

***IGE/TD/12 Edition 2
Reprint with Amendments
Communication 1757***

Pipework stress analysis for gas industry plant



*Founded 1863
Royal Charter 1929
Patron: Her Majesty the Queen*

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• 6.3	Normal sustained loads	11
• 6.4	Abnormal sustained loads	11
• 6.5	Hydrostatic test	12
• 6.6	Shakedown	12
• 6.7	Fatigue	12
7	Wall thickness and selection of pipework components	14
• 7.1	General	14
• 7.2	Straight pipe	14
• 7.3	Fittings	15
• 7.4	Thickness allowances	15
8	Stress and fatigue analysis	16
• 8.1	General procedure	16
• 8.2	Scope of pipework for analysis	16
• 8.3	Pipework modelling	16
• 8.3.1	General	16
• 8.3.2	Longitudinal pressure strain	17
• 8.3.3	Thickness for analysis	18
• 8.3.4	Estimation of soil restraint	18
• 8.4	Load case table	18
• 8.4.1	Compilation	18
• 8.4.2	Use	19
• 8.5	Stress analysis procedure and acceptance limits	19
• 8.5.1	General	19
• 8.5.2	Analysis of sustained conditions	19
• 8.5.3	Acceptance limits for sustained conditions	19
• 8.5.4	Analysis of shakedown conditions	20
• 8.5.5	Acceptance limits for shakedown conditions	20
• 8.5.6	Analysis of cyclic conditions	20
• 8.5.7	Acceptance limits for cyclic conditions	21
• 8.6	Reactions	21
• 8.6.1	Supports	21
• 8.6.2	Loads on connected equipment	21
• 8.6.3	Strain-sensitive equipment	21
• 8.7	Displacements	22
• 8.8	Buckling	22
9	Resolving stress exceptions	23
• 9.1	General	23
• 9.2	New build	23
• 9.2.1	Wall thickness	23
• 9.2.2	Forged tees to BS 1640	23
• 9.2.3	Soil restraint	24
• 9.2.4	Supports	24
• 9.2.5	Branch flexibility modelling	24
• 9.2.6	Design-by-analysis (DBA)	25
• 9.3	Existing installations	25
• 9.3.1	Design conditions	25
• 9.3.2	Operating history	25
• 9.3.3	Temperature conditions	25

	• 9.3.4 Site modifications	26
10	Verification	27
	• 10.1 General	27
	• 10.2 Operating conditions	27
	• 10.3 Other design parameters and assumptions	27
	• 10.4 Action to be taken	27
11	Documentation	28
	• 11.1 Stress analysis records	28
	• 11.1.1 Commissioning and operational records	28
	• 11.1.2 Records for situations where analysis is not required	28
	• 11.2 Stress analysis report	28
	• 11.2.1 General	28
	• 11.2.2 Design brief	29
	• 11.2.3 Register	29
	• 11.2.4 Stress model drawing	29
	• 11.2.5 Load case table	29
	• 11.2.6 Soils information	29
	• 11.2.7 Isometric plot	29
	• 11.2.8 Geometric and material properties	29
	• 11.2.9 Stress exceptions	29
	• 11.2.10 Computer program input/output data	29
	• 11.2.11 Conclusions and recommendations	30

APPENDIX

1	Glossary, acronyms and notation	31
	• A1.1 Glossary and acronyms	31
	• A1.2 Notation	34
2	References	36
	• A2.1 Legislation	36
	• A2.2 IGEN	36
	• A.2.2.1 Recommendations on Transmission and Distribution Practice	36
	• A.2.2.2 Gas Measurement Procedures	36
	• A.2.2.3 Gas Legislation Guidance	36
	• A2.3 BSI	37
	• A2.4 Overseas	37
	• A2.5 Miscellaneous	37
3	Stresses	38
	• A3.1 Notation	38
	• A3.2 Description	38
	• A3.3 Individual stress components	40
	• A3.3.1 Straight pipe, wall thickness transitions, concentric and eccentric reducers	40
	• A3.3.2 Bends, mitre bends and welding elbows	40
	• A3.3.3 Weldolets, long weld neck flanges, weldoflanges, sweepolets and tees	40

4	Stress concentration factors (SCFs)	42
	• A4.1 Scope 42 • A4.2 Dimensions 42 • A4.3 Notation 42 • A4.4 Straight pipe 46 • A4.5 Wall thickness transition 47 • A4.6 Concentric and eccentric reducers 48 • A4.7 Bends and welding elbows 49 • A4.8 Closely spaced mitre bend 50 • A4.9 Single or widely spaced mitre bend 51 • A4.10 Set-on welded branch connections 52 • A4.10.1 Weldolet 53 • A4.10.2 Long weld neck flange 54 • A4.10.3 Weldoflange 55 • A4.10.4 Fabricated tee 56 • A4.11 Other branch connections 57 • A4.11.1 Weldolet 58 • A4.11.2 Long weld neck flange 59 • A4.11.3 Weldoflange 60 • A4.11.4 Fabricated tee 61 • A4.11.5 Forged tee to BS 1640 62 • A4.11.6 Drawn/extruded and forged tee not to BS 1640 63 • A4.11.7 Sweepolet & welded-in contour insert 64 • A4.11.8 Full encirclement tee 65 • A4.11.9 Fabricated tee with pad or saddle 66	
5	Fatigue analysis	67
6	Design-by-analysis (DBA) method	73
7	Example load case table	78
8	Worked example	79
TABLES		
1	Minimum nominal wall thickness of steel pipe	14
2	Design factor (f)	15
3	Maximum permitted sustained stresses for S_s , S_{sab1} , S_{sab2} , ... S_{sabi}	20
4	Shakedown factor, K_{SD}	20
5	Fatigue analysis thresholds for carbon and austenitic steels	21
6	Straight pipe SCFs	46
7	Wall thickness transition SCFs	47
8	Concentric and eccentric reducer SCFs	48
9	Bend and welding elbow SCFs	49

