

INSPECTION OF THE 16" ERSKINE PIPELINE WITH A HIGH TEMPERATURE VARIANT OF RST'S SAAM SMART UTILITY PIG

The Erskine Pipeline, operated in the UKCS by ChevronTexaco experiences temperatures of up to 130°C. The pipeline is trenched and buried to provide sufficient insulation against wax formation. The high temperature introduces upheaval buckling propensity due to the resultant high axial stresses in the pipe wall. As part of their pipeline integrity management system the operator required a means of monitoring the shape of the pipeline to identify any regions of concern where the risk of buckling was increased due to seabed topography or where the pipeline profile was changing over time. Advance warning of potential or developing problems would allow timely action, such as additional rock dumping, to be taken.

Following a review of inspection techniques available, which showed there was no off the shelf solution available, the operator set up a development project in conjunction with RST Projects Limited, with the objective of developing a high temperature variant of RST's SAAM pipeline inspection tool. The SAAM Tool, which has been developed as a low cost means of pipeline inspection, has a number of applications, one of the most important being the detection, assessment and monitoring of pipeline out of straightness. RST had previously undertaken inspection work for ChevronTexaco in the Galley and Strathspey pipelines.

This paper presents a description of the development work undertaken as well as summarising the results of the 2 inspections carried out to date. The paper also considers the merits, in terms of cost and lead time, in the approach taken in the setting up and running of this particular project.

INTRODUCTION

It is generally recognised that Joint Industry Projects (JIPs) are difficult to organise and manage due to diversity of perceived key issues by different participants. Hence the scope of work grows to satisfy the needs of all the JIP members with an attendant increase in costs. Typically a JIP will cost anything up to £50k or £70k per

participant and it is unusual for a JIP to have less than say five or six participating contributors. Meetings have to be held on a very formal basis and plans, budget reports, minutes of meetings and so on distributed to a wide audience who in turn have to respond with corrections and acceptance. Changes have to be incorporated and the correspondence re-issued. All of that is a time consuming and costly exercise.

Nevertheless, the JIP is an appropriate method and medium for conducting large, extensive research projects, particularly those that are driven by regulatory requirements. The JIP also suits development work which is associated with high profile public concerns.

Texaco North Sea UK, on the other hand saw the opportunity to utilise a specialist research establishment to address a well defined problem, operating under the same principle as a JIP, that is, the project sponsor allocating the work in small phases, closely monitoring progress at regular intervals to assess the value of continuing or not. Having the freedom and ability to alter the scope of work to any degree without having to gain consensus from a large group of participants accelerated the response to problems as they arose. This is the manner in which the research project described in this paper was conducted between RST Projects Ltd and Texaco North Sea UK between April 2001 and February 2002.

NOMENCLATURE

HT - High Temperature

JIP - Joint Industry Project

MAOP - Maximum Allowable Operating Pressure

OOS - Out of straightness

PCM - Phase Change Material

PEEK - Polyetheretherketone

ROV - Remotely Operated Vehicle

SAAM - Smart Acquisition and Analysis Module

SWOT - Strength, Weakness, Opportunity and Threat

UKCS - United Kingdom Continental Shelf

SAAM PIPELINE INSPECTION

RST Projects Limited developed the SAAM pipeline inspection tool in the mid to late 1990s with the objective of providing a low cost means of pipeline inspection. The tool comprises a package of electronics and instrumentation that can be retrofitted to a traditional Cleaning or Utility Pig (Figure 1), rather than being a special standalone inspection pig. The SAAM tool then records the behaviour of its carrier pig as it travels along the pipeline. The results are then analysed to provide the following information:

- Pipeline out of straightness [1]
- Mechanical damage/bore restriction [2]
- Internal condition [3]
- Wax/debris
- Process parameters



Figure 1 - A typical SAAM carrier pig

SAAM has been used in over 50 projects in the North Sea and a number of other locations since it was first deployed in 1997. The development of the SAAM technology is ongoing via the PIPEAIMS joint industry project¹ which is supported by eight oil and gas companies.

