Contract No. DTRS56-95-C-0003

TEXAS TRANSPORTATION INSTITUTE

Analysis of Pipeline Burial Surveys in the Gulf of Mexico—Task 2

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

in cooperation with the
U.S. Department of Transportation
Research and Special Programs Administration
Office of Pipeline Safety

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
Task 2		

4. Title and Subtitle	5. Report Date
ANALYSIS OF PIPELINE BURIAL SURVEYS IN THE GULF OF MEXICO (TASK 2)	June 1997 Revised March 1998
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Wayne A. Dunlap, Billy L. Edge, and Gerald L. Ellsworth	Task 2

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Contract No. DTRS56-95-C-0003

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
COTR: U.S. Department of Transportation Research and Special Programs Administration Office of Pipeline Safety (DPS-13) 400 Seventh Street, SW, Room 2335 Washington, D.C. 20590-0001 ATTN: Mr. Gopala Vinjamuri	Final: June 1995 to September 1996
	14. Sponsoring Agency Code

16. Abstract

A comprehensive study was conducted to determine the need for inspections of pipeline burial depth in

17. Key Words	18. Distribution Statement
Pipelines, Pipeline Burial Inspection, Offshore Pipeline Surveys	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	100	

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ACKNOWLEDGMENTS

The authors would like to thank the many people who provided input to this study. Personnel from pipeline companies, survey companies, pipeline consultants, fishing industry and regulatory agencies were interviewed during the come of the study. All provided a warm reception and candid discussion regarding the results of depth of burial surveys and made positive recommendations concerning the frequency of future surveys. Special thanks are also expressed to Mr. Bruce Donnell for the generous loan of many reference materials and to Steve Howard for his work analyzing coastal erosion rates.

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Research Study Title: Determine if Offshore Pipelines' Condition and Depth of Burial Constitute Hazards to Navigation and Develop Potential Methods and Intervals for Periodic Inspections of Any Offshore Pipeline to Reduce Hazards to Navigation

Prepared by

Wayne A. Dunlap, Research Engineer
Billy L. Edge, Research Engineer
Gerald L. Ellsworth, Research Assistant

Sponsored by

The Office of Pipeline Safety
In cooperation with
U.S. Department of Transportation
Federal Highway Administration

June 1997
Revised March 1998

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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SUMMARY

A comprehensive study was conducted to determine the need for inspections of pipeline burial depth in the Gulf of Mexico for pipelines subject to Department of Transportation, Office of Pipeline Safety regulations. The study included analyzing the results of previous surveys which were conducted on all hazardous material pipelines greater than 4½ inches in diameter in "the Gulf of Mexico and its inlets" which lay between the high water line and 15 feet below Mean Low Water, reviewing available literature on pipeline exposure, and interviewing personnel associated with pipeline burial inspections. Interviews were conducted with ten pipeline operating companies, six survey companies, two developers of survey technology, four shrimpers, *two* fishing companies and four additional authorities. The survey results, revealing that at least 2 percent of the surveyed pipelines had inadequate cover, were sufficient to demonstrate the need for future inspections.

This study concluded that the current survey techniques using a sub-bottom profiling sonar, a gradiometer array or divers are effective when used under appropriate conditions, and that anticipated advances in intelligent pig technology have the potential to improve the quality and efficiency of future surveys. This study makes recommendations about clarifying the regulations for pipeline burial and survey requirements, and it proposes the use of risk analysis to determine the periodicity of future surveys. The risk analysis approach evaluates the probability of an individual pipeline becoming exposed and the probability of an accident resulting from its exposure.

The survey periodicity for each pipeline would be dependent on its individual level of calculated risk.

CHAPTER 1

INTRODUCTION

During the 1950s, the young offshore oil and gas production industry began to extend its reach further into the Gulf of Mexico. As technology allowed production of hydrocarbons from greater and greater water depths, more and larger marine pipelines were constructed, developing a trend that is still evident today. The U.S. Department of Transportation, Office of Pipeline Safety (OPS) has jurisdiction over nearly 13,000 miles of marine pipeline in the Gulf of Mexico, and many of these pipelines are still in operation after 30-40 years of service. While the field of pipelining continually grows in sophistication, there are still environmental factors which have not been adequately addressed, and many older pipelines have not benefited from newer technologies.

Collisions of surface 'vessels with marine pipelines have been an ongoing, although often minor, concern for years, but two accidents in the 1980s helped to focus national attention on this hazard. In 1987, the Sea Chief, a fishing boat, collided with a shallowly buried natural gas pipeline killing two crew members, but this only raised cautionary flags with a few concerned individuals. Shortly after that incident was the accident of the Northumberland which made the need for action apparent.

On October 3,1989, the fishing vessel, Northumberland collided with a partially exposed natural gas pipeline in shallow water near the Texas-Louisiana border. The collision caused a major natural gas pipeline rupture which claimed the lives of 11 Northumberland crew members. It required over 15 hours before the flow of natural gas was halted and the fire was extinguished. Although there are many who feel that the navigational prudence of this vessel is in question, the fact remains that the pipeline was not adequately covered in accordance with federal regulations and posed a significant threat to safe navigation.

As a result of this chain of events, Coast Guard Subcommittee Chairman Billy Tauzin introduced the Pipeline Safety Act of 1990 requiring that offshore pipelines be inspected and maintained at the proper burial depth. Public Law 101-599 required all pipeline operators to conduct depth of cover surveys on all marine pipelines greater than 4% inches in diameter which were located in water depths less than 15 feet below Mean Low Water and located in "the Gulf of Mexico and its inlets." The Law required that pipelines that were exposed or posed a hazard to navigation be reburied at the proper burial depth. Operators were required to inspect these pipelines between October 3,1989, the date of the Northumberland accident, and November 16,1992. This law also required the Department of Transportation to within thirty months of the Act's enactment or by May 16, 1992, establish a mandatory, systematic, and where appropriate, periodic inspection program. The permanent inspection program will be based on the initial inspection and other information the Secretary of Transportation has. In this report, the surveys performed in response to this law are referred to as the P.L. 101-599 surveys. This study was sponsored in order to provide answers to this problem.

The tasking of this study, conducted in 1995-1997, was to develop recommendations on the methods and frequency that should be required for future depth of cover surveys. In the come of investigating these issues, many other issues have arisen, and this report attempts to answer the following questions:

- How often should offshore pipelines in the Gulf of Mexico and its inlets be inspected?
- Where are pipelines most likely to be exposed or pose a hazard to navigation?
- What are the most important causes of pipeline exposure?
- What actions will most improve navigational safety?
- What are the most effective methods of measuring pipeline burial depth?

The study included reviewing literature on coastal processes, examining the initial surveys results, interviewing pipeline operators involved with the initial surveys, and interviewing companies involved With technologies for surveying pipeline burial depth. This study was necessitated by the wide range of hydrodynamic and geomorphic conditions in the Gulf of Mexico which makes the problem of regulating pipeline surveys difficult. This report represents an engineering assessment of the issue of pipeline depth of cover surveys, and it does not address the legal or political ramifications of changes to the pipeline safety regulations.

This study shows that future inspections are necessary and will be a valuable aid to navigational safety. The initial inspections found approximately 2 percent of the pipelines surveyed to have inadequate cover. That equates to 207,000 feet of pipeline exposed or posing a hazard to navigation in the coastal zone, an area of dense commercial and recreational navigation. The pipeline operators have taken many precautions to alleviate this problem since they have become aware of it. Their nearly universal perspective on this issue is that they are willing to take the necessary precautions, but they want to be able to devote their resources to the fraction of their pipelines that require attention. This has resulted in an industry consensus that pipelines should be evaluated individually according to their danger of becoming exposed and the risk associated with their exposure. The proposed risk-analysis approach has the potential to facilitate proper regulation of pipelines in the entire nearshore zone.

CHAPTER 2

PIPELINE BURIAL REGULATIONS

This report is on pipelines which are regulated by the United States Department of Transportation, Office of Pipeline Safety (OPS). The OPS pipeline safety regulations are located in 49 CFR Ch.l Parts 190-199. Relevant portions will be repeated in this section. OPS gets its jurisdiction from the Hazardous Liquid Pipeline Safety Act, the Natural Gas Pipeline Safety Act, and the Oil Pollution Act of 1990.

Natural Gas Pipelines

The OPS regulations for marine natural gas pipelines apply to "*pipeline facilities and the transportation of gas within the limits of the outer continental shelf as that term is defined in the Outer Continental Shelf Lands Act (43 U.S.C. 1331)*" as described in § 192.1, with the exception of:

§ 192.1(b)(1)

> *Ofshore gathering of gas upstreamfiom the outletflange of eachfacility on the outer continental shelf where hydrocarbons are produced or where produced hydrocarbons are first separated dehydrated, or otherwise processed whichever faciiity is farther downstream.*

The following definitions are provided in I 192.3:

> *__Exposed pipeline__ means a pipeline where the top of the pipe is protruding above the seabed in water less than 15 feet deep, as measuredfiom the mean low water.*

Gulf of Mexico and its inlets means the waters from the mean high water mark of the coast of the Gulf of Mexico and its inlets open to the sea (excluding rivers, tidal marshes, lakes, and canals) seaward to include the territorial sea and Outer Continental Shelf to a depth of 15 feet, as measured fiom the mean low water.

Hazard to navigation means, for the purpose of the part, a pipeline where the top of the pipe is less than 12 inches below the seabed in water less than 15 feet deep, as measured fiom the mean low water.

Offshore means beyond the line of ordinary low water along that portion of the coast of the United States that is in direct contact with the open seas and beyond the line marking the seaward limit of inland waters.

The OPS regulations for burial of marine natural gas pipelines are as follows:

1192.317

(a) The operator must take all practicable steps to protect each transmission line or main fiom washouts, floods, unstable soil, landslides, or other hazards that may cause the pipeline to move or to sustain abnormal loads. In addition, the operator must take all practicable steps to protect ofshore pipeline fiom damage by mud slides, water currents, hurricanes, ship anchors, and fishing operations.

(b) Pipelines, including pipe risers, on each platform located ofshore or in inland navigable waters must be protected fiom accidental damage by vessels.

§ 192.319(c)

All offshore pipe in water at least 12 feet deep but not more than 200 feet deep, as measured from the mean low tide, except pipe in the Gulf of Mexico and its inlets under 15 feet of water, must be installed so that the top of the pipe is below the natural bottom unless the pipe is supported by stanchions, held in place by anchors or heavy concrete coating, or protected by an equivalent means. Pipe in the Gulf of Mexico and its inlets under 15 feet of water must be installed so that the top of the pipe is 36 inches below the seabed for normal excavation or 18 inches for rock excavation

§ 192.327(g)

All pipelines installed under water in the Gulf of Mexico and its inlets, as defined in § 192.3, must be installed in accordance with § 192.612(b)(3).

The requirements for **a** ***one-time*** **depth of cover** inspection **of offshore** natural gas **pipelines were put** forth **as follows:**

§ 192.612

(a) Each operator shall, in accordance with this section, conduct an underwater inspection of its pipelines in the Gulf of Mexico and its inlets. The inspection must be conducted after October 3, 1989 and before November 16, 1992.

(b) If, as a result of an inspection under paragraph (a) of this section, or upon notification by any person, an operator discovers that a pipeline it operates is exposed on the seabed or constitutes a hazard to navigation, the operator shall-

(1) Promptly, but not later than 24 hours after discovery, notify the National Response Center, telephone: 1-800-424-8802 of the location, and if available, the geographic coordinates of that pipeline;

(2) Promptly, but not later than 7 days after discovery, mark the location of the pipeline in accordance with 33 CFR part 64 at the ends of the pipeline segment at intervals of not over 500 yards long, except that a pipeline segment less than 200 yards long need only be marked at the center; and

(3) Within 6 months after discovery, or not later than November 1 of the following year if the 6 month period is later than November 1 of the year the discovery is made, place the pipeline so that the top of the pipe is 36 inches below the seabed for normal excavation or 18 inches for rock excavation

Hazardous Liquid Pipelines

The hazardous liquid pipelines regulated by OPS are defined in § 195.1. These rules regulate carbon dioxide and highly volatile liquid (HVL) pipelines, but non-HVL liquid petroleum pipelines in the Gulf of Mexico and its inlets, offshore, or in waterways used for commercial navigation are also included. These rules apply only to pipeline sections downstream of *"the outlet flange of each facility where hydrocarbons or carbon dioxide are produced or where produced hydrocarbons or carbon dioxide are first separated, dehydrated, or otherwise processed, whichever facility is farther downstream."* **The definitions provided** in **§ 195.2** *for exposed pipeline, Gulf of Mexico*

and ***its inlets, ofshore,*** and ***hazard to navigation*** are identical to those for natural gas pipelines. The depth of cover requirements for hazardous liquid pipelines are provided in § **195.248** in Table 1.

Table 1. Pipeline Cover Requirements from 49CFR CH1 § **195.248.**

Location	**Cover (inches)**	
	For normal excavation	**For rock excavation'**
Industrial, commercial, and residential areas	**36**	**30**
Crossings of inland bodies of water with a width of at least 100 ft. fiom high water mark to high water mark	**48**	**18**
Drainage ditches at public roads and railroads	**36**	**36**
Deepwater port safety zone.	**48**	**24**
Gulf of Mexico and its inlets and other offshore areas under water less than 3.7m (12 ft) deep as measured from the mean low tide	**36**	**18**
Any other area	**30**	**18**

'Rock excavation is any excavation that requires blasting or removal by equivalent means.

