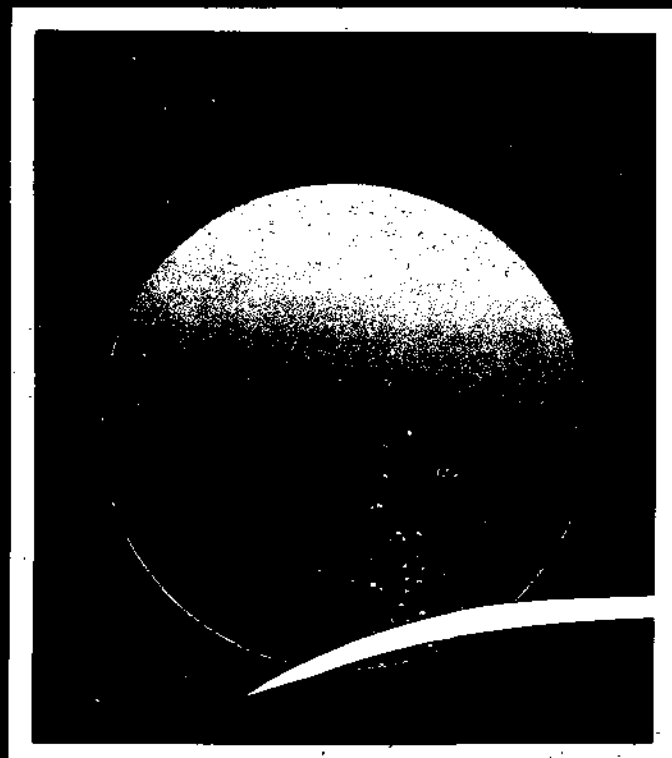


# **Underwater inspection of steel offshore installations: implementation of a new approach**



THE MARINE TECHNOLOGY DIRECTORATE LIMITED



## **ABOUT MTD LTD**

*The Marine Technology Directorate Limited (MTD Ltd) aims to promote, develop and advance, in the national interest, research, training and information dissemination in marine technology, including all aspects of engineering, science and technology relating to the exploration and exploitation of the sea.*

*MTD Ltd is an association of members having interests and capabilities in marine-related technology. They include industry, government, research establishments, academic and other learned institutions, and the Science and Engineering Research Council (SERC).*

*MTD Ltd advances marine research and development, primarily by means of its research activities in Higher Education Institutes and partly funded by SERC. MTD Ltd also provides an interface between such research and the requirements and expertise of its members. In July 1989, MTD Ltd absorbed UEG, the research and information group for the offshore and underwater engineering industries, thereby expanding its interests to include joint industry funded projects.*

*For further details, contact  
The Secretary,  
The Marine Technology Directorate Limited,  
19 Buckingham Street,  
London WC2N 6EF  
Telephone 01-321 0674.*

# **Underwater inspection of steel offshore installations: implementation of a new approach**

The project leading to this publication was undertaken by UEG. It is published by MTD Ltd as part of the arrangements for the takeover of UEG.

© MTD Ltd 1989

ISBN 1 870553 03 9

---

**THE MARINE TECHNOLOGY DIRECTORATE LIMITED**



19 Buckingham Street, London WC2N 6EF, UK Telephone 01-321 0674 Fax 01-930 4323

## Foreword

The project leading to this report was undertaken by UEG using technical services contractors for each of the seven studies directed at meeting the overall objectives. The studies and their contractors are given in Section 1.3. During the course of the work the UEG Project Managers were R.J. Simpson, R.K. Venables and R.W. Barrett.

The project was funded by the following participants:

American Bureau of Shipping  
Britoil Plc  
British Gas Plc  
BUE Group  
Comex Houlder Ltd  
Conoco (UK) Ltd  
The Department of Energy (UK)  
Det norske Veritas  
Earl & Wright Ltd  
Elf UK Plc  
Exxon Production Research Company  
Harwell Laboratory  
McAlpine Sea Services Ltd  
Marathon Oil Company  
Maersk Olie og Gas A/S  
Minerals Management Service, US Department of the Interior  
Norwegian Petroleum Directorate  
OSEL Group  
Petroleo Brasileiro S.A.  
Phillips Petroleum Company UK Ltd  
SonSub Services Ltd (formerly Sonat Subsea)  
Joint Swedish Group  
US Coast Guard  
Wimpey Offshore

A Steering Group, comprising representatives of participants, UEG and the technical services contractors, provided the forum for discussion and commented on this report prior to publication. During the course of the project the Steering Group comprised:

