Proceedings of IPC 2004
International Pipeline Conference
October 4 - 8, 2004 Calgary, Alberta, Canada

IPC04-0497

SMART UTILITY PIGS USED TO DETERMINE AND MONITOR PIPELINE OUT-OF-STRAIGHTNESS, WITH SPECIFIC REFERENCE TO INSPECTION OF BP ALASKA'S 10" NORTHSTAR CRUDE OIL PIPELINE

Bob Snodgrass
Weatherford Pipeline & Specialty Services
515 Post Oak Boulevard
Houston, TX 77027
Tel: 713-693-4000
Email: bob.snodgrass@weatherford.com

David Moore
BP Exploration (Alaska), Inc.
900 East Benson Boulevard
Anchorage, AK 99519
Tel: 907-564-4190
Email: mooredh@bp.com

Barry Nicholson
Weatherford Pipeline & Specialty Services
Unit 3, Newhailes Industrial Estate
Musselburgh EH21 6SY, Scotland
Tel: +44 (0)131 653 3700
Email: barry.nicholson@eu.weatherford.com

ABSTRACT

Through necessity many pipelines and flowlines are required to operate under conditions where their position may be displaced over time. Such movements can occur for a wide variety of reasons, but are most commonly associated with either movement of the physical surroundings of the pipeline causing movement of the pipeline itself, and/or thermal changes in the pipeline causing expansion and contraction. Displacements as described result in the pipeline experiencing increased levels of strain at local out-of-straightness events, potentially resulting in pipeline failure.

The ability to measure and monitor pipeline displacements, in particular identifying specific regions of out-of-straightness, is valuable to both the existing pipeline operator who wants to operate their assets safely, and also to the pipeline designer who is able to design future pipelines with the knowledge that such monitoring capabilities exist. Smart Utility Pig technology measures the longitudinal shape of a pipeline using an onboard accelerometer and angular velocity sensors. The data logged by these instruments allows out-of-straightness features to be identified and profiles of the vertical and horizontal shape of each to be calculated.

This paper presents an overview of the requirements for such Smart Utility Pig technology, and details of out-of-straightness measurement applications. In particular, projects are identified where the technology has been deployed in such a role, including specific reference to BP Alaska's 10" Northstar crude oil pipeline.

Keywords: pipeline inspection, out-of-straightness, pipeline movement, thermal expansion, Northstar, smart utility pig, SAAM®.

NOMENCLATURE

The following nomenclature and abbreviations have been used in this paper:

AUV Autonomous Underwater Vehicle
GPS Global Positioning System
OOS Out-of-straightness
SAAM Smart Acquisition Analysis Module (a registered trademark of Weatherford)

PIPELINE MOVEMENT

Many pipelines and flowlines are required to operate under conditions that cause them to move over time. This movement, whether lateral or vertical, is most commonly associated with either movement of the surrounding physical environment causing movement of the pipeline, or thermal changes in the pipeline causing expansion and contraction of the pipe.

Changes in the surrounding physical environment of the pipeline can be initiated through human activities and events of nature. Some examples include mining, construction, excavating, dredging, trawling (fishing), floods, mudslides, ocean currents and earthquakes. Changes in the pipeline's actual temperature can also cause pipeline movement.

When these forces are significant enough to move a pipeline, then the issue becomes one of concern for the pipeline operator and designer. When the pipeline moves, temporary or permanent changes in the pipeline's longitudinal shape may occur. This is of particular concern when anchors supporting the pipeline (natural or intended) cause the pipeline movement to occur at localized 'out-of-straightness' (OOS) events, and consequently increase strain in the pipeline.

MEASURING PIPELINE MOVEMENT

The forces that act on a pipeline and cause local out-of-straightness events are not easy to accurately predict, particularly when they act in tandem to various extents over the life of the pipeline, when operating and environmental conditions can change significantly. This results in a desire to be able to measure and monitor such pipelines for the formation of local out-of-straightness events, which are caused by pipeline movement resulting in increased levels of strain and potentially ultimately pipeline failure.

The ability to measure and monitor pipeline longitudinal shape, in particular identifying specific regions of local out-of-straightness, is valuable to both the existing pipeline operator who wants to operate their assets safely, and also to the pipeline designer who is able to design future pipelines with the knowledge that such monitoring capabilities exist.

