

TRANSIENT LEAK DETECTION IN CRUDE OIL PIPELINES

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ABSTRACT

This paper addresses the specific issues of transient leak detection in crude oil pipelines. When a leak occurs immediately after pumps are switched on or off, the pressure wave generated by the transients dominates the pressure wave that results from the leak. Traditional methods have failed to detect such leaks.

Over the years, NWO has developed and implemented various leak detection systems both in-house and by commercial vendors. These systems work effectively under steady-state conditions but they are not able to detect leaks during transients. As it is likely for a leak to develop during transients, NWO has decided to have the ATMOS Pipe statistical leak detection system installed on their pipelines.

This paper describes the application of this statistical system to two crude oil pipeline systems. After addressing the main difficulties of transient leaks, the field results will be presented for both steady-state and transient conditions.

NOMENCLATURE

ATMOS Pipe	The statistical leak detection system using SPRT
LAN	Local Area Network
NWO	Nord-West Oelleitung GmbH
PC	Personal Computer
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SPLD	The statistical pipeline leak detection system using SPRT
SPRT	Sequential Probability Ratio Test

INTRODUCTION

Nord-West oelleitung GmbH is the operator of two crude oil pipelines from Wilhelmshaven to Köln (the NWO Pipeline)

and Hamburg (the NDO pipeline) respectively (Fig.1). To comply with the applicable rules and standards in Germany, especially the TRbF 301 and TRFL (Technical Rules for Inflammable Substances), two independent, continuously working procedures are used to detect leaks. In addition, leak detection pigs are used on a regular basis to complement the surveillance systems.

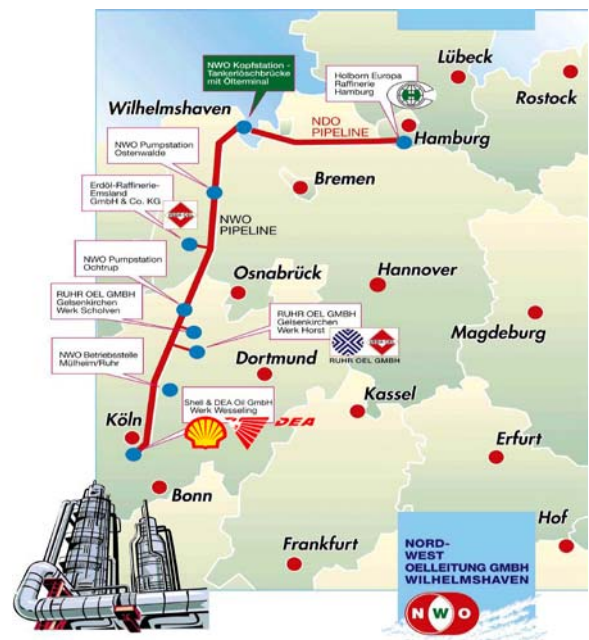


Figure 1 The Geographical Layout of NWO and NDO Pipelines

Prior to this project, NWO has used the following two real-time leak detection procedures:

- Corrected mass balance. A comparison is carried out every 5 minutes between the amount of oil entering and exiting the pipeline. The linepack change over this time period is calculated using a hydraulic model and on-line measurements. The accuracy of the mass balance depends on the accuracy of the flow meters and the linepack calculations. This procedure is designed to detect a leak of 40 m³/h within 60 minutes.
- Pressure drop monitoring. Pressure transmitters installed along the pipeline are monitored for pressure drops. If changes in the pressure readings are typical of a leak, then an alarm is reported to the operators.

The above procedures work well under steady-state operating conditions. However frequent operational changes are experienced by these pipelines. During such unsteady operations, these two leak detection procedures suffer from two major drawbacks:

- An increased number of false alarms.
- Failure in detecting leaks.

In order to overcome the above problems, NWO decided to have ATMOS Pipe (SPLD) system installed on their crude oil pipelines.

PIPELINE DESCRIPTION

As shown in Fig. 2, crude oil is supplied to tanks at Wilhelmshaven by tankers. The NDO pipeline is used to transfer crude oil from the Wilhelmshaven tank farm to Hamburg (HER). The NDO-pipeline has a total length of 144 Kilometres. The nominal diameter of the pipeline changes from 22" to 34". The main pump station at Wilhelmshaven has 3 pumps running in series.

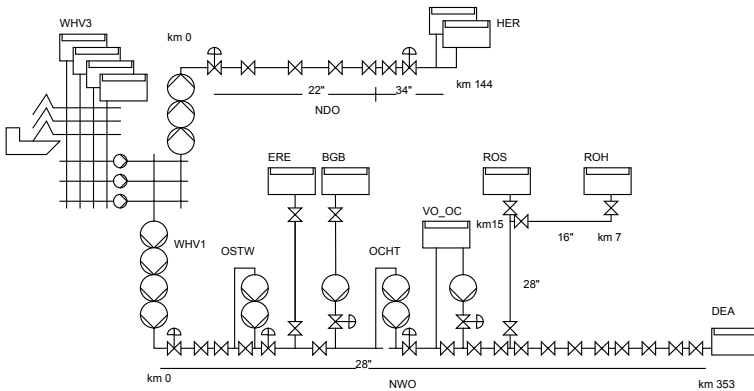


Figure 2 Schematic Diagram of the NDO and NWO Pipelines

The NWO pipeline is used to transfer crude oil from the Wilhelmshaven tank farm to six delivery points (ERE, BGB, VO_OC, ROS, ROH, DEA[SDO]). In addition both BGB and VO_OC can act as feeder stations.

The NWO-pipeline has a total length of 353 Kilometres. The nominal diameter of the pipeline is 28". The main pump station at Wilhelmshaven has 4 pumps running in series. There are two intermediate pump stations along the pipeline at approximately 93 km (OSTW) and 173 km (OCHT) from the

inlet respectively. There are a number of block valve stations along the pipeline.

Since the crude oil is imported from different sources all over the world, the property and quantity vary significantly. Table 1 summarises the range of the crude oil pumped.

Table 1 Crude Oil Properties and Batch Sizes

	Density (kg/m ³)	Viscosity (cSt@10°C)	Batch Size (m ³)
Minimum	798	2.8	93
Maximum	925	309.2	111,245
Mean Value	845	18.9	17,000

Flow, pressure, density and temperature measurements are available at all inputs and outputs of the pipelines. Pressure and temperature measurements are available at the block valve locations. Table 2 summarises all the measurements available in the SCADA system for both the NWO and NDO pipelines.

