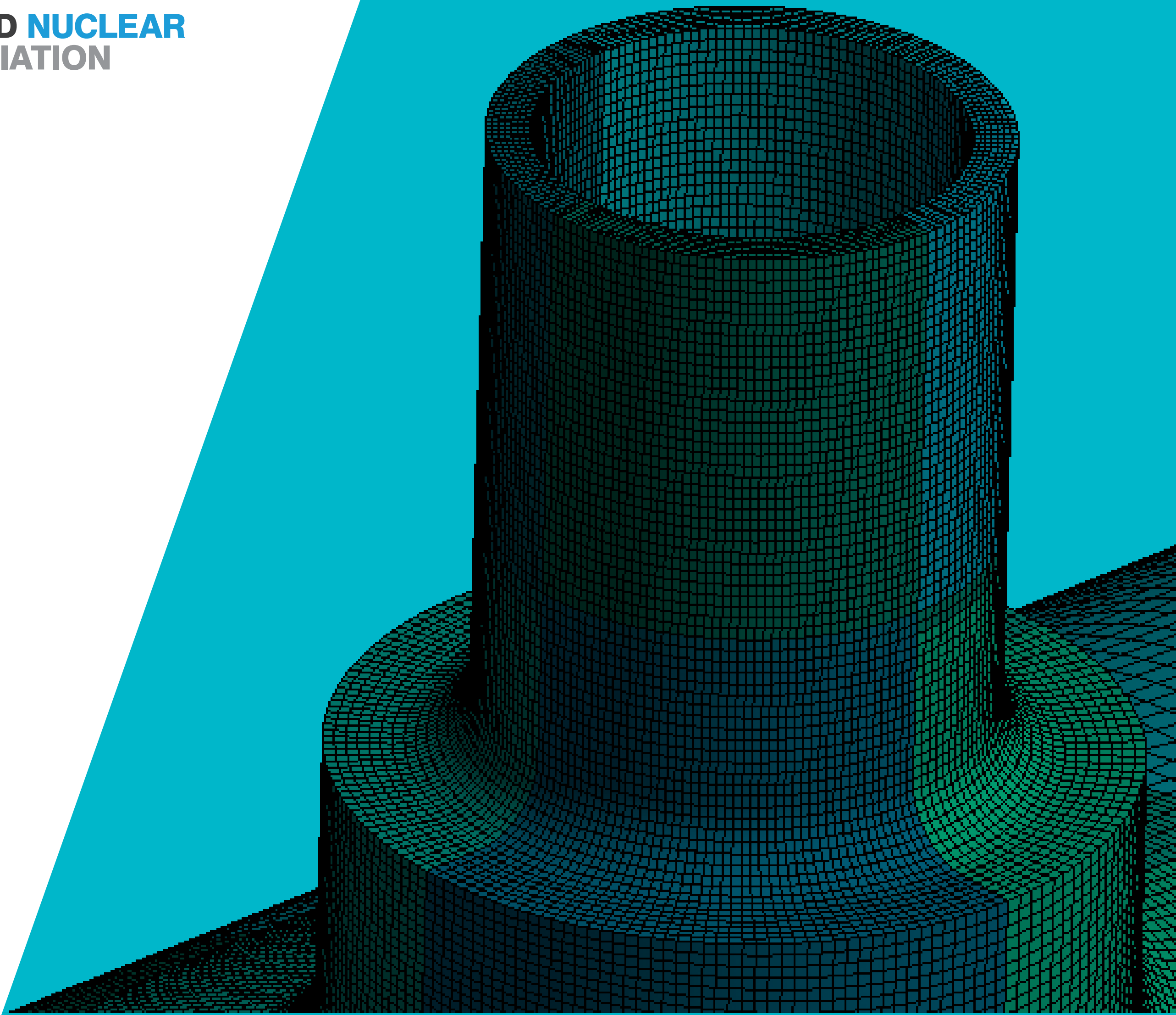

Non-Linear Analysis Design Rules

Part 2a: Specification of Benchmarks on Nozzles under Pressure, Thermal and Piping Loads

Cooperation in Reactor Design Evaluation and Licensing-Mechanical Codes and Standards Task Force

Title: Non-Linear Analysis Design Rules
Part 2a: Specification of Benchmarks on
Nozzles under Pressure, Thermal and
Piping Loads
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Foreword

In January 2007, the World Nuclear Association established the Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group with the aim of stimulating a dialogue between the nuclear industry (including reactor vendors, operators and utilities) and nuclear regulators (national and international) on the benefits and means of achieving a worldwide convergence of reactor safety standards.

The Mechanical Codes and Standards Task Force (MCSTF) of the CORDEL Working Group was set up in 2010 to collaborate with the standards development organizations (SDOs) and the Multinational Design Evaluation Programme (MDEP) Codes and Standards Working Group (CSWG) on the international harmonization of nuclear safety-related mechanical codes and standards. In September 2011, the CORDEL MCSTF pilot project was launched to investigate divergences and to promote international convergence in:

- Certification of non-destructive examination (NDE) personnel.
- Non-linear analysis design rules.

The areas were chosen from a survey sent to the CORDEL members as well as formal discussions with the SDOs and MDEP-CSWG.

This report focuses on non-linear analysis design rules. It is formed of three parts:[1]

- Part 1: Review and comparison of the current code requirements in non-linear analysis for different failure modes (plastic collapse, plastic instability, local failure and buckling) and some degradation mechanisms (fatigue, plastic shakedown) in the major nuclear and non-nuclear design codes.
- Part 2a: Specification of the two benchmarks to compare the existing analysis practices and develop harmonized 'recommended industrial practices'.
- Part 2b: Results, comparison and conclusion of the two benchmarks to develop harmonized 'recommended industrial practices'.
- Part 3: 'Recommended industrial practices' for non-linear analysis.

This report specifies two benchmarks for non-linear analysis of nozzles under pressure, thermal and piping loads. Results comparison and analysis were omitted intentionally from this report and they will be presented in a separate report Part 2b.

After extensive reviews by international expert groups and individual experts, including MDEP (Multinational Design Evaluation Programme) International Regulators Group: Codes & Standards Working Group, harmonized 'recommended industrial practices' will be proposed to SDOs as a draft code case for their own use in order to minimize future code divergence and facilitate areas of convergence.

[1] The report has been reordered based on feedback from members and SDOs to better rationalize the process.

Contents

1 Introduction

Major pressure vessel and piping codes design rules, nuclear and non-nuclear, are based on linear elastic methods associated with stress classification in primary (for load control), secondary (for strain control) and peak stresses (for thermal shocks). This stress classification is easy to apply only in simple cases, such as cylindrical shell under axisymmetric quasi-static loads. When the geometry or the loads are more complex, such classifications are not applicable, so a large part of stress is considered as primary, which is extremely conservative. In such cases, non-linear analysis methods are used but comparison of these methods (reported in Part 1) showed that many different approaches are used which eventually leads to discrepancies. The aim of these benchmarks is to identify and propose a more harmonized approach in using non-linear analysis methods.

Other complications can be associated with cyclic loading for fatigue analysis or dynamic spectrum loading for seismic analysis. Some examples for the design of these components with linear elastic methods are presented in the Part 1 report, as:

- Nozzle under complex piping loads: pressure, weight, thermal expansion, seismic and other loads.
- Independency of closed nozzles on vessel shell or closed penetration on vessel head.
- Thermal expansion stress classification in piping systems.
- Fatigue analysis: strain amplitude evaluation and plasticity correction factors K_e and/or K_v.
- Elastic-plastic shakedown analysis of piping systems.
- Seismic analysis of piping systems: inertial load/ anchor motion.

Consequently, non-linear analysis at design level can be an alternative to the linear elastic approach, using the expected non-linear behavior of the material by performing elastic-plastic analysis. One of the major advantages of this is to avoid the process of stress classification of primary versus secondary associated with elastic analysis. In some cases the elastic analysis result is not conservative, in particular when a part of primary stresses is considered secondary, such as thermal expansion in some piping systems.

This report only considers non-cracked components (mainly vessels and piping systems) excluding creep. The activities on non-linear design rules comprise three parts:

- Part 1: Review and comparison of the current code requirements in non-linear analysis for different failure modes (plastic collapse, plastic instability, local failure and buckling) and some degradation mechanisms (fatigue, plastic shakedown) in the major nuclear and non-nuclear design codes.
- Part 2a: Specification of the two benchmarks to compare the existing analysis practices and develop harmonized 'recommended industrial practices'.
- Part 2b: Result, comparison and conclusion of the two benchmarks to develop harmonized 'recommended industrial practices'.
- Part 3: 'Recommended industrial practices' for non-linear analysis.

The present report specifies two benchmarks for non-linear analysis of nozzles under pressure, thermal and piping loads (Part 2a).

2 General Introduction to Benchmarks

The Part 1 report presented a comprehensive comparison of existing nuclear and non-nuclear mechanical codes rules [1] which confirmed that there is no standard analysis methodology and that no existing code adequately covers: analysis methodology; associated material properties; criteria for pressure vessels and piping failure modes and major degradation mechanisms; and user qualification needs and validation of associated computer codes.

For Part 2a, two typical nuclear components are proposed for international benchmarking: a vessel nozzle and a piping nozzle, in order to analyze plastic collapse, plastic instability, local failure, fatigue, and ratchetting.

The main objectives of these benchmarks are:

- To compare different practices, (usability of the plastic limit load, the monotonic elastic-plastic, and the cyclic elastic-plastic), adopted by different international companies or analysts for given material non-linear properties.
- To compare and analyze results of these different non-linear analysis methods applied by benchmark participants.
- To suggest recommended industrial practices for non-linear analysis (Part 3) report based on the analysis of benchmark results.