When considering the measurement options, key considerations are ease of use, accuracy (and resolution) of results, and cost. The ideal solution will enable accurate information to be obtained easily on a cost effective, regular basis, for the length of the region of concern.

The variety of techniques employed for measuring and monitoring the longitudinal profile of a pipeline are broadly divided into two groups:

- External Surveys
- Internal Measurement Pigs

External OOS surveys of offshore pipelines are traditionally carried out by a remotely operated vehicle (ROV) housing acoustic or magnetic systems to track the pipeline. These are normally tethered, however an autonomous underwater vehicle (AUV) can be used providing more freedom of movement and better positioning capabilities [1]. Both technologies are deployed at a relatively high cost requiring a support vessel and crew for the duration of the survey, and do not always produce results of desired accuracy particularly when pipelines are buried.

External surveys of onshore pipelines are normally carried out by field crews using GPS or surveying equipment to acquire data on the physical location of the pipeline. This can also be costly and time consuming, and not always possible in the case of buried or inaccessible pipelines. However, it provides a good baseline of the as-laid profile of the pipeline when carried out during pipeline construction.

An internal measurement pig is deployed inside a pipeline and logs data on the pipeline's longitudinal profile as it traverses along its route. This provides time and cost benefits, as the pig does not require any support as it travels through the pipeline. Specifically designed and deployed pigs with strap down inertial navigations systems are one such internal measurement pig, providing good quality results [2], however the per survey cost can be quite high, thus making regular deployments unattractive.

Weatherford's 'Smart Utility Pig' technology (the 'SAAM®') provides an alternative internal measurement pig solution that can provide quality results for specific information on a more regular basis, due to its lower relative cost and ease of use. *SAAM* is a Weatherford-owned technology, and is deployed inside a standard bi-directional cleaning pig. The technology is based on the principle that as the pig travels through the pipeline its dynamics are affected by the shape, internal condition and content of the pipeline. Data logged by the unit consists of Vibration, Differential Pressure, Absolute Pressure, Temperature, Acceleration (inclination) and Angular Velocity (two channels). The tool is fitted to the cleaning pig prior to the survey and then launched by the operator as per standard cleaning pig operating procedures. Post survey, the logging unit is removed from the pig and the data uploaded for analysis.

The technology has been deployed in over 70 projects, inspecting more than 3,300 miles of pipeline. Applications of the technology include: assessment of internal corrosion [3]; identification and location of paraffin wax and debris [3,4]; identification of mechanical damage or bore restrictions [5] and logging of process conditions such as temperature and absolute pressure. In addition to these, the technology provides a cost effective solution for measuring the longitudinal profile of a pipeline to identify local OOS events. This is carried out by interpretation of the data acquired by the acceleration and angular velocity data channels.

METHODOLOGY

Pipeline vertical OOS features are identified from characteristic changes in the signal generated by the logging unit's on-board accelerometer. The accelerometer logs at a sample rate of 22.84Hz and generates a signal covering the full length of the pipeline. Changes in the acceleration signal can represent either:

- A change in the attitude of the pig as a result of a local change in the pipelines vertical profile;
- A large change in pig velocity; or
- A change in the attitude of the pig within the pipeline caused by the pig pitching. This can be caused by the pig passing over wax or debris in the pipeline.

The effects of the latter two are normally identified and accounted for, allowing the acceleration data to be used to generate a vertical OOS profile of the pipeline. A typical accuracy for the vertical plane during steady state behavior is ±0.05% to ±0.09% of the horizontal distance traveled. For example; an OOS feature with a 7ft vertical change over 650ft distance will be profiled with an accuracy between 4" – 7".

Horizontal OOS features are identified and profiled using the signal generated by the two angular velocity sensors. These sensors are fitted on-board the *SAAM* unit, orientated at 90° to each other and to the axis of the logger and pig. The sensors measure changes in the horizontal orientation of the carrier pig (in degrees per second) allowing a horizontal profile of the pipeline to be calculated. As with the vertical OOS calculations, changes of the horizontal orientation of the pig within the pipeline can result in potential inaccuracies due the effects of wax or debris. However, such changes can be identified and corrected. Horizontal OOS features are profiled with an accuracy of ±0.5% to ±0.9% of the distance traveled along the pipeline.