10	Closely spaced mitre bend SCFs	50
11	Single or widely spaced mitre bend SCFs	51
12	Weldolet SCFs	53
13	Long weld neck flange SCFs	54
14	Weldoflange SCFs	55
15	Fabricated tee SCFs	56
16	Weldolet (others) SCFs	58
17	Long weld neck flange (others) SCFs	59
18	Weldoflange (others) SCFs	60
19	Fabricated tee SCFs	61
20	Forged tee to BS 1640 SCFs	62
21	Drawn/extruded and forged tee not to BS 1640 SCFs	63
22	Sweepolet & welded-in contour insert SCFs	64
23	Full encirclement tee SCFs	65
24	Fabricated tee with pad or saddle SCFs	66
25	Fatigue classes	67
26	Equation constants for S-N fatigue design curves	69
27	Correction factors for S_R and N_T	70
28	Example load case table for shakedown, normal and abnormal sustained and fatigue	78

FIGURE

1	Adjacent branch limitations of set-on branch connections	52
2	S-N Fatigue curves for $E = 209 \times 10^3 \text{ N/mm}^2$	69
3	Basic nomenclature of set-on branch connections	72

SECTION 1 : INTRODUCTION

This Reprint with Amendments of IGE/TD/12 Edition 2 incorporates Amendments as issued in January 2005. The opportunity has also been taken to include additional enhancements such as IGEMs address. It is essential that owners of the original Recommendations i.e. those published in 2003 (Communication 1681), update those Recommendations with the January 2005 Amendments (which are available to download from IGEM's website) but it is not essential for those Recommendations to be updated with the enhancements.

For information, the enhancements have been made to 1.3. 1.3 (Note), 1.4, 2.3, 2.4, 2.6, 4.5, 5.6.2, 7.1, 7.1 (Note), 7.3.1, 8.3.3, 9.2.1, A2.2.1, A2.2.2 A5.2.1, A5.2.3, A5.2.4 and A5.7

The Amendments have been made to 2.1 (4th Bullet), 5.2.1, 8.5.7.1, A2.3, A3.3.1, A3.3.2, A3.3.3.1, A3.3.3.2, A4.10.2, A4.10.4 and A8.2.1

1.1 In 1975, the Institution of Gas Engineers (IGE) published IGE/TD/9 for offtakes and pressure regulating installations (PRIs) operating at pressures exceeding 7 bar. Within IGE/TD/9, Section 9 and the associated Appendix 4 on pipework design and stressing outlined methods for the calculation of stresses within a piping system. IGE/TD/9 has been superseded by IGE/TD/13.

In 1985, IGE published IGE/TD/12 (Edition 1), extending the scope of these methods to cover a wider application than that given in IGE/TD/9. Amendments to IGE/TD/12 (Edition 1) were issued in 1990.

This edition of IGE/TD/12, which supersedes Edition 1 (which is now obsolete), has been drafted by a Panel appointed by the Institution of Gas Engineers and Managers' (IGEM's) Gas Transportation Committee, subsequently approved by that Committee and published by the authority of the Council of IGEM. It reflects improvements and developments through calculation and analysis.

1.2 The aim of these Recommendations is to ensure that piping systems are designed to withstand the stresses within them and to ensure that forces and moments applied to connected equipment and support structures are considered.

1.3 This edition provides a revised content and improved structure compared to Edition 1. Sections on stress calculation equations, stress concentration factors (SCFs) and fatigue are now presented in appendices. Sections on pressure testing and construction have been excluded since these aspects are more appropriate to IGEM/TD/13. A worked example using the guidance on stresses, SCFs and fatigue is now included. This provides greater clarity on the sustained, shakedown and fatigue assessments.

Note: Although IGEM/TD/13 covers only PRIs, it may be deemed appropriate to use it for construction and testing of other installations.

1.4 Although much of the technical content of Edition 1 has been retained, there are a number of important changes:

- design for creep conditions is no longer considered. The revised scope is controlled by a limit placed on the maximum design temperature
- pipework stress analysis is now based on the use of a matching wall thickness for both flexibility and stress calculations. This reflects common practice in other codes
- the fatigue assessment now adopts the weld classification system and material S-N curves of PD 5500 and BS EN 1993-1-9.

- 1.5 A new section has been included on resolving code stress exceptions. This includes guidance on branch flexibility modelling and on "design-by-analysis" (DBA) using three-dimensional finite element (FE) modelling.
- 1.6 Materials and methods of analysis are subject to continuous evolution and it is intended to review these Recommendations from time to time. Regard will be paid to the publications and findings of appropriate organisations with which IGEN maintains liaison.
- 1.7 These Recommendations reflect the need to ensure adequate reliability and continuity of supply at pressures that are safe for the downstream system and equipment.
- 1.8 These Recommendations do not attempt to make the use of any method or specification obligatory against the judgement of the responsible engineer. Where new and better techniques are developed and proved, they should be adopted without waiting for modification of these Recommendations. Amendments to these Recommendations will be issued when necessary and their publication will be announced in the Journal of the Institution and other publications as appropriate.
- 1.9 The primary responsibility for compliance with legal duties rests with the employer. The fact that certain employees, for example "responsible engineers", are allowed to exercise their professional judgement does not allow employers to abrogate their primary responsibilities. Employers must:
 - (a) Have done everything to ensure, so far as is reasonably practicable, that there are no better protective measures that can be taken other than relying on the exercise of professional judgement by "responsible engineers".
 - (b) Have done everything to ensure, so far as is reasonably practicable, that "responsible engineers" have the skills, training, experience and personal qualities necessary for the proper exercise of professional judgement.
 - (c) Have systems and procedures in place to ensure that the exercise of professional judgement by "responsible engineers" is subject to appropriate monitoring and review.
 - (d) Not require "responsible engineers" to undertake tasks which would necessitate the exercise of professional judgement that is beyond their competence. There should be written procedures defining the extent to which "responsible engineers" can exercise their judgement. When "responsible engineers" are asked to undertake tasks that deviate from this, they should refer the matter for higher review.