Pipelines in the Gulf of Mexico and its inlets are specifically disallowed any exceptions from these burial requirements. The OPS requirements for a depth of cover survey to be performed on hazardous liquid pipelines are given in §195.413 and are identical to the natural gas pipeline requirements with the exception that gathering lines of 4½ inches nominal outside diameter or smaller were excluded from the survey.

CHAPTER 3

INTERVIEWS

In this study, the investigators conducted extensive interviews with a wide range of parties interested in pipeline depth of cover surveys. In all cases, the interviews included individuals having first-hand knowledge of this issue. As the complexity of this issue and the interest it has provoked became apparent, it was impossible to restrict the interviews to those originally planned. There continue to be more pipeline operators and survey technology developers that have valuable information, and many interested third parties volunteered their expertise solely from their concern over this issue,

Pipeline Operators

The interviews with pipeline operators included ten companies that ranged from relatively small operations to the largest international corporations. The companies had a variety of experiences including the recent acquisition or sale of pipelines. A common factor was that they all had experienced problems with inadequate pipeline cover.

The pipeline operators believe they firmly control their pipeline regulatory compliance programs. There were exceptions. It was evident that some companies had not devoted sufficient resources to their pipeline safety programs. While the majority of the operators had complete records of their pipelines including as-built drawings, design specifications, and maintenance/testing histories, one operator admitted receiving poor records with the purchase of some older lines and did not know if the lines had concrete weight coating. Another pipeline operator noted that their records were complete, but they were spread throughout the large organization; the problem has reportedly been corrected.

The operators gave the impression that pipeline exposure took them by surprise in the late 1980s. Only one company has regularly scheduled depth of cover surveys for all its lines. In this case, the lines are surveyed every one to ten years based on a computerized risk analysis model. Another large company has 6,000 feet of pipeline exposed by hurricane Opal; the pipeline must be reburied soon. This company admitted that it would have been a long time before this problem was detected if another pipeline company had not notified them.

Many of the pipeline companies, although originally opposed to P.L. 101-599, felt that they had gained valuable information from the initial inspection. These benefits included updating inaccurate as-built maps and identifying pipeline problems. Several operators intentionally used mbre expensive survey methods to get the most accurate data. Not all of the operators put this information to good use, however. One company had several severely exposed pipeline segments, even though these pipelines had been surveyed every five years under the regulations for navigable waterways. The operator was unaware of the results of previous surveys and had not investigated these results for trends.

The survey techniques the operating companies used were remarkably similar. The common method was to tow a survey device at right angles across the pipeline behind a differentially-corrected global positioning system (DGPS) equipped small boat. Shallow region and verification checks were generally accomplished by divers with manual probes. The survey device selection somewhat favored the Innovatum multi-system over the sub-bottom profiling sonar (Chirp) which only two of the companies interviewed used. Only one of the interviewed operators reported using the electromagnetic scanning profile (ESP) system; this company did not verify the results using divers. The companies quoted costs for both the Innovatum and Chirp at around $10,000 per day, but the greater speed of the Chirp made it a more affordable option. Diver verifications with the survey results were reported to be within six inches for the Innovatum and within 10 percent of the pipeline burial depth for the Chirp. Several of the operators who selected the Innovatum did so after seeing Chirp sonar demonstrations that they did not consider adequate. One operator stated that early in the survey period the survey companies were very disorganized, and a company that used the Chirp was the only one capable of accomplishing the project effectively. All companies reported satisfaction with the method they finally used but felt that the skill of the Surveyor was a major factor in the accuracy of the results.

The pipeline companies unanimously noted a lack of clear guidance in the survey requirements. These points of ambiguity included:

- The proper interval *spacing* for crossing the pipeline
- The definition of seabed in areas with soft bottoms
- A better interpretation of "the Gulf of Mexico and its inlets" *than* in 49CFR Ch.1 §192.3
- Proper determination of mean low water in areas predominately affected by atmospheric changes in water level

Determining the bottom location was difficult and was approached in a variety of ways. With the Innovatum, the bottom is inherently the level at which the sled is supported while in motion. One operator who used the Chirp said that the surveyor would make a judgment based on the results of the Chirp sonar and the fathometer. In all cases, divers were left to make their own judgments in situ As for crossing intervals, the techniques varied, but 250 and 500 feet were common. Many of the exposed pipeline segments were considerably shorter than this and could easily have been missed. The ambiguity with determining the mean low water level primarily affected the extent of pipeline surveyed. To avoid complication, some operators assumed that the current low tide was mean low water and then surveyed to a depth greater than 15 feet to provide the safety factor. One operator, however, terminated the shoreward extent of the surveys at two feet below MLW. Some operators reported seeking guidance from OPS to determine if their pipelines were considered to be in the Gulf of Mexico and its inlets. Many of them admitted making their own determinations despite their uncertainty about the intent of the regulations.

The pipeline operators downplayed the significance of pipelines that were exposed or posed hazards to navigation. Most of them had an indication of the factors that led to the problem. One operator with pipelines in an inland Texas waterway believes that the problem is bank erosion induced by boat wakes. This has been confirmed by the U.S. Army Corps of Engineers. Many operators reported that the worst problems were in inlets where high currents induced scour and could produce seasonal variations in cover as great as 10 feet. One operator has been forced to replace some waterway crossings using directionally drilled lines due to these seasonal scour patterns. Another operator familiar with the bottom conditions near his pipelines stated that he could control the survey results by selecting the time of year to survey.

The large majority of pipelines were originally installed in trenches and allowed to backfill by natural sedimentation. Almost all the pipeline companies maintain that this method is effective and that trenches backfill reliably. Some of the findings cast doubt on this. One experienced pipeline operator does not believe that natural sedimentation is reliable. He believes that all pipelines in less than 20 feet of water should be directionally drilled or mechanically backfilled. He believes that most of the 2,000 feet of pipeline his company reburied was inadequately covered due to errors in initial construction. Another operator has two pipelines in Matagorda Bay, Texas, which were installed years apart but run parallel, separated by 20 feet. The older line showed no problems, but the newer line lay in a trench that had never properly backfilled, leaving many segments with less than 12 inches of cover. A possible cause is that the jetted trench was very wide with a gradual slope, similar to those divers *created* with hand jets. A different operator recommended an improved method for reburying exposed pipelines. The trade name of the system is the Mud Bug. It is a self-propelled jetting device that attaches itself to the pipeline and is tended by a flexible tether. The reported advantages are that it is safer to use on an operational pipeline than a sled, and it is more effective than hand jetting. In one anecdote, the device stopped itself safely when it was obstructed by a repaired pipeline section the operators had forgotten about.

Hurricanes can uncover and damage pipelines. The actual extent of this damage seems difficult to predict, however. As previously noted, one operator had 6,000 feet of pipeline exposed by Hurricane Opal. Another operator suffered extensive exposure from a hurricane that traveled directly along one of its lines. The depth range most affected by the storm was 25-60 feet below mean low water, and the damaged sections were directly on the storm track. In contrast to that, another operator resurveyed large sections of pipeline after Andrew caused major damage to platforms in the area. In this region the 15-foot contour is several miles from shore. The surveys showed no significant changes in burial depth directly associated with the storm, although dragging anchors caused some damage. There is little known about previous storms' effects due to the lack of survey data. Some of the operators reported minor damage to pipelines from anchors and fishing vessels. A more severe hazard may come from within the petroleum industry fiom penetrations by equipment such as jack-up rigs and work boats. Only one company reported pipeline damage from a recreational boat; pipe burial depth was unknown, and this collision did not result in a rupture.

Pipeline operators wish to see depth of cover surveys regulated intelligently. They believe that a small portion of their lines will be prone to exposure and present a hazard to navigation. Because of this, they consider frequent surveys of the remaining lines to be a waste of valuable resources. Many of the operators are familiar with the concept of risk analysis and would like to see it applied to future survey regulations.

A frequent suggestion was to extend the onshore one-call system into the Gulf of Mexico and its inlets. This would be the easiest method to protect pipelines from industrial activities such as jack-up rigs and dredging, and it would force the compilation of accurate pipeline maps for public use. If this system were convenient to use, there is also the possibility of training fishermen to call in prior to shallow water fishing operations.

Most of the pipeline companies agreed that the best database of Gulf of Mexico pipelines is owned by the survey company, John E. Chance & Associates. The MMS office in New Orleans, Louisiana, also has a very complete database which has recently been released for public use. The survey company, Cochrane Technologies, has also developed a sizable database of pipelines from their extensive pipeline surveys.

Survey Companies

The interviews with survey companies included some who performed the majority of the pipeline surveys. These companies have undergone many changes, and several smaller firms have been acquired, along with their technology, by the larger ones. Where possible, these interviews included representatives from the original firms involved in the surveys. Representatives from two companies that develop survey technology were also interviewed. The purpose of interviewing these survey companies was to learn about difficulties encountered during the surveys, gain first-hand insight into various survey techniques, and to discuss the companies' experiences.

John E. Chance & Associates

This interview included two John E. Chance & Associates representatives in Houston, Texas. The first was involved with the pipeline inspections while working for Chance, and the other's participation in the inspections was under the employment of Wimpol which has since been acquired by Chance. Both had extensive experience performing depth of cover surveys using several different methods. They reported that their most successful survey configuration was an Innovatum magnetometer array mounted on a towed sled. Their procedure was to locate the pipeline starting at the beach and then perform the detailed survey working back towards the beach. In many cases, a shallow draft pontoon boat was used, allowing sled operation near the beach. The remaining areas on the beach were manually probed.

The Innovatum system John Chance used had three magnetometers and Innovatum proprietary software for data processing. This system was leased. Although there were some attempts to survey along the pipeline, the standard method was to cross the pipeline at 90 degree angles at various intervals. Intervals varied but were generally 500 feet or less. The accuracy of this method, compared with manual probing, was given as ±6 inches. The horizontal position of the pipeline was accurately determined by a differential GPS system mounted on the sled.

There were some difficulties surveying with the sled arrangement. The sled had to be towed slowly (about two knots) when crossing the pipeline. The system could make an estimated 4-5 crossings per hour, and they could survey 10,000-15,000 feet per day using intervals of 500 feet. There were only a few instances of the sled becoming snagged on an exposed pipeline. In one incident, they were unable to release the sled. There was some difficulty with following the correct line at pipe crossings, but their pipeline database helped to resolve confusion. Because of the disturbed magnetic field, the accuracy of burial depth decreases when crossing welded joints. When pipes are grouped closely together, the interactive effects of rectified cathodic protection systems will influence the depth of burial results; however, operators do not object to turning the cathodic protection system off during survey operations.

Chance has developed an extensive database of Gulf of Mexico pipeline locations. The database is updated weekly. They are working to convert it to a Geographical

Information System (GIS) format. According to another representative of Chance from their Lafayette, Louisiana office, this database is a collection of 45 years of files from their work for the U.S. Army Corps of Engineers, MMS, pipeline operators, and individual states. Such a database could be invaluable for pipeline regulatory agencies, but Chance felt that it would be difficult for the government to properly maintain it. The idea was advanced of having a private organization, such as Chance, contracted to maintain a database for public use.

The other representative's experience with Wimpol and Chance involved a semi-active detection system known as the Electromagnetic Scanning Profile system (ESP). The system operates by inducing a low voltage (less than 200V), low frequency (less than 10 kHz) signal in the pipeline. The pipeline acts as an antenna, emitting an electromagnetic field at right angles to the pipeline. A single probe is towed across the pipeline at a 90 degree angle from a small boat with a small on-board computer system. The system provides DGPS location information and a real-time display in the field to aid in tracking the pipeline.

The primary advantages of the system are low cost and simplicity of use. It is reported to be completely unaffected by the water and soil conditions. It can locate pipelines buried almost 10 feet deep. The pipeline location is more accurately determined by a second, hull-mounted probe located below the DGPS antenna. In the event the pipeline cannot be physically contacted to induce the current, the current can be induced by coils positioned on the seabed, above the pipe.

There are some drawbacks to the system. The distance along the pipeline that the signal will travel varies from hundreds of feet to tens of miles. This primarily depends on the physical integrity of the pipe and its coating. The most accuracy in measuring depth of cover that can be guaranteed is about one foot.

Both representatives noted difficulties due to the lack of specific guidance in the survey requirements. This was most significant when determining the interval spacing when surveys were performed by crossing the pipeline. Reducing the interval significantly increased the cost and duration of the survey. Other problems noted were clearly defining which lines must be surveyed and a consistent definition of bottom. Another complication for both the ESP and Innovatum sled survey methods is that they were performed from small vessels. For the many remote pipelines, more support vessels had to be used, adding to the survey expense.

Oceaneering

This interview included a representative from Oceaneering in Houston, Texas. He is active in burial depth surveys at inland river crossings, and he was involved with many of the original inspections.

Oceaneering tried many survey techniques with varying success. The system they are now using was extremely successful. They have outfitted a small boat to tow the Innovaturn from a sled and also use a hull-mounted SeaBat multi-beam sonar. They have developed their own software to integrate the multi-beam sonar output with the Innovatum system. This allows them to rapidly survey the pipeline route, getting bathymetric data and detecting obstructions or pipeline spans. Then they retrace the pipeline, crossing at intervals with the sled. The SeaBat multi-beam sonar could be used on the pipeline route to show changes in bathymetry from the initial survey. This method for future surveys would be much cheaper than the Innovatum but depends on accurate vertical positioning of the survey vessel and would not detect pipeline shift due to soil liquefaction.

Oceaneering has tried flying the pipeline to save time and money, but they were not satisfied with the results. They estimated that the survey costs using the Innovatum were $4000/day inland, $5000/day offshore. The cost of offshore surveys can vary from $5,000 to $10,000 depending on site conditions. Oceaneering also tried the Innovatum system mounted on a crawler but abandoned the idea due to mechanical complications.

