hz excitations was thought to be the OH compressors, which have a fundamental operating speed of 6.67 Hz (400rpm). This was disproved with respect to both the variations in the observed frequency up to 9.0 Hz, and the results obtained from test 13. During test 13 the OH compressors were shut off for a short period however the 6 to 7 Hz pulsation remained in the meter run piping this demonstrates that the compressors were not the source of the low frequency pulsation.

The source of this pulsation is thought most likely to be from some form of vortex shedding or Strouhal frequency at a piping branch, pressure vessel entrance or others obstacles within the piping configuration of the plant. Although an effort was made to find the exact source of this pulsation, it was not located. It was demonstrated that the 6 to 7Hz excitations are produced upstream of the NTS meter runs by stopping flow in the meter run, this was achieved by alternately closing the downstream & upstream valves. The 6 to 7Hz pulsation's remained in the piping and impulse lines with the downstream value closed but when the upstream value was closed the impulse line resonance disappeared. Because of the low level of this excitation, locating the source would most likely be of little value, as it would not be easy to filter or to eliminate at source.

The cause of the higher frequency pulsation, typically 69 to 70 Hz, seen in the differential pressure measurements close to the orifice, was also demonstrated to be an acoustic resonance. Because the dynamic differential pressure transducer could not be placed directly at the orifice, connection was made via a small length of impulse line between the orifice meter pipe wall and the transducer. The acoustic resonance of the length of piping used with high pressure gas is approximately 70 Hz. Therefore it was deduced that this frequency is a resultant of the measurements made and not a component in the meter run piping or at the end of the impulse lines where the transmitters are located.
Differential and piping pulsation were measured on Stream 3 at the EX1 inlet gas meters during Tests 7 through 10. The results here were similar to the results at the NTS meters. The low frequency 7 to 9 Hz pulsation was observed at a large amplitude at the transmitter end of the impulse line, and the 6 to 7 Hz excitation frequency was observed at a low level of approximately 0.7 KPa in the meter run piping. The higher frequency pulsation in the d ifferential pressure measurements close to the orifice were somewhat different and show intermediate frequencies, such as 42Hz, as well as the 69 to 70Hz, at lower amplitudes. These differences are most likely due to the difference in the speed of sound and the operating conditions for the higher pressure inlet gas.

5. Conclusions

The following conclusions are based on the results of the data observed and recorded at the CATS terminal and the subsequent analysis of acoustic responses of the orifice impulse lines

1. Unfiltered SRE levels gave the worst case values and often included pulsation frequency peaks. These do not effect the measurement transmitter, and therefore, should not be included in the actual SRE value

2. Low amplitudes pulsation is present at the P1NTS and the EX1 orifice meters and causes Square Root Errors of 0.25 percent or less in all normal flow conditions. The contractual limit for SRE as specified in the CATS Transport Allocation Agreement is 0.5%.

3. Flow rates that result in differential pressures of less than 10 KPa cause an increased SRE.

4. The differential pressures as measured contain a low amplitude pulsation of approx. 0.7 KPa at 6 to 7Hz and a higher amplitude of pulsation at a higher frequency around 69 to 70 Hz.

5. The cause of the high frequency pulsation 69 to 70 Hz is an acoustic resonance within the temporary connection line used.

6. Tests demonstrate that the reciprocating compressors at the CATS terminal are not the source of the low frequency pulsation.

7. Sources of excitation energy, such as turbulent flow, control valves and vortex shedding, piping configuration are attributed as the cause of the pulsation levels.
8. Differing levels of low amplitude pulsation can be observed across each of the meter tubes when in standby mode

9. The values of differential pressure used by the stream flow computers are subject in the first instance to a sampling/damping rate of 0.5 seconds by the DP transmitters. The flow computers with cycle times of approximately 3 seconds then average this signal hence the unfiltered SRE seen at the orifice do not affect the actual measurements taken at the DP Transmitters

10. Data from the tests prove that SRE at all of the orifice meters at CATS are low and for all normal operating conditions can be ignored.

11. The effects of pulsation at the EX1 meters are similar to the NTS results in terms of low levels in the meter run piping and significant amplification in the impulse lines.

12. No indication of pulsation induced error could be seen on the original Ex2 / Ex3 skids

6. Follow up Actions and Recommendations

1. Metering stations should incorporate automatic stream switching configured to maintain differential pressures above a value determined from analysis, thus would reducing SRE to a minimum level. This is a standard feature of the CATS measurement systems, station average DP's are used in conjunction with switching limits of 12.5 to 15 KPa causing meter tubes to close down before SRE levels becomes noticeable.

2. The operator should have the function to select the order of meter tube operation. This can be used to ensure the optimum use of the facility in terms of preferentially selecting the tubes least affected by pulsation. This is a standard feature of the CATS metering measurement systems.

3. Impulse lines should be kept to the minimum practicable length and if possible close coupled to the orifice boxes. It is recognised that close coupling raises differing problems with reference to calibration facilities. The CATS preferred design is for the instrument house to be placed across the meter tubes in order to provide high static calibration facility inside a temperature controlled environment. Within this enclosure impulse lines are kept to the minimum practical length.

4. A facility to obtain both dynamic pressure (pulsation) measurements and SRE effects on differential pressures should be included in the design and fabrication of the metering system. The CATS CMM lays out this requirement for all the measurement systems used within the CATS system. It does not however stipulate that measurements be taken to prove SRE levels

5. A review of possible pulsation effects on metering stations should be carried out as soon as operational constraints allow. Thus allowing the operator to obtain an understanding of each meter tubes flow characteristic and achieve optimum performance.

6. Design consideration should be given to possible pulsation issues when orifice meters are to be used in a fiscal application. Consideration should be given to the piping configuration used, in an attempt to remove or reduce areas that give raise to vortex shedding, failing this thought could be given to some form of acoustic damping.

Appendix 1

Test No.	Location	Meter Tubes Exporting	Data Type	Frequency (Hz)	SRE Unfiltered (%)	Amplitude (KPa)
1	NTS-1 Orifice	1,2 & 3	Differential	6.0 to 7.0	0.15	0.62 to 1.2
				69 to 70		3.5 to 5.2
2	NTS-1 Orifice	2 & 3	Differential	6.0 to 7.0	1.05(filtered 0.26)	0.5 to 1.1
				57 to 72.5		0.2 to 3.7
3	NTS-3 Orifice	2 & 3	Differential	6.0 to 7.0	0.15	0.5 to 1.0
				65 to 67		8.5 to 10.0
4	NTS-3 Orifice	1,2 & 3	Differential	6.0 to 7.0	0.68 (filtered 0.01)	0.5 to 1.2
				65 to 67		3.2 to 16
	NTS-1 Impulse Line		Differential	6.0 to 6.5		6.0 to 22
	NTS-1 Upstream.		Pulsation	6.1 to 7.0		0.28 to 1.4
	NTS-1 Downstream		Pulsation	14		0.97