Note: The responsible engineer is a suitably qualified, competent and experienced engineer or a suitably qualified, competent and experienced person acting under his or her supervision, appointed to be responsible for the application of all or part of these Recommendations.
- 1.10 Requests for interpretation of these Recommendations in relation to matters within their scope, but not precisely covered by the current text, may be addressed to Technical Services, IGEN, IGEN House, High Street, Kegworth, Derbyshire, DE74 2DA, email: general@igem.org.uk, and will be submitted to the relevant committee for consideration and advice, but in the context that the final responsibility is that of the engineer concerned. If any advice is given by or on behalf of IGEN, this does not imply acceptance of any liability for the consequences and does not relieve the responsible engineer of any of his or her obligations.

SECTION 2 : SCOPE

- 2.1 These Recommendations cover the stress analysis and calculation of loadings for welded and flanged pipework used in gas industry installations on pipelines.

In general, an installation on a pipeline comprises one or more of the following:

- compressor station
- line valve
- branch connection
- meter installation (see also IGE/GM/8 or IGE/GM/4, as appropriate)
- multi-junction station with or without in-line metering and which may include pig traps and/or line valves
- overhead pipe crossing
- pigging station
- PRI controlling gas flow and/or pressure from one system to another
- terminal
- other offtakes.

- 2.2 These Recommendations apply to pipework (as outlined in Sub-Section 2.1) on land, including water crossings. For pipework offshore, additional or alternative guidance may be required. However, many of the recommendations will remain valid.

Note: Offshore pipework is on the seaward side of the low water mark or special boundaries drawn at bays and estuaries.

- 2.3 These Recommendations are entirely dependent upon the application of other relevant codes and standards, appropriate to the system being designed, for example IGEM/TD/1, IGEM/TD/13, etc., to ensure overall plant integrity.

Note: The information covering materials (pressure testing and construction) is included to qualify the stress analysis recommendations and draw attention to important areas of consideration.

- 2.4 These Recommendations are entirely dependent upon the correct selection of materials compatible to the appropriate duty. These Recommendations are not intended for general application to pipelines, which are covered by IGEM/TD/1, IGE/TD/3 and IGE/TD/4 respectively. Where larger diameter pipework is above ground for a significant distance, these Recommendations may be relevant.

- 2.5 These Recommendations cover stress analysis for pipework carrying gas at a maximum operating pressure (MOP) not exceeding 100 bar and at a temperature between -25°C and 120°C inclusive.

Note: Specifically, these Recommendations apply to the range of conditions expected to be encountered in the types of plant specified in Sub-Section 2.1.

These Recommendations cover pipework handling 1st and 2nd family gases as defined in BS 1179, odourised or unodourised.

- 2.6 These Recommendations apply only to carbon and austenitic steels whose permanent elongation at tensile fracture at room temperature is greater than 14% when measured using the method outlined in BS EN ISO 6892-2.

Note 1: The use of pipe manufactured from non-metallic, cast metallic or other brittle material is not within the scope of these Recommendations.

Note 2: Materials operating above their creep threshold are not covered.

- 2.7 These Recommendations apply to pipework containing gas at a positive gauge pressure, i.e. internal pressure not less than external pressure.
- 2.8 Pipes with a diameter to wall thickness ratio (D/t) of less than 10 require special consideration.
- For pipes of D/t greater than 96, the possibility of buckling of the pipework needs to be considered.
- 2.9 All pressures are gauge pressures unless otherwise stated.

SECTION 3 : COMPETENCY AND QUALITY ASSURANCE

3.1 COMPETENCY

Any person engaged in pipework stress analysis should be competent to carry out such work. This may be achieved by an appropriate combination of education, training and practical experience.

The analyst should have documented proof of competence.

3.2 QUALITY ASSURANCE

3.2.1 General

A suitable Quality Management System to BS EN ISO 9000 should be in place for any design activity.

Note: Guidelines for Quality Plans are provided in BS ISO 10005.

3.2.2 Co-ordination

The analysis (see clause 3.2.4) should be carried out by, or under the supervision of, a responsible engineer who can, by virtue of status, ensure that effective liaison is established and maintained between the various functions which contribute to the design and construction of a plant, including procurement of materials.

3.2.3 Software

Software used to perform analyses should be checked and verified.

3.2.4 Analysis

Any model used in the analysis of pipework should be a reasonable representation of the design for construction and any existing plant.

The model should represent pipework geometry, material properties, loading and restraint conditions. Where assumptions or approximations are required in the model, details and their justification should be documented. Reference should be made to Section 8.

3.2.5 Review of the analysis

A review of the analysis should be carried out by an independent analyst. The scope of the review should include a check of load cases applied, boundary conditions, pipework geometry, material properties and compatibility with the proposed design, including any existing pipework, etc.

3.2.6 Construction

Arrangements should be made to ensure that materials and workmanship are in accordance with the approved construction design. Reference should be made to Section 10 if variations from the construction design exist.

3.2.7 Design appraisal

The design for construction and supporting analysis should be subject to a design appraisal, for example as outlined in IGE/GL/5.

SECTION 4 : MATERIALS

4.1 GENERAL

4.1.1 Materials used in pressure-containing pipework should conform to nationally-listed specifications covering chemical, physical and mechanical properties, method and process of manufacture, heat treatment and quality control applied.

4.1.2 Materials should be selected having regard to the process involved and be resistant to any adverse chemical effects of service conditions.

Note: An example, in this respect, is the phenomenon of stress corrosion cracking (SCC). Expert advice is recommended when there is a risk of SCC occurring.