Two typical light water reactor (LWR) parts of vessels and piping systems are selected for the benchmarks:

- Large class 1 vessel nozzle under pressure and piping loads.
- Class 1 reinforced piping nozzle under severe cyclic thermal loads.

These benchmarks consider 2D geometries under axisymmetric loads, and will be supplemented by sensitivity analysis, effects of 3D geometry, effects of non-axisymmetric piping loads or effects of multi-materials as Dissimilar Metal Welds (DMW).

2.1 Vessel-Nozzle

A large class 1 low alloy steel vessel nozzle can encounter difficulties when considering all the loads and their consequences on stress values in different reinforced areas of the nozzle. In these cases, material non-linearity can be considered in order to assess the following failure modes using non-linear analysis methods: plastic collapse, plastic Instability, and local failure.

Different analyses on ‘practically real cases’ are considered that involve:

- Existing elastic codified rules in references [2] and [3], elastic stress classification in the different locations along the nozzles are checked.
- Comparison with non-linear analysis.

Possible sensitivity studies could be considered:

- 3D geometry.
- Non-axisymmetric piping loads.
- DMW with two strongly different strength resistance materials.

2.2 Main Coolant Piping Line (MCL) Nozzle

Class 1 reinforced piping tee can encounter some difficulties with fatigue and plastic shakedown analyses (severe thermal loads on low linear yield strength material such as stainless steels).

The degradation mechanism to consider in this case of fatigue analysis is codified elastic approach as in reference [2] and [3], with:

- Codified K_e for simplified elastic-plastic strain amplitude evaluation.
- K_e non-linear analysis optimization.

Different analyses on ‘practically real cases’ (two severe thermal shocks) are considered:

- Fatigue codified elastic analyses [2,3].
- Simplified elastic-plastic analysis using codified K_e formulae.

In addition, the benchmarks can be extended to consider the following degradation mechanisms:

- Plastic shakedown analysis and cumulative strain evaluation.
- Detailed cyclic strain amplitude evaluations with specific material constitutive equations, supplemented by extrapolation rules for low cycle fatigue (up to 10^5 cycles).

When these degradation mechanisms are considered, different analysis methods shall be considered, such as:

- Codified Bree diagram and ratchetting analysis methods which will be compared with cyclic elastic-plastic analysis.
- Fatigue cyclic plastic analysis with proposed extrapolation rules for low cycle fatigue ($<10^5$).

3 Benchmark 1: Vessel Nozzle definition

3.1 General introduction

- Geometry: Large class 1 vessel reinforced nozzle as described in Figure 1 and Appendix 1 the design can be checked in accordance with ASME III [2] or RCC-M [3] rules.
- Loads:
  - Pressure and piping loads; no cyclic thermal loads, 300°C constant temperature
  - Pressure (including axial stresses at the boundary) and accidental piping loads;
    - Design pressure:
      P_d= 17 MPa
    - Only axial load is considered in this benchmark Other loads may be considered at a later stage
    - F_x - F_y - F_z in 10^4 N: 10; 185; 60
    - M_x - M_y - M_z in 10^7 N.mm: 150; 25; 25
- Material:
  - Low alloy steel (16MND5 or A508 Class 3)
  - Strength properties:
    - S_y, $R_{p0.2}$, R_m, S_m, E, ν at 300°C (Appendix 3.1)
    - Engineering stress-strain curves at 300°C; if needed true stress-strain can be derived
- Damage analyses:
  - Plastic collapse (excessive deformation)
  - Plastic instability
  - Local failure
- Typical analyses
  - Elastic codified rules: NB 3200 [2] and B 3200 [3]
  - Limit load analyses
  - Elastic-plastic analyses:
    - Double slope method for plastic collapse
    - Maximum strain criteria for plastic collapse (0.5% maximum strain)
    - Maximum strain criteria for plastic instability (5 or 10% maximum strain)
- Finite Element Analysis (FEA):
  - 2D model: cylinder/sphere connection, in this case the radius of the vessel will be multiplied by 2,
  - 3D model for sensitivity analysis
- Sensitivity analyses
  - 2D or 3D mesh and element type for FEA
  - 2D geometry and axisymmetric piping loads
  - 3D geometry and non-axisymmetric piping loads
  - 2D DMW between nozzle and safe end

3.2 Geometry description

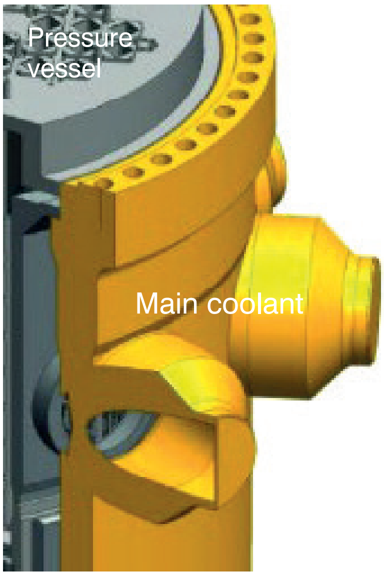

Figure 1. Typical RPV nozzle

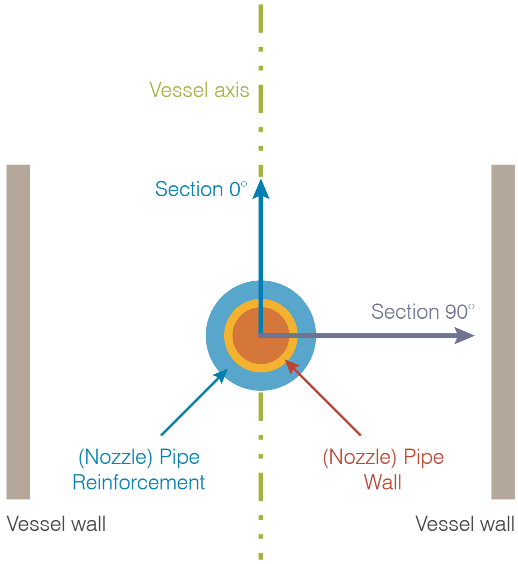

Figure 2. Vessel and reinforced nozzle

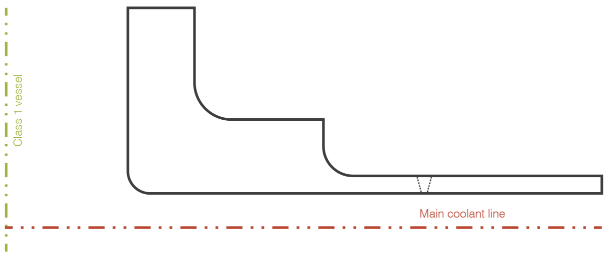

Figure 3. Vessel-nozzle – 0° section

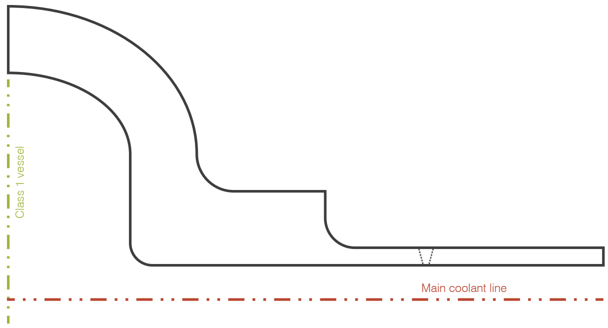

Figure 4. Vessel-nozzle – 90° section

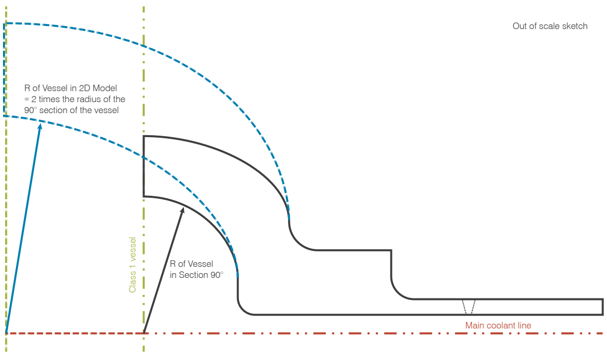

Figure 5. Vessel-nozzle – 2D model

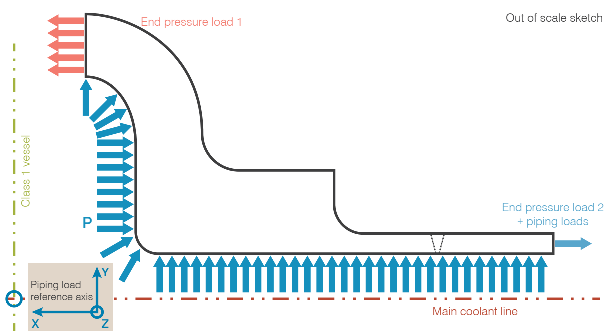

Figure 6. Vessel-nozzle – 2D model applied loads

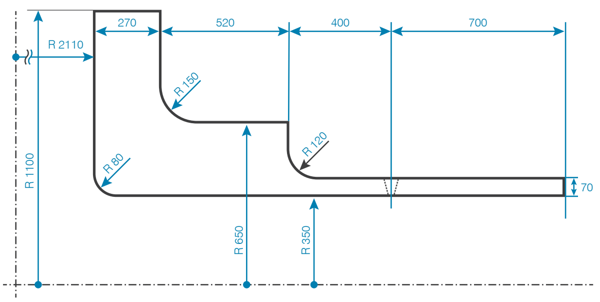

Figure 7. Vessel-nozzle sizes – 0° section
(larger Figure in Appendix 1)