Oceaneering compared survey methods for the U.S. Navy. The study compared surveys by divers, the TSS-340, and the Innovaturn. Innovatum was selected as the best method.

Odom Hydrographic Systems

This interview included a representative of Odom in Baton Rouge, Louisiana. He worked for Chance for several years during the initial inspections. He was able to provide information about some of the complications that arose in the course of the surveys.

The surveys he performed with John Chance primarily used the Innovatum in its older, three-gradiometer configuration. He reported that problems frequently occurred near other pipelines or structures and near pipe joints. The system would give accurate burial depths only 70-80 percent of the time in these situations. There were also problems identifying the correct reading where the pipelines were clustered coming ashore. He had also used the TSS-340, a pulse-induction system which is used similarly to the Innovatum. In his experience, the TSS had better range than the Innovatum, which is an advantage for ROV-mounted configurations, but it had problems getting repeatable results.

This representative had also used a Chirp sonar. It was used as a towed fish or fixed on the vessel. At first he used two transducers and one receiver but settled on one transducer and two receivers for the best results. The most commonly used unit was the 5-12 kHz version. It was difficult to optimize the configuration, and the system required careful calibration. The sonar was not able to penetrate sand easily. The best configuration eventually involved towing a receiver 100 feet behind the boat, but this became a problem in shallow water.

Cochrane Technologies

This interview was conducted with several members of Cochrane Technologies. Cochrane started doing depth of cover surveys during 1991, the final year of initial inspections, which gave them the benefit of others' experiences. They chose not to use diving methods, felt that towed sleds would be a liability around pipelines, and that ROV systems would require a large capital investment. They also looked at using underwater crawlers or a towed fish as a vehicle for a magnetometer system, but these were not used because of fears that magnetometers would not be able to resolve pipelines in congested areas. Because of these reasons and their experience with sonar, they focused on Chirp sonar methods for the surveys. Cochrane's estimated survey costs are shown in Table 2.

Table 2. Comparative Survey Costs Provided by Cochrane Technologies.

Method	Production Rate	cost
Innovaturn	1 mile/day	$8,000/mile
Divers	¼ - ½ mile/day	$8,000/mile
Chirp	15- 25 miles/day	$ 800/mile

The Chirp and Innovaturn provided depths within 5 percent of those measured by divers. After the first day of surveys, the diver verification checks were usually stopped because of satisfactory sonar results. They have surveyed over 6,000 miles of pipeline.

There were many benefits to using the Chirp. It can survey in water as shallow as 18 inches. Cochrane also removed some lead weight from the unit which reduced the weight to 150 pounds. This allowed it to be towed alongside the boat with a DGPS antenna over the top of the support. The angle at which they cross the pipe depends on the pipe size. For large lines, they may cross at 90 degrees, and they may cross at 45 degrees for lines as small as four inches. Another version of the sonar, known as the X-Star, has a higher frequency and is able to find lines as small as two to four inches. Both units cost around $90,000. The Chirp had some modifications in the course of production which degraded its performance for detecting pipelines, but the Chirp II sonar resolved some of these problems. The optimum speed to tow the unit is 3 knots.

There are some drawbacks to the Chirp sonar that make it not suitable in all locations. It is not capable of detecting pipes under rubble. Grass over a pipeline will absorb the signal. If the pipe is known to be under the rubble, the top of the rubble can be used to approximate the top of the pipe if the rubble has settled into the bottom.

Cochrane has not experienced any problems with biogenic gas absorbing the signal, but sand can reduce the signal penetration.

American Oilfield/Inland Divers

This interview included a representative of American Oilfield/Inland Divers. His background is as a technician, but he has experience with most of the methods used in burial inspections. He gave his opinions on the strengths of various technologies. He also confirmed that John Chance has the best database of pipeline maps.

He felt that the most accurate method is the Innovatum, but its high cost is a major factor. He also considers the ESP method to be very good, but its range is often too short due to degradation by the pipeline coating. He estimated that 90 percent of the initial pipeline surveys had been performed with the Innovatum. He did not favor the Chirp Sonar. He believes it is ineffective in the surf zone and is attenuated by shells and methane.

He noted a lack of guidance in the survey requirements and that certain industry practices had become de facto standards. The bottom of the water column was taken to be the surface which reflects a 200 kHz sonar signal, and the interval used for pipeline passes was 50 feet, 25 feet if less than three feet of cover was detected. Widespread acceptance of these standards has not been confirmed by other surveyors or operators.

Innovatum, Inc.

This interview was with the designer of the detection systems and software for Innovatum, Inc. He described the newest capabilities and configurations of the Innovatum multi-system. Many improvements have been made since the initial surveys were performed.

The array configuration can be customized, but the optimum sensors carried by the system are:

- 4 gradiometers - for magnetic detection
- 3 tri-axial sensors - for detecting an AC cathodic protection tone
- 3 pulse induction coils - for non-ferrous materials
- 4 gradiometers - for detecting DC cathodic protection currents
- sub-aerial DGPS antennae mounted on the sled for positioning

The sled must be on the bottom for the system to work correctly. It measures the location of the center of the pipe and subtracts the known pipe radius. It may be used either to cross the pipe or to fly the pipeline, but each requires a different sensor mounting alignment. Changing this alignment requires about 30 minutes.

The system will automatically compensate for errors of up to 30 degrees from the intended crossing angle (90 degrees for crossing, 0 degrees for flying the pipe). If the sled is heeling, however, the survey will be inaccurate.

Innovatum has developed software for controlling the system and processing the data. This program gives the Surveyor a 3-D display of the pipeline which assists with tracking. It continuously monitors the data quality fiom all of the sensors, and it automatically switches between them using the best data for the resulting survey.

The main drawback to this system is the cost. Most users lease the equipment from Innovatum at a high monthly or daily rate. Another problem is that it is difficult to use without extensive experience; an Innovatum technician must be present for many of the surveys.

TUE Systems Ltd.

This interview was with one of the principals of TUE (Systems) Ltd., UK, a firm that is purportedly the world leader in using extremely low frequency (ELF) technology for underwater surveys. This representative was very confident that his technology would improve pipeline burial depth surveys in the Gulf of Mexico, but he was also apprehensive about divulging sensitive information.

The representative described a two-way ELF system for communicating with an intelligent pig that would report the pipeline burial depth. This system appears too elaborate and costly for the purpose of burial inspections, however. He recommended a system which uses the technique known as ELF interferometry. He claimed that this method would display a real-time picture of the pipeline along with burial depth. The sensor(s) would be hull mounted on a small boat and could be used in 15 feet of water or less. The system would involve the active transmission of electromagnetic signals in the frequency range of 1-3.5 kHz.

His company does not mass produce its products. Each system is custom designed and built for a specific contract. He believed that a system appropriate for these surveys could be put together from off-the-shelf components for a reasonable cost. He would require $10,000-$20,000 to put together a demonstration model and arrange for a demonstration in the United States.

Fishers and Shrimpers

Four different shrimpers and representatives from two fishing companies were interviewed to obtain the perspective of the users. One of the shrimpers also performs site clearances .of blocks which are being abandoned as well as light pipeline construction services.

The shrimpers related stories of pipelines which were not only exposed, but which in some cases jutted above the waterline. It is not clear whether these were DOT lines, but it is suspected they were small diameter flow lines. It was also stated they had personally witnessed small diameter flow lines being moved from one wellhead to another with no attempt to bury the lines after they were replaced. Since the shrimpers work the same waters often, they are familiar with the most hazardous areas and generally try to avoid these. One shrimper worked familiar waters off the southwestem Texas coast shortly after a strong depression swept through the area in early Fall 1996 and stated shrimping was nearly impossible because of the numerous pipelines exposed by nearshore scouring resulting from this depression. Because shrimp nets hug the bottom, they are subject to hanging on obstructions such as exposed valves and pipelines. There is little likelihood of rupturing pipes during shrimping because of weak links built into the nets primarily for the purpose of preventing damage to the superstructure or overturning the vessel. Hanging nets on pipes or obstructions can result in a laborious removal process causing several hours loss of shrimping. These shrimpers felt that depth of cover inspections should be performed frequently, and that reburial of exposed lines should be done to original burial guidelines.

Both fishing companies represented had lost personnel from accidents involving pipeline collisions. The menhaden fishing operation they conduct involves entrapping the fish in a purse net drawn by two small boats. The larger mother vessel then closes in to the net and pumps the fish aboard. This is'necessarily a shallow water operation since menhaden seldom get farther than a few miles from shore. In the fatal accidents, vessels struck and ruptured partially exposed pipelines which would be classified as hazards to navigation under P. L. 101-599. Both companies denied that their vessels were operating improperly and that they had not loaded their vessels with enough fish to cause them to sink dangerously into the sediment. When questioned about frequency of burial depth surveys, they acknowledged the right of pipeline companies to exist in the same waters as fishers and did not expect frequent surveys of pipelines. They did discuss the importance of responsibility, and expected the pipeline companies to be responsible in their duties of protecting the other users of the Gulf waters by insuring that pipelines were buried to proper depth.

Interested Third Parties

The controversy over pipeline burial inspections has generated interest from lawyers, Federal and State regulators, and people who work and play in the Gulf of Mexico. The investigators had the opportunity to meet with several of these individuals who freely shared their expertise on this issue.

Louisiana Department of Natural Resources

This interview was conducted with a regulatory agent of the Louisiana Department of Natural Resources, Pipeline Operations. He has regulatory jurisdiction over a small number of pipelines in State waters, navigational hazards, and claims for damaged fishing nets due to hangs, He has a strong personal interest in the issue of pipeline exposure, and he shared a number of his ideas for minimizing the hazards.

His top pipeline priority is creating a national, mandatory one-call system for marine pipelines. This is an extension of the current system which is used on land. It would provide the most protection against planned activities such as dredging or construction, but he thinks fishermen might also agree to use the system, He suggested that some creative warning devices such as short range radio beacons might be effective at keeping vessel traffic away from pipelines.

This agent has had some experience with risk analysis, and he advocates its use for regulating pipeline burial inspections. Each pipeline is unique, and this method would help determine the level of monitoring that each requires. He questions the sufficiency of the current depth of cover requirements and feels that these should be reevaluated in the context of minimizing the risk each pipeline imposes. He thinks that the area near where the pipelines make landfall is the most critical because the areas used by different parties intersect here.

Pipeline Consultant (A)

The investigators met with an independent marine pipeline consultant based in Louisiana. He has 20 years experience in marine construction, and he has been in pipeline consulting for several years. Much of his work has been as an expert witness in court cases involving damage to pipelines. His viewpoints are summarized as follows:

- Flocculent or highly underconsolidated silt or clay (fluff) has nearly zero shear strength and shouldn't count as cover. It may show up on a fathometer, but it moves readily with tidal flow and offers little pipeline protection.
- Identifying fluff should be based on soil shear strength. Soil must have at least 0.1-0.2 ksf undrained shear strength to provide some pipeline protection.
- Pipelines in trenches that are not covered are still a hazard to navigation.

- Pipeline trenches do not reliably backfill by natural sedimentation.
- A one-call system has merit, but it really just formalizes common sense.
- Most pipeline-associated accidents and deaths occur in the inland waterways instead of offshore.
- Inspections should be based on bank erosion, areas where flow changes are likely to produce bottom changes, mudslide areas, and storm tracks.
- The greatest amount of sediment shifting due to storms occurs in Eastern Louisiana.
- Even small lines, e.g., 2% inch, have been known to cause accidents and deaths.
- A properly covered pipeline cannot be expected to protect against anchors and jack-up rigs. It should protect against boat hulls, nets, and other relatively shallow intrusions.
- The trawl boards and equipment used by shrimpers do not penetrate deeply if they are properly rigged.
- A well-designed shrimp boat generates 25 lbs/HP of thrust. Most shallow water shrimpers have around 175 HP resulting in ≈4000 pounds of thrust which is not enough to cause much pipeline damage. A six-inch valve assembly weighs 6,000-8,000 pounds in water.

Minerals Management Service Agent

This interview was conducted with an employee of the Minerals Management Service (MMS) in Louisiana. He was in charge of pipeline compliance for a major petroleum company in 1989 during the Northumberland accident. A parallel line his company operated was also found to be exposed but escaped contact by the Northumberland. This agent was speaking in the role of a former pipeline operator and was not representing the MMS. His company had paid very little attention to pipeline burial until an exposed section was noticed by helicopter overflights. Even after that, little was done until the initial inspections. He thinks that three feet of cover would prevent over 90 percent, of the accidents. Major construction activities, such as jack-up rig work, are extensively planned, and surveys are done beforehand. Even so, he recalled an incident where a jack-up rig damaged a pipeline even though surveyors were onboard to help identify hazards.

He felt that some problems arise from the ambiguity in governmental jurisdiction and that approval of a new memo of understanding between MMS and DOT will help.

Pipeline Consultant (B)

This meeting was with a self-employed pipeline consultant working from Louisiana. The consultant stated that he has lobbied for improved operation practices by pipeline operators for a number of years. He provided many photographs and reference materials which he has collected concerning this issue. Some of his comments include:

- Some pipeline operators have forsaken good engineering practice and are using regulation guidance as their engineering specifications.
- Each pipeline location is unique, and the pipeline operators have the responsibility to monitor and protect each pipeline in accordance with good engineering practice.
- While there are many factors which affect the cover of marine pipelines, the most prominent and indicative of these is the chronic erosion of the adjacent shoreline. If one factor should be chosen as a trigger for burial surveys, then this should be it.
- There is ambiguity in defining "bottom" for the purposes of determining the cover over a pipeline. Loose sediment which provides little structural protection to the pipeline should not be considered as cover. Pipeline surveys should determine a meaningful interface which provides pipeline protection to

serve as the upper limit of pipeline cover. This interface should be clear from an engineering standpoint.