4.1.3 For carbon or low alloy steel pipework, either the specified minimum yield strength (SMYS), or the 0.2% proof stress, should not be greater than 85% ultimate tensile strength (UTS), throughout the temperature range for which the pipework will be used.

4.1.4 For austenitic stainless steel pipework, the 1.0% proof stress (R_p) should not be greater than 60% UTS at room temperature.

4.1.5 Materials should have adequate fracture toughness properties throughout the design temperature range.

Note: Detailed guidance is given in PD 5500 and ASME B31.3.

4.1.6 Consideration should be given to the requirements for weldability and fracture toughness, as well as stress, when deciding the suitable pipework material, particularly where low temperatures are to be encountered in service. The weldability of pipe and fittings should be confirmed and a welding procedure proved.

Note: Detailed guidance is given in Reference A2.5.8, ASME B31.3 and BS 4515.

4.1.7 Any limitation on the use of materials should be taken into account.

Note: Ranges of materials are listed in piping system codes such as ASME III, ASME B31.3 and BS 806. The quoted values of material properties may need to be adjusted to eliminate factors specific to the selected code in order to derive values which are necessary for these Recommendations.

4.1.8 Gaskets and welding materials should comply with nationally-listed specifications and be entirely compatible with the other elements comprising the pipework system.

Note: This section does not address gaskets and welding materials.

4.2 ELASTIC MODULUS (E)

E should be taken as the value for the material at 10°C or the value appropriate to the lowest temperature of operation below 10°C.

4.3 COEFFICIENT OF THERMAL EXPANSION (α)

α will vary with temperature. For the purposes of determining forces and moments for assessment using these Recommendations, a single value may be taken.

4.4 **POISSON'S RATIO (ν)**

ν should be considered in determining forces and moments for assessment using these Recommendations.

Note: For carbon or low alloy steel, ν may be taken as 0.3.

4.5 **PROOF STRESS (R_p)**

R_p is the stress at which the non-proportional elongation is equal to the specified percentage of the original gauge length. Reference should be made to BS EN ISO 6892-2.

4.6 **FATIGUE**

Reference should be made to Sub-Section 6.7 and Appendix 5 for information on fatigue properties of materials.

SECTION 5 : LOAD AND RESTRAINT CONDITIONS

5.1 GENERAL

Pipework should be designed for the most severe conditions of coincident pressure and temperature as specified in the design brief.

Note: This section defines the pressure, temperature and various forces applicable to the design of pipework systems.

5.2 PRESSURE

5.2.1 The following formula for determining minimum wall thickness should be used:

$$t_{\min} = \frac{PDX}{20fS_{YT}}$$

$t_{\min}$ = minimum wall thickness of pipe (mm)
 P = design pressure (bar)
 D = outside diameter of pipe (mm)
 f = design factor determined from Table 2
 S_{YT} = specified minimum yield strength (N/mm²)
 X = $\frac{MIP}{MOP}$ and is an overpressure factor.

5.2.2 The design pressure should be the target MOP.

5.2.3 The maximum incidental pressure (MIP) should include overpressure above the design pressure and should be applied to shakedown analysis and normal sustained analysis. For fatigue cyclic loading where stress ranges are evaluated between two load cases at different pressures, the overpressure factor, X , should be applied only in the load case which has the higher pressure value (see A3.2).

5.3 TEMPERATURE

5.3.1 Design temperatures

Design temperatures should take account of any foreseeable fault condition or temperature reduction due to de-pressurisation of the pipework.

5.3.2 Tie-in temperature

Tie-in temperature should be taken as the average pipework metal temperature at the time of final attachment of the sub-assembly.

Note: This is the reference temperature used for thermal loading assessments.

5.3.3 Ambient temperature

Due account should be taken of the degree of exposure of pipework to ambient temperature.

Where pipework is not protected from the sun, an estimate should be made of the metal temperature due to solar gain. This temperature and the maximum gas temperature should be considered under clause 5.3.1 and the higher value should be used in the design.

Where pipework is not protected from ambient loss, the lower temperature considered under clause 5.3.1 should be the minimum ambient air temperature that is likely to be sustained or the gas temperature, whichever is the lower.

5.3.4 **Thermal expansion and contraction**

The following thermal effects should be taken into account:

- thermal loads due to restraints

Note: These loads consist of forces and moments that arise when pipework is prevented from free thermal expansion or contraction because of restraints.

- loading due to differences in thermal expansion characteristics

Note: These loads result from differences in thermal expansion where materials with different thermal expansion coefficients are joined, for example in bi-metallic piping where pipe is lined or coated with a metal of different properties.

5.4 **WEIGHT EFFECTS**

The following weight effects should be taken into account:

- live loads

Note: Live loads comprise the weight of the gas transported, or the medium used for test or cleaning, in addition to snow and ice loads in localities where such conditions exist. It may also be necessary to take into account the effect of traffic on buried pipework.

- dead loads

Note: Dead loads comprise the weight of the pipework, including valves, strainers, insulation and other superimposed permanent loads supported by the pipework, including soil loading in areas where the buried pipework has poor bed support (which may occur in the area of buried supports).

5.5 **CONSTRUCTION LOADS**

Where there is a likelihood of significant construction stresses, these should be assessed accordingly.

Where pre-strain due to cold pull is stipulated in the design, this should be incorporated into the analysis.

5.6 **OCCASIONAL, EXCEPTIONAL AND OTHER LOADS**

5.6.1 **Shock**

Effects caused by sudden changes in external or internal conditions, for example hydraulic shock, reductions in pressure and surge conditions, should be taken into account in the analysis.

5.6.2 **Wind**

The effect of wind loading should be taken into account in the analysis of pipework exposed to the wind. The loading should be calculated in accordance with an appropriate code such as BS EN 1991-1-4.