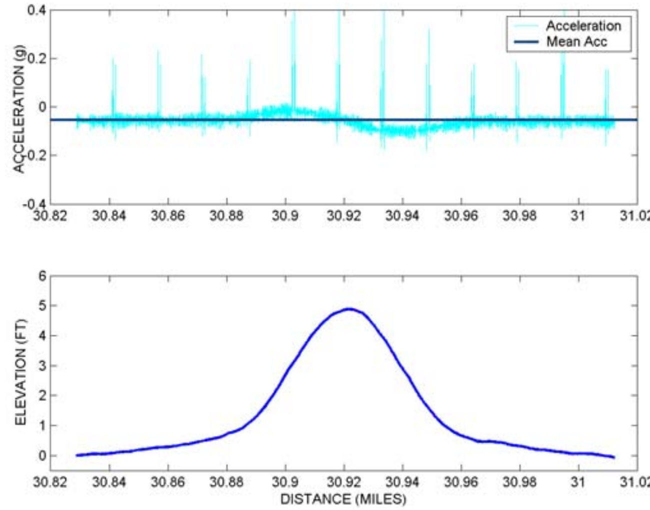
The process involved in OOS calculations is illustrated in the following worked examples originating from data acquired from a *SAAM* survey of the BP GAEL 24" Southern Spur Oil Pipeline in the UK North Sea. This was completed in December 2002 with the objective of calculating the longitudinal profile of the pipeline at regions containing local changes in vertical or horizontal OOS.

The procedure followed to calculate a local vertical OOS profile from the acceleration signal consists of two stages:

- A correction is applied to the raw acceleration data across in order to correct for the static orientation of the pig within the pipeline. This is carried out by subtracting the mean value of acceleration across the region being profiled from the raw acceleration signal. This consequently results in a mean acceleration of zero across the region to be profiled.
- The corrected acceleration trace is integrated with the distance traveled by the pig to generate a local elevation profile.

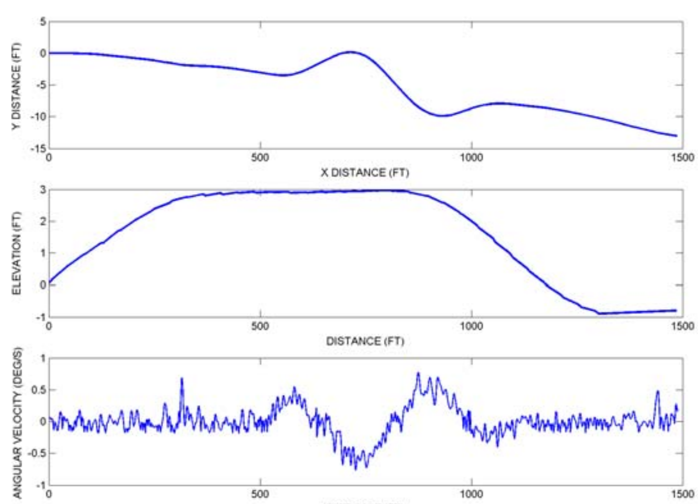
This is demonstrated by Fig. 1 showing the raw acceleration signal and resulting vertical profile at a pipeline crossing in the GAEL pipeline. Also plotted is the mean value of the acceleration signal showing the correction to be applied.

Figure 1 – Raw acceleration data and resulting elevation profile



The procedure to calculate local horizontal OOS profile is slightly more complex. The signals generated by the two angular velocity sensors are combined to form a single trace and a correction is applied to remove the effects of the static offset of the pig within the pipeline, and the effects of temperature on the angular velocity sensors. The vertical component of the pipeline profile is removed from this combined signal leaving only the horizontal component of the pipeline profile. This is integrated with the distance traveled by the pig to generate a horizontal profile of the pipeline. Figure 2 contains an example horizontal profile (top panel) calculated from the data acquired in the GAEL pipeline. Also shown is the local vertical profile (middle panel) and the combined signal from the angular velocity sensors (bottom panel).