Interview Conclusions

The resulting conclusion from these numerous interviews is that all parties are interested in arriving at an intelligent and responsible resolution to the problem of pipeline burial inspections. The pipeline operators generally accept the need for the surveys, but they understandably want the requirements to be clear. They also want to ensure that the money they spend on pipeline surveys is only spent where it is necessary. The survey companies appear to have gained a great deal of knowledge and experience with these surveys which will make future efforts even more expedient and productive. It is also apparent that the available survey technology is continuing to improve, and the proliferation of directional drilling will help minimize pipeline exposures near the shoreline.

Fishers and shrimpers have divergent views on the frequency of surveys. Shrimpers lose time and money when they hang nets on exposed pipelines, and they feel that all pipes should be surveyed often to ensure proper burial depth. Fishers, who are not so likely to hang nets but are faced with the possibility of collisions with pipelines, seem more prone to co-exist with the pipeline industry, but believe that the industry should be responsible to other users of the shared waters by insuring that their pipes are safely buried.

CHAPTER 4

CAUSES OF PIPELINE EXPOSURE

Because of the thousands of miles of marine pipeline in the Gulf of Mexico that routinely transport hazardous materials and the threat to the marine environment and human life a pipeline rupture causes, ensuring the physical integrity of these pipelines is important to operators and the general public. In shallow waters, the primary protection from accidental damage for these pipelines is burial. These shallow water regions are critical because of the powerful current and wave forces present, and the density of vessel traffic. A shallowly-buried pipeline poses a risk since many vessels may impinge into the bottom. If a pipeline becomes exposed in the surf zone, it endangers people and the environment. It will undergo accelerated scour (Herbich, 1991) which increases the exposed length. The loss of pipeline cover in shallow water represents the failure of its primary mode of protection. This section will describe some of the prevalent mechanisms which lead to pipeline exposure.

The foremost natural process that can expose a pipeline is scour caused by waves and currents. Herbich (1991) defines scour as "a large-scale transport of the *seabed* due to a momentum exchange between rapidly moving water and the individual grains that make up the bed itself." Scour is much more extreme in the high energy conditions of severe *storms,* but there are many other factors. Beaches can be susceptible to scow, but the majority of pipeline exposures that have been attributed to current scour are in inlets. The tidal forces that serve to fill large bays through narrow inlets can develop high currents. The factors that determine if the inlet will accrete sediment or be subject to scour are a complex interaction of the size of the bay, the range of the tide, the dimensions of the inlet, and the amount of available sediment. In general, however, stable inlets that connect large bays with the Gulf will experience the greatest current velocities which in turn serves to keep the inlet scoured to a nondepositional depth. Morton and Paine (1990) provide data to classify stable and unstable inlets along the Texas coast, but little information seems to be available for other Gulf coast states.

Figure 1 shows the typical equilibrium scour profile and its dependence on the initial slope of the beach. This shows that a steeper beach will have a more pronounced scour trough, increasing the likelihood of pipeline exposure. The susceptibility of a region to scour also depends on the nature of the bottom material since different materials resist scour differently. Silts and clays resist scour with cohesion, but sand has only its weight to deter movement. While silty sands and soft clays can move significantly in water bottom velocities of two feedsecond (Herbich, 1991), major storms can generate bottom velocities in excess of 3.2 feedsecond as deep as 40 meters (Machemehl, 1978). Herbich (1991), recognizing the difficulty in predicting scour effects, recommends studying offshore surveys taken over the course of years, especially before and after storm data. These data showing year-round underwater profiles will better indicate trends and seasonal variations than surveys conducted before construction. He also points out that aligning the pipeline perpendicular to the shoreline will minimize the effect of wave induced scour should the pipeline become exposed.

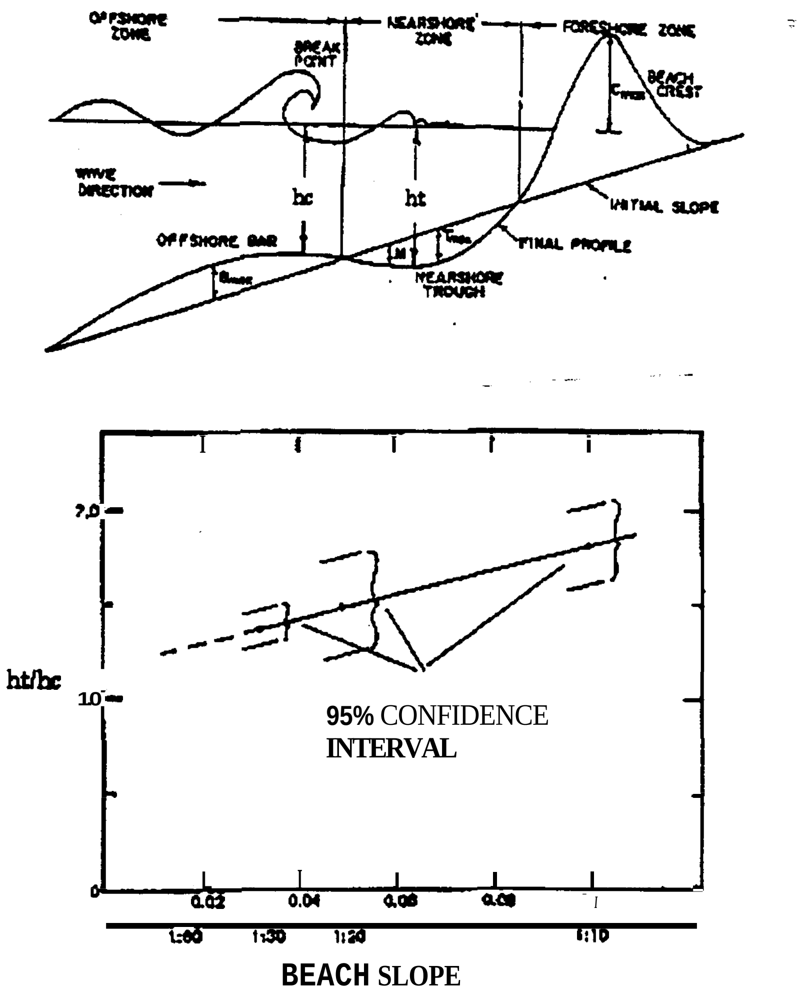

Figure 1. Typical Equilibrium Scour Profile and Dependence on Beach Slope!. (From Herbich, 1991 with permission)

Another mechanism that can cause a pipe to become uncovered is soil liquefaction, Under certain conditions, the backfill sediment covering the pipe may liquefy, acting as a high density liquid with little or no shear *strength.* This sediment suspension may have specific gravities as high as 2.0 (Manley and Herbich, 1976), which is sufficient to float the pipeline causing it to rise up to the seabed.

A pipeline is especially vulnerable to flotation soon after it is constructed. Manley and Herbich (1976) give typical specific gravities ranging from 1.00 to 1.91 for empty oil lines and from 1.58 to 2.47 for filled lines. In practice, the specific gravities of natural gas pipelines often range from 1.24 to 1.37. The specific gravity of the pipeline may be at its lowest value before placing the line in service if the line has been purged, putting it in greater danger of flotation. The pipeline trenches are generally allowed to backfill naturally, and this sedimentation may form the dense mixture needed to float the pipe. According to Dunlap and Thompson (1974) however, "Indiscriminate backfilling of the trench is not the answer either. If a trench is backfilled by discharging material from a bottom-dump scow or barge, the resulting suspension may have a unit weight high enough to immediately float the pipeline."

Even *after* the trench has been filled, a pipeline may still be susceptible to flotation. If the pipeline overburden is composed of loosely deposited silts and fine sands, forces fiom large waves, currents, and earthquakes may cause it to liquefy or move (Dunlap and Thompson, 1974). Unless the specific gravity of the pipe is greater than that of the suspended sediment, the pipe will tend to float up to the soil/water interface.

The investigators constructed a simple model to show the extent of soil liquefaction for conditions commonly encountered in the Gulf of Mexico. The model uses a linear wave theory solution for partially saturated sediments that Okusa (1985) presents. The details of the structure and basis for this model are from Ellsworth (1996), but the model has several limitations:

- Only approximate solutions are given due to the use of linear wave theory
- Liquefaction cannot be demonstrated for completely saturated sediments

- The model only calculates a solution from one of many theories
- The model does not consider the effect of the pipeline body on soil liquefaction

This model is only intended to demonstrate the effect that large waves can have on pipelines, and it is not considered to be a thoroughly developed solution.

For these comparisons; reasonable wave and soil conditions for the Gulf of Mexico were used. The common conditions are: 1.0 meter (3.3 feet) waves with a 13 second period, 3.0 meter (10 feet) water depth, and 99.5% saturation of the soil with water. Figure 2 shows the results of the model for a loose sand bottom which has a liquefied bulk specific gravity of around 1.5. The lines depicting zero values of effective normal stress and mean normal stress show the possible extent of soil liquefaction. It can be seen that the liquefaction extends more than a meter into the seabed; therefore, a pipeline with a specific gravity of 1.35 would be susceptible to flotation even if it were covered by 3.0 feet of sediment. Figure 3 shows similar results for a fine silt bottom, and the resulting bulk specific gravity is around 1.42. These results show the importance of pipeline weight coating to resist flotation and the necessity of performing surveys in locations which are prone to this phenomenon.

There arc mechanisms that can cause pipelines to gradually rise from their original installation depth. Gerwick (1986) points out one such example that may affect pipelines buried on a beach exposed to heavy surf. The pounding breakers cause a cyclic increase in the pore pressures in the sand which, over a period of time, may "jack the pipe up out to exposure.'* Extra weight is needed on pipelines in the surf zone to counter this effect. There is another mechanism that may result in a pipeline moving to the surface -

if a pipeline is installed in a trench left to backfill by natural sedimentation. If this process proceeds at a slow rate, sediments can accumulate below the pipeline, forcing it up. By the time the trench has backfilled, the pipeline is no longer at its design depth. When the pipeline involved in the Northumberland accident was installed in 1973, it had 8-8½ feet of cover; erosion studies indicated that only 2-4 feet of cover was removed by erosion at the time of the accident (National Transportation Safety Board, 1990). The mechanism explained above is a possible explanation for the pipeline being partially exposed at the time of the accident.

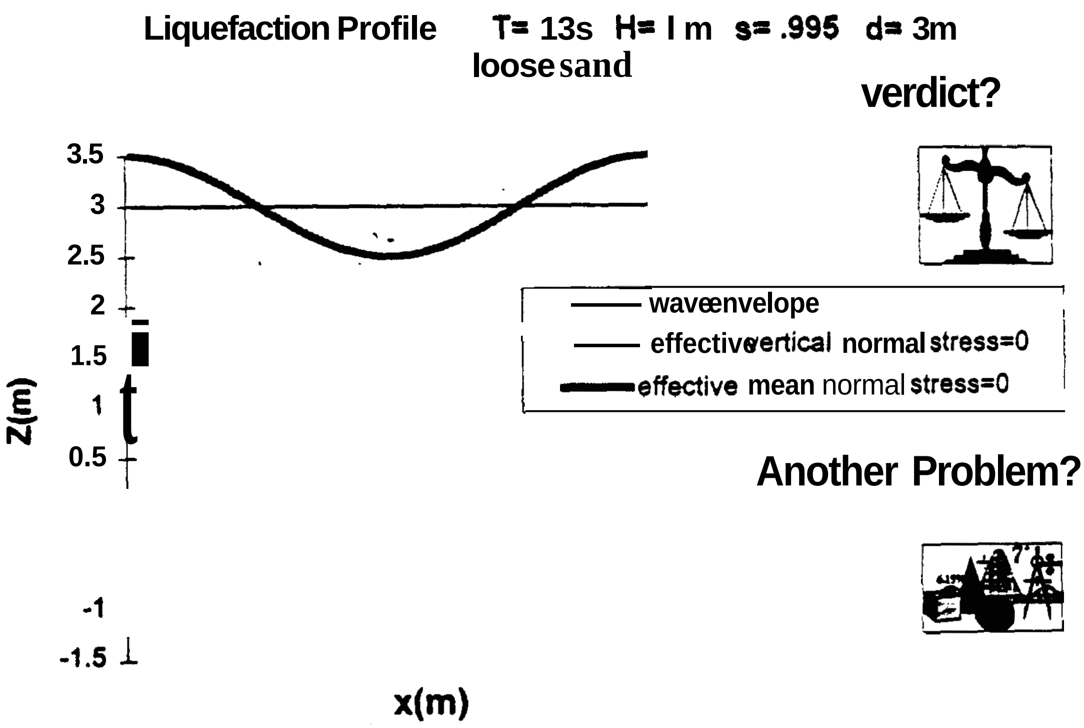

Figure 2. Results of Liquefaction Model for Loose Sand Bottom. Bulk specific gravity of 1.5 extends to 1 meter (3.3 feet) below seabed.