### **Participants**

Dr. P.I. Abrams	Exxon Production Research Co.
Mr. D. Adams *	Comex Houlder Ltd
Mr. D.J. Alexander	Britoil Plc
Mr. M. Allitt *	Wimpey Offshore
Mr. J. Balch	OSEL Group
Mr. R. Bates	Phillips Petroleum Company UK Ltd
Dr. C. Baxter *	BUE Group
Mr. A. Bennett	British Gas Plc
Mr. K. Bitting	US Coast Guard
Mr. R.E.F. Blowers	Phillips Petroleum Company UK Ltd
Mr. J. Le Breton	Elf UK Plc
Mr. F.T. Brown	Conoco (UK) Ltd
Mr. C.S. Camarini	Petroleo Brasileiro S.A.
Mr. P. Chilton	Sonat Subsea Services (UK) Ltd
Mr. M.J. Collard	McAlpine Sea Services Ltd
Dr. P.J. Cookson *	Wimpey Offshore
Mr. A. Cruickshanks	Comex Houlder Ltd
Mr. V. Davey	Department of Energy
Dr. N.T. Dick *	Britoil Plc
Mr. C. Dudfield	John Brown Group
Mr. J. Eng *	John Brown Group
Mr. L. Eriksson	Joint Swedish Group

Dr. G. Gage	Marine Technology Support Unit
Dr. W.E. Gardner *	Harwell Laboratory
Mr. J.L. Goldstick	American Bureau of Shipping
Cdr. J. Graffman	Joint Swedish Group
Mr. G. Hogg	Sonsub Services Ltd (formerly Sonat)
Mr. M. Light	Conoco UK Ltd
Mr. D.J. Mackay	Britoil Plc
Mr. J. Marti *	Elf UK Plc
Mr. E.J. Mavrommatakis	Det norske Veritas
Mr. P. Nelson	Britoil Plc
Mr. A. Newham	Marathon Oil (UK) Ltd
Dr. K. Newton	Harwell Laboratory
Dr. R.W. Nicholson	Wimpey Offshore
Mr. J.A. Nielsen	Maersk Olie og Gas A/S
Mr. K.L. Nilsson	Norwegian Petroleum Directorate
Mr. G. Poss	Phillips Petroleum Company UK Ltd
Mr. F.V. Poulsen *	Maersk Olie og Gas A/S
Mr. L. Robberstad Jr.	Elf Aquitaine Norge A/S
Mr B.J. Robinson	American Bureau of Shipping
Mr. J.F. Saunders	Marathon Oil Company
Mr. W.J. Sember	American Bureau of Shipping
Mr. C.E. Smith	Minerals Management Service
Mr. M.J. Teer	Earl and Wright Ltd
Mr. J. Thebault *	Elf Aquitaine Norge A/S
Mr. R.L. Thomas	American Bureau of Shipping
Mr. J. Turner *	OSEL Group
Dr. C.J.A. Watson *	Marine Technology Support Unit
Dr. F.A. Wedgwood	Harwell Laboratory
Mr. H. Westermarck *	Joint Swedish Group
Mr. C.J. White	Conoco (UK) Ltd

#### ***Technical services contractors***

Aberdeen University Marine Studies Ltd	Dr. G.B. Picken
Comex Houlder Ltd	Mr. D. Adams
	Mr. A. Cruickshanks
	Mr. H. Iravani
Earl & Wright Ltd	Mr. D. Loader
	Mr. M.J. Teer
Inspection Integrity Quest Partners	Mr. K. Allen *
McAlpine Offshore Ltd	Mr. J.M. Skillman
Techword Services	Mr. M.J. Wright
Thalassa Advanced Technologies Ltd	Mr. R. Herries *
A/S Veritas Research	Dr. H.O. Madsen
Wimpey Offshore	Mr. M.P. Allitt *
	Mr. R. Fraser
	Dr. R.W. Nicholson
	Mr. D. Stannard
	Mr. S. Walker

#### ***Project management †***

Mr. R.J. Simpson *	Project Manager (to Dec 86)
Mrs. L. Negus *	Project Administrator (to Sept 87)
Mr. R.K. Venables	Steering Group Chairman and Project Manager (to Dec 87)
Mr. R.W. Barrett	Steering Group Chairman and Project Manager to completion

\* No longer at this organisation

† During the course of the project, UEG staff

## Summary

This report is the outcome of a major joint industry sponsored project initiated by UEG. Its overall aim is to improve the effectiveness of underwater inspection of offshore installations, particularly through the use of a more rational method of planning inspection operations. The heart of this method is that that an installation owner should be provided with a level of confidence in the condition of each component of the installation commensurate with the consequences of failure of that component.