Figure 2 – 3D OOS feature: plan view, elevation view & raw data



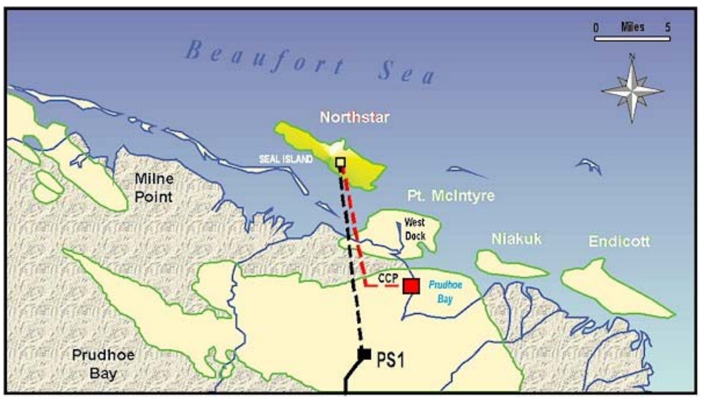
THE NORTHSTAR FIELD

Northstar is an offshore oil field, encompassing about 60 square miles, located in the Alaskan Beaufort Sea [Fig. 3]. It is about 4 miles northwest of the Point McIntyre field and 6 miles from Prudhoe Bay. Seal Island is a gravel island of approximately 5 acres constructed over the remains of the island built by Shell Oil Company to conduct exploratory activities during the 1980's. Northstar Development Project came on-stream in October 2001.

Two pipelines have been buried in a single trench from the island to existing onshore facilities to transport hydrocarbons to and from the Northstar Unit. The pipelines include one 10-inch common carrier pipeline from the island to Pump Station No. 1 to transport the sales oil to TAPS. The second 10-inch pipeline facilitates the import of hydrocarbon gas from the Central Gas Facility in the Prudhoe Bay Unit to assist with the gas cycling process used to produce the Northstar Pool.

The Northstar pipelines are the first buried subsea pipelines constructed offshore in the Beaufort Sea. The pipelines are buried 7-11 feet below the seafloor to avoid ice impacts.

Figure 3 – Northstar field and pipelines



ENVIRONMENTAL LOADS ON THE NORTHSTAR PIPELINES

Several environmental loads can cause pipe movement and subsequent strains. The Northstar pipelines have been designed to allow for up to 1.2% strain as a result of soil displacements. Ice gouging, thaw settlement, upheaval buckling, and strudel scour were considered.

During the winter and spring break-up months, driven by winds and currents, grounded and floating first-year sea ice ridges and rubble fields may drag on the Arctic seafloor causing the formation of ice gouges. In addition, multi-year ice invasions during the summer and freeze-up periods may also contribute to the formation of ice gouges. Ice gouging can move the pipe either by direct contact or indirectly by soil movement below the keel of the ice. In the case of Northstar the pipeline burial depth was chosen to avoid excessive strains as the result of ice gouging.

Warming of the frozen soils by the production fluid causes thawing. The degree of thaw settlement will depend on the soil properties and the presence of excess ice. Many permafrost soils may be thawed without causing settlement. At Northstar ice bonded permafrost exists in the shallower waters near shore. The trench was over-excavated and backfilled with a thaw-stable material to reduce settlement in ice-bonded permafrost areas.

Upheaval buckling is not unique to the arctic. It occurs when vertical forces at pipeline overbends exceed the soil restraint of the backfill. The pipe moves up and may or may not become exposed. This does not necessarily result in a buckle. It does induce additional bending and strain on the pipe. In the case of Northstar it also increases the exposure to ice impact.

Strudel scour can occur in the spring during river breakup. Large areas of sea ice along the arctic coast are flooded by the discharge from coastal rivers. The floodwaters drain through holes in the ice forming a whirlpool that can cause craters on the sea floor in shallow water areas. These craters have been called strudel scours [6]. Strudel is the German name for whirlpool. Strudel scour can lead to upheaval buckling or settlement as a result of the loss of backfill and supporting soil.

THE NORTHSTAR 'SMART UTILITY PIG' PROJECT

A *SAAM* Smart Utility Pig was deployed in the Northstar 10" Crude Oil Pipeline in October 2003 housed within a Girard Bi-directional cleaning pig [Photograph 1]. The main objective of the project was to identify and profile locations of 3D OOS and a secondary objective was to assess the internal condition of the pipeline with respect to paraffin wax formation. Data was available from three surveys from which to assess the pipeline profile. The pigs were launched on successive days from Seal Island Production Module and pushed through the pipeline with a pigging speed between 9ft/s – 10ft/s resulting in an average transit time of 2h 44min. On receipt, the logger was removed from the pig in order to upload the acquired data. The logger was then re-housed in the pig and returned to the launch site for the next survey.