5.6.3 **Discharge reactions**

Reaction forces due to discharge of the contained fluid, including temperature changes that may occur, should be taken into account in the analysis.

5.6.4 **Vibration**

Consideration should be given to the effects of vibration, the analysis of which is beyond the scope of these Recommendations. Expert advice should be sought.

5.6.5 **Earthquake**

Consideration should be given to the effects of earthquake phenomena, the analysis of which is beyond the scope of these Recommendations. Reference should be made to technical literature, for example References A2.5.1 and A2.5.2.

5.6.6 **Traffic**

Consideration should be given to the possibility of "live" loading due to vehicles on buried pipework.

Note 1: The selection of the appropriate loading for design will depend on the surface type and usage above the buried pipework and on any fixed barriers for control of vehicle access.

Note 2: The available guidance for transient loading on buried rigid pipes, for example References A2.5.3 and A2.5.4, is considered particularly relevant.

5.7 **SUPPORTS, ANCHORS AND APPLIED DISPLACEMENTS**

Pipe guides and anchors will reduce free movement. The rigidity of either type of resistance against pipe movement should be included in the analysis.

Additionally, the effects of movement of pipe supports and connected equipment should be taken into account.

5.8 **SOIL**

The soil around buried pipework will act as a restraint on the movement and deflection of the pipe structure and, therefore, should be taken into account.

Note: Soil restraint will reduce movement of pipework by a combination of frictional resistance on pipe coating and by transverse restraint in the vicinity of bends and tees. Bending moments at bends and tees may be increased due to reduced system flexibility.

SECTION 6 : PERFORMANCE

6.1 GENERAL

- 6.1.1 The mechanical design of pipework should ensure safety with adequate performance for the design life.

Note: This can be achieved by verifying, through analysis, that material stress levels are within specified acceptance limits and that displacements, internal forces and reactions can be accommodated by supports and connected equipment.

- 6.1.2 Analysis should involve the initial determination of pipework wall thickness requirements based on rules for basic pressure design. Overall pipework response should then be assessed to verify structural and pressure-retaining integrity under the design loading conditions. This assessment should demonstrate that pipework will not fail by rupture due to internal pressure and other sustained loading or by progressive plastic deformation or fatigue cracking due to cyclic loading.

- 6.1.3 System deflections and load transfer at supports should be checked to confirm support design and performance assumptions used in the modelling. Similar checks should be performed for any connected equipment.

6.2 INTERNAL PRESSURE

- 6.2.1 The primary stresses in pipework components due to direct loading from internal pressure should be controlled according to the area classification of the installation and SMYS of the selected material at the maximum design temperature.

Note: The area classification controls the hoop stress to 30%, 50% or 67% of the appropriate SMYS.

- 6.2.2 The wall thickness values calculated to control pressure stress are considered a minimum and should be increased to accommodate allowances for manufacturing under-tolerances, corrosion and erosion. Pipework components should then be selected to meet or exceed the total required wall thickness values.

Note: The selection of pipework components according to pressure (including allowances) provides the initial condition for subsequent stressing calculations or analysis under other system loads.

6.3 NORMAL SUSTAINED LOADS

The pipework stress state, system deflection and load transfer to supports and equipment should be acceptable under the action of all normal sustained loads. They include internal pressure, MIP, weight and normal wind loading, if applicable (see clause 5.6.2). If the design includes for the pre-loading (cold-pull) of connections/joints during construction, these should be also treated as sustained loads.

Note: For this analysis, MIP is considered to be a normal sustained load.

Acceptance should be based on keeping the von Mises equivalent stress throughout the system to a defined proportion of SMYS.

6.4 ABNORMAL SUSTAINED LOADS

Pipework and components may experience temporary or occasional sustained loads which are either additional to, or higher than, the normal sustained load

case. These may include "live" loading due to vehicles, ground settlement, abnormal wind, snow and ice loading, and seismic loading.

Acceptance should be based on keeping the von Mises equivalent stress throughout the system to a defined proportion of the SMYS.

Note: The acceptance stress level for abnormal loading is approximately 12% higher than for the normal sustained case.

6.5 HYDROSTATIC TEST

The hydrostatic pressure test condition should be assessed as an abnormal sustained loading case.

Note: This includes the additional weight loading from water and an internal pressure in excess of the design pressure.

This load case is likely to be the most onerous in relation to pipework components and equipment support design, although additional temporary supports can be specified.

Acceptance should be based on keeping the hoop stress to within 90% of the SMYS at the test temperature and the von Mises combined stress to within the requirements of the abnormal sustained case (see also clause 8.5.3).

6.6 SHAKEDOWN

6.6.1 The maximum stress range experienced by the pipework and components due to variations in coincident pressure and temperature should be controlled in order to avoid progressive plastic deformation (also termed incremental collapse or ratchetting).

Shakedown assessment should be performed between pairs of load cases and the limiting pair identified.

Acceptance should, generally, be based on keeping the maximum von Mises stress, based on component stress ranges, to within a multiple (typically 1.8 to 2.0 (see Table 4)) of the material mean SMYS over the temperature range associated with the pair of load cases.

Note: This ensures elastic shakedown occurs and that the fatigue design curves are valid for use.

6.6.2 If the maximum von Mises stress based on component stress ranges exceeds the elastic allowable range, it may still be possible to demonstrate that progressive deformation does not occur. Alternative calculation methods, such as finite element analysis (FEA), should be used to determine if the region that exceeds the elastic allowable range is sufficiently localised so that global elastic behaviour occurs without any progressive deformation. Hence, the localised region will have achieved shakedown to elastic-plastic cyclic behaviour due to the surrounding elastic body.

Note: Resolving code stress exceptions is described in Section 9.

6.7 FATIGUE

6.7.1 The maximum stress range experienced by the pipework and components due to variations in coincident pressure, temperature and other loadings should be assessed in order to avoid local structural failure due to fatigue cracking.