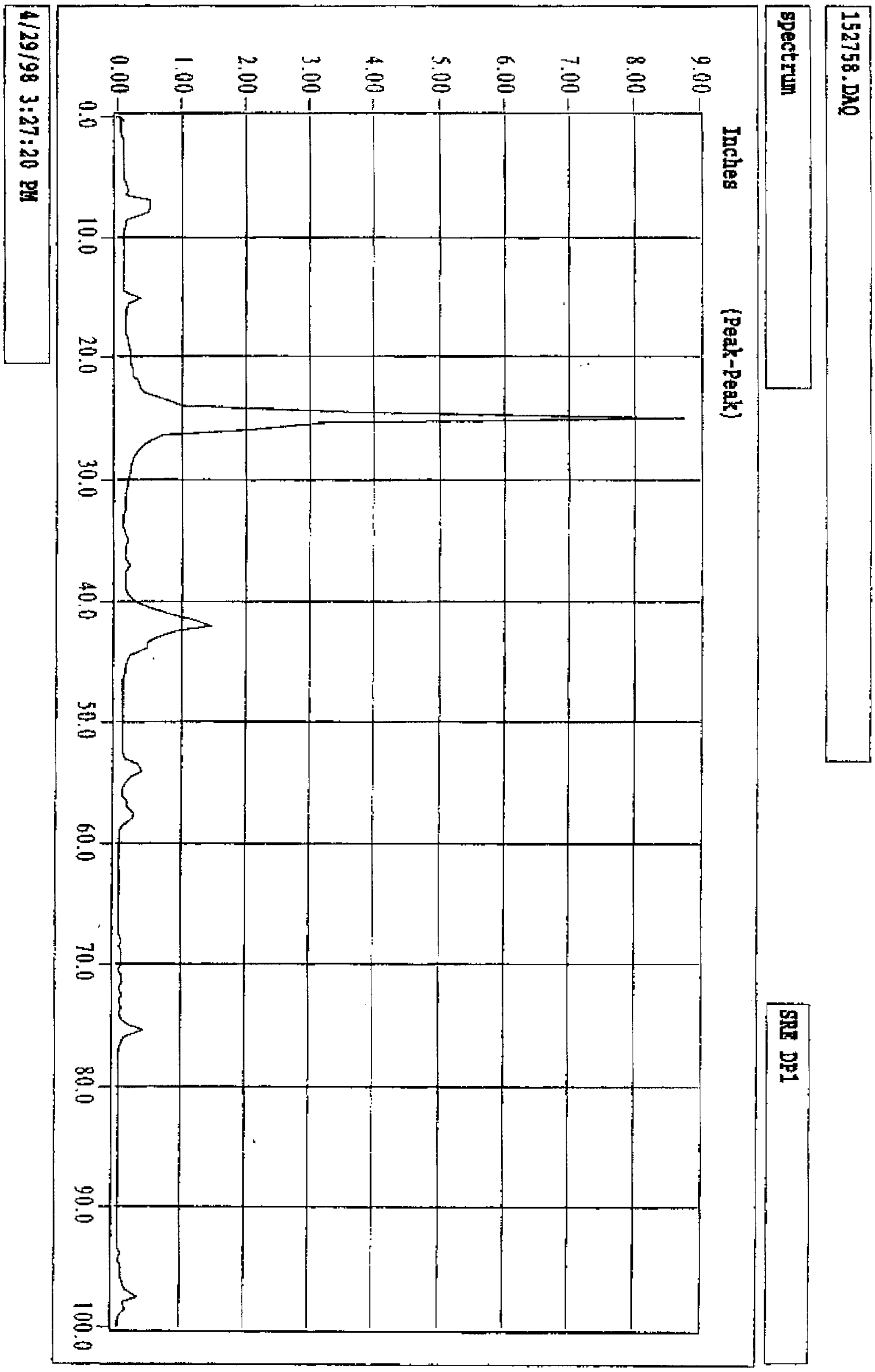
5	NTS-3 Orifice	1,2 & 3	Differential	67	0.44(filtered 0.01)	8.5
	NTS-2 Impulse line		Differential	7.0		to 10.5
	NTS-1 Upstream.		Pulsation	7.0		to 0.7
	NTS-1 Downstream		Pulsation	7.0		0.55 to 1.17
6	NTS-3 Orifice	1,2 & 3	Differential	to 7.5	0.22	0.06 to 1.2
				67		to 4.4
	NTS-3 Impulse Line		Differential	7.0		1.4 to 4.4
7	EX1-3 Impulse Line	1&2	Differential	7.0 to 9.0	---	0.7 to 5.0
8	EX1-3 Orifice	1,2 & 3	Differential	42	0.01	to 0.5
	EX1-3 Impulse Line		Differential	to 8.5		to 3.5

9	EX1-3 Orifice EX1-3 Impulse Line EX1-3 Upstream. EX1-3 Downstream	2 & 3	Differential Differential Pulsation Pulsation	42 to 9.5 to 7.0 6.0 to 7.0	0.01	to 0.7 to 11.2 0.7 0.7 to 1.4
10	EX1-3 Orifice (with/Flow) EX1-3Orifice (without Flow) EX1-3 Impulse Line (with Flow) EX1-3 Impulse Line (without Flow) EX1-3 Upstream. EX1-3 Downstream	1 & 2	Differential . Differenti al . . Pulsation Pulsation	25,42,55 . 25,42,55 . 7,5,25 . 7.5,25 . 5,15,25 11	---	to 2.2 . to 0.2 . 3.0 to 5.2 . . 0.7 0.7 to 1.4

11	EX2/3-1 Impulse Line	1,2 & 3	Differential	11 to 12.5	---	to 4.7
	EX2/3-2 Impulse Line		Differential	11 to 12.5		0.7 to 1.1
12	NTS- 1 Orifice	1 & 2	Differential	69 to 70	0.01	to 2.2
	NTS-1 Impulse Line		Differential	6.0 to 6.5		2.7 to 13.2
13	NTS- 1 Orifice	1 & 2	Differential	69 to 70	0.02	to 2.0
	NTS-1 Impulse Line		Differential	6.0		to 15
	NTS-3 Impulse Line HP		Pulsation	to 7.0		to 6.9
	NTS-3 Impulse Line LP		Pulsation	7.0		t 6.2
	NTS-1 Upstream		Pulsation	6.0 to 7.0		0.3 to 0.7
14	NTS- 1 Orifice	1 & 2	Differential	69 t 71.5	0.01	to 1.9
	NTS-1 Impulse Line		Differential	to 6.5		to 16.2
	NTS-3 Impulse Line HP		Pulsation	6.0to 7.0		to 6.2
	NTS-3 Impulse Line LP		Pulsation	to 7.0		to 11.7
	NTS-1 Upstream		Pulsation	6.0 to 7.0		0.3 to 1.0

15	NTS- 1 Impulse Line	1 & 2	Differential	to 6.5	0.02	to 17.4
	NTS-1 Orifice		Differential	to 71.5		to 3.2
	NTS-3 Impulse Line HP		Pulsation	6.5		to 8.3
	NTS-3 Impulse Line LP		Pulsation	to 7.5		to 7.6
	NTS-1 Upstream		Pulsation	6.0 to 7.5		0.3 to 0.7
16	NTS- 1 Impulse Line	1 & 2	Differential	6.0	0.07	to 12.4
	NTS-1 Orifice		Differential	69 to 69.5		to 2.2
	NTS-3 Impulse Line HP		Pulsation	7.0		to 9.0
	NTS-3 Impulse Line LP		Pulsation	to 7.5		4.1 to 15.9
	NTS-1 Upstream		Pulsation	6.0 to 7.0		0.3 to 0.7