The SAAM OOS capability (in the vertical plane) is provided by an on board sensor which measures the inclination of the pig. This is then used in conjunction with the

¹ The PIPEAIMS project is funded by: BP, Shell, Texaco, Kerr McGee, Marathon Oil, Enterprise Oil, Veba Oil and Gas and TotalFinaElf. It will result in the production of a Recommended Practice for the Use of Smart Utility Pigs.

speed of the pig to provide the localised vertical profile of the pipeline. Validation work carried out by RST [1] has demonstrated that the accuracy of the SAAM vertical OOS capability is within +/-0.09% of the horizontal distance travelled and that an accuracy of +/-0.05% was achievable in 80% of the cases. Examples of the vertical OOS capability of the SAAM tool are shown in Figure 2 and Figure 3. The former shows the profile of an upheaval buckle in a 10” oil pipeline in the North Sea from 2 separate SAAM surveys, the latter shows a relatively good tie-in between the SAAM data and that acquired from a ROV inspection of the same 10” pipeline.

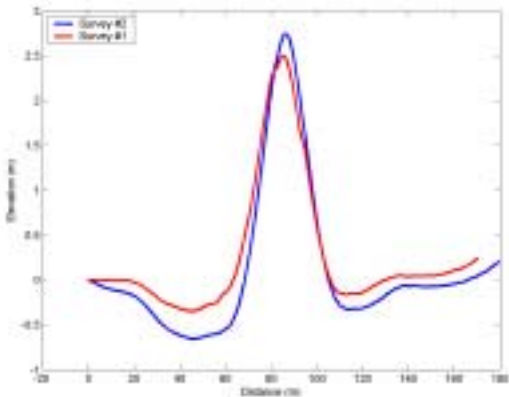


Figure 2 - SAAM generated profiles of an upheaval buckle

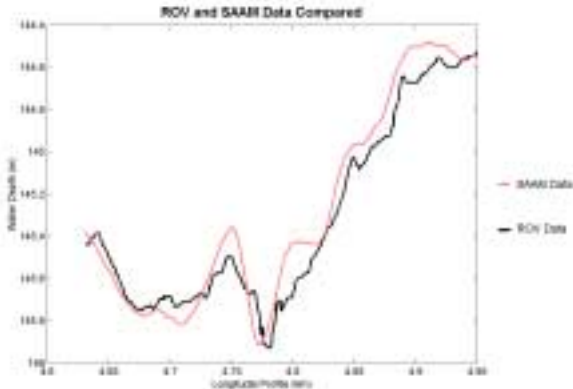


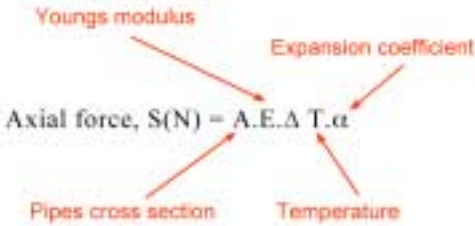
Figure 3 - Comparison between SAAM and ROV data

RST are currently working on extending the OOS capability of the SAAM tools to full 3D OOS. This development is based on the use of angular velocity sensors (solid state gyros) in conjunction with the existing inclination sensing capability.

HIGH TEMPERATURE PIPELINE DESIGN PRINCIPLES

The phenomenon known as Upheaval Buckling is well understood in relation to long metal components such as railway lines or pipelines which are subjected to wide

variations in temperature. Railway lines are affected by changes in ambient temperature. Pipelines are installed at ambient sea water temperature of say between 4° C and 10° C. If the operating temperature of the product being conveyed by the pipeline is substantially higher than the surrounding sea water temperature it will expand. The theory is straightforward. The force required to prevent that expansion can be calculated as:



The resistance to the expansion is provided only by frictional interaction between the pipeline and the sea bed but that will exceed the expansion force at an easily calculated point from the end of the pipeline. For example, for any nominal pipe size with a given wall thickness, grade, contents density and seabed to pipeline coefficient of friction and assuming a flexible tie in spool at the pipe end, the friction resistance at the end of the pipeline will be zero, increasing along the pipeline linearly in accordance with:

$$F = \mu * \text{mass}(\text{pipe} + \text{coating(s)} + \text{contents}) * g * \text{length}$$

It can be seen that the force generated by thermal expansion decays exponentially from the hot end of the pipeline along its length as a function of temperature which in turn is a function of insulation afforded to the pipeline by its protective coating supplemented further by soil cover if the pipeline is trenched and buried. High insulation may be a feature of the design if there are benefits in maintaining a high temperature to, for example, prevent the formation of wax on the pipeline internal wall. The graphical representation is:



Figure 4 - Thermal profile of a subsea pipeline

Equating frictional resistance to thermal expansion force demonstrates that extension of the pipeline by expansion is fully restrained at a point distant from the end of the pipeline. Hence the pipeline structure will be in compression, liable to the effects of Euler buckling. In practical terms, a pipeline is not absolutely straight on the sea bed and the locked in force will be applied eccentrically to the pipeline as a structural member, the eccentricity being dictated by the as laid out of straightness of the pipeline. In the event that the force is sufficient for the out of straightness to develop vertically and / or laterally, the integrity of the pipeline will be adversely, possibly seriously, compromised.