Acceptance should be based on keeping the maximum principal stress range to below the value from the relevant fatigue design curve for the number of cycles anticipated over the design life.

- 6.7.2 For varying stress range amplitudes over the service life of the pipework, the fatigue assessment should involve a cumulative damage calculation.
- 6.7.3 The fatigue design curves assume that shakedown to an elastic cycle has been demonstrated. Where shakedown to elastic-plastic cyclic behaviour occurs, and has been demonstrated to be acceptable against progressive plastic deformation, the subsequent fatigue analysis should include the use of plasticity correction factors (see Appendix 5).

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SECTION 7 : WALL THICKNESS AND SELECTION OF PIPEWORK COMPONENTS

7.1 GENERAL

Calculations should be made for pipe and fitting wall thickness for sizing components for the intended main load. IGEM/TD/13 details recognised standards used for component selection and should be consulted prior to performing any stress analysis.

Note: The wall thickness calculations given in IGEM/TD/13 are only applicable for pipework components whose main load is internal pressure.

7.2 STRAIGHT PIPE

7.2.1 The thinnest manufactured wall thickness for the specified pipe should be equal to or greater than the sum of the calculated minimum wall thicknesses and, when applicable, the corrosion and erosion allowances stated in Sub-Section 7.4.

The formula from clause 5.2.1 and the value from Table 1 should be used to determine minimum wall thickness.

NOMINAL DIAMETER OF PIPE (mm)	MINIMUM NOMINAL WALL THICKNESS (mm)
50	3.9
80	4.78
100	4.78
150	4.78
200	6.35
250	6.35
300	6.35
400	6.35
450	6.35
500	7.92
600	7.92
750	9.52
900	9.52
1050	11.91
1220	12.7

Note: At lower pressures, these minimum nominal wall thicknesses are necessary to withstand handling during construction and while in service.

TABLE 1 - MINIMUM NOMINAL WALL THICKNESS OF STEEL PIPE

The classification of Area Types, should be as shown in Table 2.

SITE DESCRIPTION	AREA TYPE	MAX f
Process plant manned by process personnel	All	0.67
Locations protected against external interference and unmanned	R	0.67
	S	0.5
	T	0.3
Locations unprotected against external interference and unmanned	All	0.3

Notes:

- Type R Rural areas with a population density not exceeding 2.5 persons per hectare.
- Type S Areas intermediate in character (between Types R and T) in which the population density exceeds 2.5 persons per hectare and which may be developed extensively with residential properties, schools, shops etc.
- Type T Central areas of towns or cities, with a high population density, many multi-storey buildings, dense traffic and numerous underground services.

TABLE 2 - DESIGN FACTOR (f)

7.3 FITTINGS

7.3.1 IGEM/TD/13 details recognised standards used for selection of fittings, i.e. bends and tees, and should be consulted before proceeding with stress analysis.

7.3.2 Existing fittings should be checked to determine whether they meet the minimum design requirements of the appropriate standard.

7.4 THICKNESS ALLOWANCES

7.4.1 Reduction in wall thickness caused by chemical action, oxidation, scaling, abrasion or erosion should be taken into consideration in the selection of wall thickness.

7.4.2 Where thinning is expected to occur, the minimum nominal wall thickness of pipework components should be increased by an allowance (C) to compensate for the resultant expected reduction during the design life.

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SECTION 8 : STRESS AND FATIGUE ANALYSIS

8.1 GENERAL PROCEDURE

- 8.1.1 The flexibility of pipework is made up from the flexibilities of pipe, fittings and equipment. Equipment should be assumed rigid unless a flexibility factor (k) can be assigned.

Note: The flexibilities of pipework fittings are given in Appendix 4, together with associated notes.

- 8.1.2 A method should be used that calculates the following for the pipework and components:

- pressure stresses that are produced in both the axial and hoop directions solely to contain internal pressure
- bending stresses, shear stresses and axial stresses induced by the combined effects of temperature and pressure in the pipework, by applied end thrusts, externally applied loads, weight of pipework/fittings and contents and effects due to soil restraint
- stresses from occasional loads such as hydrostatic test, wind, earthquake, traffic etc., if deemed necessary.

- 8.1.3 An analysis should be performed on pipework between points where boundary conditions are known or sufficiently remote as to not affect the pipework of interest.

- 8.1.4 Analyses to cover sustained, shakedown and fatigue conditions should be performed to satisfy the design brief and the performance criteria outlined in Section 6.

- 8.1.5 The minimum wall thickness of any pipe, fitting or equipment should be determined in accordance with Section 7, after considering the appropriate design factor for the area type where the item is to be installed.

- 8.1.6 Any pipework component that does not meet the design requirements of Sub-Section 8.5 may be re-examined and this should be carried out using techniques outlined in Section 9.

8.2 SCOPE OF PIPEWORK FOR ANALYSIS

All pipework should be considered for analysis, unless documentary proof is already available to show that the pipework, or equivalent pipework, already satisfies this edition or IGE/TD/12 Edition 1 (see also clause 11.1.2).

8.3 PIPEWORK MODELLING

8.3.1 General

A pipework model should be established in accordance with good modelling practice, with particular attention being given to the considerations outlined in clauses 8.3.1.1 to 8.3.1.7.

8.3.1.1 *Geometric and material properties of components*

The correct combination of geometric and material properties should be applied.

Note: This is illustrated particularly for set-in or set-on tees, where the tee material may be different to the attached pipe.

8.3.1.2 *Element type and length*

The appropriate element type should be selected to represent the appropriate mass, stiffness and rotational degree of freedom of the component.

The element size should be sufficiently refined in the model to ensure that any non-linear behaviour is represented accurately.

For straight pipe which is close to components of interest, such as bends, tees, etc., element lengths should be reduced.