Appendix 2



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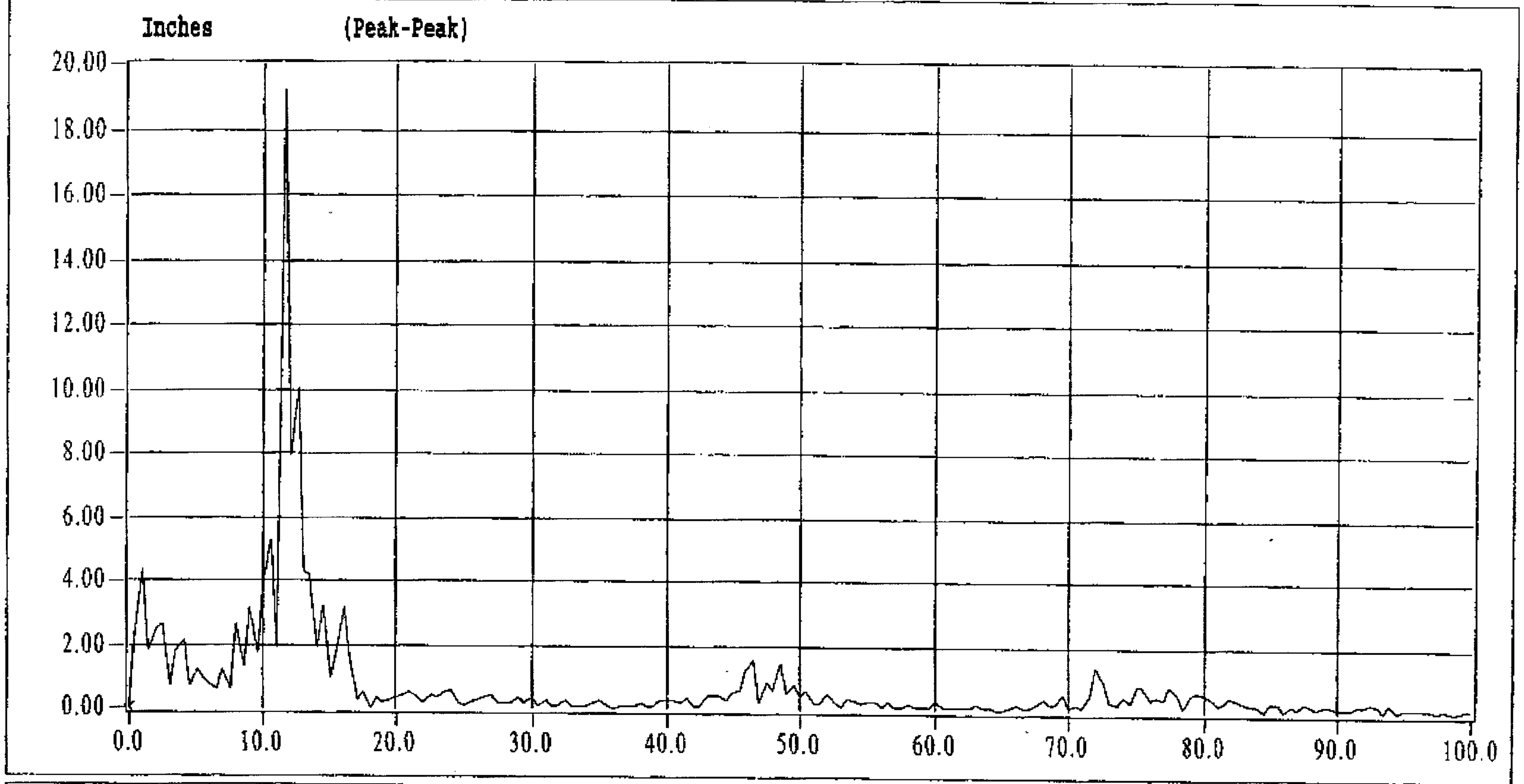

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test 11

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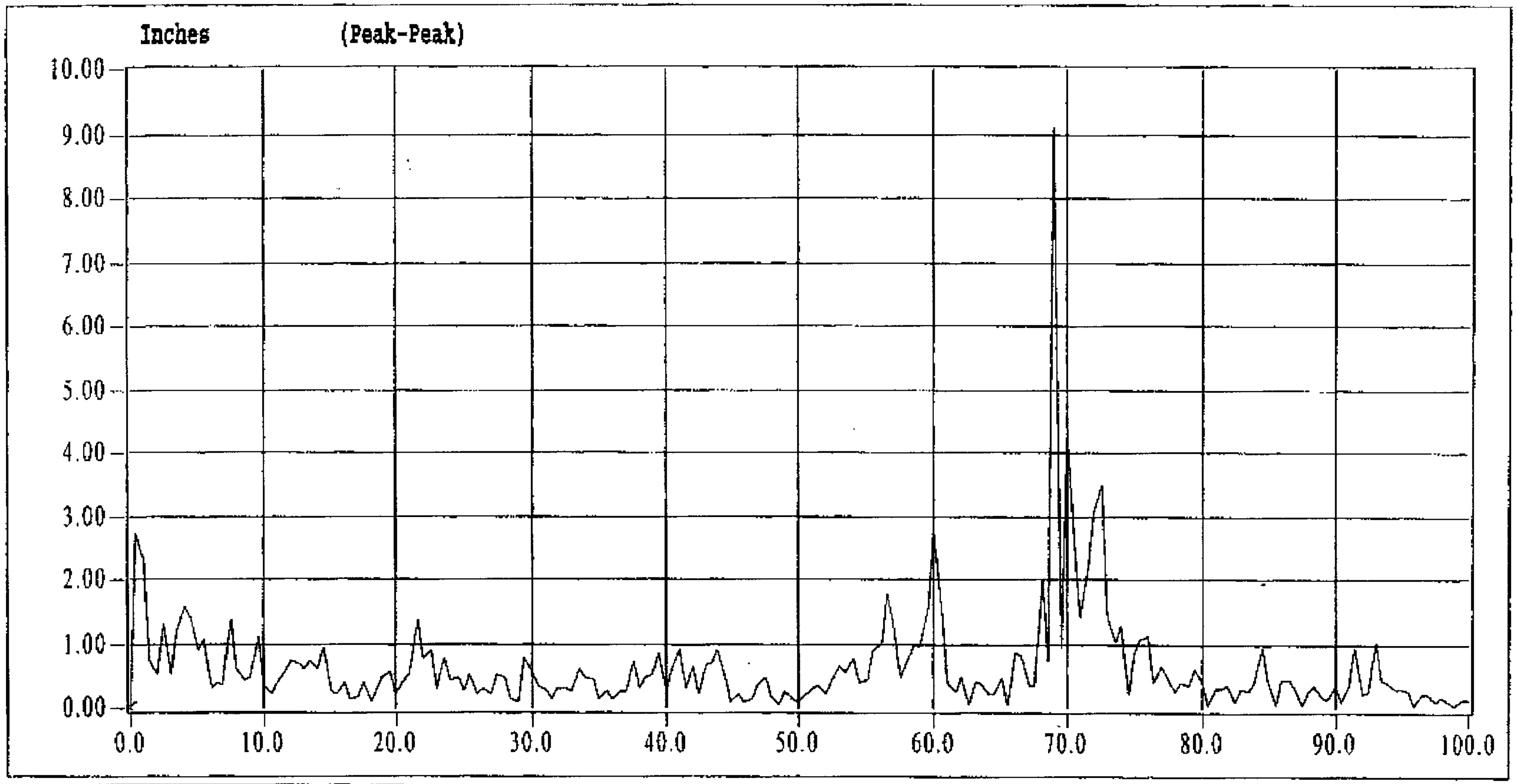