After an introductory Part which outlines this method and sets it in the context of other inspection planning philosophies, major chapters of a second Part review and discuss:

- types of damage and deterioration
- applying the proposed inspection planning method to existing installations
- the management of inspection operations offshore
- inspection operations – including inspection methods, cleaning, intervention and monitoring
- the assessment of any damage found.

A final Part discusses the adaptation of the proposed planning method to the design of new installations, and suggests how attention to detail design of new structures can ease the practical tasks of underwater inspectors in future.

# Contents

	<i>Page</i>
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 BACKGROUND TO THE PROJECT	1
1.2 SCOPE AND LIMITATIONS	1
1.3 STUDIES WITHIN THE PROJECT	2
1.4 LAYOUT OF THIS PROJECT REPORT	2
 <b>PART A:</b> <b>THE NEED FOR CHANGE AND THE BASIS OF A NEW APPROACH</b> 	
<b>2 UNDERWATER INSPECTION IN CONTEXT</b>	<b>3</b>
2.1 WHY INSPECT?	3
2.1.1 Overall objectives	3
2.1.2 Consequences of failure	3
2.2 STATUTORY REQUIREMENTS	4
2.3 TYPES OF DAMAGE AND DETERIORATION	4
2.4 LEVELS OF INSPECTION	5
2.4.1 Appropriate levels of inspection	5
2.4.2 Monitoring continuing performance	6
2.4.3 Assessing the integrity of damaged structures	6
2.5 CURRENT PRACTICE IN THE PLANNING OF INSPECTION	7
2.5.1 Introduction	7
2.5.2 Fixed platforms	7
2.5.3 Floating installations	8
2.5.4 Pipelines and risers	9
2.5.5 Attitude of the certifying authorities	10
2.6 PROBLEMS AND LIMITATIONS OF CURRENT PRACTICE	10
2.7 THE NEED FOR A MORE RATIONAL APPROACH	11
2.8 ALTERNATIVE APPROACHES	12
2.8.1 Aims	12
2.8.2 Practical considerations	12
2.8.3 Probabilistic versus deterministic approaches	12
2.8.4 Possible alternative approaches	13
<b>3 BASIS OF A RATIONAL APPROACH</b>	<b>18</b>
3.1 OBJECTIVES	18
3.2 PRINCIPLES OF THE PROPOSED RATIONAL APPROACH	18
3.2.1 Rationale	18
3.2.2 Discussion	19
3.2.3 The review panel	20
3.2.4 Summary	20
3.3 DEVELOPMENT OF THE METHOD	20
3.3.1 Overall approach	20
3.3.2 Practical considerations	21

## **PART B: EFFECTIVE IMPLEMENTATION**

<b>4</b>	<b>DAMAGE, DETERIORATION AND FOULING</b>	<b>27</b>
4.1	INTRODUCTION	27
4.2	TYPES OF DAMAGE AND DETERIORATION	28
4.2.1	Design details	28
4.2.2	Fabrication defects	28
4.2.3	Transportation and installation damage	29
4.2.4	Damage from operational activity	29
4.2.5	Corrosion	29
4.2.6	Fatigue damage	30
4.2.7	Seabed deterioration and seabed debris	31
4.2.8	Damage to submarine pipelines	31
4.2.9	Damage to floating and other non-fixed installations	32
4.2.10	Unexpected defects	32
4.3	MARINE FOULING	32
4.3.1	Introduction	32
4.3.2	Effects of fouling	32
4.3.3	Types of fouling	34
<b>5</b>	<b>MANAGEMENT OF INSPECTION PLANNING</b>	<b>42</b>
5.1	INTRODUCTION	42
5.1.1	Objectives of the approach	42
5.2	PRINCIPLES OF THE RATIONAL APPROACH	42
5.2.1	General	42
5.2.2	Philosophy of inspection, maintenance and repair	43
5.2.3	Review panel	44
5.2.4	Inspection priority ranking	44
5.2.5	Detailed studies to optimise the weightings and ranking	45
5.3	PRACTICAL FACTORS AFFECTING THE WEIGHTINGS	46
5.3.1	Preliminary weightings	46
5.3.2	Consequences of failure	46
5.3.3	Likelihood of failure	47
5.3.4	Criticality rating	49
5.3.5	Inspection history	50
5.3.6	A note of caution	50
5.4	CHOOSING INSPECTION METHODS	50
5.4.1	Relative costs and reliabilities of inspection methods	50
5.4.2	Component category for inspection	51
5.5	INSPECTION PLANNING IN PRACTICE	52
5.5.1	Inspection in year 1	52
5.5.2	Inspection in year 2	52
5.5.3	Inspection in year N	52
5.6	WORKED EXAMPLE	53
5.6.1	History	53
5.6.2	End of inspection year 19N8	53
5.6.3	Subsequent action	54
5.6.4	Lessons from the example	55
5.7	APPLICATION TO OTHER UNDERWATER INSTALLATIONS	55
5.8	BENEFITS AND COSTS OF THE RATIONAL APPROACH	56
5.8.1	Benefits	56
5.8.2	Costs and savings	57