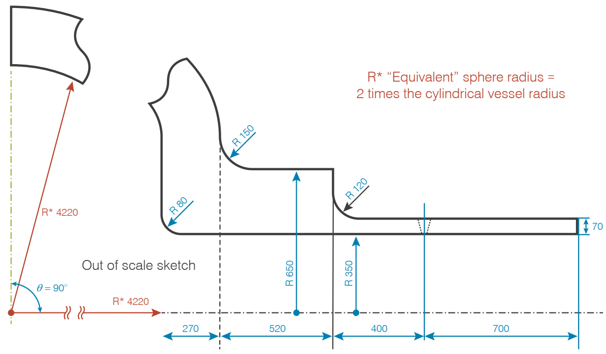

Figure 8. Vessel-nozzle sizes – 2D model
(larger Figure in Appendix 1)

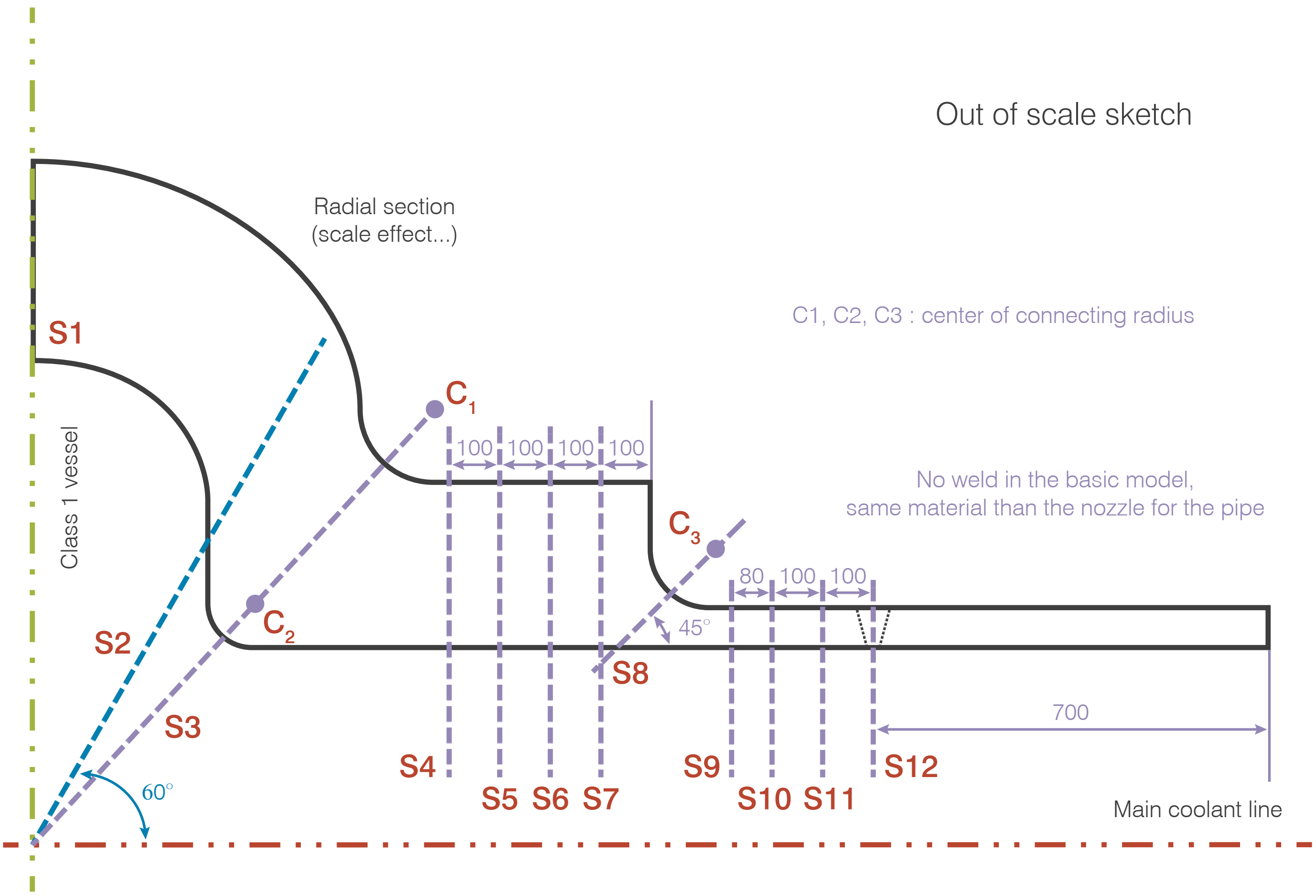

Figure 9. Vessel nozzle analysis sections for 2D model

3.3 Low alloy steel mechanical properties

The material properties used in Benchmark 1 are presented in Appendix 3.1 for low alloy steel (LAS).

3.4 Benchmark 1.0: Vessel-Nozzle elastic codified approach

The purpose of this Benchmark 1.0 is to perform linear elastic stress analysis using FEA and to classify the stresses in order to perform assessment against codified rules.

3.4.1 Loads, model and analysis sections

- Loads:
  - Design pressure value of 17 MPa at 300°C: boundary conditions are presented in Figure 6
  - For some benchmarks: added piping loads
- Models: 2D model with equivalent spherical vessel radius of 2 times the vessel radius on a 90° angle is presented Figures 1-5, 7 and 8
- Analysis sections: S1 to S12 are presented in Figure 9; any other sections can be added by the analysts

3.4.2 Elastic codified rules

- Analysis method: elastic codified rules B 3200 [2] or ASME III NB 3200 [3] and dedicated stress classification rules
  - For design pressure load only, including pressure end effects at the boundary of the model in accordance with Figure 6
  - No piping loads
- Results presentation as described in Appendix 5.1:
  - Initial and deformed shape at maximum pressure for information
  - $(P_m + P_b)$ and $(P_L + P_b)$ for Sections S1 to S12 (Figure 9) compared to level 0 criteria:
  - $P_m < S_m$ or $P_L < 1.5\ S_m$
  - $P_L+P_b < 1.5\ S_m$
  - $P_m+P_b < 1.5\ S_m$
- three larger values of sum of the principal stress $(\sigma I + \sigma II + \sigma III)$ and corresponding locations everywhere in the nozzle compared to level A criteria:
  - $(\sigma I + \sigma II + \sigma III) < 4\ S_m$

3.5 Benchmark 1.1: Vessel-Nozzle plastic collapse and local failure

The purpose of this benchmark is to perform non-linear (inelastic) analysis using FEA to obtain local plastic collapse (C_L) and check on local failure (decohesion).

3.5.1 Plastic collapse under design pressure

- Damage and criteria:
  - Plastic limit load C_{L1} with flow stress S_y at 300°C
  - Elastic-plastic analysis with monotonic engineering stress-strain curve at 300°C (C_{L2} and C_{L3})
- Criteria:
  - Limit load: $P_d < C_{L1} / 1.5$
  - 'double slope method' : $P_d < C_{L2} / 1.5$
  - C_{L3} for maximum total strain of 0.5%: $P_d < C_{L3} / 1.5$
- Results presentation:
  - As described in Appendix 5.1:
  - Maximum plastic collapse pressure obtained from the different methods (from the three C_L values)

3.5.2 Local failure under pressure load

- Based on elastic-plastic analysis
- Three larger values of $(\sigma I + \sigma II + \sigma III)$ and corresponding locations in the nozzle
- Maximum of $(\sigma I + \sigma II + \sigma III)$

3.5.3 Comparison of results with elastic analysis

- Comparison of C_{L1}, C_{L2} and C_{L3}, discussion and recommendation
- Comparison of Benchmark 1.1 results with Benchmark 1.0, validation of codified elastic stress classification
- Discussion and recommendation

3.6 Benchmark 1.2: Vessel-Nozzle plastic instability

3.6.1 Analysis methods and criteria:

- Analysis methods:
  - Plastic limit load C_{l1} with flow stress $(S_y+R_m)/2$ at 300°C
  - Elastic-plastic analysis with true stress-strain curve at 300°C
  - (The true stress-strain curve has to be derived from the engineering stress-stress curve presented in Appendix 3.1)

- Criteria:
  - Maximum total strain: 5% (C_{l2}) and 10% (C_{l3})
  - $P_d < C_{l1} / 2.5$ and $P_d < C_{l2} / 2.5$ and $P_d < C_{l3} / 2.5$
- Results presentation
  - As described in Appendix 5.1:
  - Maximum plastic instability pressure obtained from the different methods (from the three C_l values)

3.6.2 Comparison of results with elastic analysis

- Comparison of C_{l1}, C_{l2} and C_{l3}, discussion and recommendations.
- Comparison of Benchmark 1.2 results with Benchmark 1.0
- Discussion and recommendations

3.7 Benchmark 1.3: Piping load effects on Benchmarks 1.0 and 1.2

3.7.1 Model, loads and criteria

- Finite element model: 2D
- Loads: combined pressure + axial load (pressure + piping) at 300°C
  - Pressure: 17 MPa
  - Accidental piping axial load: $F_x = 10^6$ N
- Criteria
  - Level D criteria

3.7.2 Consequences on codified elastic approach

- Same as Benchmark 1.0
- Comparison of results with Benchmark 1.0

3.7.3 Consequences on plastic instability loads

- Same as Benchmark 1.2
  - Limit load with $(S_y + R_m)/2$ at 300°C: C'_{l1}
  - Elastic-plastic analysis with true stress-strain curve
- Criteria:
  - Limit pressure + piping load (constant ratio): C'_{l1}
  - Maximum total strain 5% and 10%: C'_{l2} and C'_{l3}
- Results presentation:
  - As described in Appendix 5.1:
  - Maximum plastic instability pressure obtained from the different methods (from three C'l values)

3.7.4 Comparison of results with elastic analysis

- Comparison of C'_{l1}, C'_{l2} and C'_{l3}
- Comparison of Benchmark 1.3 results with Benchmarks 1.0 and 1.2
- Discussion and recommendations

3.8 Benchmark 1.4: 3D effects on Benchmarks 1.0 to 1.3

This benchmark requires a 3D model in which non-axisymmetric piping accidental loads are included and assessed to level D criteria.