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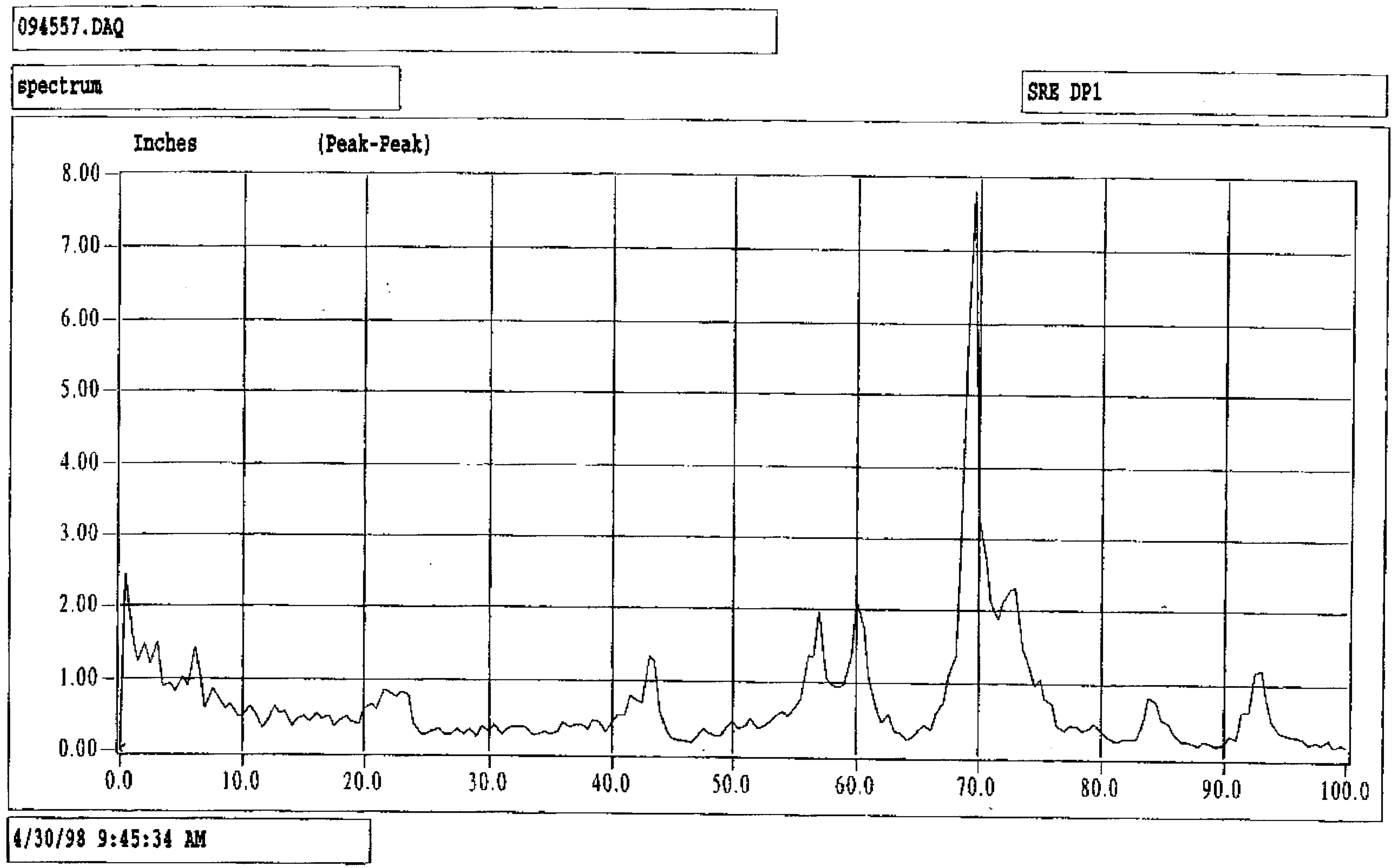
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spectrum
SRE DP1
Inches
(Peak-Peak)
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5.00
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1.00
0.00
0.0
10.0
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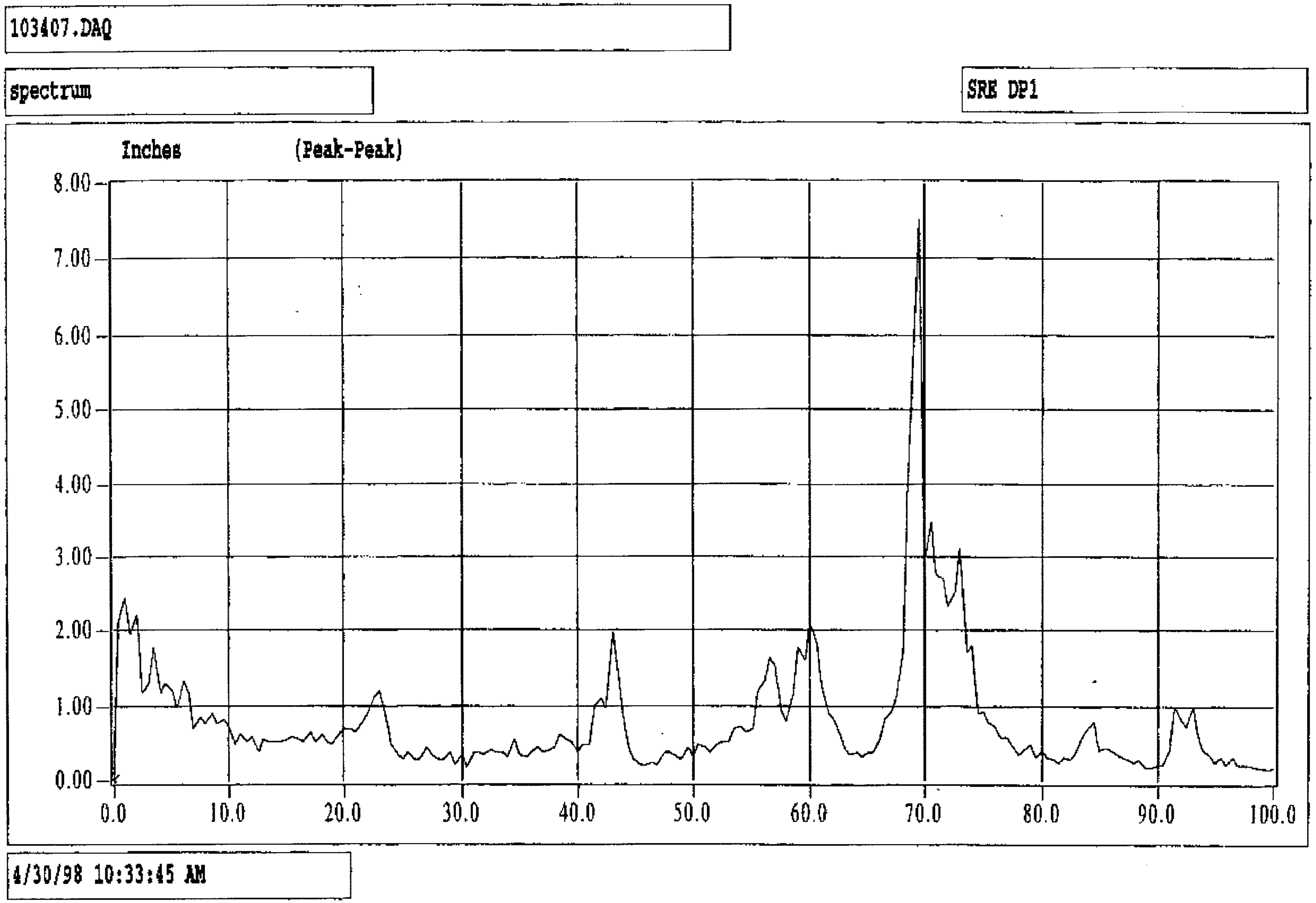

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SRE DP1
Inches
(Peak-Peak)
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7.00
6.00
5.00
4.00
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1.00
0.00
0.0
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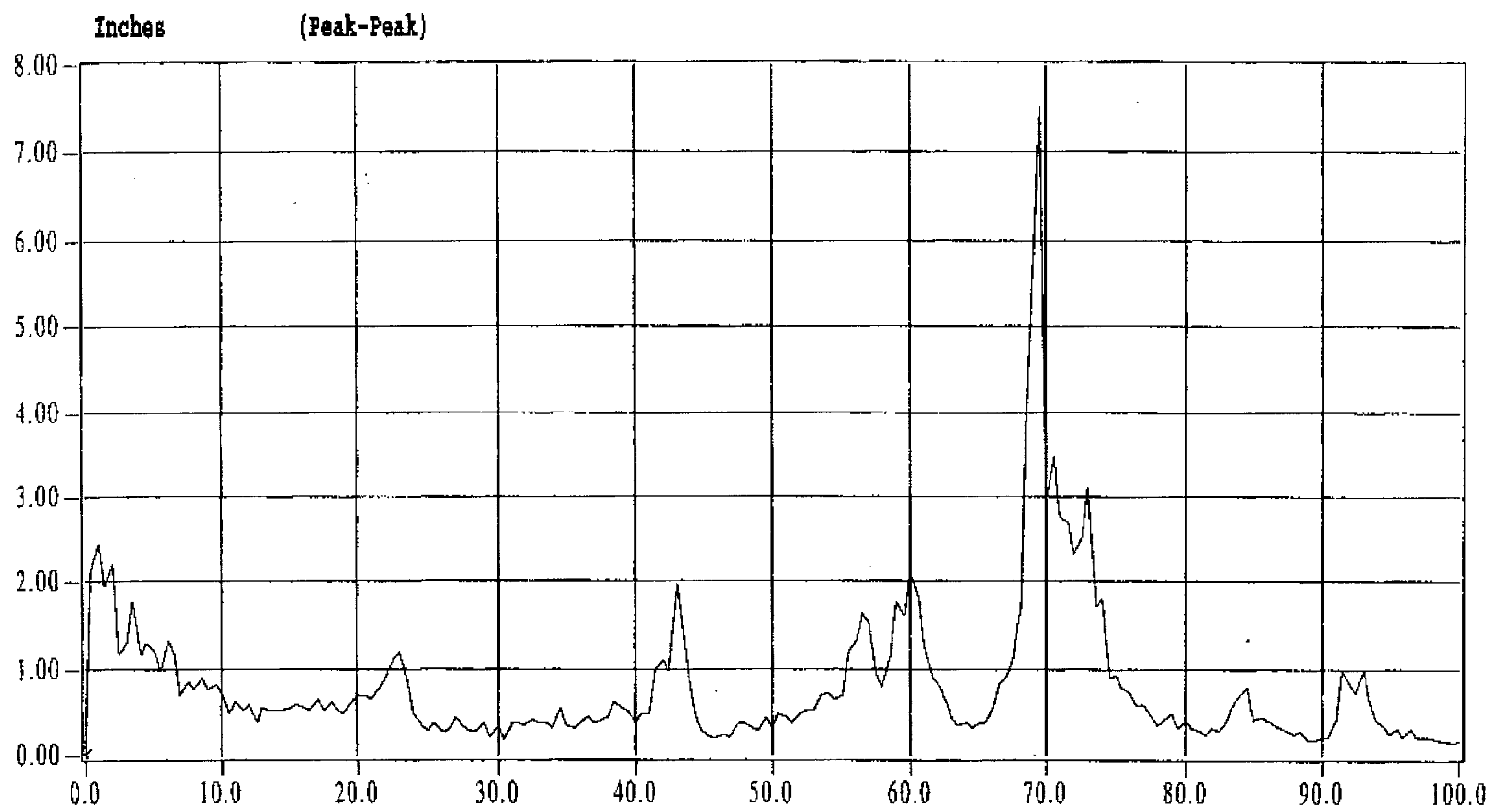