This phenomenon is represented by the figures below:

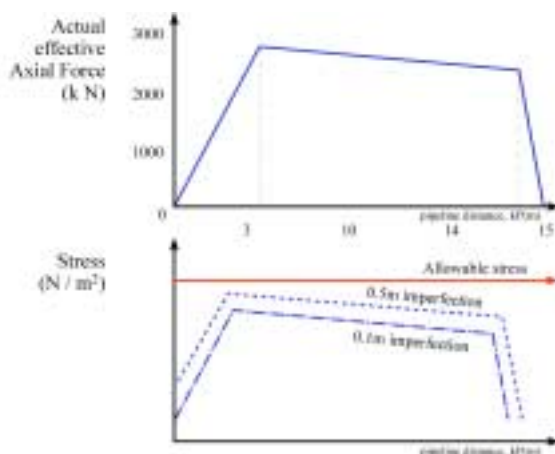


Figure 5 – Pipeline axial force imposed by seabed friction against thermal expansion

Figure 6 - Equivalent maximum stress in a pipeline wall for various values of out of straightness

The number of design options available when considering the installation of a subsea pipeline operating at a high temperature is limited to two:

- Allow the pipeline to expand through lateral deflection in order to keep stress levels within acceptable levels

- Lock the pipeline in place and allow for large, locked in forces during operation.

In either case, it is necessary to carefully monitor the shape of the pipeline during operation to ensure that:

- The deflections are within amplitude and geometric constraints set during design
- The pipeline has not changed from the locked in shape set at installation

Whilst, the former can be achieved by external monitoring of the shape of the pipeline in operation, in relation to its shape at installation, and whilst the shape of the locked in pipeline can be monitored by utilising standard subsea inspection techniques, both require equipment which is deployed and supported by a vessel. Mobilisation, demobilisation and daily running costs make both of these monitoring methods expensive. A more practicable method is to run a semi-intelligent pig which can report on the geometric configuration of the pipeline; such tools are readily available. However, in the case of a product which anywhere has a temperature much above 80° C, the ability of economically viable electronic components to withstand such a temperature becomes an issue. That therefore is the design challenge for such a semi-intelligent pig.

INSPECTION OF THE ERSKINE PIPELINE

The design of the replacement Erskine pipeline resulted in a trenched and buried pipe in pipe solution with a departure temperature of 130° C at the Erskine platform and an arrival temperature at the Lomond platform of 85° C. It was considered critical that the shape of the pipeline be monitored at appropriate intervals during the operational life of the pipeline. The perceived through life cost of achieving survey results by traditional methods was considered to be extremely high whereas the use of an inspection tool such as SAAM being many orders of magnitude less. This provided considerable motivation to develop a tool that could cope with the elevated temperature. RST were therefore commissioned to instigate a research programme to establish the possibility of extending the temperature capability of the electronic components carried within the SAAM tool. The project was managed on the basis

that the work would be carried out in small well defined phases. The process followed in achieving a successful outcome is described in the sections of this paper which follow.

THE DESIGN CHALLENGE FOR THE NEW SAAM TOOL

Overall Objective

The challenge the project team faced can be summarised as follows:

”To develop a special SAAM pipeline inspection tool for deployment in the HT Erskine pipeline to provide accurate vertical OOS and other information”

Environment Specification

The standard SAAM tools have a temperature limit of 60°C. whereas the maximum temperature in the Erskine line is 130°C. The time/temperature environment that is experienced by a pig in the Erskine pipeline is shown in Figure 7. It is clear that the duration of exposure to the elevated temperature is relatively short, of the order of a few hours. The SAAM was also specified to operate at 120bar, the MAOP of the pipeline.