Table 2 List of Available Measurements

Station	Pressure		Temperature		Density		Flow	
	SITRANS P	TEW	TEU	Firm IMS	Firm Berthold	Ultrasonic	Orifice	
WHV1	•	•		•		•	•	
KM45	•	•						
KM71	•							
OSTW	•	•						
EREAB	•	•			•			
ERE	•		•			•		
BGB-E	•					•		
BGB-A	•	•		•		•		
OCHT	•	•			•			
VO-OC	•					•		
KM213	•		•					
KM221	•							
KM234	•							
KM238	•	•		•				
ROAB	•	•		•				
ROS	•		•				•, Treib.	
ROH	•							
KM256	•	•						
R1	•							
MLH			•					
R2	•							
HLD	•		•					
RDN	•							
RDS	•							
KM321	•	•						
EFF	•							
DEA	•		•			•	•	
WHV3	•			•		•	•	
LV1	•		•					
LV2	•							
LV3	•							
MST	•		•					
HER	•					•		

The above instrument measurements are collected by remote terminal units (RTUs) and transmitted to the PACOS SCADA system.

The field data are transferred to the SPLD PC by means of text files over a LAN at 3 second intervals. The leak detection results are then passed back to the PACOS SCADA system for display on the operator interface.

PRINCIPLE OF THE SPLD SYSTEM

The key to the SPLD (statistical pipeline leak detection) system is Sequential Probability Ratio Test (SPRT). Comprehensive data validation is carried out after receiving pipeline data from the SCADA system. The validated data is then used to calculate the corrected flow imbalance, which is fed into the SPRT in order to decide if there is an increase in the flow imbalance. Finally pattern recognition is applied to distinguish a leak from operational changes.

The SPLD system is unique as it applies three CPM (Computational Pipeline Monitoring, API 1130) methods simultaneously:

- Modified volume balance
- Pressure and flow monitoring
- Statistical analysis.

The use of the above methods, combined with a comprehensive data validation procedure and a rigorous decision making mechanism, makes the SPLD system reliable yet sensitive in detecting leaks.

Since the principle design criterion for the SPLD system is **Minimum False Alarms**, a leak alarm is generated only after systematic checks that pipeline flow and pressure changes do conform to the patterns of a leak.

Leak determination is based on probability calculations at regular sample intervals. The basic principle used for the probability calculations is mass conservation and hypothesis testing: leak against no-leak. Although the flow and pressure measurements in a pipeline fluctuate due to operational changes, statistically the total mass entering and leaving a network must be balanced by the inventory variation inside the network. Such a balance cannot be maintained if a leak occurs in a network. The deviation from the established balance is detected by an optimal statistical test method - Sequential Probability Ratio Test (SPRT).

The combination of the probability calculations and pattern recognition provides the SPLD system with a very high level of system reliability i.e. minimum spurious alarms.

Under leak-free operations, the mass balance principle determines that the difference between the ingress and egress flow-rate should be equal to the inventory variation in a pipeline. Therefore the following term is calculated:

$$\tau(t) = \sum_1^M Q_i(t) - \sum_1^N Q_o(t) - \sum_1^L \Delta Q_j(t) \quad (1)$$

where $\tau(t)$ is called the corrected flow imbalance term at time t . In practice $\tau(t)$ usually fluctuates around a non-zero value due to the inherent differences in the instruments and fluid compressibility.

$Q_i(t)$ represents the flow measurement at the ingress points and $Q_o(t)$ at the egress points. M is the number of ingress points, N the number of egress points and L is the number of pipeline sections.

$\Delta Q_j(t)$ is a correction term for the inventory variation over the sample period of $t-1$ to t . $\Delta Q_j(t)$ is a function of pressure and temperature in the pipeline. Different product properties in the pipeline will introduce changes in the inventory calculations.

The mean value of the above signal $\tau(t)$ remains unchanged unless a leak develops in a pipeline or an instrument error occurs. The distinction between these two failure modes has to be made by further analysis, e.g. instrument change pattern identification. The SPLD system can identify typical instrument faults thus informing operators of possible faulty instruments.

To detect leaks efficiently with a low false alarm rate, SPRT is used to decide between the leak-free and leak-present hypotheses, e.g.

H_0 : $\tau(t)$ is gaussian with mean m and variance σ^2

H_1 : $\tau(t)$ is gaussian with mean $m+\Delta m$ and variance σ^2

where m represents the mean value of $\tau(t)$ under normal (leak-free) operations and

Δm is a parameter determined by the leak size to be detected. To take into account instrument drifts over time, m is tuned slowly using measurements available during a no leak alarm period. The value σ^2 depends on the fluctuations of the flow and pressure signals in a pipeline. For changing operating conditions in the pipeline, different values of σ^2 are used. Usually three operating modes are identified automatically in a pipeline:

- Steady state operation, operating status = 0,
- Small operational change, operating status = 1,
- Large operational change, operating status = 2.

After a large operational change, it takes longer for the SPLD system to detect a leak than during steady state operations. The choice of the different σ^2 values is determined to achieve maximum system reliability, without loss of leak detection functionality.

The SPRT for testing hypothesis H_1 against H_0 is transformed to the calculation of the following cumulative sum:

$$\lambda(t) = \lambda(t-1) + \frac{\Delta m}{\sigma^2} (\tau(t) - m - \frac{\Delta m}{2}) \quad (2)$$

By comparing the on-line calculated value $\lambda(t)$ (Lambda) with a preset threshold value 4.6, a leak alarm can be generated.

The above scheme is implemented using operational data provided from NWO and NDO pipelines, in order to optimise the performance of the leak detection system. Parameter tuning is carried out both during the design stage and after the initial installation.

One key feature of the SPLD system is that it has learning capability, e.g. operational changes introduced after the installation are used to further tune the system automatically and gradual instrument drift is incorporated for eliminating false alarms. Since no hydraulic models are used, variations in fluid properties e.g. composition change, viscosity variations, do not present a problem to the SPLD system.

LEAK TEST RESULTS

The above SPLD system was first installed in July 2002. The first leak test was carried out in August 2002. To date more than 47 leak tests have been carried out under both steady-state and transient conditions. The transient is usually introduced by one of the following methods:

- Pump switches 30 seconds before a leak test and during testing;
- Control valve action;
- Supply and delivery changes.

An example of typical pipeline transients is shown in Fig.3.

One of the most important criteria of this project is the ability of detecting leaks under similar transient conditions as shown in Fig. 3 above. This is because other technologies have failed to detect leaks during pipeline transients. Over the last two years, NWO has conducted over 35 transient leaks that are all detected successfully. Some examples of such leak tests are shown in this section.

As shown in Fig. 4 and 5, continuous transients were experienced by the pipeline during the 5 hour operating period on the 27th September 2002. When a leak was generated at 10:20 hour, the SPRT showed an increased probability of a leak and a leak alarm was generated at 10:28 hour (Fig. 6). The recorded leak size was 186 m³/h i.e. 12.4% of the throughput.