Note: In particular, this is important for buried pipework to enable the soil restraints to be realistic, especially at branch connections.

8.3.1.3 *Boundary conditions*

Boundary conditions should be applied carefully to ensure their influence does not invalidate the stress analysis results of items that may be affected by them.

Pipework should be modelled as a complete system. Where this is not possible, consideration should be given to the use of overlapping models. If this approach is inappropriate and the system has to be broken down into discrete models, representative boundary conditions should be applied.

8.3.1.4 *Supports and restraints*

Supports and restraints should be modelled to realistically represent their behaviour.

Note: Further details are given in clause 9.2.4.

8.3.1.5 *Flexibility of branch connections*

The flexibility factors stated in Appendix 4 for branch connections are assumed to be unity, which is conservative. If a better estimate of the forces and moments at these connections is required, it should be made by improved modelling of the flexibility of branch connections.

Note: This latter approach can be applied to the initial pipework model, or applied where the analysis results show stress exceptions in branch connections. Further details are given in clause 9.2.5.

8.3.1.6 *Temporary pipework*

Consideration should be given to the inclusion of temporary pipework in the stress model.

Note: Where such pipework is to be installed for a significant period of time, a fatigue analysis may be appropriate in addition to an assessment of stress levels.

8.3.1.7 *Model verification*

The model should be verified to ensure, as far as reasonably practicable, that the model represents the design of the pipework system, or that which exists.

8.3.2 **Longitudinal pressure strain**

Changes in the length of pipework will induce loads into restrained pipework systems. Such changes, due to internal pressure and offset by the Poisson effect of hoop expansion, should be taken into account.

8.3.3 Thickness for analysis

Where pipework components are used which comply with "recognised industry standards", for example those listed in IGE/TD/13 (thus ensuring that manufacturing tolerances on wall thickness are adequately controlled) the nominal wall thickness less any corrosion allowance should be used in performing the flexibility and stress analyses.

Where this is not possible, the flexibility analysis and stress analysis should be performed using both maximum (including corrosion allowance) and minimum (less any corrosion allowance) wall thickness. In each case, the same wall thickness values should be used in the flexibility analysis and for the stress calculations.

8.3.4 Estimation of soil restraint

The calculation of soil restraint values for stress analysis requires the application of several algorithms based on theoretical and empirical techniques. These require input parameters that define the installation geometry and pipe dimensions, soil mechanical properties, water-table level and pipe coating frictional properties.

The reliability of soil restraint modelling will be influenced by the pipe/soil structural modelling capability, the choice and performance of predictive algorithms, and the ability to select appropriate geo-technical parameters for a specific site.

The minimum capability for routine analysis should be elastic flexibility analysis using a line element representation with forces and restraint springs applied at element-to-element nodal points. For soil restraint simulation, the springs should offer, as a minimum, a bi-linear force/displacement relationship and each buried pipe node should have four springs in multiple directions with different stiffness values (where appropriate) to cater for the directional dependence of soil restraint.

Both upper and lower bound soil restraint conditions should be considered.

Note: Guidance on appropriate predictive techniques and soil property requirements can be found in NEN 3650 Code 1 and in ASCE Publication 2.

In some cases, site-specific investigation of existing installations will allow load cases to consider a single soil restraint condition. For this to also apply to new piping proposals, the site-specific ground investigation should be supported by construction requirements and controls (see References A2.5.3 and A2.5.4).

8.4 LOAD CASE TABLE

An example load case table is given in Appendix 7.

8.4.1 Compilation

The validity of a stress analysis depends on the modelling of the system and the proper selection of feasible combinations of operating conditions. The load case table should be identified at the outset of any pipework stress analysis based on the design brief.

Note: Subsequent modifications to a load case table will require the stress and fatigue analysis to be updated.

8.4.2 Use

Piping analysis for the load cases covering the following should, normally, be performed for both a lower bound and an upper bound soil restraint condition:

- operating conditions (for shakedown and fatigue)
- normal sustained (pressure and weight)
- stresses from occasional loads, for example hydrostatic test, wind, earthquake, traffic, etc. if deemed necessary.

Note: The range between bounds will reflect the uncertainty over installation and geo-technical conditions.

8.5 STRESS ANALYSIS PROCEDURE AND ACCEPTANCE LIMITS

8.5.1 General

8.5.1.1 Commercially-available software for the static and dynamic analysis of pipework systems, and their support structures, is readily available. However, the software used in the analysis of the pipework should be supported by appropriate verification documentation. Hand calculations may be undertaken as an alternative to the use of software but care should be taken in the choice of any simplifying assumptions that are made and checks should be carried out on results.

8.5.1.2 The procedure should include the calculation of stresses for the following conditions:

- S_s = maximum equivalent stress induced by internal pressure, pipe weight, weight of contents and insulation, steady applied loads, effects of soil and normal winds and long range thermal stresses that include significant elastic follow up
- S_{VM} = maximum von Mises equivalent stresses from the component stress ranges due to cyclic load which will allow the pipework to shakedown
- S_R = principal stress ranges causing fatigue in the pipework.

Note 1: In certain circumstances, it may also be necessary for stresses to be calculated for abnormal sustained conditions. These are denoted by S_{sab1} , S_{sab2} , ..., S_{sabi} . S_{sab1} , S_{sab2} , ..., which equate to maximum equivalent stress, as for S_s , but including effects due to each of the occasional abnormal loads, 1 to i , in turn.

Note 2: The formulae to calculate the principal stresses and the equivalent von Mises stresses are given in Appendix 3. The individual stresses used in these formulae are defined in Appendix 3.

8.5.2 Analysis of sustained conditions

The maximum sustained stress throughout the pipework should be calculated using the method given in Appendix 3 and should satisfy the criteria given in clause 8.5.3. If the design includes pre-loading (cold-pull) of connections/joints during construction, these loads should be treated as sustained loads. If the temperature at assembly of the pipework is outside the range of operating conditions, this temperature should be taken into account.