5.9	INCORPORATION OF PROBABILISTIC METHODS	57
5.9.1	The probabilistic approach and its advantages	57
5.9.2	Application of probabilistic techniques in inspection planning	58
5.9.3	Extension of the probabilistic method	59
6	MANAGEMENT OF INSPECTION OPERATIONS	69
6.1	INTRODUCTION	69
6.1.1	Definitions of terms used in this chapter	69
6.1.2	Management structure	70
6.2	THE INSPECTION SYSTEM	71
6.2.1	Principles of the anomaly-based system	71
6.2.2	Overview of the system	71
6.2.3	Structural inventory	72
6.2.4	Inspection drawings	73
6.2.5	Inspection specification	74
6.2.6	Job Pack	76
6.2.7	Offshore operations	78
6.3	DATA MANAGEMENT	78
6.3.1	User specification	79
6.3.2	System sophistication	79
6.3.3	Design data	80
6.3.4	Fabrication yard data	80
6.3.5	Underwater inspection data	81
6.3.6	Operational data	82
6.4	COMPUTERISATION	83
6.4.1	Why use computers in inspection information work?	84
6.4.2	Experience from computer systems currently in use	84
6.4.3	A proposed development approach	85
7	INSPECTION AND MONITORING OPERATIONS	87
7.1	INTRODUCTION	87
7.1.1	Inspection methods and techniques	87
7.1.2	Cleaning	88
7.1.3	Intervention methods	88
7.1.4	Monitoring operations	89
7.1.5	Influence of water depth and structure type	90
7.2	INSPECTION METHODS	91
7.2.1	Visual inspection	91
7.2.2	Cathodic protection checking	92
7.2.3	Thickness measurements	93
7.2.4	Magnetic particle inspection	94
7.2.5	Ultrasonic defect characterisation	96
7.2.6	Flooded member detection	97
7.2.7	Radiography	98
7.2.8	Eddy current testing	99
7.2.9	Alternating current potential drop method	100
7.2.10	Photogrammetry	101
7.2.11	Future developments	101
7.3	CLEANING METHODS	103
7.3.1	Brushes and grinders	103
7.3.2	High pressure water jetting	103
7.3.3	Clean and paint machines	104
7.3.4	Relative performances	104

7.4	INTERVENTION METHODS	106
7.4.1	Diving	106
7.4.2	Atmospheric diving suits	108
7.4.3	Manned submersibles	109
7.4.4	Remotely operated vehicles	110
7.4.5	Underwater navigation	112
7.5	MONITORING METHODS	114
7.5.1	Components of monitoring systems	114
7.5.2	Vibration monitoring methods	115
7.5.3	Acoustic emission methods	117
7.5.4	Cathodic protection condition	118
7.5.5	Steelwork internal pressures	118
7.5.6	Fibre-optic crack monitoring	119
7.5.7	Performance-based monitoring	119
7.5.8	Crack propagation monitoring	120
7.5.9	Flooded member monitoring	120
7.6	SPECIAL INSPECTION APPLICATIONS	121
7.6.1	Inspection in deep water	121
7.6.2	Export risers and conductors	121
7.6.3	Secondary components and attachments	122
7.6.4	Seabed pipelines	122
7.6.5	Seabed production equipment	123
7.6.6	Inspection pigging	123
7.6.7	Non-jacket platforms	123
8	ASSESSMENT OF DAMAGE	139
8.1	THE ROLE OF DAMAGE ASSESSMENT	139
8.2	DENTED AND BENT MEMBERS	139
8.2.1	Types of damage	139
8.2.2	Review of published literature	140
8.2.3	Buckling behaviour	140
8.2.4	Residual strength and stiffness	141
8.2.5	Fatigue behaviour of damaged tubulars	143
8.2.6	Suggested method for defect assessment after collision damage	143
8.3	FATIGUE CRACKS	144
8.3.1	Introduction	144
8.3.2	The assessment of fatigue crack growth	145
8.3.3	Suggested method for analysing part-through cracks	147
8.3.4	Analysis methods for through-thickness cracks	150
8.3.5	Benchmark studies	150
8.4	CRACK STABILITY	151
8.4.1	Introduction	151
8.4.2	General background	152
8.4.3	Material property behaviour	154
8.4.4	Benchmark studies	157
8.5	ASSESSMENT OF STRUCTURAL REDUNDANCY	159
8.6	CASE STUDIES	160