3.8.1 General

- Model: 3D
- Effects on all the previous benchmarks: (1.0, 1.1, 1.2 and 1.3)
  - Geometry closer to real geometry
  - Non-axisymmetric piping load consideration
  - Level D criteria (roughly 2 times level A)

3.8.2 Loads

- Pressure and temperature for normal operation
  - Design pressure: 17 MPa
  - Design temperature: 300°C
  - Benchmark temperature: 300°C, constant
- Maximum piping loads in accident condition
  - For weight, thermal expansion, accident conditions and seismic accidental load
  - F_x - F_y - F_z in 10^4 N: 10; 185; 60
  - M_x - M_y - M_z in 10^7 N.mm: 150; 25; 25

3.8.3 Analysis methods

3.8.3.1 Elastic codified analyses

- P_m : general membrane stress
- $P_m + P_b$: general membrane+ bending stress
- $P_L + P_b$: local membrane+ bending stress
- Q : secondary stress
- In accordance with level D criteria
  - Appendix F of [2] or ZF of [3]
  - On different sections S1 to S12 (Figure 9)
- Level D Criteria:
  - $P_m < 2.4\ S_m$
  - $P_L < 3.6\ S_m$
  - $P_L + P_b < 3.6\ S_m$

- Results presentation following Appendix 5.1
  - Comparison of analysis methods
  - Comparison with Benchmark 1.0 and discussion

3.8.3.2 Plastic collapse

- Only for pressure loads
- Same analyses as for Benchmark 1.1 on 3D geometry instead of 2D geometry
- Results presentation following Appendix 5.1:
  - Maximum plastic collapse pressure with the different methods (3 C''_L values)
- Comparison of analysis methods
  - Comparison with Benchmark 1.1 and discussion

3.8.3.3 Plastic instability

- for design pressure and 2 sets of piping loads
  - $F_x = 10^6$ N
  - F_x - F_y - F_z in 10^4 N: 10; 185; 60
  - M_x - M_y - M_z in 10^7 N.mm: 150; 25; 25
- Same analyses as for Benchmark 1.3 on 3D geometry instead of 2D geometry
- Results presentation following Appendix 5.1:
  - Maximum plastic collapse pressure obtained from the different methods (from three C''_l values) for each piping load value
- Comparison of analysis methods
  - Comparison with Benchmark 1.3 and discussion

4 Benchmark 2: Main coolant line nozzle definition

4.1 General introduction

- Reinforced nozzle Figure 10 and Appendix 2 in accordance with ASME III [2] or RCC-M [3] rules
- Small nozzle submitted to cyclic thermal loads under constant pressure
- Cyclic loads: two thermal transients with associated number of cycles
- Degradation mechanism analyses:
  - Fatigue
  - The benchmark can be extended to include shakedown analysis
- Material properties at constant temperature of 350°C:
  - Material: 316L stainless steel
  - S_y, $R_{p0.2}$, R_m, S_m, E, ν at 350°C in Appendix 4
  - Engineering stress-strain curves presented in Appendix 4
  - (S, N) fatigue curve: ASME BPVC Section 3 Appendix I (in air)
  - Cyclic stress-strain curve presented in Appendix 4
  - If the benchmark is extended to cover shakedown analysis then more complex constitutive models (mixed hardening or Chaboche model) may be required
- Elastic codified rules B 3200 [3] and NB 3200 [2]:
  - Fatigue usage factor without environment effects (S-N air data)
- Simplified elastic-plastic fatigue cyclic analysis:
  - Evaluation of K_e in different sections: S20 to S29 Figure 18
  - Evaluation of corresponding fatigue usage factor for two transients
  - For each transient without combination
  - Transient combination rules
- Finite element: 2D Model

4.2 Geometry description

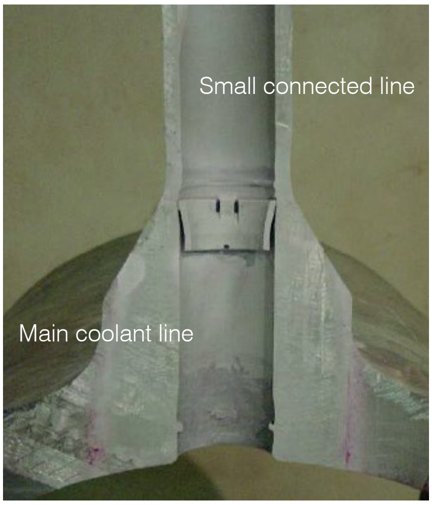

Figure 10. Typical main coolant line nozzle

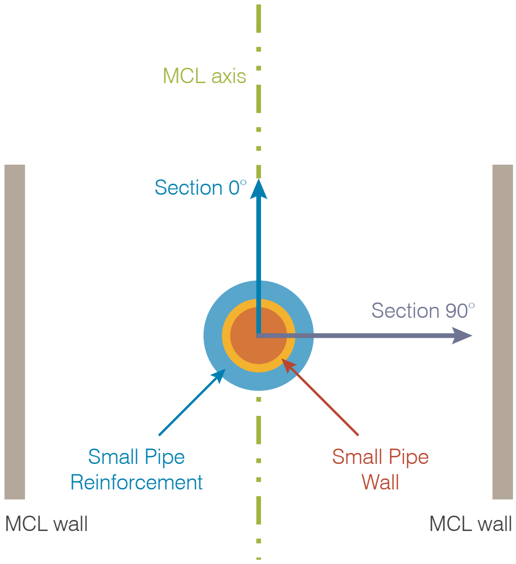

Figure 11. Stainless steel piping nozzle

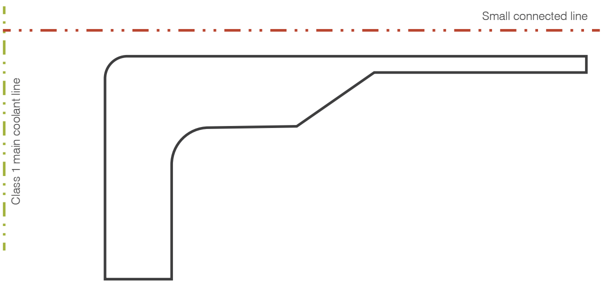

Figure 12. Stainless steel piping-nozzle – 0° section

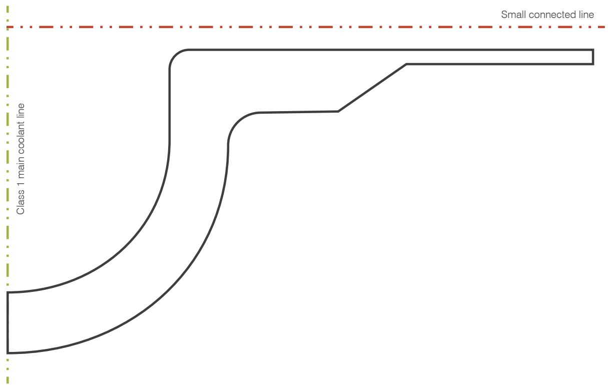

Figure 13. Stainless steel piping-nozzle – 90° section

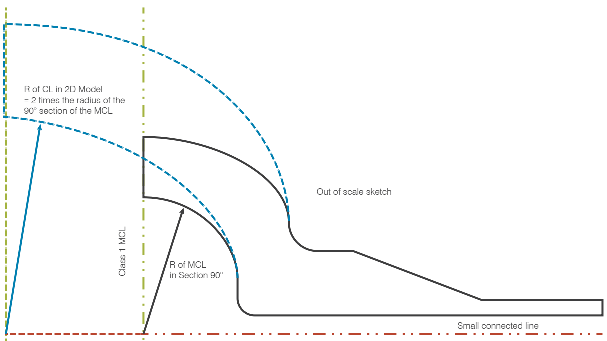

Figure 14. Stainless steel piping-nozzle – 2D model

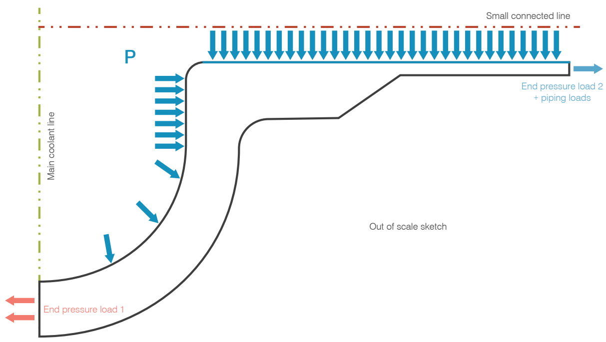

Figure 15. Stainless steel piping-nozzle – 2D model - applied loads

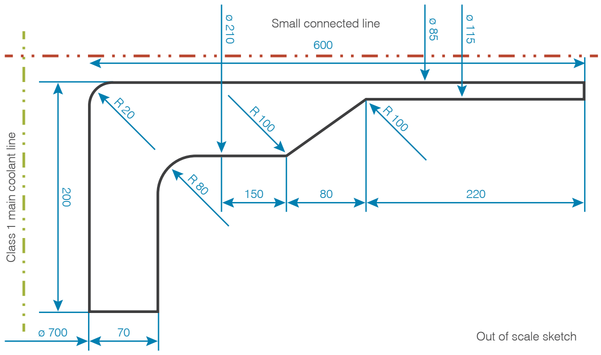

Figure 16. Stainless steel piping-nozzle – sizes – 0° section
(larger Figure in Appendix 2)