When calculating the sustained stresses S_s and S_{sabi} , SCFs should be included from Appendix 4. The weight of any liquid hydrostatic test should also be included in determining this stress.

8.5.3 Acceptance limits for sustained conditions

The maximum permitted sustained stresses for normal and abnormal conditions should be taken from Table 3. In addition, reference should be made to Sub-Section 6.5 for the assessment of hydrostatic test conditions.

f	NORMAL (S_s)		ABNORMAL ($S_{sab1}, S_{sab2}, \dots, S_{sabi}$)	
	$\frac{SMYS}{UTS} \leq 0.74$	$\frac{SMYS}{UTS} > 0.74$	$\frac{SMYS}{UTS} \leq 0.74$	$\frac{SMYS}{UTS} > 0.74$
0.67	0.80 SMYS	0.34 (SMYS + UTS)	0.90 SMYS	0.38 (SMYS + UTS)
0.50	0.60 SMYS	0.25 (SMYS + UTS)	0.67 SMYS	0.28 (SMYS + UTS)
0.30	0.36 SMYS	0.15 (SMYS + UTS)	0.40 SMYS	0.17 (SMYS + UTS)

Note: SMYS and UTS values are obtained at the maximum design temperature or, if known, the maximum temperature appropriate to the sustained load case being analysed.

TABLE 3 - MAXIMUM PERMITTED SUSTAINED STRESSES for S_s , S_{sab1} , S_{sab2} , ..., S_{sabi}

8.5.4 Analysis of shakedown conditions

The maximum von Mises equivalent stress (S_{VM}) based on the component stress ranges (S_a , S_h , S_q) should be evaluated by the method outlined in Appendix 3 for each component in the pipework. The calculation should be based on the range of coincident pressure and temperature, from minimum to maximum pressure and from minimum to maximum temperature and should also include any changes in dead weight and external loads. If the temperature at assembly of pipework is outside the range of operating conditions, this temperature should be taken into account. Loadings should be investigated to ensure that no greater stress ranges exist at intermediate pressure and temperature conditions.

8.5.5 Acceptance limits for shakedown conditions

The calculated maximum von Mises equivalent stress (S_{VM}) based on the component stress ranges (S_a , S_h , S_q), should not exceed S_{PR} defined by:

$$S_{PR} = 0.5 K_{SD}(S_Y + S_{YT})$$

S_{PR}	=	maximum von Mises equivalent stress range due to cyclic load to ensure elastic shakedown of the pipework.
S_{VM}	=	maximum von Mises equivalent stress range from the component stress ranges due to cyclic load.
S_Y	=	SMYS or, for materials which do not exhibit a clear yield point, the stated proof stress of the material at room temperature.
S_{YT}	=	SMYS or, for materials which do not exhibit a clear yield point, the stated proof stress of the material at maximum temperature.
K_{SD}	=	shakedown factor for the material (see Table 4). If evidence exists to show that this factor is higher than that given in Table 4, the higher value may be used.

MATERIAL	K_{SD}
Carbon steel	1.8
Austenitic steel	2.0

TABLE 4 - SHAKEDOWN FACTOR, K_{SD}

8.5.6 Analysis of cyclic conditions

The maximum principal stress range (S_R) at each component in pipework should be evaluated using the method described in Appendix 3 for each combined pressure and temperature range during service life.

If the conditions in clause 8.5.7 are not satisfied, a cumulative damage assessment should be carried out for the predicted stress cycles due to variable amplitude loading according to Appendix 5.

8.5.7 Acceptance limits for cyclic conditions

If the S_R levels from Table 5 are not exceeded, the pipework component may be considered satisfactory without the need for a fatigue analysis.

- 8.5.7.1 Alternatively, if the S_R levels from Table 5 are exceeded, but the total number of equivalent stress cycles occurring in the design life does not exceed the number specified in Table 5, the pipework system can also be considered satisfactory without a fatigue analysis. This latter threshold only applies when the component loading is due to pressure only and the elastic shakedown limits are met. Otherwise, a detailed fatigue analysis should be carried out as described in Appendix 5. An equivalent stress cycle is defined as the number (n_{eq}) of maximum operating pressure range cycles that cause the same damage as the summation of (n_i) cycles of pressure range (P_i) for each transient from the load case table.

$$n_{eq} = n_1 [P_1 / MOP]^m + n_2 [P_2 / MOP]^m + n_i [P_i / MOP]^m$$

m = see Table 26.

- 8.5.7.2 If a detailed fatigue analysis is necessary, the calculated fatigue damage should not exceed unity.

FATIGUE DESIGN CURVE (see Appendix 5)	FATIGUE ANALYSIS NOT REQUIRED IF EITHER OF FOLLOWING THRESHOLD VALUES ARE NOT EXCEEDED	
	PRINCIPAL STRESS RANGE S_R (N/mm ²)	NUMBER OF EQUIVALENT STRESS CYCLES (PRESSURE ONLY)
Class D	53	100
Class E	47	100
Class F	40	100
Class G	29	100
Class W	25	100

TABLE 5 - FATIGUE ANALYSIS THRESHOLDS FOR CARBON AND AUSTENITIC STEELS

8.6 REACTIONS

8.6.1 Supports

For the analysis of pipework, pipe supports are usually often modelled by applying boundary conditions to the pipe. The forces and moments reacted at these boundary conditions should be used to check that the design of the supports is acceptable.

8.6.2 Loads on connected equipment

The forces and moments applied by pipework to connected equipment should be checked against manufacturers' allowable limits or, if these are not available, against calculated limits.

8.6.3 Strain-sensitive equipment

The forces and moments imposed by pipework on strain-sensitive equipment should be checked against manufacturers' allowable limits.