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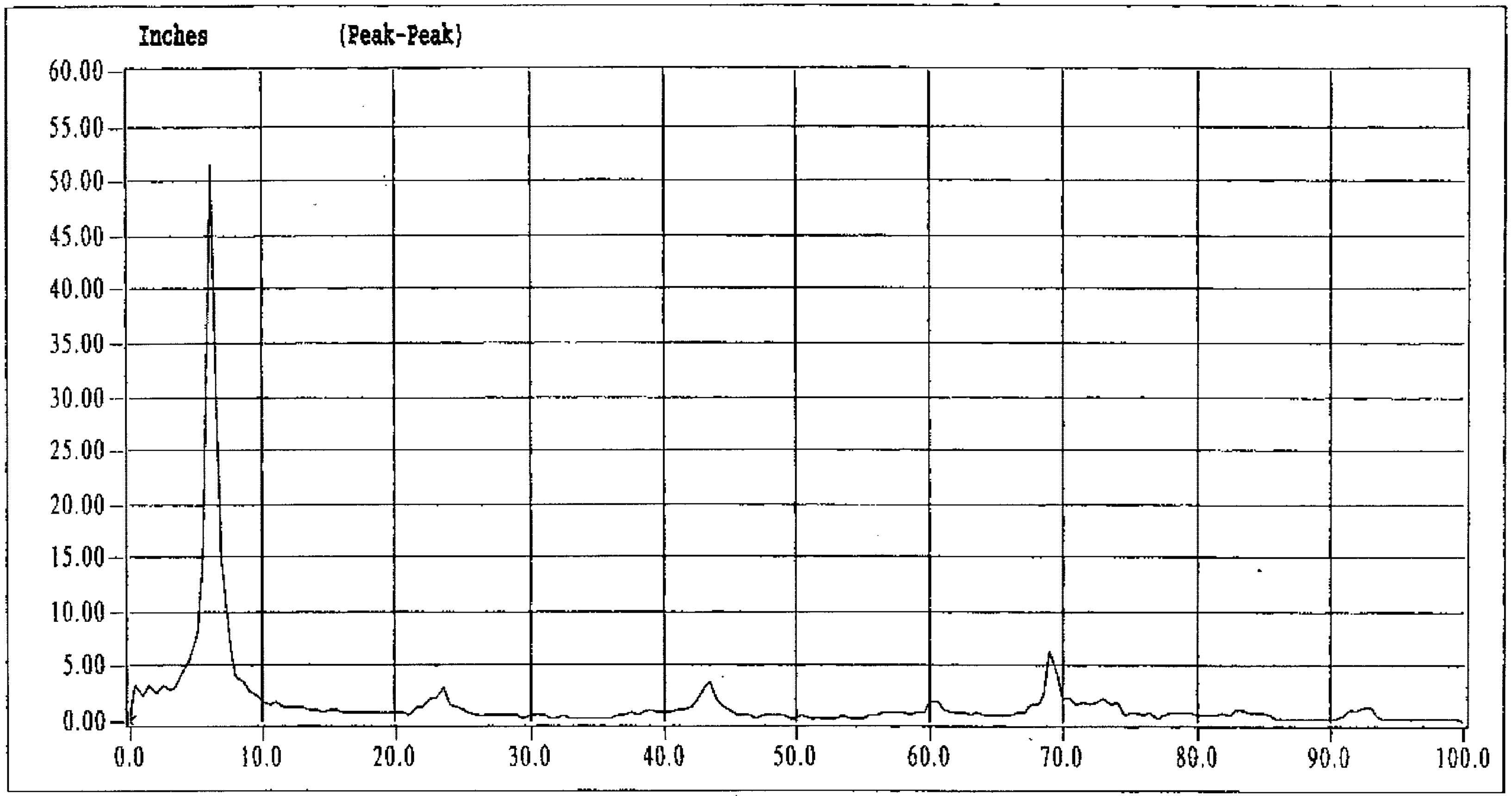

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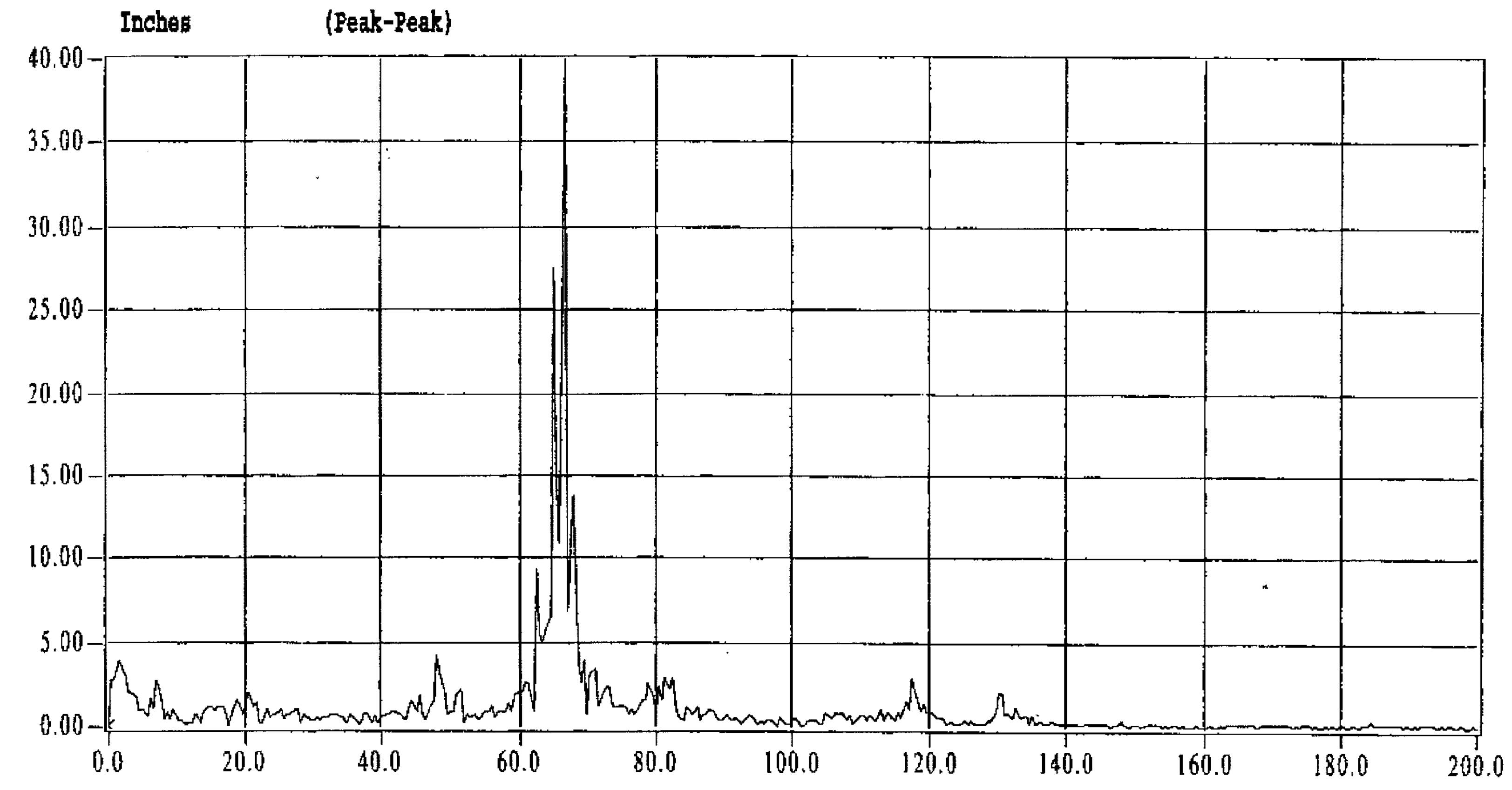