Fig. 7 and 8 show the flow and pressure measurements over a two hour period on the 3rd October 2002. It is difficult to visualise when a leak was started. However Fig. 9 shows that Lambda1 and Lambda2 started to increase at 10:36 hours and when they became greater than the threshold value of 4.6, a leak alarm was generated at 11:06 hours. The recorded leak size was 286 m³/h i.e. 17.9% of the throughput.

It is of interest to note that there is a deadband of 0.3 bar in the pressure readings received from the SCADA system. A careful examination of the pressure changes in Figure 8 indicates that the minimum variation in the pressure is 0.3 bar. This is caused by the limited bandwidth of the telemetry system. While this has minimum effect on the detection time, it does introduce errors in the leak location estimates.

Fig. 10 and 11 show the flow and pressure measurements over a 17 hour period on the 9th May 2003. The pipeline was under steady state operating condition for the most of the day. As shown in Fig. 12, two leak alarms were generated at 9:39 and 11:14 hours respectively. Note that after each of the leak tests, Lambda1 and Lambda2 went back to -7 immediately and they stayed well below zero for the remaining part of the day. For example, large transient occurred between 16:00 and 16:50 hours when Lambda1 reached -3.4. However it was still well below zero indicating a low probability of leaks.

As shown in Fig. 13, 14 and 15, three leaks were generated on the 27th May 2003. The first two were under normal steady-state operating conditions. The first leak was started at 10:12 hours with a size of 106 m³/h i.e. 6.7% of throughput. The leak

was detected in 9 minutes (at 10:21 hours, Fig. 15). The second leak was started at 11:01 hours with a size of 123 m³/h i.e. 7.8% of throughput. The leak was detected in 7 minutes (at 11:08 hours, Fig.15).

The third leak was generated 30 seconds after a pump switch over at 11:47 hours and it was detected in 12 minutes (at 11:59 hours, Fig.15). The recorded leak size was 280 m³/h i.e. 12.8% of throughput.

A summary of the leak test results is given in Table 2, which demonstrates that all the leaks have been detected within the specified time. For all the steady state leaks, the location error was less than 10 kilometres for the 353 KM long NWO line. Some of the transient leaks were also located within 10 kilometres. Due to the pressure transmitter deadband and uncertainties in the speed of sound in the varying crude, it has proven difficult to locate all the transient leaks within 10 kilometres.

In addition to detecting leaks successfully under transient conditions, the another important criterion is the lack of false alarms during leak-free conditions. The NWO specification states a maximum of 4 false alarms per year i.e. no more than 1 false alarm for a three month period. The above examples show Lambda1 and Lambda2 always stayed below zero, indicating a very low probability of leaks even when the pipeline went through large transients. The ability to distinguish between a leak and operational changes is unique among real-time leak detection systems.

OBSERVATIONS

The SPLD system was installed on the NWO pipelines based on the existing instrumentation and SCADA system. During the implementation of the SPLD system, several issues have been encountered that have made the project completion more difficult.

Flow meter discrepancy

The main supply and delivery flow meters available are in line two-pass ultrasonic type. The only exception is the flow meter at ROS delivery point where an orifice flow meter is used. When the crude type changes or when temperature varies, the flow meter discrepancy may change by as much as 3%.

Fig.16 shows the flow meter readings and the corresponding flow difference under steady-state operating conditions, between the 12th and 15th April 2002. An increase of 30 m³/h occurred when the delivery changed from ROS to DEA. As the minimum leak to be detected was specified as 1.25% or 25 m³/h at a throughput of 2000 m³/h, a false leak alarm could be generated if no action were taken by the SPLD system in learning the flow meter discrepancy.

Table 2 List of Leak Tests Performed

Test #	Date & Time	Size (m3/h)	Size (%)	Detection Time (min)	Specified Det. Time (Min)	Transient Type
1	8 Aug 02 12:00	190	10.6	05:45	09:00	None
2	8 Aug 02 13:11	195	11.0	16:48	45:00	P6 P7 Change-over
3	12 Aug 02 11:00	90	6.9	11:25	55:00	P6, P12 off, P6 on later
4	27 Sep 02 10:21	186	10.3	08:47	40:00	P1 off, CV OSTW, P11 off
5	3 Oct 02 10:50	200	14.3	16:20	35:00	P6 on, P11 off/on, P6 off, P6 on
6	4 Oct 02 10:40	78	4.6	07:00	59:00	P11 off, P6 off, P12 on, P6 on
7	31 Oct 02 8:00	240	17.1	21:14	30:00	P1 off, P3 P4 change, P4 P3 change, P12 off, on
8	20 Nov 02 19:00	160	9.1	08:02	10:00	None
9	10 Dec 02 10:27	77	4.1	33:45	60:00	P11 off, P7, P6 change, P6, P7 change, P12 off, on, CV OCHT
10	13 Dec 02 10:45	250	13.9	13:20	30:00	P1 off, P11 off, P7 off, P6 on, P12 off
11	15 Jan 03 9:46	213	10.6	23:00	35:00	P1 off, P7 off, P6 on, P11 off, on, P1 on, P6 off, P7 on, off, P11 off
12	15 Jan 03 12:04	119	5.7	07:48	55:00	P11, P12 Change, P12 on, P2 on, P11 off, P3 off, P11 on, P7 off, P12 off, P7 on, P12 on, P3 on, P11 on) CV OSTW, CV WHV
13	15 Jan 03 13:38	392	19.6	24:51	28:00	P3 off, on, P1 on, off, P3 off, on
14	25 Feb 03 14:09	90	6.4	06:13	25:00	none
15	25 Feb 03 15:02	170	12.1	08:06	10:00	None
16	26 Feb 03 13:31	300	23.0	10:36	28:00	P12 off, P11 on, P12 on, off P3 on, P1 on, P2 off, P1 off, on, P12 on, P1 off, P3 off, P2 on
17	26 Feb 03 15:04	100	5.9	35:13	55:00	P2, P1 change-over, P1, P2 change-over
18	27 Feb 03 8:25	95	7.3	21:48	55:00	P1 on, off
19	27 Feb 03 9:32	170	11.3	17:26	45:00	None
20	3 Mar 03 10:47	67	3.5	13:36	28:00	None
21	3 Mar 03 11:53	91	4.8	09:33	20:00	None
22	3 Mar 03 13:14	180	10.0	09:33	40:00	P1 off, P11 off, P12 off, on, CV OSTW P3 off, P1 off, P7 off, P6 on
23	8 May 03 15:22	300	18.8	07:18	28:00	CV OCHT
24	9 May 03 9:34	140	6.4	05:48	10:45	P11 off, on, CV OCHT
25	9 May 03 11:07	150	6.8	07:25	45:00	None
26	27 May 03 10:12	106	6.6	10:22	20:00	CV OCHT
27	27 May 03 11:00	123	7.7	08:33	50:00	P1, P2 change-over
28	27 May 03 11:47	280	13.3	12:38	30:00	CV OCHT
29	6 Jun 03 09:30	210	9.5	36:35	39:00	CV OCHT, CV WHV
30	23 Jun 03 12:30	65	4.2	27:17	28:00	P6 on, CV OCHT
31	23 Jun 03 13:50	50	3.3	34:50	>60	None*
32	25 Jun 03 8:50	440	31.0	08:20	03:24	None
33	25 Jun 03 9:40	75	5.3	14:50	28:00	CV OCHT failure, Hidden operations
34	25 Jun 03 10:33	360	25.7	03:22	28:00	P2 off, P3 on
35	25 Jun 03 12:19	240	18.5	13:40	30:00	CV OCHT, PI-EREAB failure
36	6 Aug 03 08:50	100	5.9	07:41	15:00	None
37	20/10/2003 11:26	220	12.0	08:00	10:00	Delivery switch from ROS to DEA
38	20/10/2003 12:57	185	12.0	49:00	50:00	None
39	31/10/2003 10:47	109	5.0	08:00	27:00	None
40	31/10/2003 11:45	235	10.0	14:00	40:00	P1 off
41	17/12/2003 13:25	280	13.0	10:00	30:00	P1 on
42	19/12/2003 10:34	261	15.0	02:00	07:30	None
43	19/12/2003 12:37	75	4.0	16:00	60:00	P1 on/off
44	30/01/2004 10:18	291	19.0	10:00	28:00	P1 on/off
45	18/03/2004 14:27	235	10.0	12:00	28:00	Pipeline start up
46	21/05/2004 10:02	133	8.0	11:00	50:00	P12 off, P11 on
47	21/05/2004 10:37	73	3.0	52:00	>60	Delivery switch from DEA to ROS