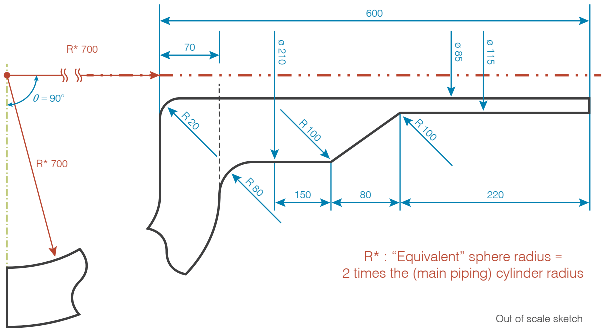

Figure 17. Stainless steel piping-nozzle – 2D model
(larger Figure in Appendix 2)

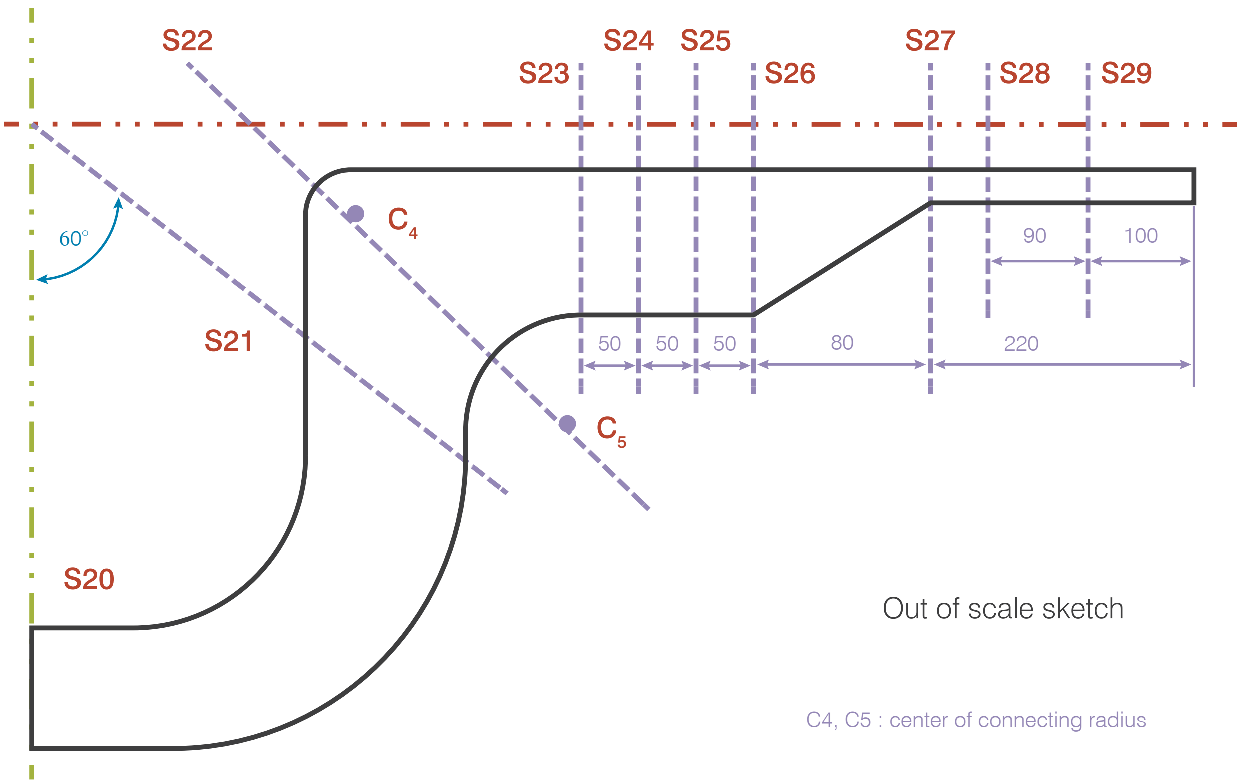

Figure 18. Stainless steel piping-nozzle – analysis sections for 2D model

4.3 Loads

4.3.1 Operating pressure and temperature

- Constant operating pressure: 15.5 MPa + end pressure effects Figure 19
- Operating temperature: 300°C and 200°C Figure 19

4.3.2 Thermal transients and pressure loads

- Initial temperature 300°C for Transient 1 and 200°C for Transient 2 Figure 19 and 20
- Transient 1: 100 cycles of 220°C thermal shocks Figure 19 and 20
- Transient 2: 800 cycles of 150°C thermal shocks + pressure drops Figure 19 and 20
- Thermal boundary conditions:
  - Imposed temperature (infinite heat transfer coefficient) on all the inner surface of the nozzle
  - Perfectly insulated on the outer surface

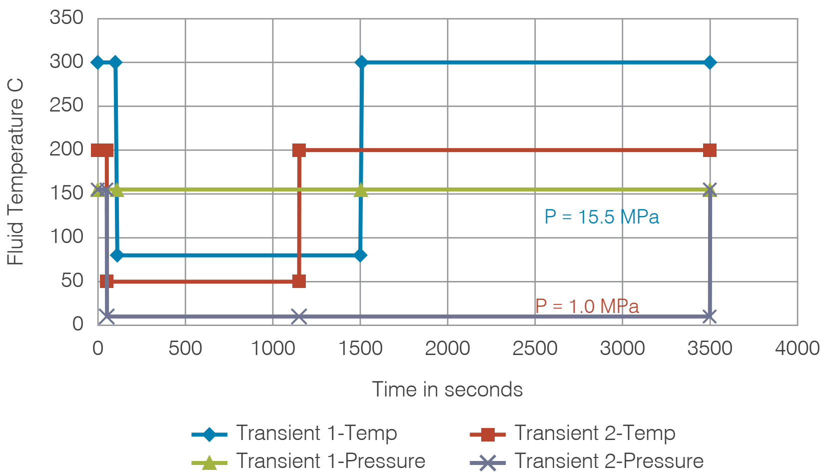

Figure 19. Transients 1 and 2 plots

Transient 1: 220°C thermal shock 100 cycles

Time (s)	P in MPa	T in °C
0	15.5	300
100	15.5	300
111	15.5	80
1500	15.5	80
1510	15.5	300
3500	15.5	300

Transient 2: 150°C thermal shock 800 cycles+pressure drop

Time (s)	P in MPa	T in °C
0	15.5	200
50	15.5	200
51	1	50
1150	1	50
1151	1	200
3499	1	200
3500	15.5	200

4.3.3 Piping loads

- F_x, - F_y - F_z in 10^4 N: neglected
- M_x - M_y - M_z in 10^7 N.mm: neglected
- Only end pressure effects at the boundary of the model have to be considered

4.4 Stainless steel thermal mechanical properties

The material properties are presented in Appendix 4:

- Monotonic engineering stress-strain curve Appendix 4.1
- Cyclic stress-strain curve Appendix 4.2
- Thermal-mechanical properties Appendix 4.3
- Fatigue (S, N) curve in air Appendix 4.4

For this benchmark, the material properties are not temperature dependent; a 350°C fixed temperature is selected for all the material properties (simplification and lower material properties).

4.5 Analysis methods

4.5.1 Elastic codified analyses

- On sections S20 to S29 presented in Figure 18
- Usage factor of each transient and combined transient usage factor

4.5.2 Elastic-plastic simplified fatigue analysis

- K_e evaluation by elastic-plastic finite element analysis using:
  - Cyclic stress-strain curve considered as monotonic stress-strain curve
  - Isotropic hardening

4.5.3 Elastic-plastic shakedown analysis with specific material constitutive equations

To be defined later

4.5.4 Elastic-plastic detailed fatigue analysis

To be defined later

4.5.5 FEA models

- 2D :
  - Cylinder / spherical
  - Sphere radius: 2 times the cylinder radius Figures 12 to 14 and 16-17
- 3D :
  - To be defined later

4.6 Benchmark 2.0: MCL Nozzle – codified elastic fatigue analysis

- Based on 2D detailed elastic finite element analysis of the nozzle
- Using B3200 [3] and NB3200 [2]fatigue analysis rules for:
  - Transient 1 fatigue analysis in sections S20 to S29 Figure 18, inner and outer surface
  - Transient 2 fatigue analysis in sections S20 to S29 Figure 18, inner and outer surface
  - Combined Transient 1 and 2 fatigue analysis in sections S20 to S29 Figure 18, inner and outer surface
- Codified shakedown and thermal ratchet analysis in sections S20 to S29 Figure 18
- Results presentation following Appendix 5.2:
  - Three usage factors for two points by section:
    - Transient 1and Transient 2,
    - Combined Transient 1 and 2

4.7 Benchmark 2.1: MCL Nozzle – fatigue simplified non-linear analyses

- Elastic-plastic monotonic stress analysis using cyclic stress-strain curve from Appendix 4.4
- K_e analysis: 2D “simplified” elastic-plastic analysis under isotropic hardening

- Results presentation following Appendix 5.2:
  - $K_e = \Delta\varepsilon_{plastic}/\Delta\varepsilon_{elastic}$ values versus time in S20 to S29 sections, inner and outer surface as defined Figure 21
  - Usage factors on S20 to S29 sections Figure 18, inner and outer surface
  - Three different cases: Transient 1, Transient 2 and combined Transient 1 + Transient 2
- Comparison of analysis methods
- Comparison with benchmarks 2.0 and discussion

$$K_e = \frac{1+\nu}{1+\nu^*}\,\frac{\Delta\varepsilon^t_{eq,\,VM}}{\Delta\varepsilon^e_{eq,\,VM}}$$