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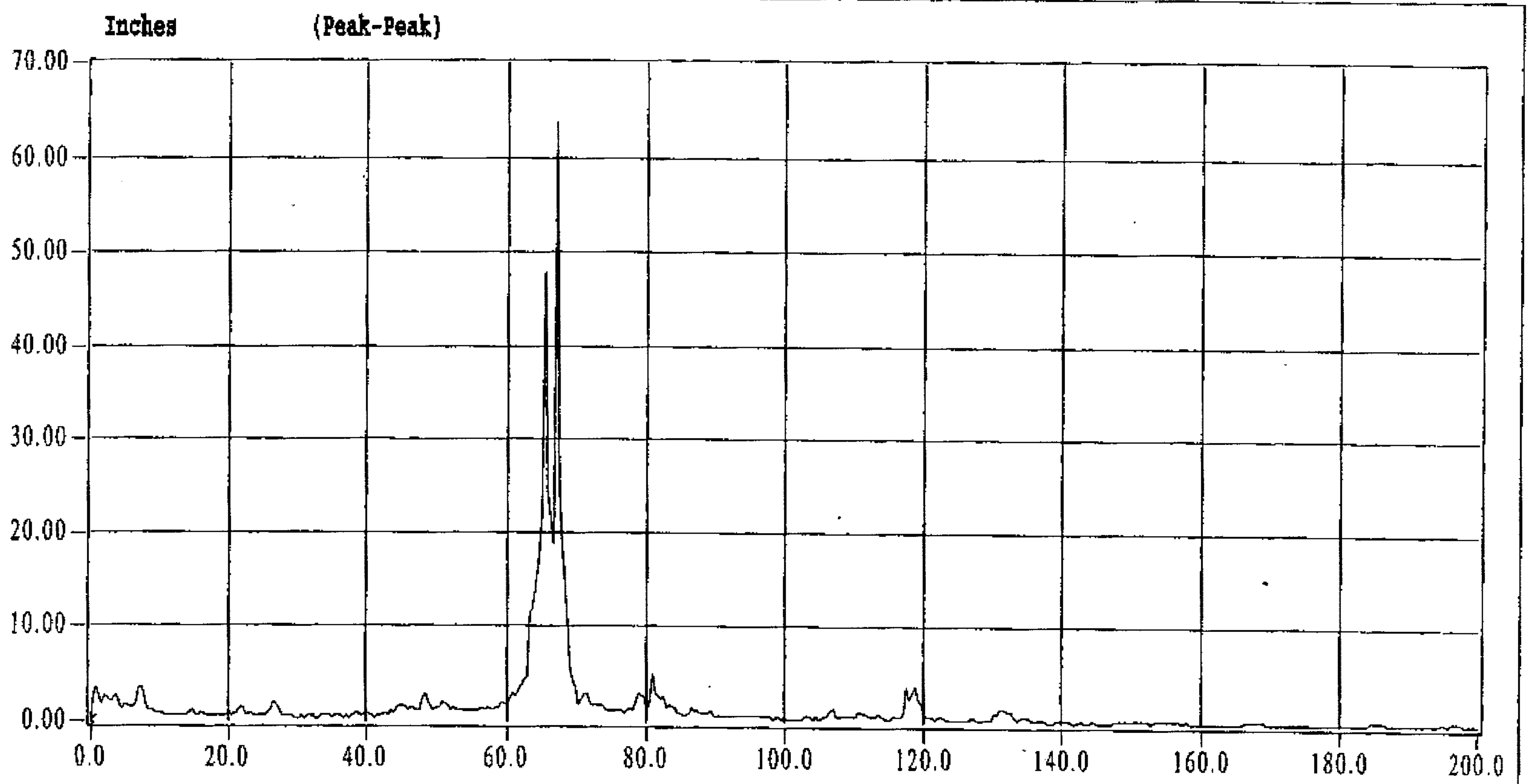
PK spectrum

SRE DP1



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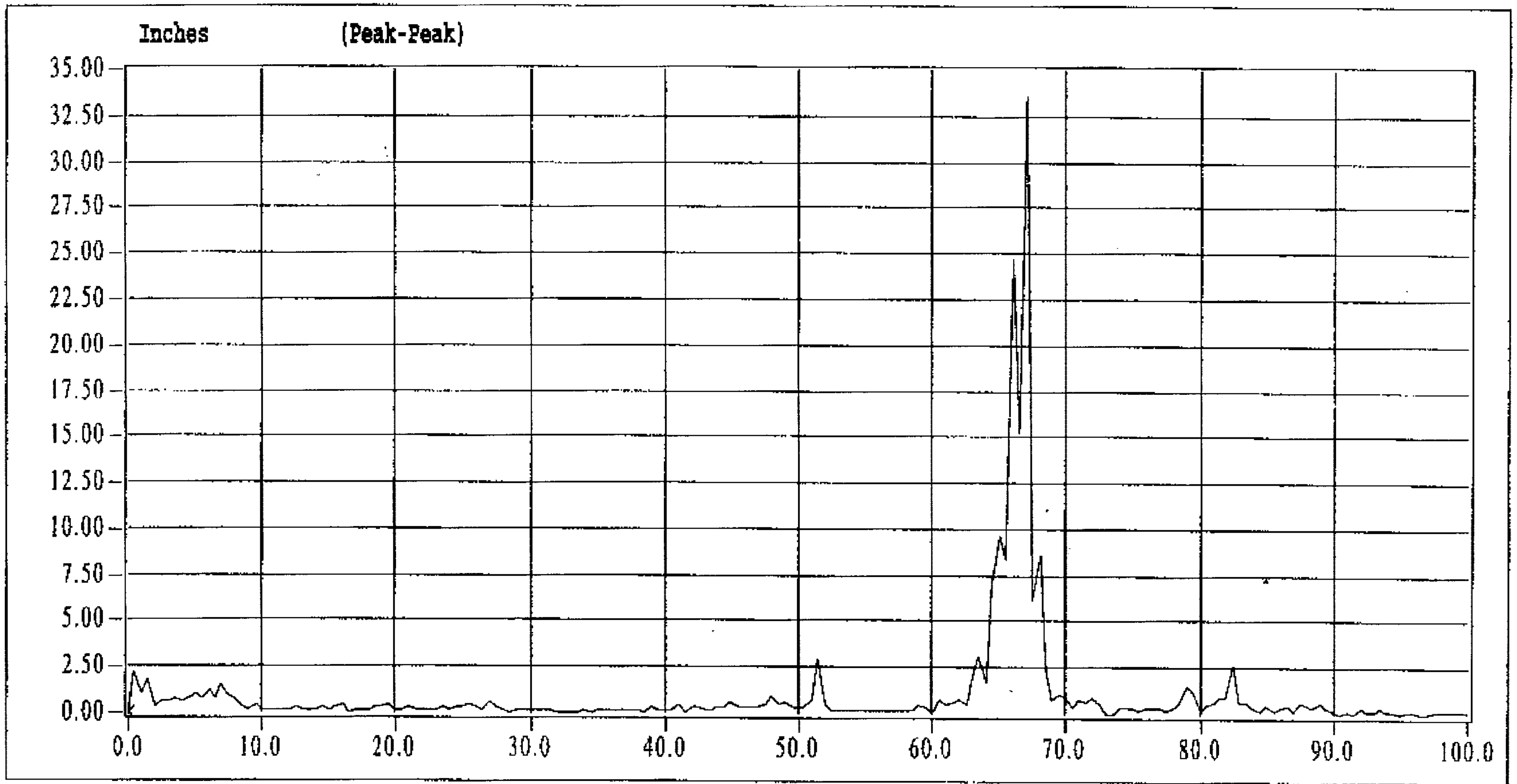
spectrum