* The inlet flow meter was stuck when the leak test started, resulting a longer detection time than specified.

There are three main reasons for the flow discrepancy to occur:

1. Crude oil property changes either due to tank switch or batch variation.
2. Temperature change in the crude oil.
3. Water in oil.

The first time when the flow discrepancy increased by more than, say 30 m³/h, the SPLD system generated a false alarm. However such alarms were removed by tuning the system to recognise such unusual events.

Communication system bottleneck

The existing communication hardware has limited bandwidth that makes it difficult for the dead band of the pressure transmitter readings to be reduced below 0.3 bar. This restriction has had some negative effect on the leak location estimates as an additional delay may be introduced in the pressure readings sent to the SCADA system after a leak. Such a delay is unpredictable depending on the leak size, location and crude oil in the pipeline.

Numerous operational scenarios

NWO pumps more than 400 types of crude through their pipelines. The properties of the crude vary significantly: density between 798 and 925 kg/m³, viscosity between 2.8 and 309 cSt at 10 °C. It is certain that none of the leak tests was carried out under the same condition as another test. Such variability makes it impossible to estimate the leak location accurately under transient conditions.

Another operational scenario experienced is slack flow that is caused by draining the pipeline after the main pumps stop. The SPLD system can cope with such slack flow conditions without false alarms but the system sensitivity is reduced during such operations.

NWO also practices some operations that are similar to leak tests when a pigging section gets filled or when a bypass is introduced. Such operations do introduce leak alarms, which are defined as “self-induced leak alarms”. As the operators are in control of such operations, no action is taken to block such alarms.

CONCLUSIONS

ATMOS Pipe has been installed and tested successfully under both steady-state and severe transient conditions. It has detected more than 47 leaks on the NWO pipeline over a period of 20 months. No false alarm has been generated due to normal transients in the pipeline, while leaks occurring during such transients are detected reliably. The following conclusions can be drawn from the implementation of the SPLD system on the NWO and NDO pipelines:

1. It is essential for the end user and vendor to work as a team to drive both the hardware and software technology forward.
2. The system has detected leaks under severe transient conditions where model-based technology has failed previously.
3. Reliable instrumentation system is an important factor in reducing false alarms, particularly when crude type changes. In addition the learning capability of the SPLD system improves its reliability by allowing it to adapt and handle flow meter discrepancy changes caused by crude batch changes.
4. The SPLD system has performed well given the following adverse conditions:
 - The communication system has a deadband of 0.3 bar.
 - The density of the crude batch varies between 798 and 925 kg/m³, viscosity between 2.8 and 309 cSt at 10 °C.

- More than 400 types of crude is pumped with batch sizes between 90 and 111,245 m³.
- Flow meter discrepancy changes by more the 3% when the crude type varies.

ACKNOWLEDGMENTS

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REFERENCES

1. API, 2002, “Computational Pipeline Monitoring”, API Publication 1130.
2. API, 1995, “Evaluation Methodology for Software Based Leak Detection Systems”, API Publication 1155.
3. Bruce Tindell, J. Zhang, 2004, “Liquid Pipeline Leak Detection: The Esso Experience”, Pipeline & Gas Journal, Feb 2004, P40-42
4. John Lewis, Joep Hoeijmakers, 2002, “Pipeline leak detection methodology change on the crude oil pipeline network for NV Rotterdam Rijn Pijpleiding Maatschappij (RRP) in the Netherlands”, Presented at the International Pipeline Conference 2002, between 29th September and 3rd October 2002 in Calgary, Canada
5. TUV, 2002, “TRFL: Technische Regel für Rohrfernleitungsanlagen”, Ausgabe 2002 (Stand 16.09.2002)