Photograph 1 – Standard bi-di pig containing SAAM unit

Following the surveys the raw data traces were accurately positioned in the pipeline by identifying each of the welds from the characteristic kick in the vibration signal, and reference to pipeline drawings aided in fixing the locations of physical components in the pipeline such as crossings or valves. For each survey a full length vertical profile of the pipeline was generated [Fig. 4]. Analysis of these identified a ¾" midspan sag between each of the pipeline supports throughout the whole onshore section of the pipeline [Fig. 5].

Figure 4 – Full length elevation profile

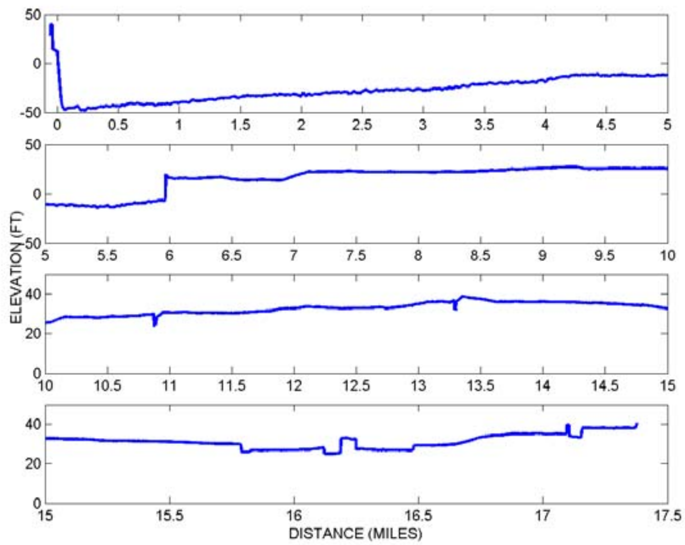
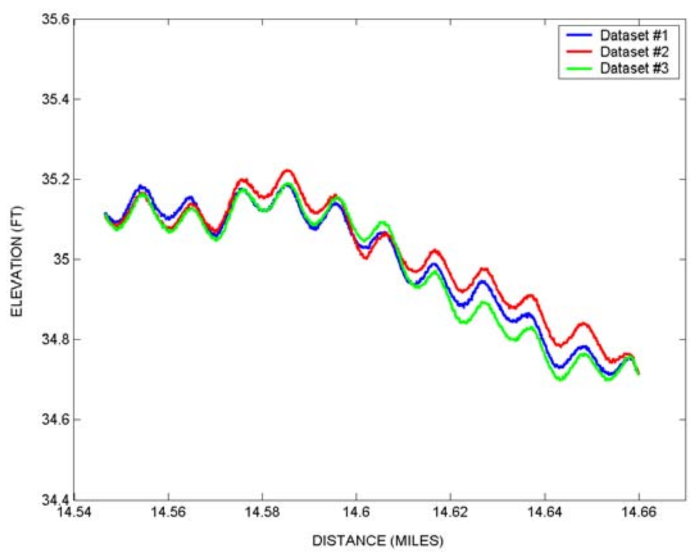


Figure 5 – Onshore midspan sags



The analysis provided the operator with 3D profiles of 21 locations of local pipeline OOS. All were vertical in nature, containing a change in elevation between 1.2ft to 4.4ft, and all except one were located in the offshore section of the pipeline. At each location, the lateral and vertical profile of the pipeline was calculated using each of the three datasets, and a composite profile was generated. Two OOS features were highlighted as significant. The first of these was located in the offshore section of the pipeline consisting of a 4.4ft peak in elevation over a distance of less than 200ft [Fig. 6]. The second feature was located in the onshore section of the pipeline, consisting of a 1.5ft sag at the downstream end of a supported river crossing [Fig. 7]. It should be noted however that the pipeline strains are what is critical to determining the integrity of the line. Large out of straightness events with gentle even curvature are not necessarily an integrity problem.