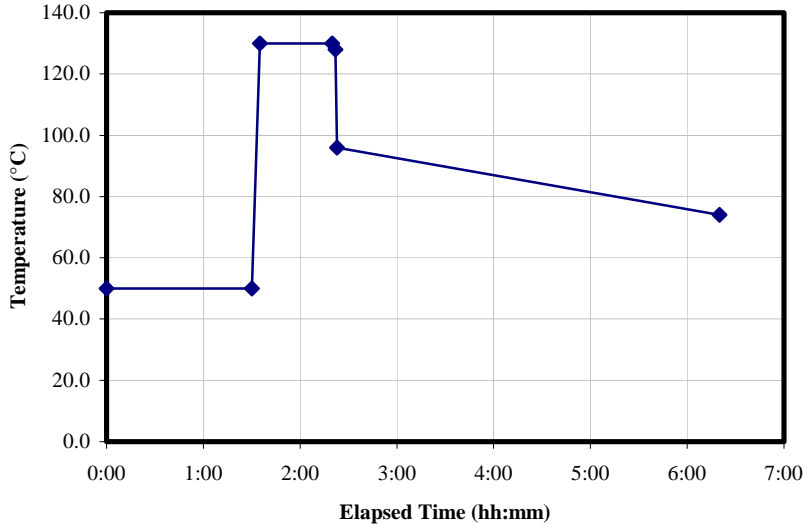


Figure 7 - Time/Temperature environment

Measurement Requirements

As well as logging the inclination data required for the vertical profiling it was specified that the SAAM unit would also log the following parameters:

- temperature and absolute pressure to provide process information;
- differential pressure to identify any variations that may indicate restrictions in the pipeline internal bore, and;
- angular velocity to provide a limited lateral out of straightness capability.

Physical Constraints

Apart from the high temperature the other main challenge of the project was to make the SAAM unit sufficiently small to fit in a 16" pig suitable for the Erskine pipeline. The SAAM carrier pig was specified as one of the standard Erskine pigs which incorporates 10% fluid bypass for pig speed control. In order that the SAAM did not interfere with this bypass it was required to have a diameter of 107mm or less. The maximum length of the SAAM of 450mm was again dictated by the pig design. It was also required that careful consideration be given to the total additional weight and the weight distribution with respect to pig behaviour.

DEVELOPING THE NEW SAAM TOOL

A project team comprising several engineers from RST, ChevronTexaco and Subsea7 were assembled to bring together experience in a number of areas including SAAM inspection tool development, pigging and pipeline engineering and thermal analysis.

Potential Solutions to the HT Challenge

The development process started by trying to generate as many potential solutions as possible to the primary challenge, namely that of the HT environment. It was then a process of systematically evaluating these ideas to determine the optimum solution. It was clear at the outset that there were a number of situations within industry in which data acquisition is successfully carried out at high temperature. As a consequence one of the main thrusts of the early investigations was to make contact with individuals and organisations with experience in this field whilst also looking for other novel technologies with potential application to the particular

challenges of the project. At the culmination of the initial research stage a total of 22 different potential solutions to the HT challenge had been generated. A selection of these are included in the Table 1.

Design and build a new SAAM with components capable of operating at 130°C	This option would involve sourcing suitable components capable of operating at 130°C. Where such components could not be sourced they would have to be developed. This approach has been adopted (by others) for situations where the exposure to the HT environment is permanent. It was very quickly determined that the costs and timescales associated with this method were likely to be relatively high.
Insulating Materials	Conventional insulating materials, such as polyurethane foams could be utilised to protect the SAAM unit from exposure to the HT environment.
Phase change materials (PCMs)	Phase change materials (PCMs) are "latent" heat storage materials. The thermal energy transfer occurs when a material changes from a solid to a liquid, or from a liquid to a solid. Initially these materials perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional materials, when PCMs reach the temperature at which they change phase (their melting point) they absorb large amounts of heat without getting hotter. PCMs are used in a number of different products including: protective clothing (fire-fighters equipment); building heating where they absorb heat by day and discharge it at night, and; for protection of sensitive electronic equipment during short term exposure to sunlight.
Vacuum flask	The entire SAAM system could be contained within a vacuum flask.
Pre-cooling the SAAM tool	By lowering the temperature of the SAAM tool prior to its deployment in the line its final temperature after the pigging

	run would be lower.
Heat pump system (refrigeration)	A range of technologies exist which utilise different refrigeration techniques. One particular product is designed to be integrated with a drinks cans to provide "instant cooling" of the contents
Run the SAAM pig in a pig train with a cool slug of liquid	The SAAM pig would be surrounded by a slug of (cool) liquid protecting it from exposure to the HT environment