With:

$$\nu^* = 0.5 - \frac{Es}{E}(0.5 - \nu)$$

$$Es = \frac{2(1+\nu^*)}{3}\,\frac{\Delta\sigma_{eq,\,VM}}{\Delta\varepsilon^t_{eq,\,VM}}$$

- $\Delta\varepsilon^t_{eq,VM}$: total equivalent Von Mises strain amplitude
- ν : Poisson ratio

4.8 Benchmark 2.2: Plastic shakedown analysis

To be defined later

4.9 Benchmark 2.3: MCL Nozzle – fatigue cyclic non-linear analyses

To be defined later

4.10 Benchmark 2.4: 3D effects on Benchmarks 2.0 to 2.3

To be defined later on the basis of the 2D results

5 References

[1] Non-linear Analysis Design Rules - Part1 : Codes Comparison; World Nuclear Association- Cooperation on Design Evaluation and Licensing - Codes and Standards Task Force

[2] ASME Boiler & Pressure Vessel Code, Section III - Rules for Construction of Nuclear Facility Components, ASME 2010 Edition

[3] RCC-M : Design and Construction Rules for Mechanical Components of PWR Nuclear Island, AFCEN 2010 Edition

Appendix 1 | Vessel-Nozzle detailed geometry

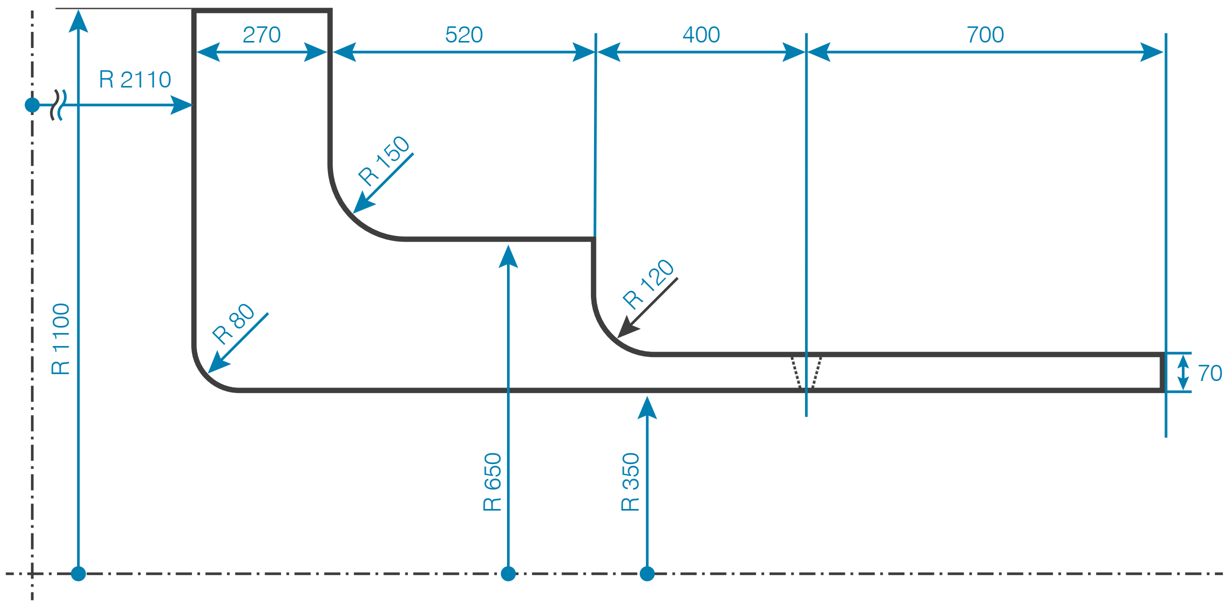

Figure 7. Vessel-nozzle sizes – 0° section

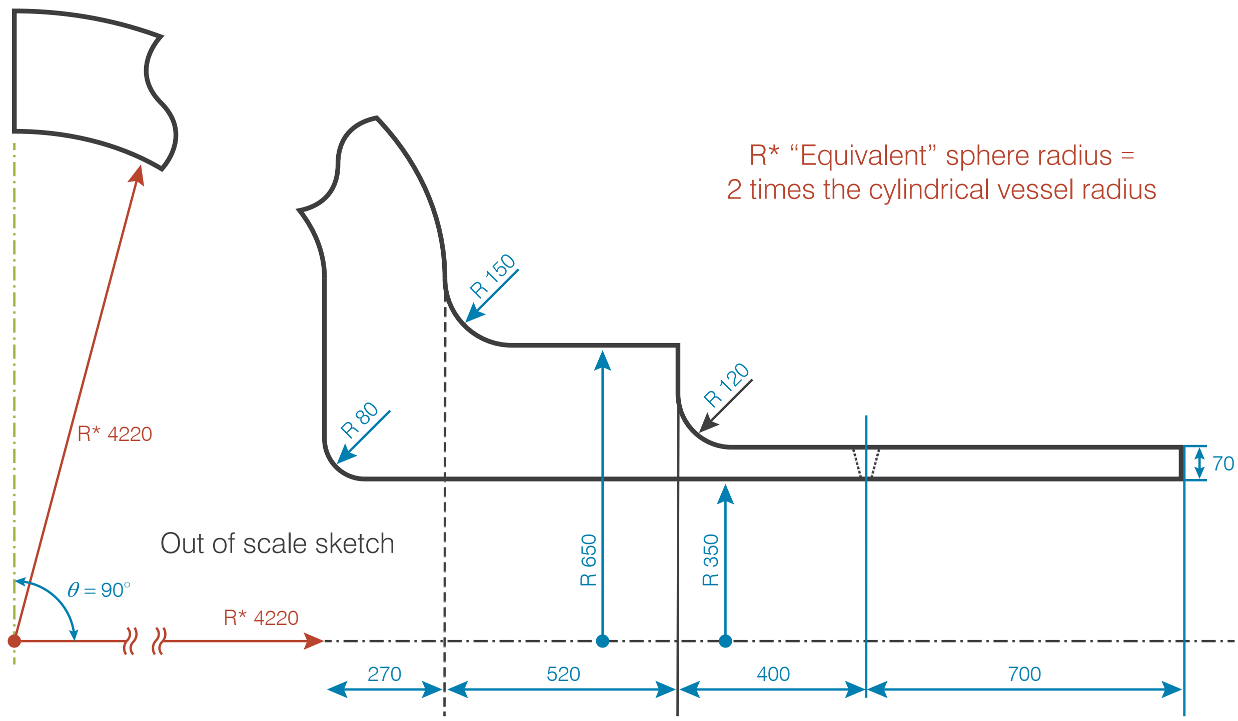

Figure 8. Vessel-nozzle sizes – 2D model

Appendix 2 | MCL SS Nozzle geometry

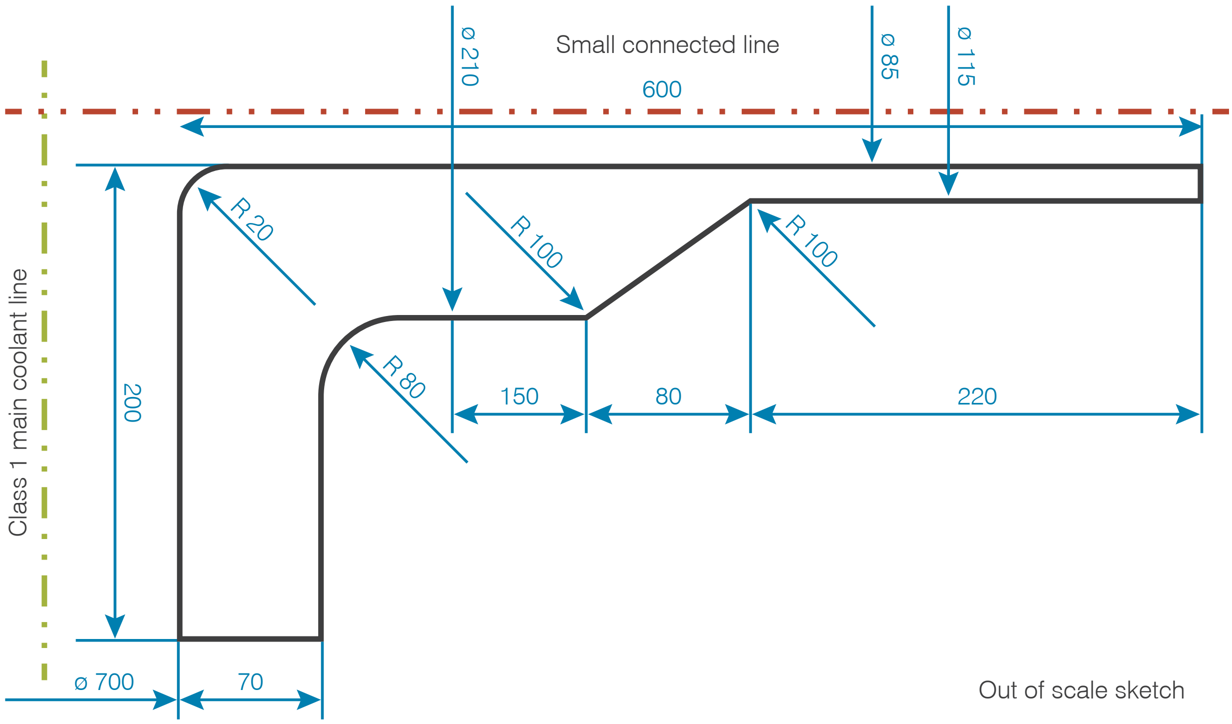

Figure 16. Stainless steel piping-nozzle – sizes – 0° section

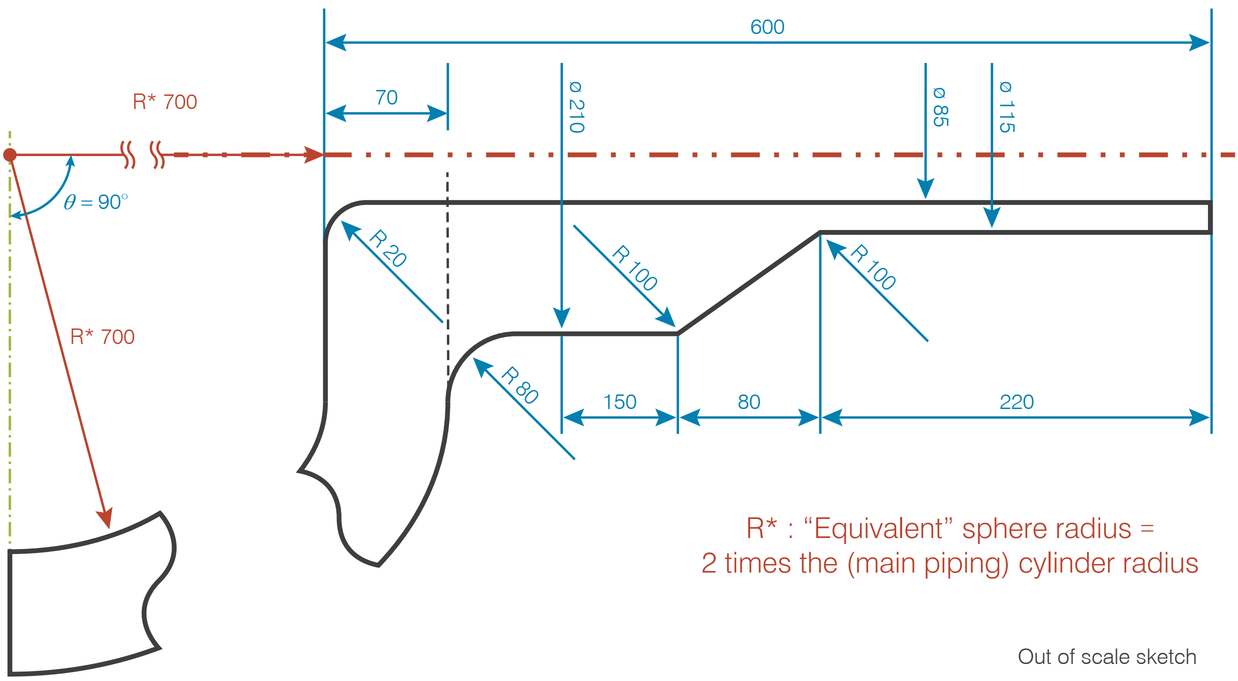

Figure 17. Stainless steel piping-nozzle – 2D model

Appendix 3 | Low alloy steel mechanical properties

A3.1 A508 (16MND5) Monotonic Engineering Stress-strain curve – Elastic Modulus

Low Alloy Steel Mechanical Properties (16MND5)

Monotonic Stress Strain curve

									in Mpa				
16MND5	300°C	ν	0.3	E	185000	$R_{p0.2}$	383	S_y	303	R_m	538	S_m	184
σ	0	303	318	341	360	372	383	398	410	421	425	448	467
ε_p		0	0.0001	0.0002	0.0005	0.0010	0.0020	0.0040	0.0060	0.0080	0.0100	0.0150	0.0200
ε_{tot}	0.0000	0.0016	0.0018	0.0020	0.0024	0.0030	0.0041	0.0062	0.0082	0.0103	0.0123	0.0174	0.0225

σ	494	509	525	540
ε_p	0.0300	0.0372	0.0472	0.0571
ε_{tot}	0.0327	0.0400	0.0500	0.0600

Elastic Modulus

Temperature	(°C)	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	300	~~350~~
Elastic Modulus	MPa	~~204000~~	~~203000~~	~~200000~~	~~197000~~	~~193000~~	~~189000~~	185000	~~180000~~