## **PART C: INTERACTION BETWEEN DESIGN AND INSPECTION**

<b>9</b>	<b>DESIGN-INSPECTION INTERACTION</b>	<b>193</b>
9.1	INTRODUCTION	193
9.2	DESIGN FOR OPTIMUM INSPECTION	193
9.3	TRADE-OFF BETWEEN CAPITAL AND OPERATING EXPENDITURES	194
9.4	HANDOVER FROM DESIGNER TO OPERATOR	195
<b>10</b>	<b>DESIGN FOR EASE OF INSPECTION AND MONITORING</b>	<b>197</b>
10.1	INTRODUCTION	197
10.2	CONCEPTUAL ENGINEERING	197
10.2.1	Tubular joints	198
10.2.2	Effect of the inspection intervention system	198
10.3	DETAIL DESIGN	200
10.3.1	Diving considerations and safety	200
10.3.2	Access for inspection	202
10.3.3	Structural monitoring	203
10.3.4	Redundancy and defect tolerance	204
10.3.5	Antifouling procedures	204
10.4	FABRICATION AND DESIGN CLOSE-OUT	205
10.4.1	Design data for inspection planning management	205
10.4.2	Extra documentation	206
10.4.3	Design data input to the inspection programme	206
10.4.4	Input for damage assessment	207
	<b>REFERENCES</b>	<b>215</b>
	<b>APPENDIX 1: STATUTORY REQUIREMENTS, CERTIFICATION AND GUIDANCE</b>	<b>221</b>
A1.1	UNITED KINGDOM	221
A1.1.1	Fixed offshore installations	221
A1.1.2	Mobile offshore installations	222
A1.1.3	Submarine pipelines	222
A1.2	NORWAY	223
A1.2.1	Offshore installations	224
A1.2.2	Submarine pipelines	224
A1.3	OTHER COUNTRIES	225
A1.3.1	Denmark	225
A1.3.2	Netherlands	225
A1.4	CERTIFYING AUTHORITIES	225
A1.4.1	Det norske Veritas	225
A1.4.2	American Bureau of Shipping	226
A1.5	REFERENCES	227
	<b>APPENDIX 2: PRINCIPLES OF PROBABILISTIC TECHNIQUES</b>	<b>231</b>
A2.1	BASIC CONCEPTS	231
A2.2	RELIABILITY THEORY	232
A2.3	REFERENCES	233

## TABLES

Table 4.1:	Summary of underwater inspection findings for 21 steel jackets in the North Sea
Table 4.2:	Checklist to identify potential failure mechanisms
Table 4.3:	Submarine pipeline failures discovered after laying but prior to start-up
Table 4.4:	Number of pipeline incidents during operation needing remedial action
Table 4.5:	Summary of the effects of marine fouling organisms on offshore steel structures
Table 4.6:	Drag and inertia coefficients for various types of fouling on cylinder surfaces
Table 5.1:	Suggested weightings for individual items affecting the consequences of failure, Y, of one specified joint
Table 5.2:	Suggested weightings for individual items affecting the likelihood of failure, X, of one specified joint
Table 5.3:	Categories of components for inspection purposes
Table 5.4:	Possible inspection methods for different inspection categories
Table 5.5:	Preliminary estimates of costs of introducing the rational approach to inspection planning
Table 5.6:	Sources of uncertainty
Table 7.1:	The hierarchy of underwater inspection tasks on steel structures
Table 7.2:	Advantages and limitations of visual inspection techniques
Table 7.3:	Summary of commercial diving methods
Table 7.4:	Vibration monitoring results due to damage on a northern North Sea platform
Table 7.5:	Depth limitations of intervention methods
Table 8.1:	Properties of damaged members illustrated in Figures 8.1 and 8.2
Table 8.2:	Suggested constants for the SWRI crack growth law
Table 8.3:	The benchmark studies of Section 8.3.5
Table 8.4:	Values of notch stress concentration factor, $K_t$ , for weld toe stress concentrations for Grade 50D steel
Table 8.5:	Initial crack depths for fatigue crack studies for Grade 50D steel
Table 8.6:	Measured Charpy V notch impact toughness and CTOD toughness for Grade 50D steel
Table 8.7:	Benchmark studies – material properties
Table 8.8:	Benchmark studies – applicability of the three methods
Table 10.1:	Summary of inspection-related design activities detailed in Sections 10.2–10.4
Table A2.1	Normal distribution