Table 1 - Potential Design Solutions

Selection of the Optimum Solution

A SWOT analysis was carried out on the different potential solutions and the following final short list of options was developed, namely:

- PCMs
- Vacuum flask
- Insulating Materials

The final selection was carried out on the basis of the following criteria:

- Final temperature of the SAAM electronics based on the results of computer modelling, using an adaptation of a software package used in pipeline design.
- Technical risk. An assessment of the probability that the option would yield a solution to the challenge.
- Physical size (diameter and length) and weight.
- Cost.
- Lead time

PCMs were an attractive solution however there was some concern relating to their containment in the liquid phase. They would require containment in a cylindrical sleeve that would fit between the SAAM electronics and the pressure casing, this presented significant difficulties in fabrication whilst also introducing significant additional weight.

While the use of insulating materials represented the cheapest option the modelling predicted both the diameter and the internal temperature would be at the limit of the specification resulting in significant technical risk.

The preferred solution was to utilise a vacuum flask. A US based supplier of custom designed vacuum flasks for downhole instrumentation packages was identified and it was determined that their product could be readily customised to meet the requirements of the project. These flasks, designed and manufactured by Mitco and known as the Thermoshield, are also pressure rated and the materials specified for the hydrocarbon environment. These factors had the effect of significantly reducing the technical risk associated with this option.

Detail Design of the SAAM Tool

The main parts of the new SAAM tool are identified in Figure 8.

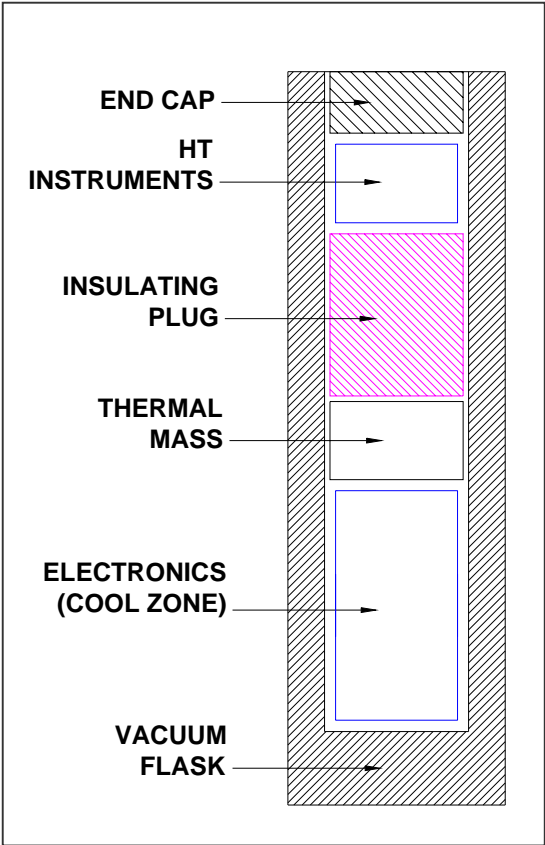


Figure 8 - Schematic of the HT SAAM system

- The Vacuum Flask - This part was custom designed to meet the specific thermal and dimensional requirements of the project.

- The End Cap - This part houses the seals that maintain the pressure integrity as well as holding various instruments.
- The HT Instruments - Due to the limited insulation afforded by the end cap the components in this part of the SAAM require to be rated to the full 130°C. These components, which included the pressure gauges, temperature gauge and pressure switch, were all readily available adaptations of "standard" parts.
- The Insulating Plug - As with a drinks flask the main source of heat "leakage" is through the opening. This insulating plug acts to minimise the heat transfer from the hot to the cold zones. Based on the requirements of a low thermal conductivity, with good strength at a relatively high operating temperature (130°C), and good machinability, a PEEK resin was selected. The effectiveness of the PEEK as an insulator was highlighted when the thermal analysis subsequently predicted the heat transfer along the electrical loom (several copper wires) from the hot to the cold zone would be far greater than that through the insulating plug. In fact this heat transfer along the wiring had such a significant effect that the final design incorporated running this loom in a spiral around the PEEK in order to maximise the length of the heat transfer path. This feature can be clearly seen in Figure 9.
- The Thermal Masses - These are required to absorb the heat generated internally by the SAAM electronics (self heating). The thermal modelling predicted that in the final design the self heating effect would be greater than the effect of the heat transferred through the vacuum flask and the insulating plug. These masses act as heat sinks absorbing the heat thereby preventing the temperature of the electronics rising to unacceptable levels.
- The Electronics - The standard SAAM electronics were modified slightly to increase their maximum operating temperature from 60°C to 85°C. In addition the power supply circuitry was redesigned to increase its efficiency thereby minimising the self heating effect.