Figure 6 – Elevation peak in Northstar pipeline

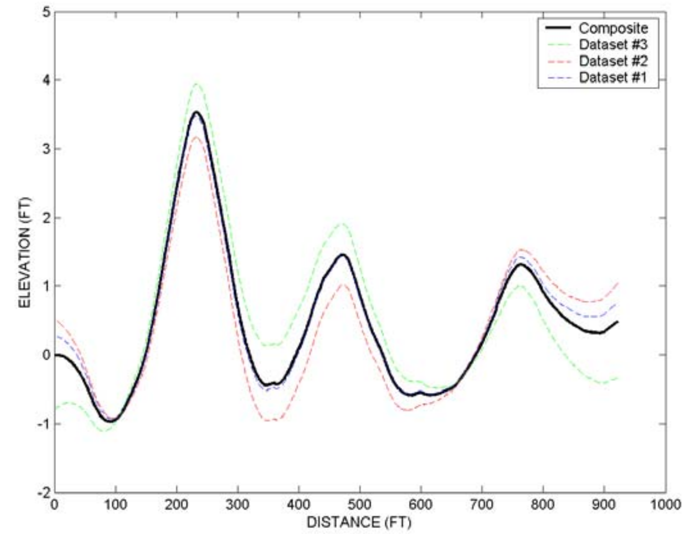
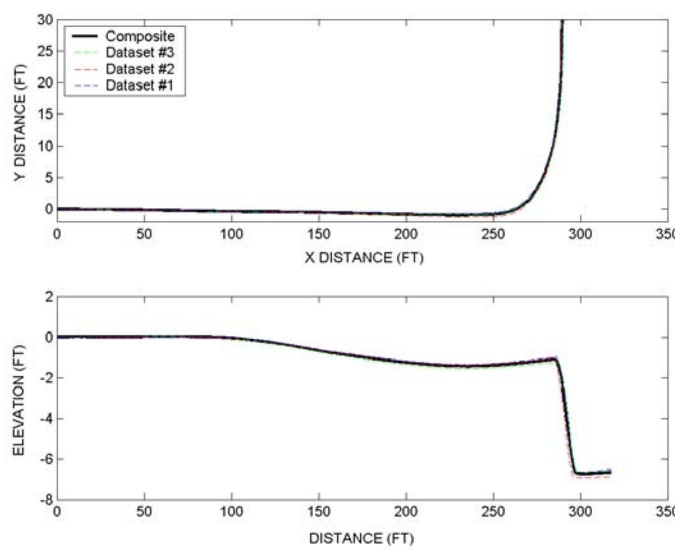


Figure 7 – Sag at end of pipeline crossing



The results provided the operator with the pipelines longitudinal profile. This profile can be compared with the known as-laid profile of the pipeline and with past and future surveys of the pipeline in order to monitor for potential vertical or horizontal movement. The profile and OOS information are being further processed by the operator to develop pipeline curvature and strain profiles for the line.

CONCLUSIONS

A successful program of surveys was completed in the Northstar Oil Export pipeline. The subsequent results confirmed to BP that there were no OOS features in the pipeline that give cause for concern at the time of the surveys. In addition the work, in conjunction with previous projects such as described in BP GAEL, has proven the suitability of the *SAAM* Smart Utility Pig technology in profiling pipeline local OOS events.

REFERENCES

[1] – Doyle, Howie and Troscinski, Susan. "From Survey to Start-Up New Technologies Conquer the Ocean Deep". Underwater Magazine, 1997.

[2] – Czyz, Jaroslaw and Wainselboin, Sergio. "Monitoring Pipeline Movement and its Effect on Pipe Integrity Using Inertial / Caliper In-Line Inspection". Rio Pipeline Conference & Exposition, 2003.

[3] - Short, Gordon and Flett, Dave. "New Approach To Pipeline Condition Monitoring Of The Beatrice 16" Oil Export Line". 4th International Pipeline Conference, Calgary, Alberta, Canada 2002

[4] – Case, Richard; Hare, Simon and Snodgrass, Bob. "Smart Pigging During Deep Flowline Cleaning Demonstrated By Weatherford". Pipeline & Gas Journal, December 2003.

[5] - Russell, David and Short, Gordon. "Pipeline Mechanical Damage Detection, Assessment and Monitoring Using the SAAM Pipeline Inspection Tool". Brazilian Petroleum & Gas Institute - IBP 3rd Seminar on Pipelines, Rio de Janeiro, Brazil, 2001

[6] - Reimnitz and Bruder, 1972; Johnson, 1985