## FIGURES

Figure 2.1:	Variation with time of inspecting a joint containing a crack with percentage of joints inspected as a parameter
Figure 2.2:	Simplified decision tree illustrating current practice in inspection planning in year N
Figure 2.3:	Typical flow diagram for 'fail-safe' design
Figure 3.1:	Part of decision tree for development of an optimised inspection strategy
Figure 3.2:	Proposed philosophy (simplified) for inspection planning, year N
Figure 3.3:	Flow diagram to indicate the formulation of the annual inspection/repair programme
Figure 3.4:	Load and strength distributions showing the probability of load exceeding strength
Figure 4.1:	Hypothetical jacket structure indicating which members can accommodate most damage and deterioration
Figure 4.2:	Causes of damage to North Sea fixed platforms that resulted in repairs
Figure 4.3:	Mussel fouling
Figure 4.4:	Deepwater barnacle fouling
Figure 4.5:	Aggregate tubeworms
Figure 4.6:	A 'turf' of hydroids

- Figure 4.7: Anemones
- Figure 4.8: Soft coral fouling
- Figure 4.9: Sea squirts
- Figure 5.1: A rational approach to planning the annual inspection programme
- Figure 5.2: Computation of overall inspection weighting,  $Z$
- Figure 5.3: Relationships between load-carrying capacity and load in a component
- Figure 5.4: Example of spreadsheet layout showing inputs to overall inspection weightings of joints
- Figure 5.5: Flowchart for operational review of components requiring inspection
- Figure 5.6: Worked example – part of the first subsea horizontal framing panel on a steel jacket
- Figure 5.7: Spreadsheet showing the ranking of joints at end of inspection year 19N8
- Figure 5.8: Spreadsheet showing the ranking of joints at end of inspection year 19N9
- Figure 5.9: Crack growth and inspection
- Figure 5.10: Overall determination of inspection weighting – probabilistic method
- Figure 6.1: Response activity guidelines
- Figure 7.1: Operation of ultrasonic equipment for measuring remaining ligament thickness after grinding (or depth of corrosion pits)
- Figure 7.2: The principle of ultrasonic flooded member detection and typical screen displays
- Figure 7.3: Radiographic source and film layout to detect internal corrosion or blockage of an underwater pipe
- Figure 7.4: Principle of operation of the ACPD method for measuring crack depths
- Figure 7.5: Typical plant and equipment for bounce diving
- Figure 7.6: Typical plant and equipment necessary for saturation diving
- Figure 7.7: Examples of mid-water ADSs
- Figure 7.8: Tethered 'eyeball' ROV
- Figure 7.9: One-atmosphere tethered one-man submersible (can also be operated as an ROV)
- Figure 7.10: ROV deployed from an underwater cage
- Figure 7.11: Cross-section of a typical piezoelectric accelerometer
- Figure 7.12: Typical overall mode shapes from vibration monitoring
- Figure 7.13: Layout of the components of a forced excitation vibration monitoring system covering a complete platform
- Figure 7.14: Principle of operation of monitoring steelwork internal pressures
- Figure 7.15: Principle of operation of fibre-optic crack monitoring
- Figure 8.1: Damage history – Example A
- Figure 8.2: Damage history – Example B
- Figure 8.3: Effect of reduced slenderness ratio on column compressive strength
- Figure 8.4: Bulge-type imperfections introduced by circumferential welds
- Figure 8.5: Illustration of interaction between column and local buckling
- Figure 8.6: Sub-division of cross-section into 'fibres'
- Figure 8.7: Numerical characterization of dents
- Figure 8.8: Idealization of a sharp dent
- Figure 8.9: Dent damage theoretical model
- Figure 8.10: Effect of the slenderness,  $\lambda$ , of a simply supported damaged tubular on its residual strength
- Figure 8.11: Effect of the slenderness,  $\lambda$ , of a clamped damaged tubular on its residual strength
- Figure 8.12: Effect of weld-induced residual stress on load-shortening curves for simply supported tubes
- Figure 8.13: Residual stress distributions
- Figure 8.14: Contribution of residual stress to damage effect
- Figure 8.15a: Effect of length of dent on ultimate load of a damaged tubular
- Figure 8.15b: Effect of location of dent on ultimate load of a damaged tubular
- Figure 8.16: Collapse of thin-walled tubular columns
- Figure 8.17: Growth of dent depth as a function of axial load
- Figure 8.18: Ultimate load of a dented tubular member as a function of  $D/t$  ratio