The completed SAAM tool is shown in Figure 9.



Figure 9 - The Erskine SAAM system

Temperature Testing

Upon completion of the build of the new tool, and prior to deployment in the Erskine pipeline, a series of tests were carried out in an environmental test facility. When exposed to the time/temperature environment that is experienced by a pig in the Erskine pipeline (see Figure 7) the temperature measured in the cool zone of the tool increased from 20°C to 48°C, well within the limit of the electronics. This served to validate the thermal modelling work and to confirm the tool was capable of withstanding the temperature environment in the Erskine pipeline.

A subsequent test, the results of which are presented in Figure 10, further demonstrated the effectiveness of the chosen solution. After 10hours exposure to an external temperature of 130°C the cool zone temperature of 80° was still within the 85°C limit of the electronics.

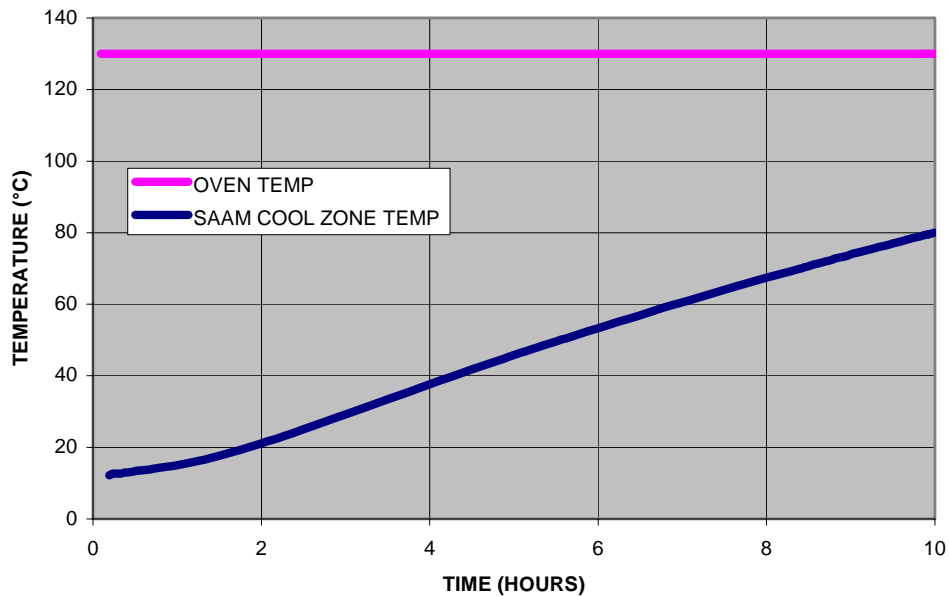


Figure 10 - Temperature test results

SAAM SURVEY RESULTS

First (Hot) Survey

The newly developed SAAM tool was deployed for the first time in the Erskine pipeline in May 2002. The pipeline was in normal operation at elevated temperature. The tool successfully logged data from all instruments for the entire length of the pipeline enabling an elevation profile of the pipeline to be calculated thereby meeting the primary objective of the project. The analysis of the data [4] produced the following results/observations:

- The elevation profile, part of which is shown in Figure 11, revealed no significant OOS features.
- The pig stopped for a period of 2hours 7minutes in the Erskine tie in spool. As can be seen from Figure 12 this resulted in the exposure of the tool to the elevated temperature lasting significantly longer than was anticipated.
- Behaviour consistent with slug flow was observed in the latter part of the line with the pig actually stopping on several occasions.
- There were no differential pressure anomalies consistent with mechanical damage or other bore restrictions.