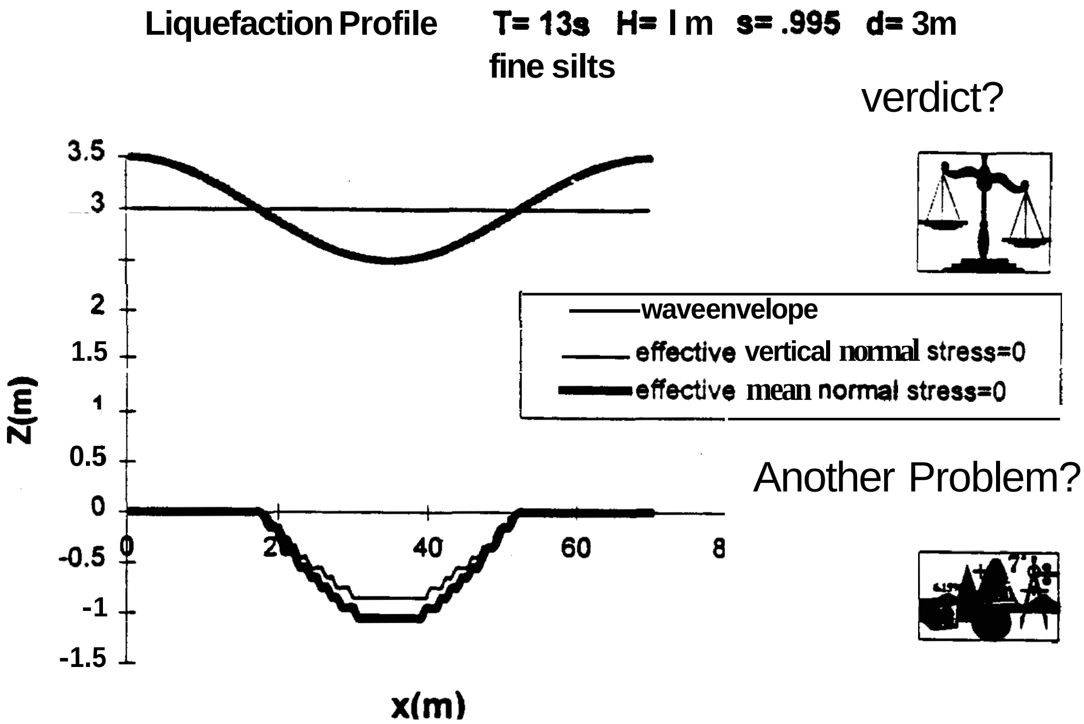

Figure 3. Results of Liquefaction Model for Fine Silt Bottom. Bulk specific gravity of 1.42 extends to 1 meter (3.3 feet) below the *seabed.*

While scour is a localized condition that *can* affect pipelines, there is a danger from overall erosion in the region. A beach will attempt to maintain a certain profile when it is in equilibrium with the wave conditions. The *shape* of this profile is determined by the sediment characteristics in the region. Using typical sediment parameters for the coast of the Gulf of Mexico (Dean and Dalrymple, 1996), the *shape* of the original beach and the effect that 80 feet of erosion has on a pipeline that *started* with three feet of cover *can* be illustrated, as shown in Figure 4. These erosion rates are typically defined by the horizontal retreat of the high water line. It is clear that there is a concentrated loss of cover near shore, but the actual conditions are highly dependent on the geometry of the pipe at the beach approach. The most important effect is the significant loss of cover over the entire area of erosion that could exacerbate other exposure mechanism or, in severe cases, expose the pipe itself.

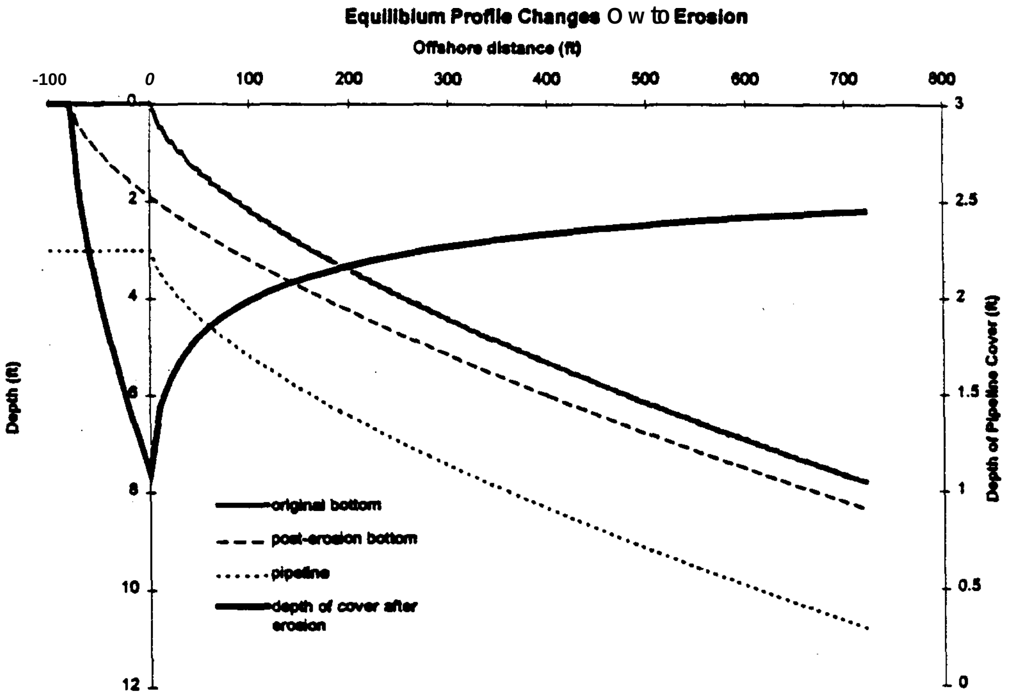

Figure 4. Equilibrium Beach Profiles and the Effect on Pipeline Cover from 80 feet of Erosion. (The beach profiles are typical of the Gulf of Mexico coastal region.)

In many areas of the Gulf of Mexico, erosion can be very severe. Texas loses an average of 250 acres per year of coastal land (Morton and Paine, 1990). The region between Sabine Pass and Rollover Pass, where the Northumberland accident occurred, experienced severe erosion. The factors contributing to the erosion in this area near the Texas-Louisiana border are the deficiency of sand-sized sediment, the high angle of wave approach, and the relative rise in sea level. The erosion rates can be as high as 80 feet per year, and average rates of 40 feet per year are common (McGowan, et al., 1977). These erosive forces are also at work in certain regions of Louisiana, and there are portions of

Louisiana which have erosion rates as high as 100 feet per year (Howard. 1996). Figure 5 shows a natural gas pipeline in this area that is exposed at the beach, and Figure 6 shows an exposed tank that appears to have originally been buried well onshore. Comparing all of the location coordinates. about 80 percent of pipelines found to be exposed were located in erosive areas. The exposed pipelines in **Texas** all occur in areas of erosion. This corroborates the opinion of experts that erosion rates are a significant predictor of pipeline exposure.

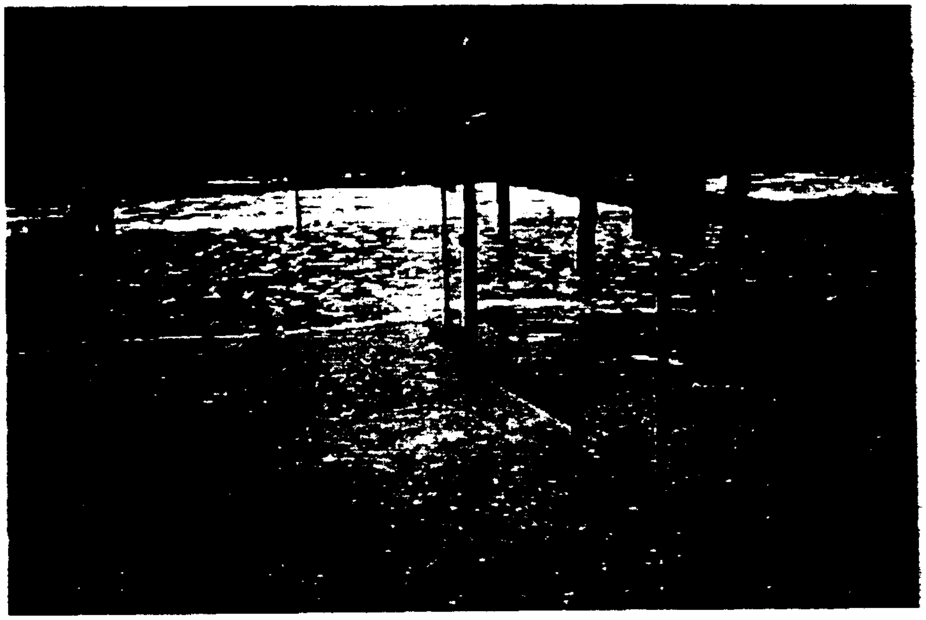

Figure 5. Exposed Natural **Gas** Pipeline in **the** Texas Region from Sabine **Pass** to **Rollover Pass.** (Photo taken July 1996)

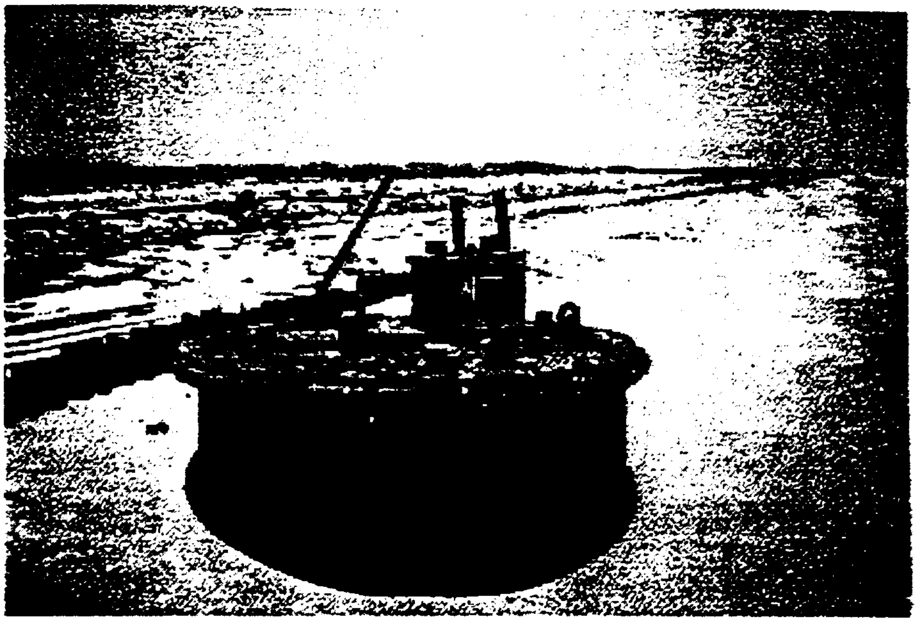

Figure 6. Large Tank Exposed on the Beach Between Sabine Pass and Rollover Pass, Texas. (Photo taken July 1996)

There are many factors working together in the Gulf of Mexico to cause coastal erosion. Morton and Paine (1990) have explained in detail the interactions for the Texas Coast, and their discussion is representative of other areas on the Gulf Coast as well. One common trait among some of these factors is the interference with the littoral drift, preventing replenishment of the damage caused by waves and currents. In some locations, the littoral drift has been interrupted by coastal structures such as jetties and groin fields. Many of these structures protect their coastline at the expense of downdrift beaches. Morton and Paine (1990) have thoroughly documented the erosion of the Texas coast; erosion data for the Louisiana coast can be obtained from the U.S. Geological Survey (1992).

There are other ways that humans have disrupted the natural flow of sediment. There is a long term reduction in the quantity of sediment introduced to the Gulf by rivers. This is due to inland developments such as dams and other flood control projects, Industrial activities such as dredging and offshore mining can also reduce and redirect the flow of sediment.

One more factor contributing to the erosion of the coastline is the relative rise in sea level. While global warming is causing sea level to rise about 0.05 inches/year, increases of as much as 0.5 inches/year have been measured along the Texas Coast (Morton and Paine, 1990). This is a result of the subsidence of the coastal plain caused by the removal of groundwater from shallow aquifers and by hydrocarbon production from moderate depths (Erickson, 1993). The subsidence due to hydrocarbon production is generally concentrated around faults. Subsidence can be an even greater problem in parts of Louisiana where the consolidation of geologically recent sediment deposits leads to a rapid relative rise in sea level. Not only does this cause landloss by submergence of low-lying areas, it also accelerates the damage caused by waves.

The force in the Gulf of Mexico with the greatest potential for destruction over short time periods is the tropical hurricane. At least 16 named tropical cyclones have made landfall on the Coasts of Texas and Louisiana since 1980. These storms are accompanied by large waves, and the higher water levels due to storm surges expose normally onshore areas to wave attack. The waves induce powerful currents that can expose and damage pipelines and, combined with elevated water levels, lead to extreme shoreline erosion. A water level 15 feet above normal high tide is not uncommon for a major storm. The surge can be as great as ten feet a large distance from where the storm's eye makes landfall (Bomar. 1985). Slow-moving storms can be especially damaging, even if they are only moderately powerful, due to the duration of intense wave attack. In some cases, a pipeline may be exposed during a storm, subjecting it to additional stresses and hazards, and then reburied as the storm subsides making the exposure difficult to detect (Herbich, 1991).

Hurricane Andrew was a powerful category 4 storm that passed through a region densely populated with pipelines in 1992. This storm had sustained winds of around 140 miles per hour and significant wave height estimated at 35-40 feet (Mandke, 1995). Surveys and inspections following this storm provided unprecedented information about the susceptibility of pipelines to hurricanes. Mandke (1995) presented a *summary* and analysis of the resulting data to show damage patterns. Nine pipelines this storm exposed were medium to large lines, greater than eight inches in diameter. These data *can* be misleading because some lines may be reburied as the storm subsides. The greatest amount of pipeline *damage* was in 20-50 feet of water. There was greater damage to pipelines built in the last 20 years than to older lines. The surveys were conducted in the 85-mile wide path of the storm; MMS has retained the resulting failure data. There is still a great deal to learn about the damaging effects of hurricanes to pipelines because of the lack of comprehensive depth of cover surveys following storms.