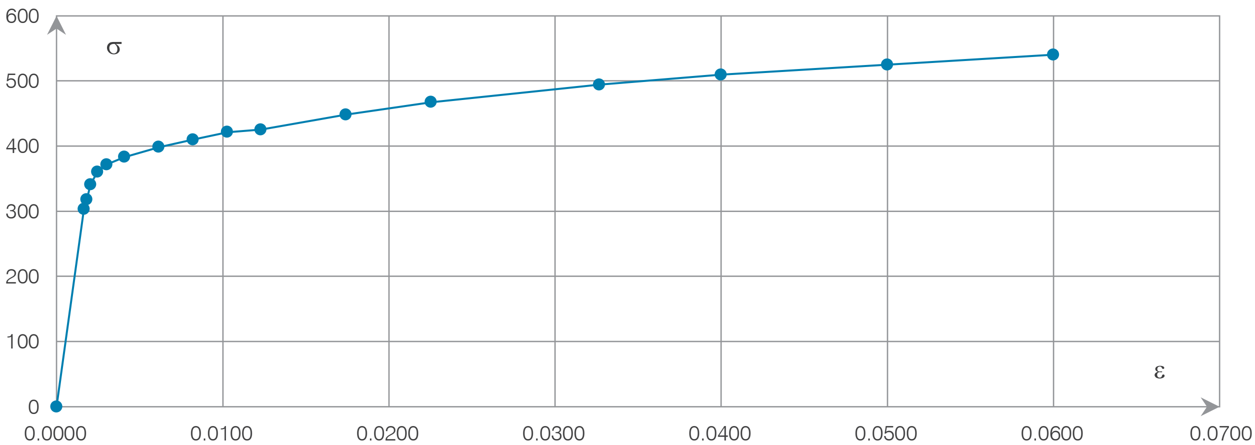

Figure XXX. Traction 16MND5 300°C - E 185000 MPa - Sy 303 MPa - Rp0.2 383 MPa

Appendix 4 | Stainless steel thermal-mechanical properties

A4.1 316L SS Monotonic Engineering Stress-Strain curve – Elastic Modulus

Stainless steel Mechanical Properties (316L - Type 17.12 Mo)

Monotonic Stress Strain curve

									in Mpa				
316L	350°C	ν	0.3	E	172000	$R_{p0.2}$	113	S_y	92	R_m	380	S_m	102
X2CrNiMo17-12-2		RCC-MRx-A3-3S		$\varepsilon_t=100*\sigma/E + (\sigma/(C_0\ R_{p0.2}))^{1/n0}$				C_0	1.198	n_0	0.1125		
σ		92	96	100	110	113	120	125	130	135	140	145	150
$\varepsilon_p=(\sigma/C_0\ R_{P0.2})^{1/n0}/100$		0.000000	0.000471	0.000677	0.001632	0.002007	0.003425	0.004923	0.006976	0.009757	0.013481	0.018415	0.024892
$\varepsilon_{el}=\sigma/E$		0.000535	0.000558	0.000581	0.000642	0.000657	0.000698	0.000727	0.000756	0.000785	0.000814	0.000843	0.000872
σ		155	160	165	170	175	180	190					
$\varepsilon_p=(\sigma/C_0\ R_{P0.2})^{1/n0}/100$		0.033315	0.044177	0.058075	0.075724	0.097980	0.125860	0.203520					
$\varepsilon_{el}=\sigma/E$		0.000901	0.000930	0.000959	0.000988	0.001017	0.001047	0.001105					
σ		200	220	240	260	280	290						
$\varepsilon_p=(\sigma/C_0\ R_{P0.2})^{1/n0}/100$		0.321085	0.749126	1.623503	3.307118	6.390513	8.729756						
$\varepsilon_{el}=\sigma/E$		0.001163	0.001279	0.001395	0.001512	0.001628	0.001686						

ε_{tot}	0.0000	0.000535	0.001029	0.001259	0.002274	0.002664	0.004122	0.005650	0.007732	0.010542	0.014295	0.019258	0.025764
ε_p		0.000000	0.000265	0.000677	0.001632	0.002007	0.003425	0.004923	0.006976	0.009757	0.013481	0.018415	0.024892
σ	0	92	96	100	110	113	120	125	130	135	140	145	150
ε_{tot}	0.0342	0.0451	0.0590	0.0767	0.0990	0.1269	0.2046	0.3222	0.7504	1.6249	3.3086	6.3921	8.7314
ε_p	0.0333	0.0442	0.0581	0.0757	0.0980	0.1259	0.2035	0.3211	0.7491	1.6235	3.3071	6.3905	8.7298
σ	155	160	165	170	175	180	190	200	220	240	260	280	290

Elastic Modulus

Temperature	(°C)	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	~~300~~	350
Elastic Modulus	103 MPa	~~197~~	~~195~~	~~191.5~~	~~187.5~~	~~184~~	~~180~~	~~176.5~~	172