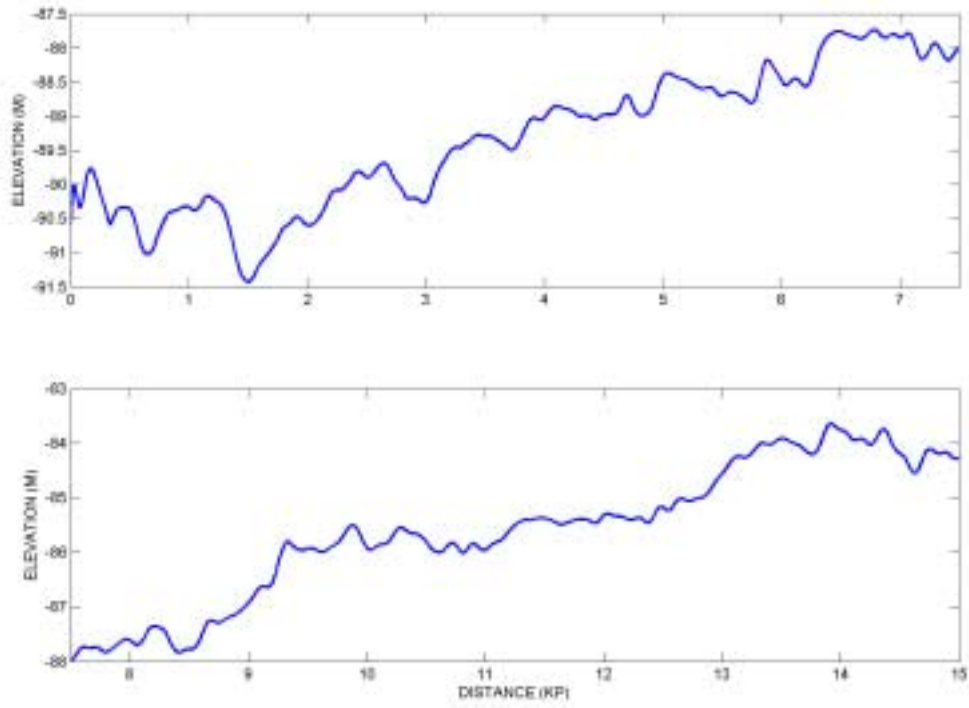


Figure 11 - Partial elevation profile from SAAM survey no. 1

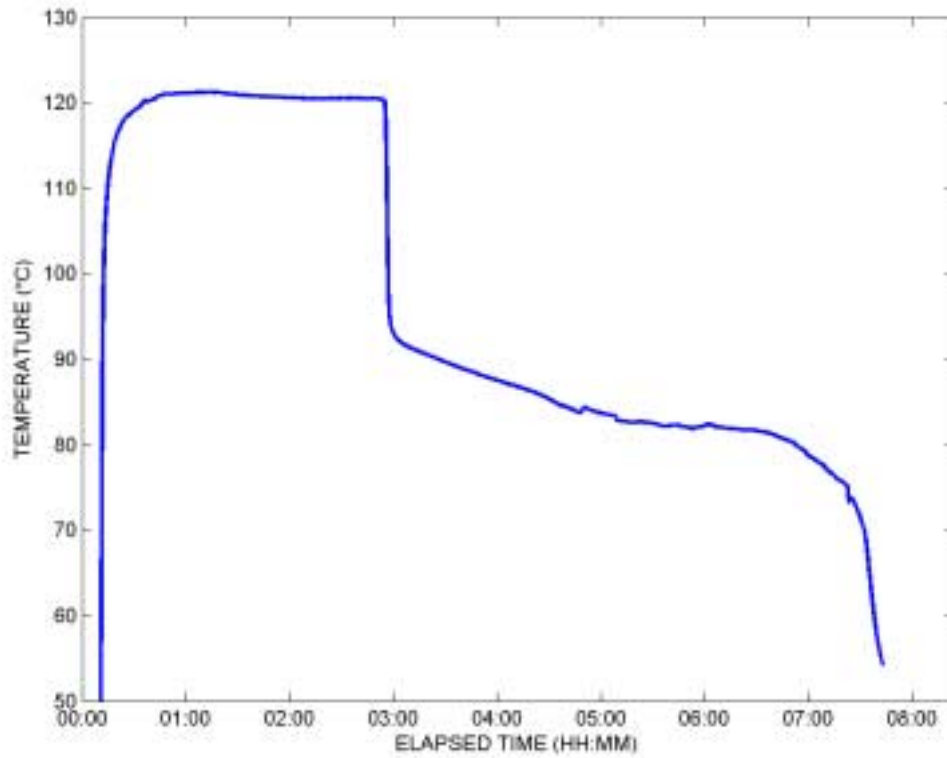


Figure 12 - Temperature sensor measurements from SAAM survey no. 1

Second (Cold) Survey

The tool was deployed in the Erskine line for the second time in September 2002 immediately following a shutdown of the pipeline. The objective on this occasion was to inspect the line in a cooler condition in order to identify possible changes in the pipeline profile due to thermal effects. The SAAM was in fact pigged into the line for a short distance immediately prior to the shutdown. It then remained in a "power saving" mode for several days until the SAAM vibration sensor detected the pig motion as production was restarted, at which point the SAAM recommenced the inspection. The pipeline temperature at this stage was approximately 40°C cooler than during the first SAAM survey. The analysis of the data [5] produced the following results/observations:

- There was no evidence of movement of the pipeline, the correlation between the 2 profiles was good. An example is shown in Figure 13.
- The pig did not stop at the Erskine tie in spool as it had in survey 1.
- As in survey 1 there was behaviour consistent with slug flow.
- As in survey 1 there were no differential pressure anomalies consistent with mechanical damage or other bore restrictions.

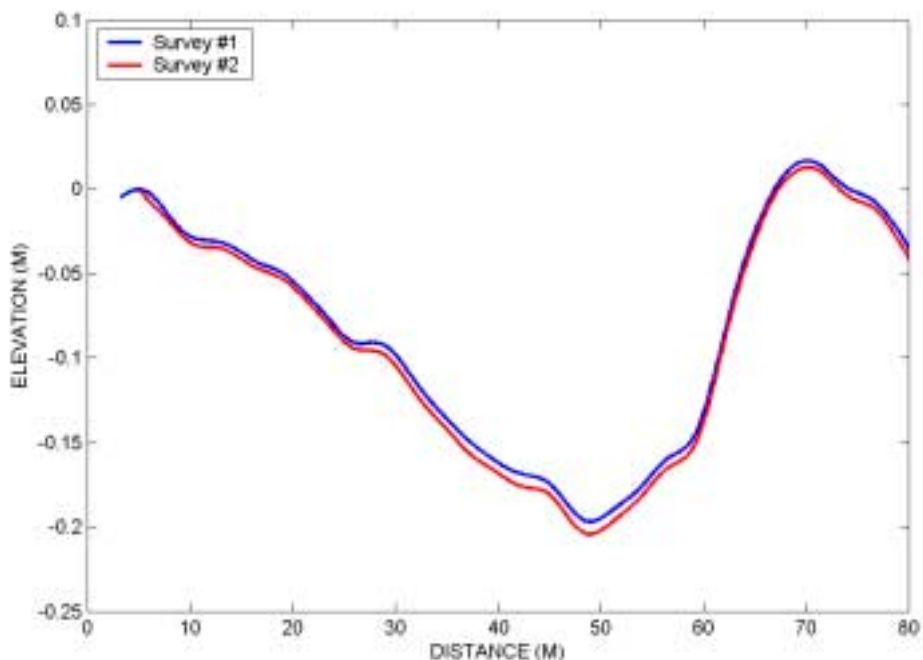


Figure 13 - Out of straightness feature comparison from SAAM surveys 1 & 2

CONCLUSIONS

The project was a technical success as is clear from the fact that the SAAM pig was deployed and recovered without any adverse effect on either the pipeline normal operating conditions or the SAAM electronic components. The pipeline operator now has a relatively low cost means of monitoring the vertical out of straightness of the pipeline, whilst RST have extended the operational temperature range of their SAAM tool. However the key critical success factor was the speed with which the technical challenges were discovered and overcome by both parties. Had this been undertaken in using the normal JIP route, the outcome may have been the same, but it would have taken considerably longer; the option identification, analysis and filtering process can be considered as instrumental in that respect. The work was conducted within what might be considered as being a low band of expenditure in relation to the complexity of the design challenge. Certainly, the expenditure to reach this satisfactory solution is extremely low when compared against the technology it replaced. The commercial success is extended by the fact that the work was completed in a time frame which enabled the high temperature version of a proven tool to be introduced within a predetermined inspection window.

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