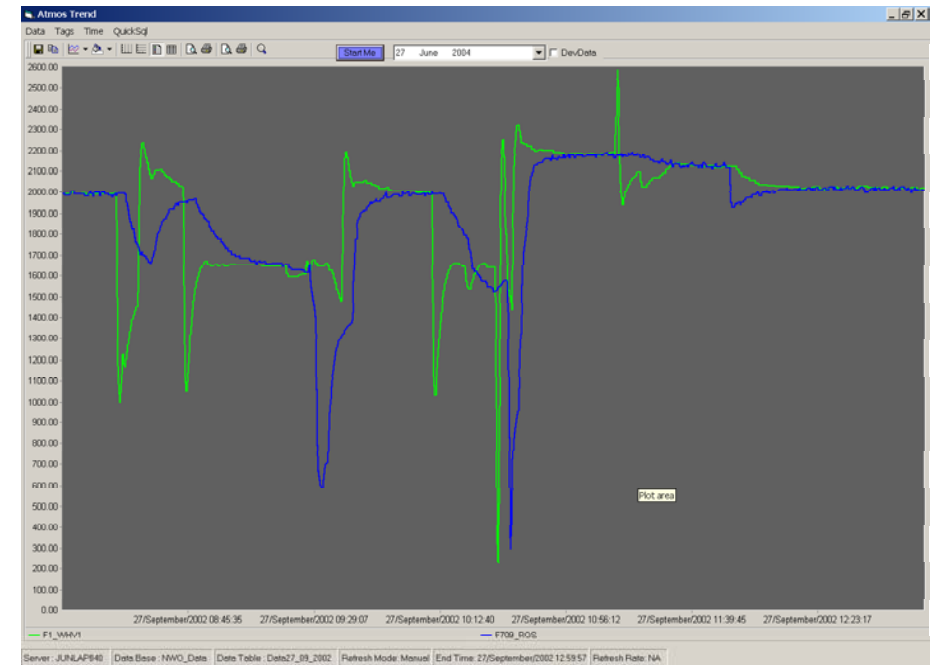


Figure 4 Flow Measurements Between 8:00 and 13:00 hours on 27/September/2002

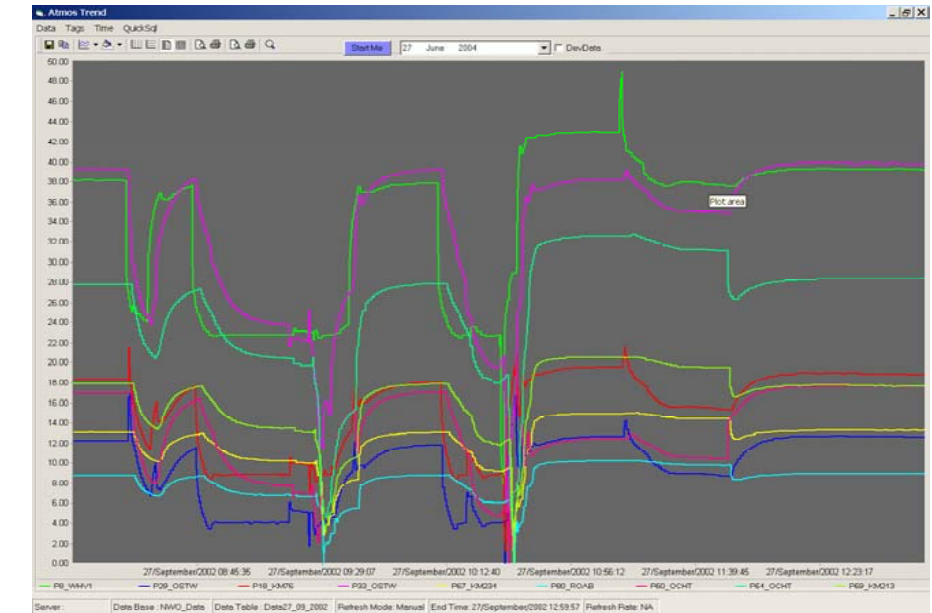


Figure 5 Corresponding Pressure Measurements as Shown in Figure 4 above

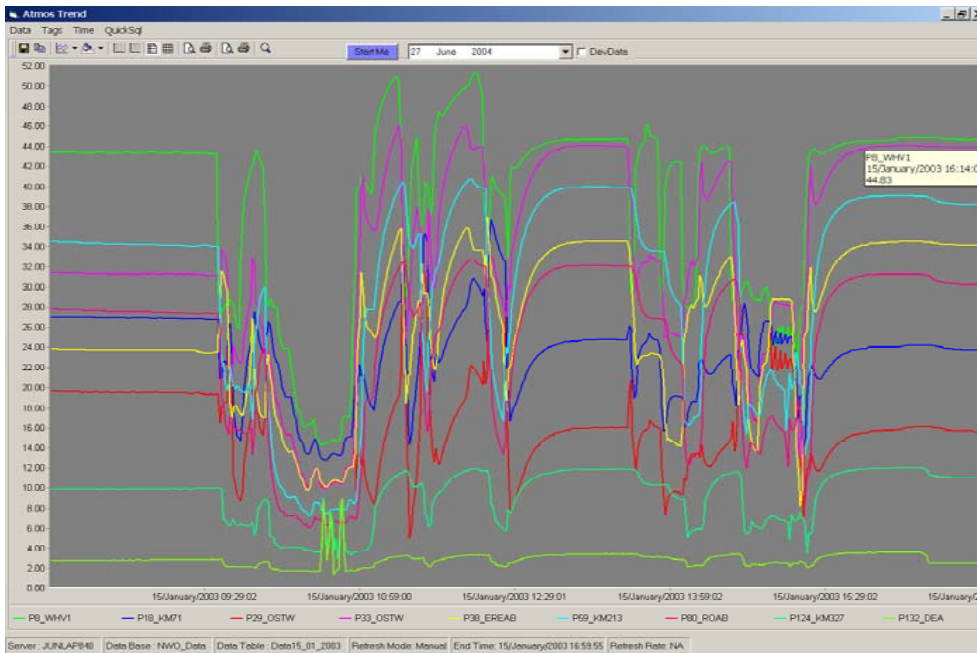


Figure 3 Transient Pressure Behaviour Along the Pipeline Over a 9 hour Period

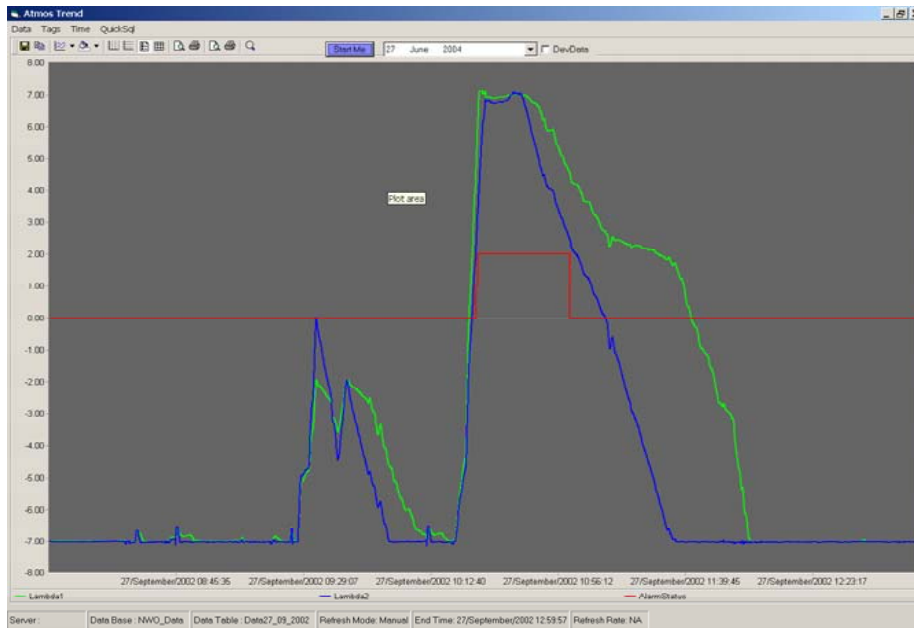


Figure 6 Lambda1 and Lambda2 Increase to Alarm a Leak At 10:28 hours (AlarmStatus Changes from 0 to 1, then 2). This is the same time window as shown in Fig. 4 and 5.