A large number of factors can come together to cause pipeline exposure. These conditions are unique to each location, and their interaction can be complex. There are some human factors to contend with. Some cases of severe erosion have been attributed to *the* wakes fiom vessel traffic, and some pipeline exposures may result from fishermen's attempts to release entangled gear. To predict the potential for exposure of any given pipeline, some consideration must be given to each of these factors.

CHAPTER 5

PIPELINE SURVEY TECHNOLOGY

Prior to the initial inspections, there was little interest in surveying pipeline burial depth in the Gulf of Mexico. Two of the pioneering technologies in this field, Chirp Sonar and Innovatum, primarily marketed their products outside the United States. Once these surveys were required, products were improved and new technologies developed. But the practical application of most of the new technologies is still on the horizon. Numerous devices are designed to locate or identify particular buried pipelines, but this discussion will be limited to devices to accurately measure pipeline burial depth, excluding divers. Figure 7 lists the methods expected to be available for use in pipeline burial surveys. Only three methods were widely used in the initial inspections: Chirp sonar, Innovatum, and ESP, to some extent. Table 3 shows some data comparing these methods' cost and use. Cost is given as a daily rate instead of cost per mile. This is because the controlling factor when calculating the cost per mile is the interval distance in which the pipeline is crossed.

Available Products

Due to the high cost of surveying many miles of pipeline, most pipeline companies, especially the larger ones, examined many different survey methods before choosing. The most commonly used methods were the Innovatum and the Chirp sonar used in combination with manual probing. A few companies used divers only to perform the surveys. It is not always clear, but it appears that the main sonars used were the Chirp

II and its predecessor, Chirp, which are manufactured by Datasonics. Electromagnetic methods have been primarily used in river crossing surveys. It does not appear that the TSS-340 was used for a significant number of surveys.

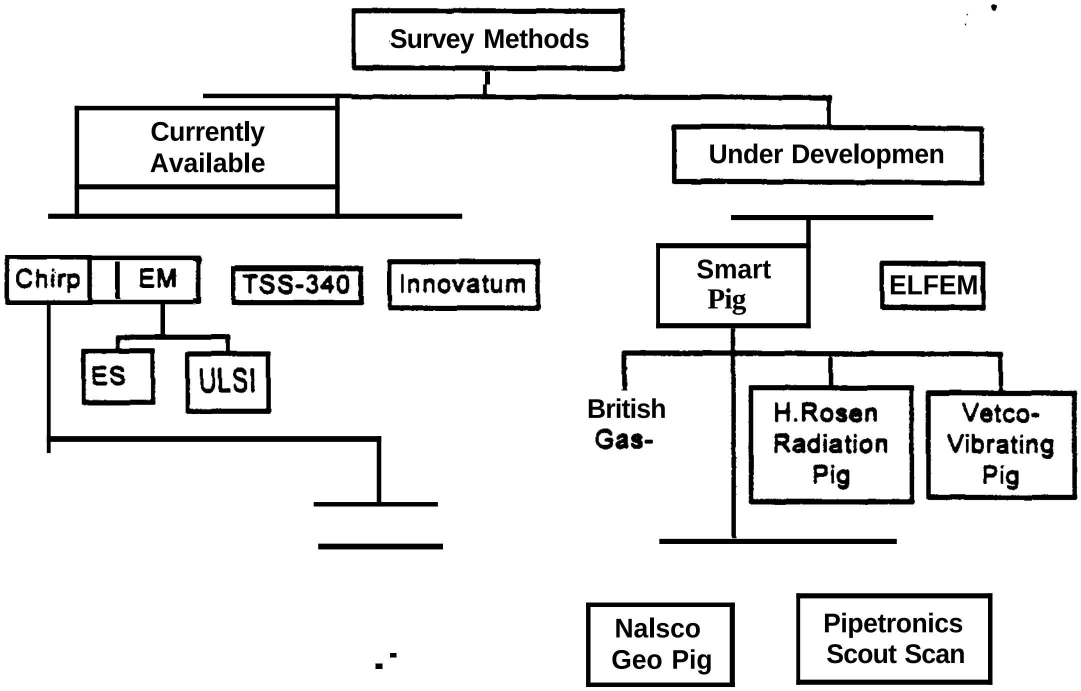

Figure 7. Diagram Listing Current and Upcoming Technologies for Pipeline Burial Surveys.

Innovatum

The Innovatum multi-system has gained a reputation for being a high-end solution for pipeline burial depth surveys. The system consists of an array of sensors typically mounted on a sled or a remotely operated vehicle (ROV), although it has been used with a crawler. The system is able to track pipelines in four different modes:

- AC Tone Tracking
- DC Current Tracking
- Passive Tracking (gradiometer)
- Pulse Induction Tracking

Table 3. Comparison of Methods Used in Surveys

Survey Type	Cost	Accuracy	Ease of Use	Pros	Cons
"Chirp" type sonars	$10,000/day	10% of pipe depth	Difficult	• Flexible configurations • Low cost/mile • Rapid survey • Use in shallow water	• Dependent on bottom conditions • Difficult to calibrate and use • Requires good soil data
Innovaturn	$10,000/day	Within 6 inches	Difficult	• Multiple tracking methods • High quality data	• Difficult to use • High cost • Shallow water difficult
Electromagnetic scanning profiler	$3,000/day	Within 1 foot	Fairly easy	• Low cost • Good shallow water use	• Lower accuracy • Limited range (depends on pipeline condition)

The system software automatically monitors the response from all modes and provides burial depth information based on the best data. This is connected to a topside computer and display that provides a real-time, 3-D picture of the seabed and pipe. The mode primarily used for the shallow water pipeline inspections is the passive mode. In the sled-mounted configuration, system accuracy has been verified to be within six inches. The system is capable of tracking the pipeline longitudinally; transverse crossings are normally used with the sled because of the sled's limited maneuverability.

This system is generally leased rather than bought. Its complexity makes it necessary to hire an Innovatum engineer for training on the first surveys. System leasing in the most basic configuration starts at $1250.00 per day, and there are additional expenses for added equipment and personnel.

Innovatum, Inc.
2020 Southwest Freeway, Suite 203
Houston, Texas 77098-4807
Ph: (713) 526-6333; Fax: (713) 526-2555

Chirp 11

This sub-bottom profiling sonar is manufactured by Datasonics. It is also distributed in the Houston area by ORE. The sonar operates at the frequencies of 1-10 kHz or 8-23 kHz, depending on the model. The basic system consists of a towed fish and a shipboard enclosure, but the configuration is very flexible. The improvements over the first Chirp include:

- lighter weight tow vehicle
- enhanced digital signal processing
- offers simultaneous dual-frequency operation; selectable bandwidths and frequencies from 500 Hz to 23 kHz to allow penetration and resolution to be optimized
- higher frequency allows detection of smaller pipelines

The Chirp reportedly had some crystals removed in production which made pipeline detection more difficult, but the Chirp II has resolved these problems. The system incorporates a user fiiendly, graphical interface, but there is reportedly a great deal of skill required to interpret the results. The manufacturer recommends using it with a magnetometer to help identify pipelines. The verified system accuracy is within 10 percent of the pipeline depth.

This system, as with all of the sonar systems used, is towed from a small boat at right angles to the pipe. It is rated for a maximum depth of 2000 feet, and surveyors have reported using it in as little as two feet of water. The system costs approximately $90,000.

Datasonics, Inc.
1400 Rt. 28A
P.O. Box 8
Cataumet, Massachusetts 02534
Ph: (508) 563-5511; Fax: (508)563-9312

ORE International, Inc.
10430 Stancliff, Suite 115
Houston, Texas 77099
Ph: (713) 879-7277; Fax: (713) 879-9213

X-Star

This device is a sub-bottom profiling sonar which is designed by one of the originai developers of *Chirp* technology. It is produced by the Marine Instruments division of EG&G, currently EdgeTech Division of Victoreen, Inc. A number of different towed fish are available. The smallest unit with the best resolution operates at frequencies of 4-24 kHz, and there is a unit designed for integrated operation with a side scan sonar. The signal processing deck unit includes a UNIX workstation and a 17-inch color display monitor. The manufacturers claim an optimum vertical resolution of one and one half inches, and one surveyor reports the ability to track lines as small as two inches with this unit. The X-Star sells for approximately $90,000.

Edge Tech
455 Fortune Blvd.
Milford, Massachusetts 01757
Ph: (508) 478-9500; Fax: (508) 478-1456

GeoChirp

This is a sub-bottom profiling sonar sold by Klein and Associates. There have been no reports of its survey use; therefore, all of the available information is from the manufacturer. The system uses a signal of 2-8 kHz for high penetration or 1.5-11.5 kHz for high resolution. The system is compatible with other ORE sonars, and it is available as an upgrade for those already owning an ORE system. The primary advantage touted by the manufacturer over other chirp systems is its ease of use. They claim that the device can almost be considered as a **"black box"** requiring minimal adjustment in the field.

Klein and Associates
Salem, NH
(603) 893-6131

TSS-340

This sensor uses pulse induction technology to determine the location and burial depth of pipelines and cables. The sensor is an array of coils mounted on a sled or ROV, similar to the Innovatum. Only two coils are required for the survey, but having three coils allows an auto-calibration feature. The system will detect non-ferrous as well as ferrous metals, and the manufacturers claim that it can detect objects as small as 1½ inch non-armored telephone cables at a vertical range of 5.0 feet. Other advantages noted are a more rapid calibration procedure than magnetometer based systems, and rapid data acquisition. The system provides real-time plan and profile displays of the pipeline. Surveyors reported that the system had good range but had some problems with repeatability of results. **One** surveyor who tested the system was able to maintain continuous longitudinal tracking of buried lines as small as **six** inches. The accuracy of the system is listed as two inches or five percent of the range to the target.

TSS (UK) Ltd.
4 Weston Business Park
Weston-on-the-Green
Oxfordshire, OX68TN UK

SUBMAR
520 Mitchelldale, Suite E-17
Houston, Texas 77092
Ph: (713) 685-6235; Fax: (713) 688-2327

ESP

The Electromagnetic Scanning Profiler System (ESP) was developed by Wimpol and is now owned by John E. Chance and Associates. The system uses a low frequency AC signal generator to inject a signal into the pipeline at an above-ground block valve or cathodic test station. In the event that the pipeline is not accessible, there is an induction coil that can inject the signal if set on top of the pipeline location, even if the pipeline is buried underwater. The sensors measure the electromagnetic field radiated by the pipeline as the survey vessel crosses it at right angles. One hull-mounted sensor, located directly below the DGPS antenna, finds the pipeline, and a second towed sensor measures pipeline burial depth.

The shipboard display provides real-time information on boat and pipeline location, but the depth of burial data is not processed until after the survey. The best accuracy in measuring depth of cover claimed by the manufacturer is within one foot. Typical survey costs are around $3,000 per day.

Other surveyors familiar with the system thought it was an accurate survey method, but the surveyable distance away from the current injection point is too dependent on the physical condition of the pipeline.

John E. Chance and Associates, Inc.
6100 Hillcroft
P.O. Box 740010
Houston, Texas 77274
Ph: (713) 773-5670; Fax: (713) 773-5698

U.L.S.I.

This company based in Houston has developed **an** electromagnetic detection system for pipeline burial depth. The system injects a low frequency **AC** signal into the pipeline, but it requires that the pipeline make a closed circuit. To accomplish **this, an** insulated cable is attached to valves or cathodic test leads at either end of the section to be surveyed. The system is primarily designed to survey waterway crossings, but it can also be used in shallow bays. The sensors are normally mounted aboard a 15-foot survey vessel that crosses the pipeline at right angles. The vessel makes two complete surveys to verify consistent results. **A** third survey is performed if there are discrepancies. Location **data** are provided by a microwave positioning system which is referenced to **onshore** benchmarks. The company performed some of the early initial inspections but was unable to bid competitively once more surveyors became involved. The cost for this method are **a** minimum of **3** 1.05 per foot.

U.L.S.I., Inc.
***P. O.** Box 218787*
*Houston, **Texas 7721%***
Ph: (713) 578-9777; Fax: (713) 578-9181

Upcoming Survey Technologies

When P. L. 101-599 required pipeline operators to inspect their pipelines for burial depth, new methods for performing the surveys were sought. International companies have developed products for overseas markets. **A** few new methods such **as** the helicopter-based magnetometer system were med with little success, but most are still in the development stage. **One** attractive method is an intelligent **pig** survey system. Advantages of pigging include the positive identification of the pipe being surveyed and its easier use in congested areas. A pig can survey the entire pipe length rather than crossing at intervals. Due to increases in using pigs for corrosion inspections. many, but not all, major pipelines in the Gulf of Mexico are able to accommodate them. At least four different survey techniques in development use pigs. Another method is the ELFEM, which is non-invasive and does not require any cumbersome tows. It is unproven in the U.S. market.

Vetco Vibrating Pig

In a cooperative effort with Cambridge University, UK, Vetco Pipeline Services has developed a vibrating internal pig system to measure pipeline burial depth. The intended application of this technology is shallow water burial inspections in the Gulf of Mexico. The pig is equipped with a shaker that induces vibrations in the pipeline. Accelerometers mounted on the pig measure the pipeline's vibratory response. This signal can be processed for information about depth of cover and external support. One of the challenges with this method is designing the polymer support cups so that the pig will be adequately supported within the pipe and will not damp out the pipeline's vibratory response. Although promising, the system has not been tested in the field yet.