SRE DP1



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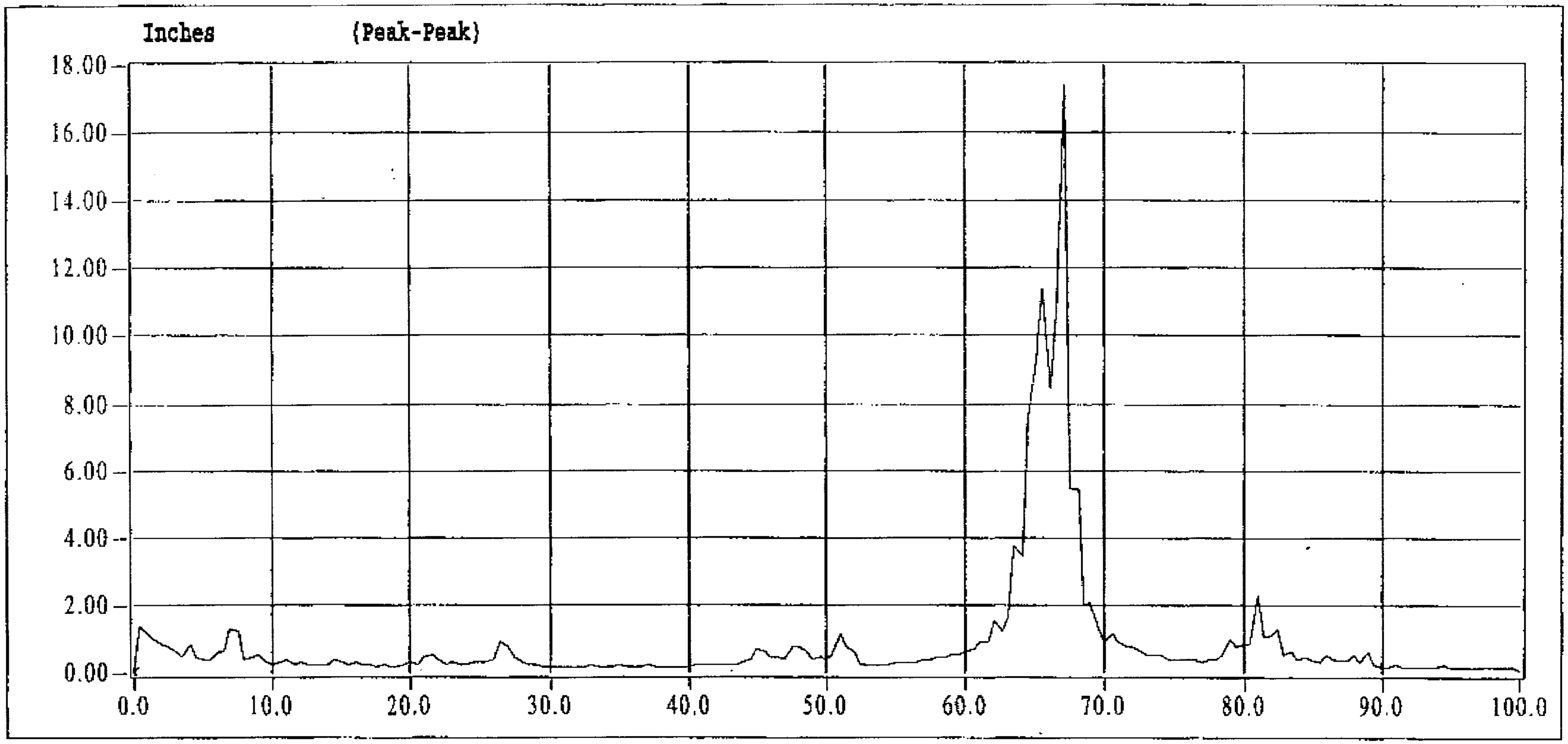
test5