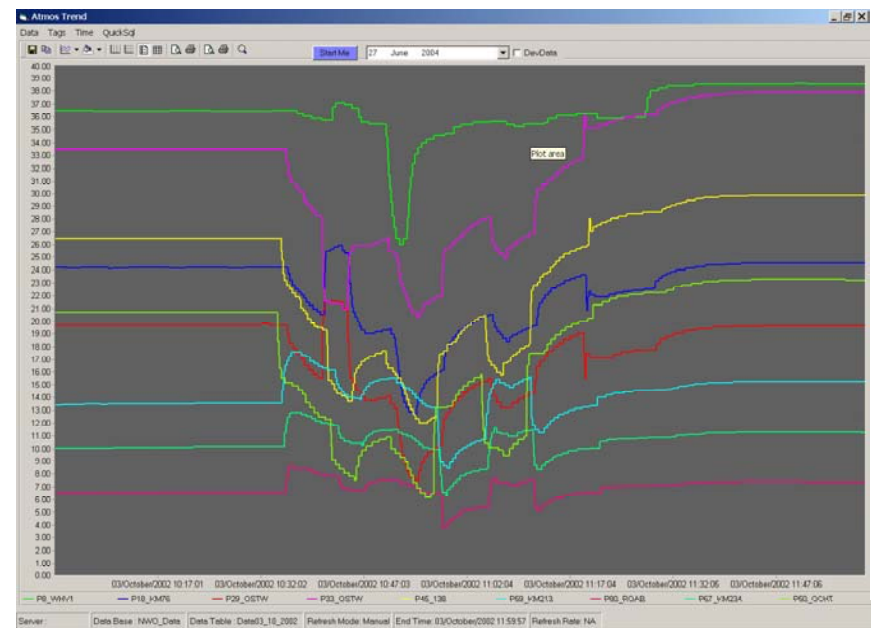


Figure 8 Corresponding Pressure Measurements as Shown in Figure 7 above

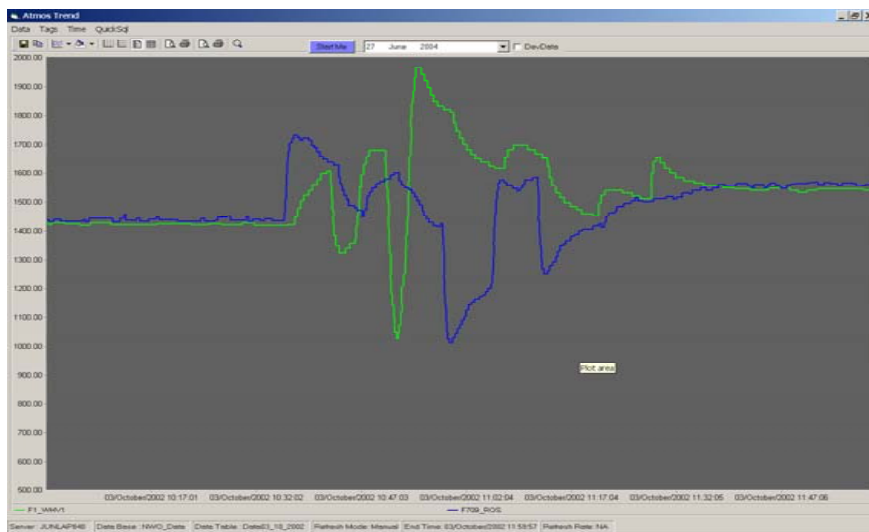


Figure 7 Flow Measurements Between 10 and 12 hours on 03/October/2002

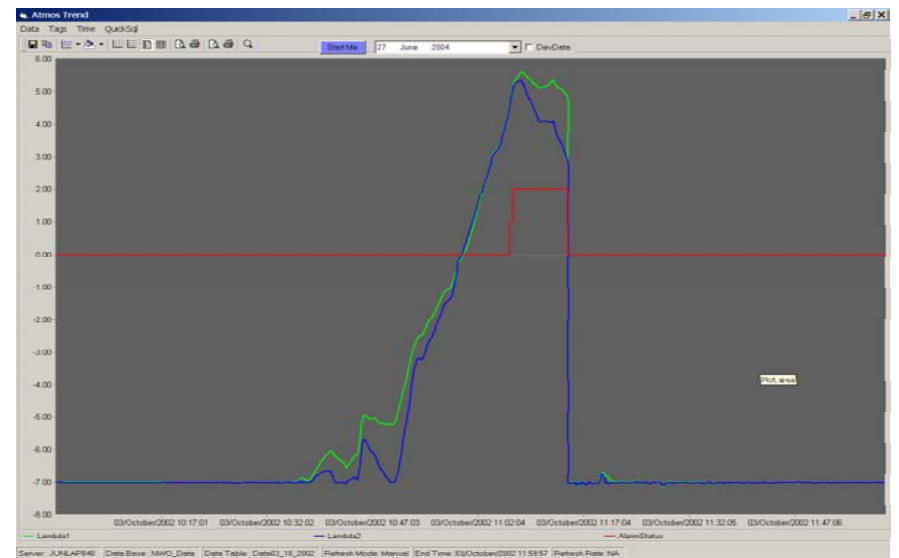


Figure 9 Lambda1 and Lambda2 Increase to Alarm a Leak At 11:06 hours (AlarmStatus Changes from 0 to 1, then 2)