Vetco Pipeline Services, Inc.
1600 Brittmoore Rd
Houston, Texas 77043
Ph: (713) 461 6112; Fax: (713) 461-9236

British Gas- Neutron Interrogation Pig

This system has been developed by British Gas, and it is reported to provide the following information:

- pipeline depth of cover

- nature and disposition of surrounding sediments
- detection and quantification of weight coating loss
- location of joints and anodes

The pig contains a neutron radiation source at its core that is shielded during all handling operations. During the survey, the source is exposed, and a collimated neutron beam is sent radially outward from the center of the pipe in all directions. Neutrons have a high penetration capability, and they induce gamma radiation emissions characteristic of the material they interact with. Radiation sensors located around the perimeter of the pig measure the backscattered radiation that is later processed. The system is operated with two pigs in a train, the lead pig bearing the data acquisition package and the second carrying the source and sensors.

Full scale offshore trials of this system have already been conducted with no safety problems and good survey results. The smallest size currently available is for 34-inch pipelines, but a 24-inch unit should be available soon. The manufacturer claims that the system will not cause any activation or contamination of pipeline or product components, but it is important for this claim to be scrutinized. Neutron radiation is the most hazardous because of its unknown biological effects and its unique ability to make certain materials radioactive.

British Gas
On Line Inspection Centre
Nelson Way
Nelson Industrial Estate
Cramlington, Northumberland NE23 9BJ
Ph: 011 441 670 713 401; Fax: 001 409 862 1542

H. Rosen- Radiation Detection Pig

This system is not yet capable of detecting pipeline burial depth, but it is advertised as being able to find free spans. There are no technical details available, but it detects radiation from naturally occurring radio-isotopes in the surrounding sediments. Presumably, it notes the absence of a signal along a free span. The only size currently available is 30 inches.

H. Rosen USA, Inc.
1400 N. Sam Houston Pkwy. East
Suite 100
Houston, Texas 77032
Ph: (713) 442-8282; Fax: (713) 142-8866

Nalsco and Pipetronics- Gyro Pig

This pig developed by Nalsco is a two part system that requires that a detailed bathymetric survey be done over the top of the pipeline. The pig is equipped with sensitive accelerometers which will show the pipeline location relative to an onshore benchmark. The pipeline positions can be overlaid with the bathymetry to yield pipeline burial depth. There have to be reference points in order to maintain sufficient accuracy. The manufacturer stated that reference depths of cover would be needed around every quarter of a mile and could be provided by divers, in order to ensure an accuracy within one foot of cover. The data processing is extensive, but it provides data for maps of pipeline location. The smallest unit is for ten-inch pipelines, but a six-inch model is expected in 1997. Another firm, Pipetronics, has a similar system under development. This system has been tested successfully in Europe, and tests are planned for the Gulf of Mexico. The smallest feasible size of the Pipetronics unit is eight inches, but the smallest current size is about 14 inches.

Nalsco Pipeline Services
P.O. Box 8898
Houston, Texas 77249-8898
(713) 224-1105

Pipetronics'
2207 Oil Center Court
Houston, Texas 77073
Ph: (713) 821-7633; Fax: (713) 821-7596

ELFEM Systems

This acronym stands for extremely low frequency electromagnetic, discriminating it from acoustic ELF technology. TUE Systems in the UK is the reputed world leader in using this technology for survey applications. The ELFEM signals are almost completely unaffected by water, soil, gas, and concrete, but the pipeline steel can absorb much of the signal. The system can carry information at a slow rate, but this corporation can track buried cables and communicate with internal pig systems. Its usefulness for pipeline burial surveys still needs to be demonstrated. A major advantage with the system is that it could be operated from a surface vessel without a lengthy tow. The known interferences with ELFEM signals are emissions fiom shipboard AC generators and communications from naval submarines.

Trident Underwater Engineering, Ltd.
The Offshore Scientific Centre
Provincial House
3, High St.
Ryde, Isle of Wight, PO33 2PN
Ph: 0983-615344; Fax: 0983-811079

CHAPTER 6

CONCLUSIONS

While there is still a great deal to be learned about offshore pipeline exposure, this study **has** revealed some facts about the initial inspections and pipeline exposure. It is valuable to study the actual survey results, but much important information **has** come from those involved with the performance of the surveys and with pipeline operation.

Performance of Surveys

Some operators conducting the initial inspections were confused about the requirements. **This** confusion may include the regulatory agencies' jurisdiction. The major points of confusion are: exactly which areas were required to be surveyed, what material from a strength standpoint qualifies **as** pipeline cover, and, to a lesser extent, what specific methods or techniques must be used in the performance **of** these surveys.

Almost all of the pipeline operating companies made a good faith effort to meet the **initial inspection** requirements. Some companies went above and beyond their obligations to inspect their pipelines. While most of the surveyors provided detailed pipeline maps and reports which could be used for research on the depth of burial problem **and** to improve navigational safety, the terse survey reports by the operators to the **OPS are of** little value in **this** respect.

Both the sub-bottom profiling sonars and the Innovatum appear to provide accurate survey results when they are used in appropriate conditions, e.g., the **sonar** should not be **used** with a dense sand bottom or in gassy sediments due to low penetration. Diver surveys are accurate as long as the divers survey the correct pipe. Those involved in the inspections showed that they were conscientious about selecting the appropriate methods.

The survey results show that the pipelines were surveyed at least 15 feet below mean low water and usually more. Confusion over interpreting "the Gulf of Mexico and its inlets" resulted in discrepancies over which lines were to be surveyed. The vast majority of pipelines were surveyed using transverse crossings, but the proper interval spacing was never specified. The selected crossing interval was most commonly 250-500 feet, but over 27 percent of the 77 pipeline segments reported to have inadequate cover were 150 feet in length or less; the shortest was 38 feet. A Louisiana Department of Natural Resources employee believes there are significantly more exposed pipelines than those reported from the initial inspections.

The best accuracy for the majority of the survey methods is ±6 inches. It is not clear whether the pipeline operators always used the nominal depth or used the accuracy range to their advantage. If a pipeline was shown to be buried just below 1.0 feet, it is possible that the pipeline could be at 0.5 feet or at 1.5 feet. In the former case, the pipeline is clearly in violation and poses a hazard.

Potential for Pipeline Exposure

The initial inspections demonstrated there is a problem with exposed pipelines in shallow waters. The reports showed that 2 percent of the lines surveyed, or 207,000 feet, had insufficient cover and that this quantity of pipeline poses a significant threat to safe navigation.

Initial inspections show that the causes of pipeline exposure are manv and varied. often interacting in a complex fashion. One statistic, that 85 percent of the exposed segments were installed prior to 1980, implies that the lower specific gravities used on older pipeline designs are a major contributor to exposure. In other cases, the progression of severe erosion in the region is clearly the overriding factor. Isolated incidents point to some alternate explanation. One example is the parallel, identical lines that have been affected very differently, and the only differences are in the initial construction practices. Thus, many factors must be considered when writing permanent inspection regulations.

Certain practices help protect pipelines fiom exposure. The final approach to shore is a critical region due to coastal erosion and man-made activities. Directionally drilling these approaches provides a great deal of added protection in this area. However, these lines are typically drilled to depths up to 50 feet which puts them beyond the range of most depth of cover survey methods. Due to these extreme depths, it is unreasonable to require surveys of these drilled segments, but the endpoints must still be monitored. The shoreward end is often set back 250-500 feet, a distance which can be devoured by erosion over the lifespan of a pipeline. At least one case of exposure has been noted at the seaward termination of the drilled segment.

Pipeline Cover Requirements

Discussions about pipeline surveys in the Gulf of Mexico inevitably turned to the adequacy of the requirements for cover. The confusion with this issue concerns the materials that acceptably constitute cover as well as the adequacy of cove: requirements in various depths of water.

The problem of what material constitutes cover is a significant one, although many parties have different perspectives on the issue. To most, the challenge is to resolve some clear seabed or mudline in order to perform the surveys. In the many areas with very soft, organic sediments this is not an easy task, whether using divers or electronic methods. Other concerned individuals contend that, even with a discernible mudline, the upper layers of soft sediments provide little or no pipeline protection and that cover requirements should be tied to soil-strength criteria.

The pipeline depth of cover requirements are intended to protect people and the environment from the risks of pipelines that are exposed or pose a hazard to navigation. Three feet of cover does seem adequate to prevent damage from small fishing vessels and their equipment, anchors from small vessels, and recreational boats, provided that the cover consists of substantial sediments. Intrusions such as anchors from large vessels or the spuds of jack-up rigs can penetrate well beyond the three feet of required pipeline cover. Other procedural mechanisms must be in place to provide protection from these dangers.

CHAPTER 7

RECOMMENDATIONS

Based on a review of the pipeline survey results, the available literature, and the collective opinions of many experts in the pipeline industry, a number of recommendations for future steps to improve pipeline and navigational safety are provided below.

Administrative

1) A database of all pipelines within the Outer Continental Shelf and in navigable inland waterways should be developed and made available to the public. This GIS database should include the following information at a minimum:

   - pipeline location maps
   - pipeline burial depth
   - pipeline product
   - pipeline specific gravity
   - locations of valves and subsea equipment
   - pipeline operating company and emergency contact information
   - pipeline regulatory authority
   - locations of fishing net hangs

   Pipeline operators should be required to provide information for the pipelines under their operation. A maintenance plan for this database should be instituted to guarantee that the information is kept up-to-date.

2) A mandatory "one-call" system should be developed for marine pipelines. This system should include all natural gas and hazardous material pipelines within the

Outer Continental Shelf and navigable inland waterways. Central to this system is the pipeline database which would facilitate rapid response times.

Depth of Cover Requirements

1) Pipelines transporting natural gas and hazardous liquid, as defined in 49CFR Ch.I§195.2, should be controlled identically under the regulations. Although natural gas poses a greater threat to human life, hazardous liquid releases can have a devastating environmental impact, and both demand full regulatory protection.

2) All natural gas and hazardous liquid pipelines, regardless of size, less than 15 feet below mean low water level should be maintained three feet below the natural bottom. The term " hazard to navigation" should be redefined to reflect the fact that remediation is required for such lines if they are found to have less than three feet of cover.

3) The natural bottom should be defined as the surface which reflects a fathometer signal of a specified frequency until adequate soil strength tests and parameters can be agreed upon. The frequency specified for the fathometer may be a point of debate, but the use of a 50 kHz signal, instead of 200-300 kHz, may improve the ability to detect a layer of substantial sediment through loose sediment. In order to meet burial requirements, the pipeline cover must consist of soil or solid material; a pipeline laying in an open trench is not covered.

4) After a pipeline is installed in a trench which is allowed to backfill by natural sedimentation. a depth of cover survey should be performed at reasonable intervals until the trench is tilled. Conventional sonar bathymetry is insufficient because it

will not detect if the pipeline has been repositioned within the trench. If a pipeline trench is mechanically backfilled, an as-built depth of cover survey should be perfonned following the operation to verify the pipeline position.

5) The use of articulated concrete mats should be allowed, on an individual case basis, to protect pipelines that are difficult to rebury. In all cases, they should be allowed to provide erosion protection for adequately buried pipelines.

Survey Requirements

1) In order to facilitate the planning of future survey regulations, a complete depth-of-cover survey should be performed on ail pipeline segments which were found to be exposed in the initial inspections. By the time this can be implemented, over five years will have elapsed since the first survey, and this will allow the evaluation of exposure trends in problem areas and the effectiveness of remediation efforts.

2) The reporting requirements for all future surveys should include a copy of the full survey report, as well as the pipeline mapping data. This wil! allow more effective research, and it will provide the necessary information to update the pipeline database.

3) The frequency of future depth of cover surveys should be determined using risk analysis methods. A proposed approach for this analysis is detailed in the Appendix and each pipeline would be evaluated individually. This approach bases the survey periodicity on the likelihood of the pipeline becoming exposed, as well as the threat posed by the pipeline if it were to become exposed. The re-survey of previously exposed lines will provide important information for this analysis. and

the operating companies will **also** be **required** to **submit the** full **survey** reports from **their initial surveys.**

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APPENDIX

A PROPOSED RISK ANALYSIS MODEL FOR PIPELINE BURIAL INSPECTIONS

Introductiou

The use of risk analysis methods for pipeline maintenance and regulation is becoming more common, and there is agreement within the pipeline industry that its use should be extended to pipeline survey regulations. The attraction is that an up-front investment in research can identify problem locations, allowing maintenance expenditures to be more focused.

The National Research Council (NRC) Committee on the Safety of Marine Pipelines (1994) developed a simplified risk analysis model in order to demonstrate its applications. The risk analysis model proposed here differs from theirs by considering only the issue of pipeline exposure and does not address problems such as corrosion. The perspective of risk is also different. The NRC model examines the risk to a vessel due to all of the pipelines in the area; an example of this is that the density of pipelines is a prominent risk factor. The proposed model is designed to determine the hazard that an individual pipeline under specific conditions poses to the environment and to human life, and therefore pipeline density is not an issue. Use of this model will provide regulators with the tools to determine financially and socially acceptable levels of risk and to dictate appropriate pipeline survey regulations. It provides the additional advantage of calculating the changes in risk associated with modifications to the existing requirements for pipeline burial.

Overall Model Structure

The structure of the proposed model is shown in Figure A-1. The most significant components will be discussed in detail. but it can be seen that a great deal of data are needed to make reliable predictions. Collection of these data will be an ongoing process. but much of it has likely been collected and is spread throughout numerous organizations. In the cases where concrete information is not available, the use of expert opinions is a legitimate approach to obtain estimates.