192324.DAQ

spectrum

SRE DP1



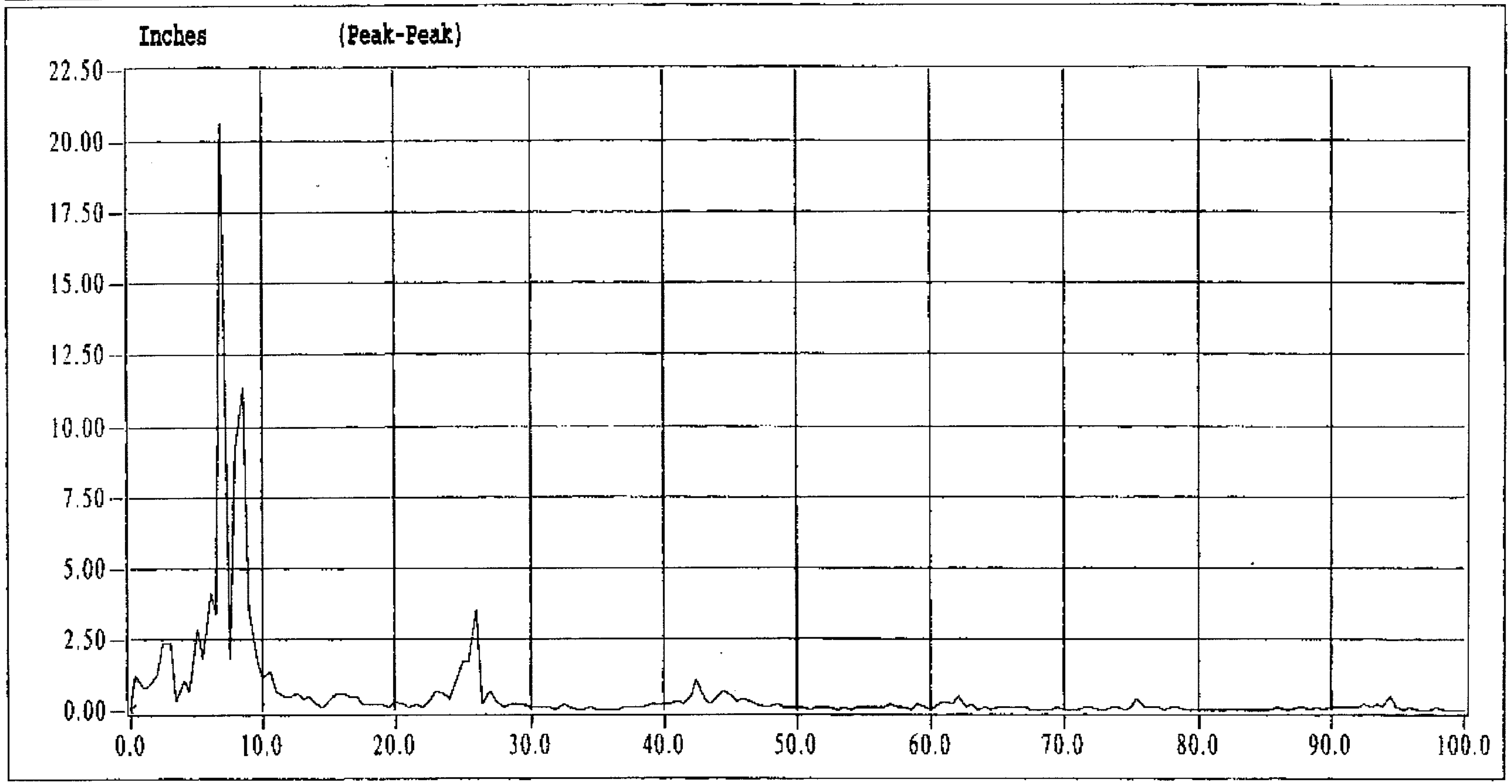
4/28/98 7:23:18 PM

test6

111714.DAQ

spectrum

SRE DP2



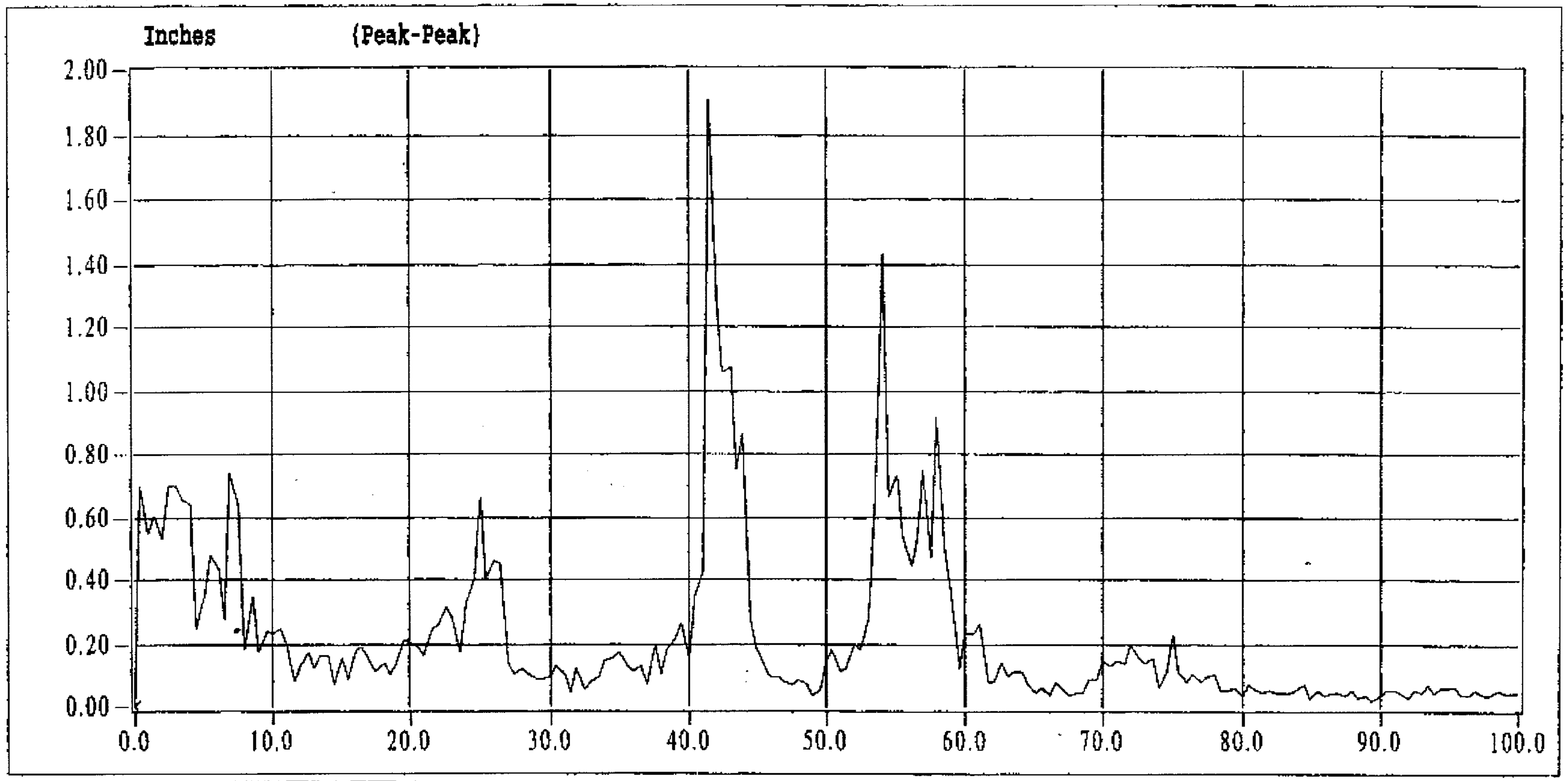
4/29/98 11:16:04 AM

test7

140817.DAQ

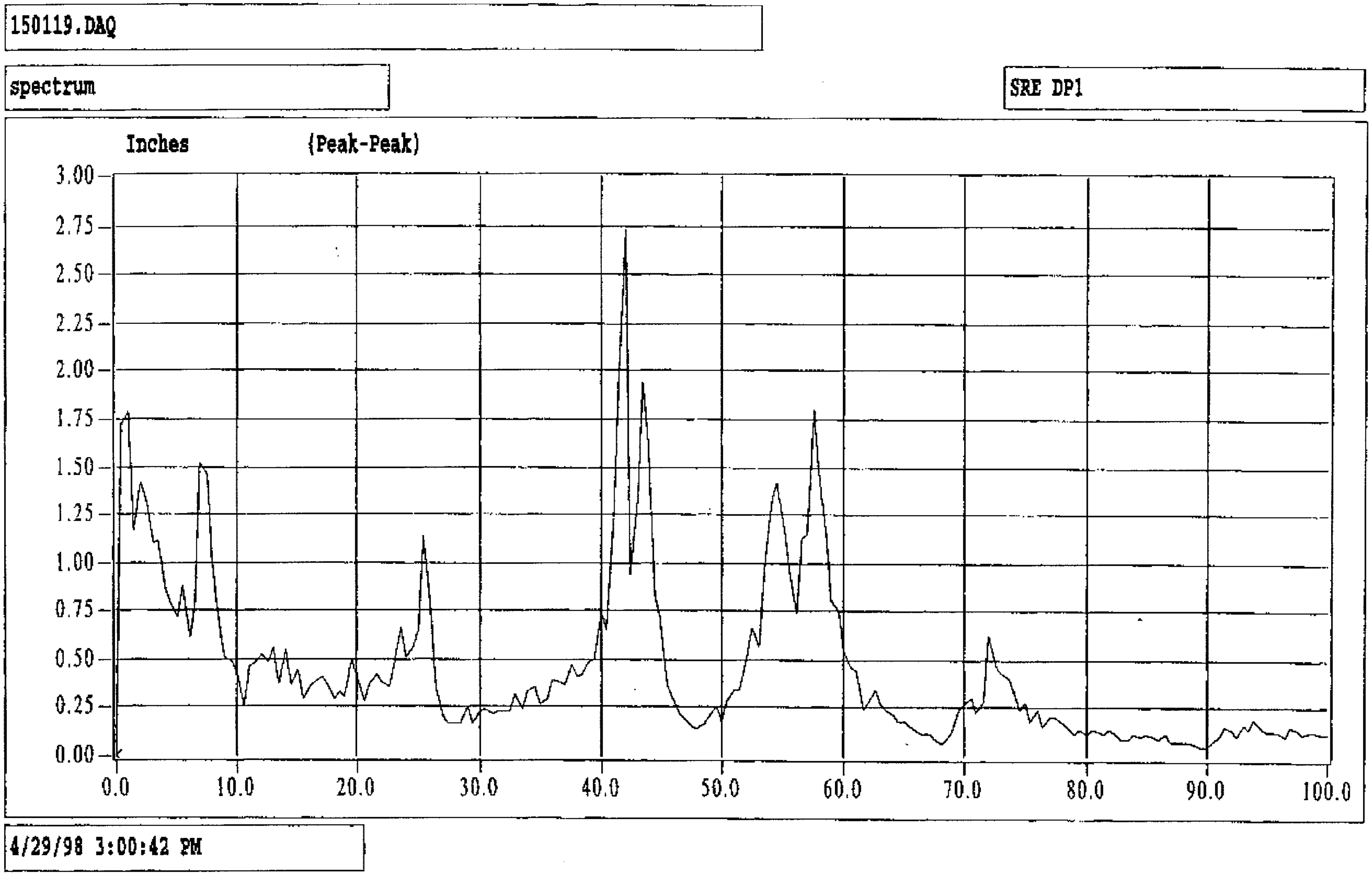
spectrum

SRE DP1



4/29/98 2:07:23 PM

test8


150119.DAQ
spectrum
SRE DP1
Inches
(Peak-Peak)
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
4/29/98 3:00:42 PM

test9

Acknowledgements

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Mr Alan J Nicholl	Shail Ltd
Mr R.J. McKee	South Western Research Institute
Dr R.J.W. Peters	Daniel Industries

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.