- Figure 8.19: Ultimate load of a dented tubular member as a function of the depth of the dent
- Figure 8.20: Effect of uniform lateral load-interaction curves
- Figure 8.21: Schematic presentation of crack growth
- Figure 8.22: SWRI crack growth law for different environments
- Figure 8.23: The crack growth law of Equation 11 compared with a Paris law
- Figure 8.24: Surface crack in a flat plate
- Figure 8.25: Development of stress intensity solution from the case of wedge opening forces
- Figure 8.26: Aspect ratio correction factor,  $Y_a$
- Figure 8.27: Flowchart for fatigue crack growth computation – part-through cracks
- Figure 8.28: Typical through-thickness crack geometries in a tubular member remote from a joint
- Figure 8.29: Correction factors,  $Y_t$  and  $Y_b$ , for use in stress intensity factor solution of Equation 21
- Figure 8.30: Crack growth model with varying  $\lambda$  compared with experimentally derived S–N curve
- Figure 8.31: Effect of stress distribution factor,  $\lambda$ , on crack growth characteristics
- Figure 8.32: Effect of wall thickness on fatigue life
- Figure 8.33: Effect of environment on fatigue life
- Figure 8.34: Crack depth versus residual life for three environments
- Figure 8.35: Effect of plasticity on crack behaviour
- Figure 8.36: CTOD design curve
- Figure 8.37: The R6 failure assessment diagram
- Figure 8.38: Load-displacement graphs for CTOD showing various types of behaviour
- Figure 8.39: Comparison of predicted  $K_{IC}$  curves with experimental  $K_{IC}$  values for Grade 50D steel with Charpy transition curve as shown above
- Figure 8.40: Benchmark studies – internally cracked cylinder under tension
- Figure 8.41: Benchmark studies – stress-strain curve (Ramberg-Osgood model)
- Figure 8.42: Benchmark studies – stress intensity factor solution
- Figure 8.43: Benchmark studies – stability diagram
- Figure 8.44: Possible failure modes at tubular joint
- Figure 9.1: Relationship between component strength and applied load
- Figure 10.1: Structure coverage from a single-point DDS
- Figure 10.2: Structure coverage from a multipoint DDS
- Figure 10.3: Typical pig trap dimensions for 900-mm diameter pipeline
- Figure 10.4: Intake catch grid
- Figure 10.5: Anode configurations
- Figure 10.6: Layout for diver work platform
- Figure 10.7: Pressure-detection of through-wall cracks in piles at the mudline
- Figure 10.8: Example of structural member redundancy diagram to be used by untrained personnel
- Figure 10.9: Example of designed fatigue life diagram
- Figure A1.1: UK certification procedures for offshore installations
- Figure A1.2: UK authorisation procedure for submarine pipelines
- Figure A1.3: Norwegian certification procedures for offshore installations and submarine pipelines
- Figure A2.1: Probability density function,  $f(s)$
- Figure A2.2: 100-year return period design value,  $S_{100}$
- Figure A2.3: The standard deviation,  $\sigma_s$
- Figure A2.4: The cumulative probability distribution function,  $F(s)$
- Figure A2.5: Relationship between load-carrying capacity and load in a component
- Figure A2.6: The reliability index,  $\beta$
- Figure A2.7: Sensitivity index,  $\partial\beta/\partial S$

# 1 Introduction

## 1.1 BACKGROUND TO THE PROJECT

Underwater inspection and defect assessment are of great concern to all involved in ensuring the long-term integrity of offshore installations. Over the years since first gas and then oil were developed from North Sea fields, the offshore industry has made substantial technical progress and gained considerable experience of structural inspection under water and of defect assessment.

The industry drew on experience gained on offshore installations elsewhere in the world but, as in many other facets of North Sea operations, the harsh environment there has led to stringent inspection requirements and associated technical advances. The industry has also drawn on the considerable research and experience of non-destructive testing and defect assessment in the nuclear and aircraft industries.