In Figure A- 1, the portions above the line provide calculations of the burial status of the pipeline resulting from the combined effects of erosion, strong currents, and hurricanes. The resulting pipeline status is submitted to the rest of the model which determines the probability of an accident occurring and the damage which would be caused by the accident. The model attempts to reconcile the short term effects of hurricanes and the long term processes of erosion and current scour.

Construction Method Factor

This is a mechanism to correct for the varying effectiveness of different construction methods; It will also apply to the method last used to rebury a pipeline. This study has demonstrated that certain installation methods, such as directional drilling, are more effective at maintaining the original amount of cover over the pipeline than other methods, such as natural sedimentation. This factor will determine a reduced effective depth for pipelines installed with less effective methods.

Erosion Model

This component will first determine the pipeline's configuration using the effective burial depth and a theoretical equilibrium profile for the local soil type. A more advanced alternative would be to use actual bathymetric data, but this would make

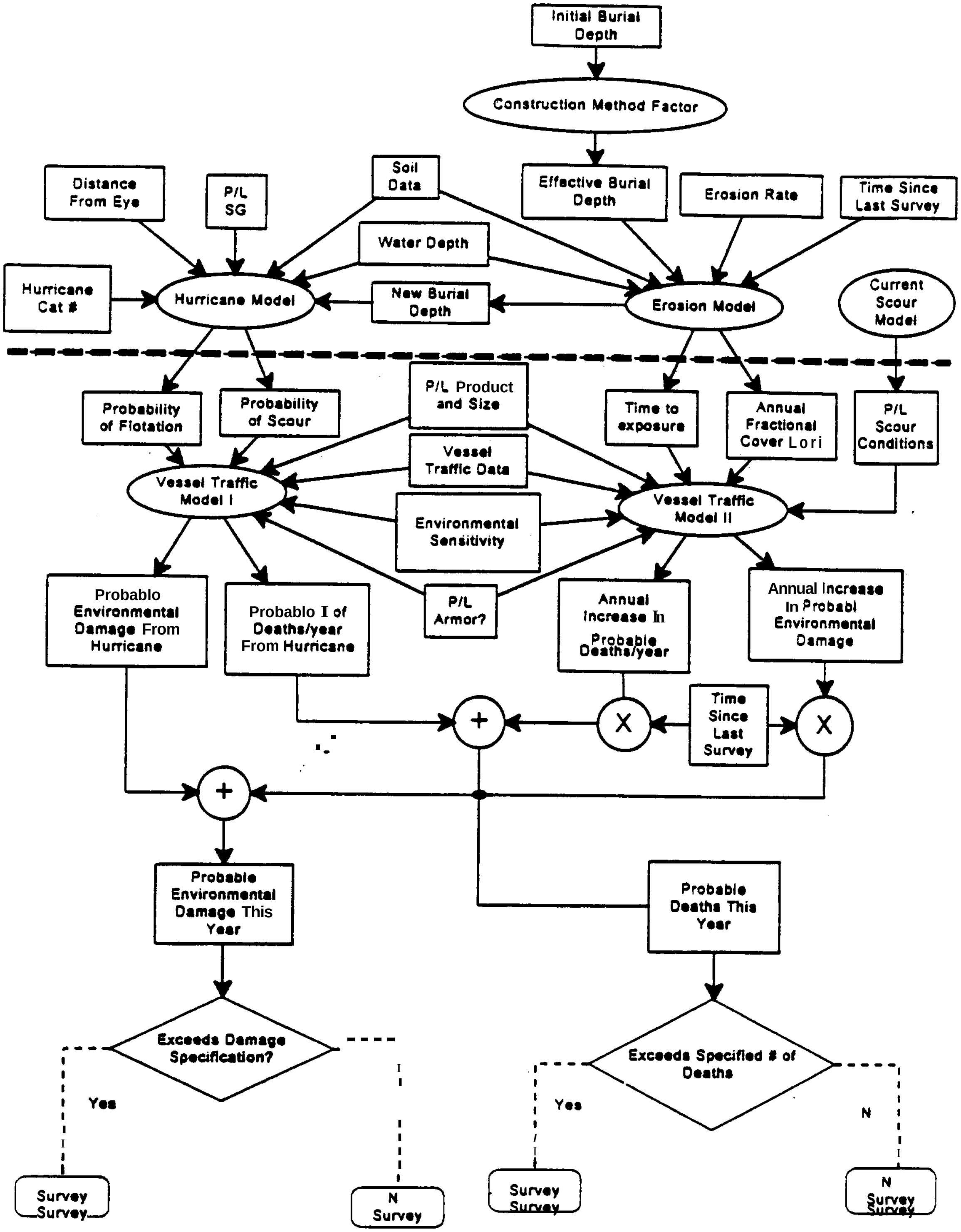

Figure A-1. Flow Chart of the Proposed Risk Analysis **Model** for Pipeline Burial.

the model more cumbersome to use and would increase the data collection requirements. From the local erosion rates, for which there is much data, and the time since the pipeline was last surveyed, this model will predict the time required to expose the pipeline and the fraction of the pipeline's cover which is lost each year. It will also calculate a new depth of cover at the time before a hurricane passes through the area.

Hurricane Model

This model considers two possible consequences of a hurricane: the chance that a large wave will liquefy the cover causing the pipeline to float and the chance that hurricane-induced water motions will expose the pipeline by scour. The possibility of direct pipeline damage could also be considered, but this is a less likely event. In some locations, however, it may be prudent to include the effects of mudslides.

For simplicity, the model will use built-in values of the maximum winds or hydrodynamic conditions expected for each category of tropical storm. In order to further simplify the model, the dependence of the storm conditions on the distance from the eye could be grouped into categories as well, e.g. 0-10 miles, 10-25 miles, etc. The calculations of soil liquefaction will be performed by the computer model which has already been partially developed in the course of this study. The determination of scour conditions will include calculating the storm-driven water motions at the bottom and estimating the resistance of the soil to disturbance.

Current Scour Model

The controlling factors for this model require further study, but it is needed to describe pipeline exposure by scour which is distinct from erosion of the adjacent shoreline. This is primarily a concern in inlets harboring strong tidal currents. This model would also incorporate the effects of large seasonal variations in the distribution of bottom sediments which is prevalent in some locations.

Vessel Traffic Models I and II

These two components are very similar, but they will vary slightly to account for the different timescales of hurricanes and erosion. In both cases, they receive the burial status of the pipeline as input, and they determine the consequential risk posed by the pipeline. They will consider the density and nature of vessel traffic, as well as the pipeline's resistance to damage. The pipeline product, capacity, and the local environmental sensitivity will help determine the nature and extent of damage if a rupture should occur.

Hazard Criteria

The hazard criteria are separated into environmental damage levels and the number of deaths in a given time period. For each category, an annual increase in risk is multiplied by the number of years since the last survey. This level of risk will determine the routine survey periodicity. In the event of a hurricane, the additional risk is added to this value to determine the necessity for earlier surveys.

Determination of Acceptable Levels of Risk

This model will initially be used to evaluate the acceptable risk criteria. This is not only an issue of protecting the public welfare, but it also must consider the cost to the pipeline industry. One method to develop acceptable risk criteria is to develop a number of scenarios by varying the survey periodicity and the storm conditions for which surveys were performed. Assuming that each policy was practiced for a set period of time, the level of risk which was maintained and the accumulated survey costs can be calculated. Figure A-2 shows a theoretical curve which might result from these scenarios.

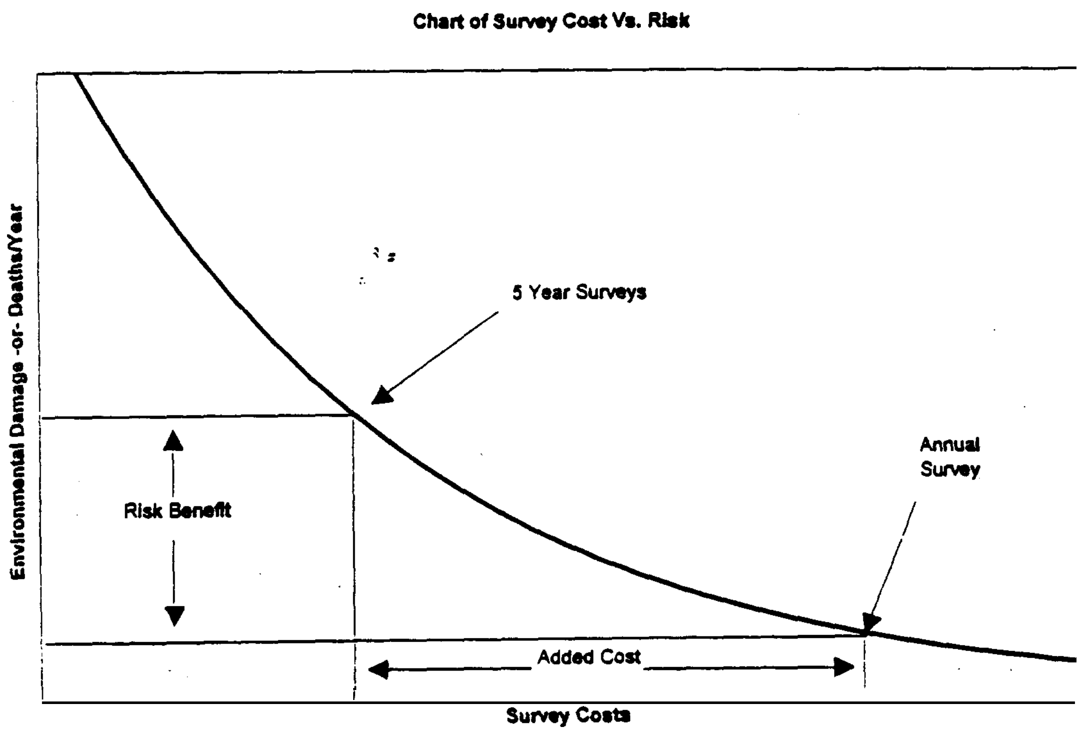

Figure A-2. Sample Chart of S w e y *Costs* vs. Associated Risk to Compare the Effects of Different S w e y Policies.

Evaluating these factors is a subjective process that will touch on many social issues. It is clear, however, that there will be a point of diminishing returns for additional survey expenditures. This model can only serve as a tool to facilitate intelligent debate on this issue.

Use of the Model

In order to use this model, geographical areas and pipelines will be broken into portions small enough to provide some precision but large enough to lend continuity to the pipeline surveys and to be commensurate with the accuracy of the data. Figure A-3 shows a simplified representation of this methodology. Maps of regional parameters, such as water depth and soil type, will be generated and overlaid. Maps of the pipelines will also be added as a layer along with the pipeline attributes, such as specific gravity and size. Each pipeline segment will be characterized by its pipeline attributes and its position within these juxtaposed regions. For the pipeline segment shown in Figure A-3, section ACB-1A-2, its survey requirements will be evaluated based on the pipeline attributes ACB and the regional parameters 1A and 2.

The frequency of burial surveys is determined from the decision tree shown in Figure A-4. A survey periodicity is first determined for conditions absent of tropical storms. The passage of tropical storms with various intensities and at various distances is then considered. If the hurricane immediately increases the risk beyond acceptable levels, then an earlier survey must be performed. These results can be tabulated as in the example, Table A-1. The values in the table are the maximum number of years that may have elapsed since the previous survey for which post-hurricane surveys do not have to

·1

be performed. In most cases, the longer it has been since the previous *survey,* the more important it is to re-survey after the storm. The numbers in this table *are* merely intended to demonstrate the process of evaluating storm effects. They are not the result of any calculations, and each pipeline would have an individual table for each major segment.

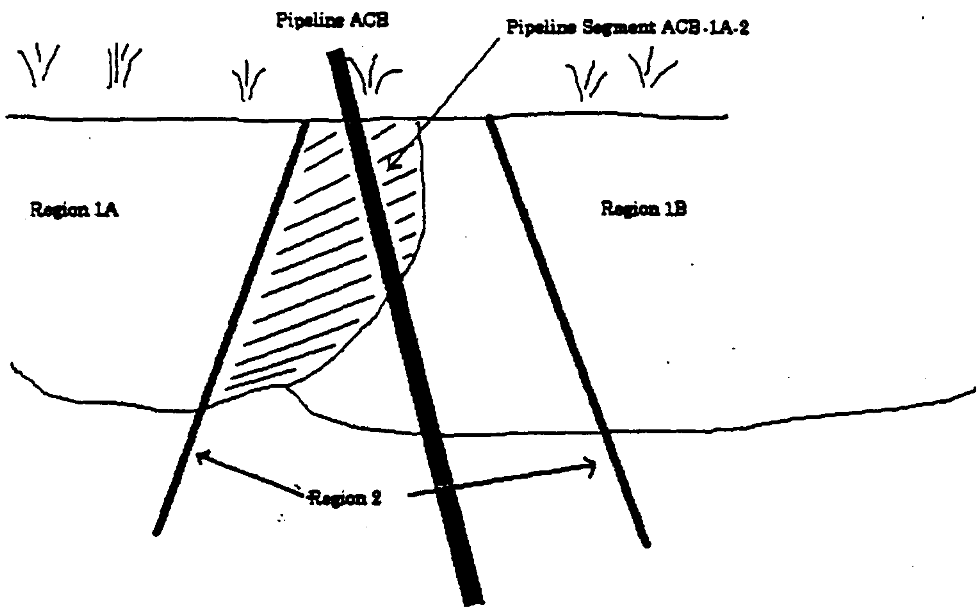

Figure A-3. Sample Chart of Overlapped Regional Parameters and Maps of Pipelines.