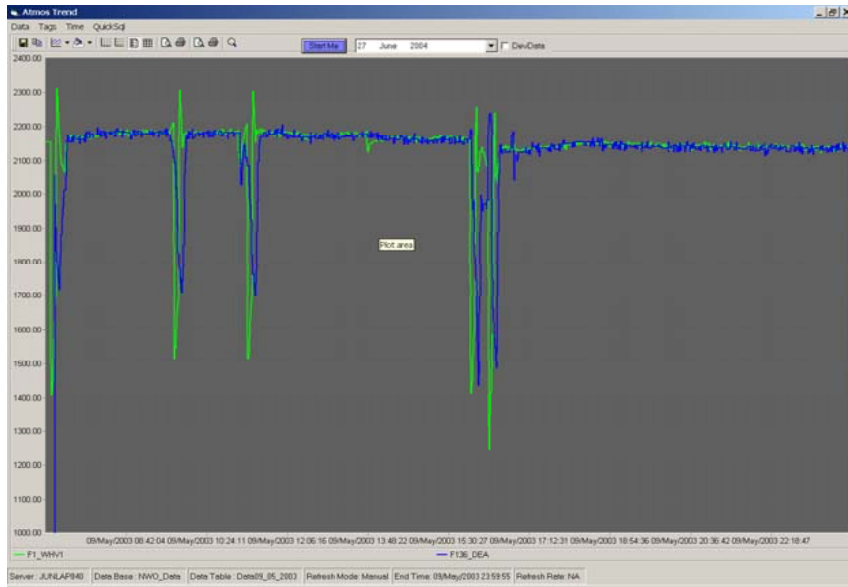


Figure 10 Flow Measurements Between 7 and 24 hours on 09/May/2003

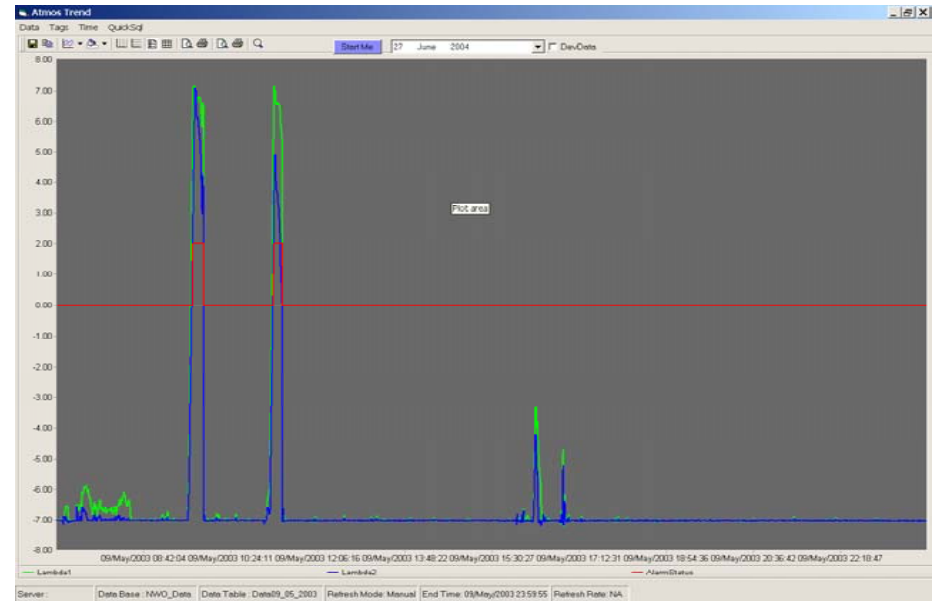


Figure 12 Lambda1 and Lambda2 Increase to Alarm a Leak At 9:39 & 11:14 hours (AlarmStatus Changes from 0 to 1, then 2)