And yet, despite these advances, it was clear that many questions – some of fundamental importance to improving the effectiveness of underwater inspection – remained:

- What items should be inspected and how often?
- Will defects be recognised when they are 'seen'?
- How are the items to be inspected to be selected?
- What is the smallest detectable defect?
- How frequently should we inspect?
- How does the design, and particularly the estimated fatigue life of particular structural elements, affect the need for, and the objective, nature and frequency of any inspection.
- What type and size of defect is sufficiently small not to jeopardise the continued safety of an installation?
- What is the significance of a given defect in a given position?
- How does the underwater environment affect the feasibility, accuracy and frequency of any inspection?

UEG was, from the start of its work on offshore structures, actively involved in many aspects of in-service performance of installations. In 1978, still the 'early days' of North Sea development, UEG published its Report UR10 'Underwater inspection of offshore installations: guidance to designers'<sup>(1,1)</sup> which addressed and provided recommendations on actions which designers could take to ease and reduce the underwater inspection of the installations they design. Its recommendations remain remarkably pertinent today.

Whereas UR10 concentrated on design detailing, this project addressed broader issues of philosophy behind inspection planning and how a new approach could be brought to inspection of existing structures as well as to the design of new structures.

With that background, UEG set up the project which has led to this report. The aims were:

- to provide a forum for offshore industry representatives to discuss and develop a cogent philosophy for the underwater inspection of offshore installations and pipelines
- to prepare detailed practical guidance to match the results of the first objective.

## 1.2 SCOPE AND LIMITATIONS

The ensuing project was targetted at the underwater inspection of installations world-wide, drawing on the extensive experience already gained in the major offshore oil and gas production areas. It was aimed to cover all types of installations, and concrete platforms were the subject of one of the studies within the project – see Section 1.3.

This report, however, concentrates on providing analysis, a new approach and practical guidance on the underwater inspection of steel offshore installations. The majority of the report concentrates on fixed structures, with relevant comments added on the special considerations for some other kinds of installations. Within the studies related to steel structures, advice was sought on aspects of inspection appropriate to different types of installations as follows:

- fixed steel tubular structures
- floating structures moored long term on station
- tethered buoyant platforms
- production risers, fixed and compliant
- pipelines
- subsea installations.

The project was undertaken by UEG using technical services contractors for seven studies – see Section 1.3. The project was funded by a group of interested organisations, including oil companies, governments, contractors, designers, suppliers and a certifying authority.

A Steering Group comprising contributors' representatives, UEG staff and representatives of the technical services contractors provided the forum for discussion and commented on this report prior to its circulation to contributors. UEG were project managers and provided the Chairman of the Steering Group.

### 1.3 STUDIES WITHIN THE PROJECT

Several studies have been undertaken within the project, all directed towards meeting the overall objectives and the preparation of this and other reports. The seven studies and their technical services contractors were:

- Study One: Methods of underwater inspection and intervention for steel structures and subsea installations – Inspection Integrity Quest Partners
- Study Two: Interaction between design and inspection of steel structures – Earl & Wright Ltd
- Study Three: Inspection of concrete structures – McAlpine Offshore Ltd
- Study Four: Damage assessment – Wimpey Offshore
- Study Five: Management of resources and manpower planning – Thalassa Advanced Technologies Ltd
- Study Six: Significance and inspection of marine fouling – Aberdeen University Marine Studies Ltd
- Study Seven: The potential for probabilistic methods in underwater inspection – A/S Veritas Research.

Apart from the individual study contractors, considerable additional input was provided by Mr J de Prey of UEG in preparing Chapter 6.

Reviews and appraisals of various chapters were undertaken by Mr R D Allen of ATOM and Mr J Bevan of Submex Ltd.

The whole report was technically edited and prepared for printing by Mr M J Wright of Techword Services.

### 1.4 LAYOUT OF THIS PROJECT REPORT

This report is presented in three distinct but complementary parts:

- *Part A: The need for change and the basis of a new approach* – is aimed at all readers interested in improving the effectiveness of underwater inspection. It reviews the motivations behind inspection planning appropriate to different structures and circumstances, reviews current practice (and its limitations), analyses the need for a more rational approach and a number of alternatives, and finally presents the basis of a new, more rational approach to inspection planning.
- *Part B: Effective implementation* – reviews damage and deterioration, provides practical guidance in the management of inspection (including implementation of the new approach to inspection planning outlined in Part A), provides practical guidance on inspection and monitoring operations, including inspection methods, cleaning, intervention methods and monitoring, and concludes with a major section on the assessment of damage.
- *Part C: Interaction between design and inspection* – discusses the adaptation of the principles developed in Part B to the design of new structures. Aspects of design detailing to ease the practical tasks of inspection are also addressed.