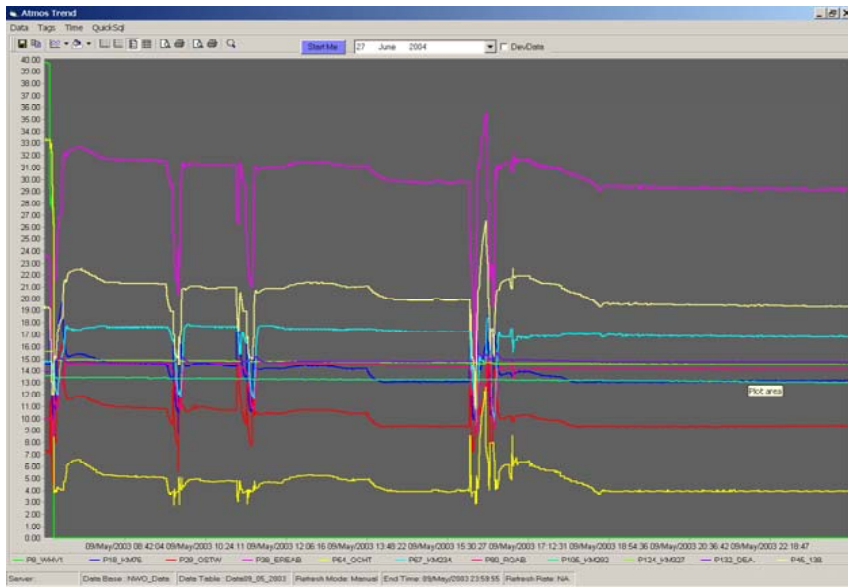


Figure 11 Corresponding Pressure Measurements as Shown in Figure 10 above

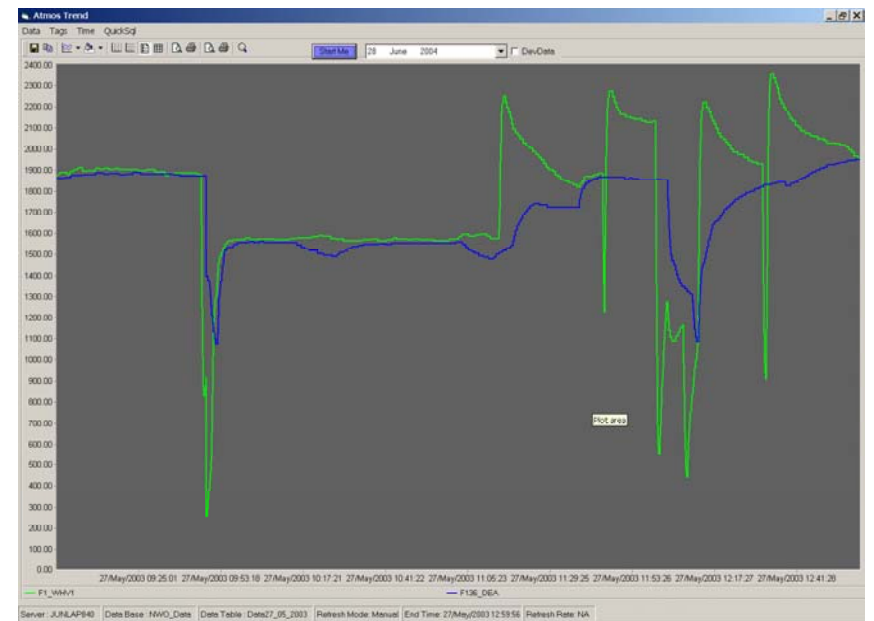


Figure 13 Flow Measurements Between 9 and 13 hours on 27/May/2003

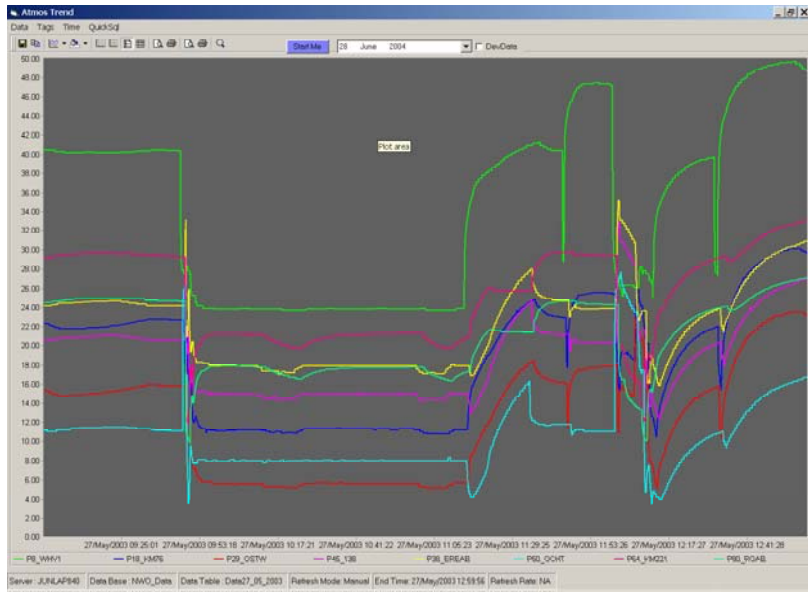


Figure 14 Corresponding Pressure Measurements as Shown in Figure 13 above

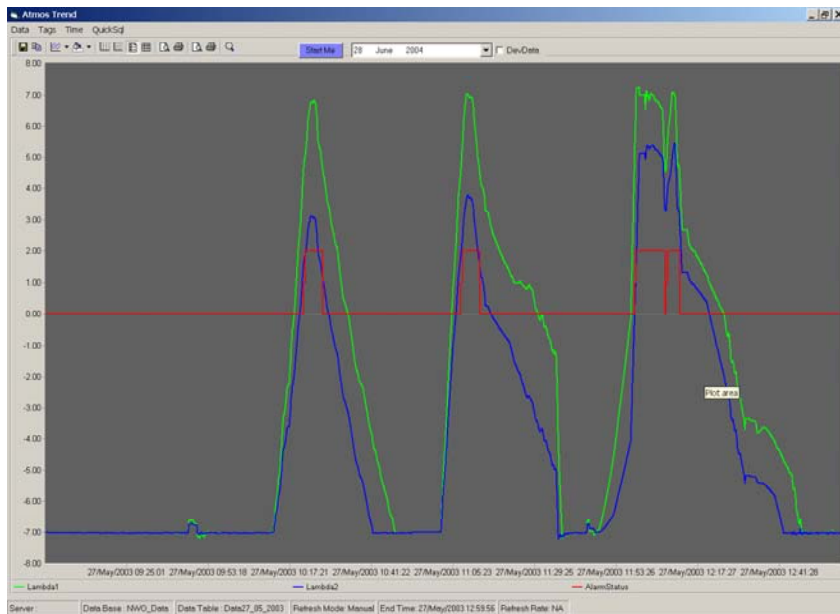


Figure 15 Lambda1 and Lambda2 Increase to Alarm a Leak At 10:21, 11:08 & 11:59 hours (AlarmStatus Changes from 0 to 1, then 2)

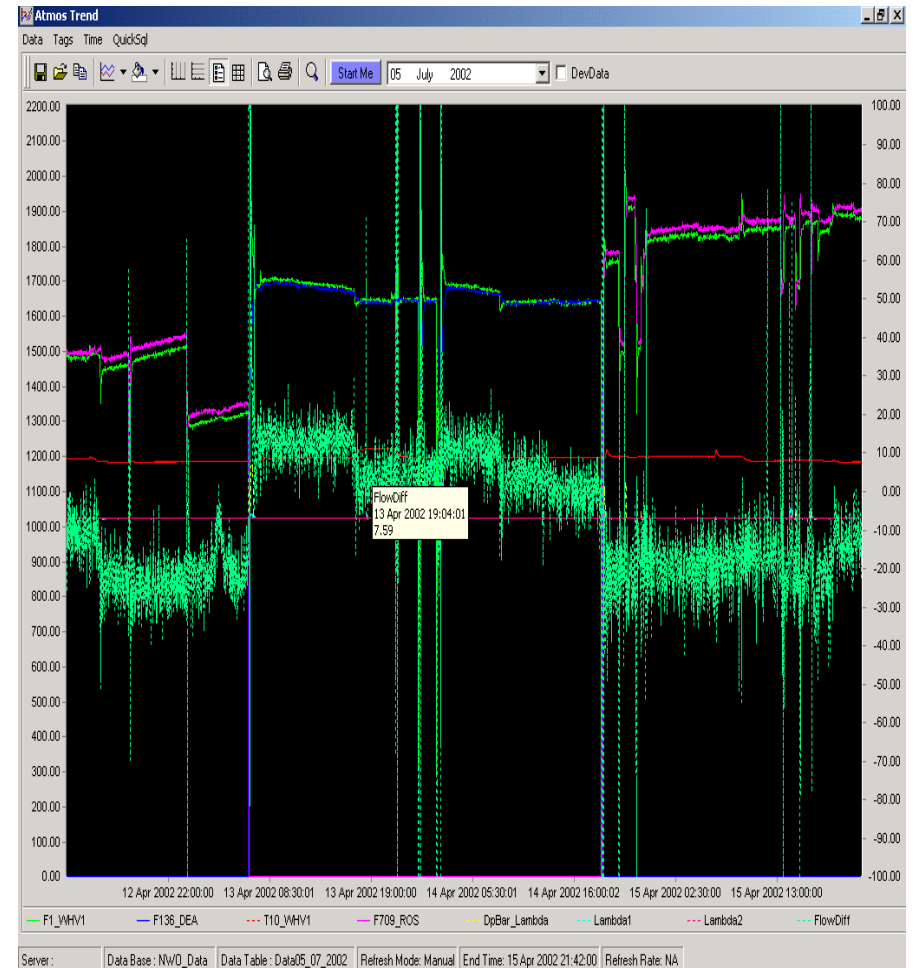


Figure 16 Flow Measurements and the Corresponding Flow Difference Under Steady-State Operating Conditions. Flow Difference (light green noisy line, scale on right hand axis) started at around $-10 \text{ m}^3/\text{h}$ at the start of the trend, it decreased to -20 when there was a small change in the flow-rate probably due to tank change. When the delivery changed from ROS (magenta line) to DEA (blue line), the flow difference increased from -20 to $+10 \text{ m}^3/\text{h}$, and it decreased slightly during this transfer. When the delivery switched back to ROS, the flow difference went back to $-20 \text{ m}^3/\text{h}$ and it increased slightly before the end of the trend.