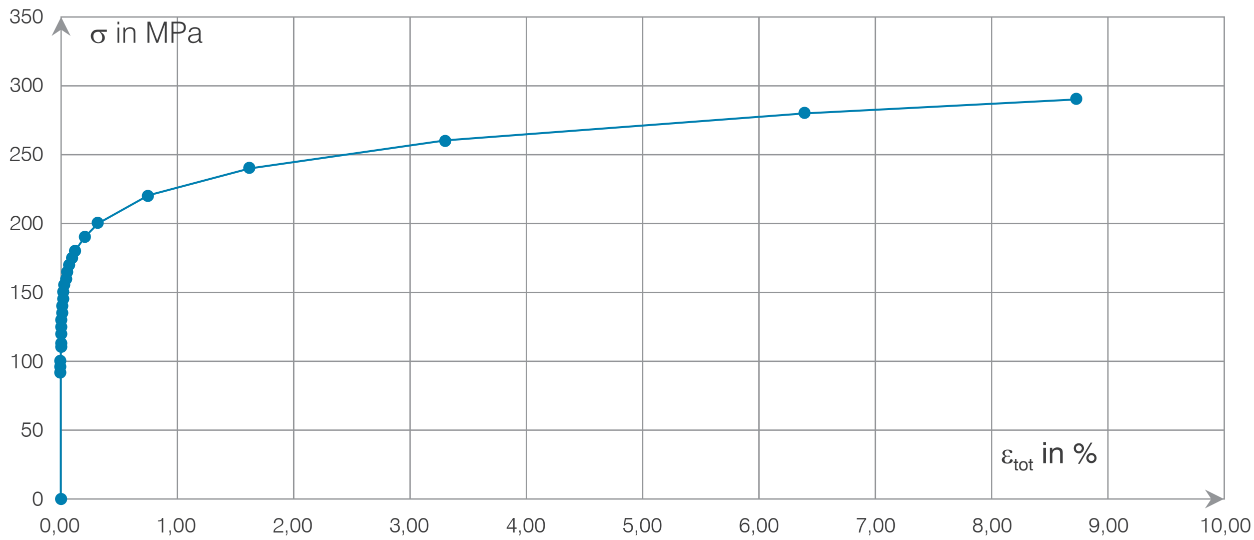

Figure XXX. Engineering Tensile Curve 316L - 350°C - E 172000 Mpa Sy 92 MPa Rp0.2 113 Mpa.

A4.2 316L Stainless Steel Cyclic Stress-Strain curve

Cyclic Stress-strain curve	Δσ in MPa	Δε in %	E in Mpa

$\Delta\varepsilon$ in % = $(100.2*(1+0,3)/3/E \,.\, \Delta\sigma) + (\Delta\sigma/K)^{1/m}$ at 350°C: K= 730 m= 0.31 E= 172000

Δσ in MPa	0	100	150	200	250	300	350	400	450
Δε in %	0.000	0.052	0.082	0.116	0.158	0.208	0.270	0.345	0.437
Δσ in MPa	500	600	800	1000	1200	1400	1600	1800	2000
Δε in %	0.547	0.834	1.747	3.264	5.574	8.876	13.376	19.287	26.828

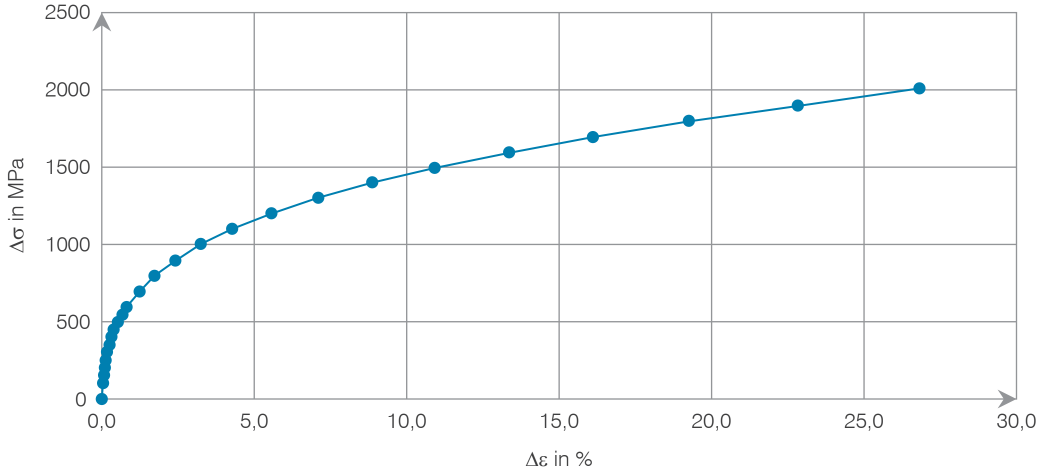

Figure XXX. ASME VIII - 304 / RCCMRx - 316L : Cyclic curves

For information Comparison of RCC and ASME VIII cyclic curves

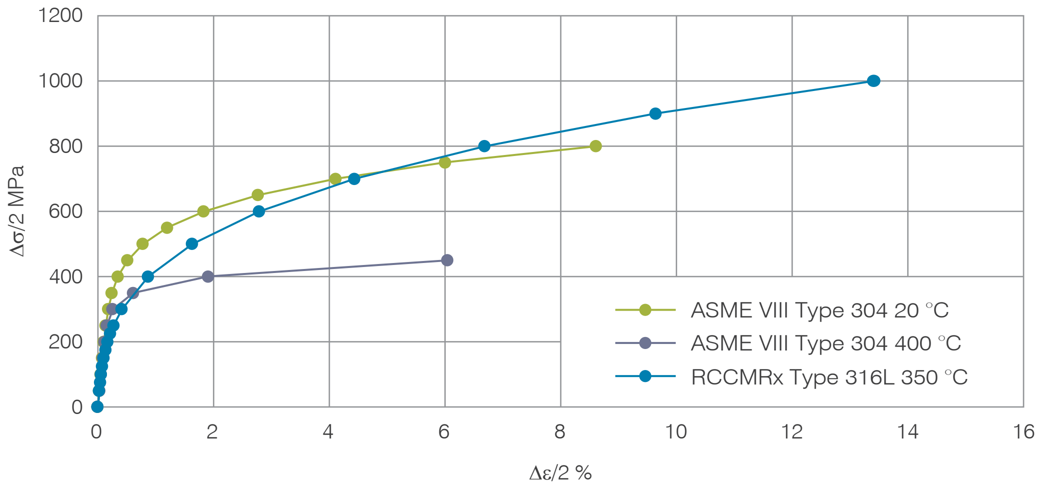

Figure XXX. Stainless Steel Cyclic Stress-strain curve 316L - 350°C

A4.3 316L Stainless Steel Thermal-mechanical properties

Thermal Expansion Coefficient α in 10^{-6} / °C

Temp. °C	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	~~300~~	350
A	~~15.54~~	~~16.00~~	~~16.49~~	~~16.98~~	~~17.47~~	~~17.97~~	~~18.46~~	18.95
B	~~15.54~~	~~15.72~~	~~16.00~~	~~16.30~~	~~16.60~~	~~16.86~~	~~17.10~~	17.36

A:	Instantaneous thermal expansion coefficient	in 10^{-6}/°C
B:	Mean thermal expansion coefficient between 20°C and T	in 10^{-6}/°C

Thermal Conductivity λ in W / m.°C

Temp. °C	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	~~300~~	350
λ	~~14.28~~	~~14.73~~	~~15.48~~	~~16.23~~	~~16.98~~	~~17.74~~	~~18.49~~	19.24

Density ρ in kg/m^3

Temp. °C	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	~~300~~	350
ρ	~~7930~~	~~7919~~	~~7899~~	~~7879~~	~~7858~~	~~7837~~	~~7815~~	7793

Specific Heat Capacity C_p in J / kg.°C

Temp. °C	~~20~~	~~50~~	~~100~~	~~150~~	~~200~~	~~250~~	~~300~~	350
C_p	~~472~~	~~485~~	~~501~~	~~512~~	~~522~~	~~530~~	~~538~~	546

Thermal Diffusivity μ in m^2 / s

μ = thermal conductivity λ (W/m.°C) / [density ρ (kg / m^3) * specific heat C_p (J / kg.°C)]

A4.4 316L Stainless Steel Fatigue Curve

N	Salt in Mpa
1.00E+01	6000
2.00E+01	4300
5.00E+01	2748
1.00E+02	1978
2.00E+02	1440
5.00E+02	974
1.00E+03	745
2.00E+03	590
5.00E+03	450
1.00E+04	368
2.00E+04	300
5.00E+04	235
1.00E+05	196
2.00E+05	168
5.00E+05	142
1.00E+06	126
2.00E+06	113
5.00E+06	102
1.00E+07	99
1.00E+08	97.1
1.00E+09	95.8
1.00E+10	94.4
1.00E+11	93.7

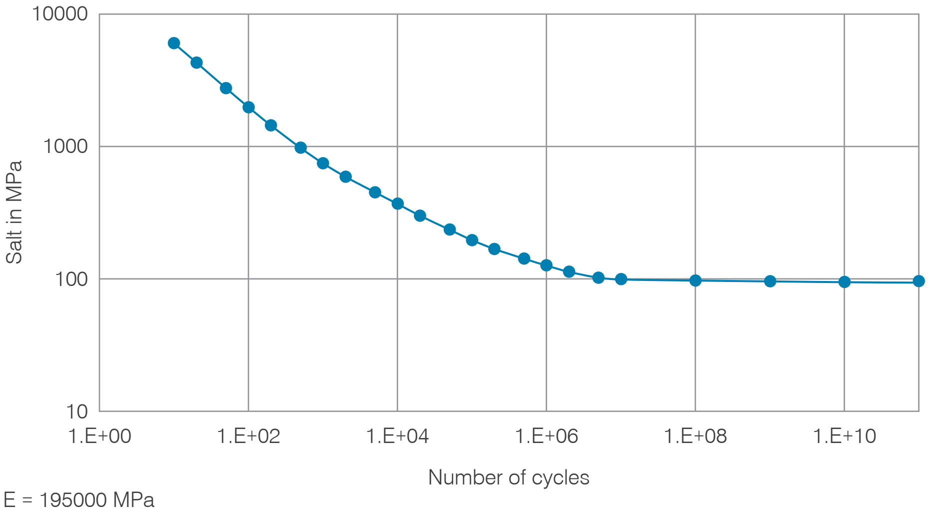

Figure 1. ASME 2015 – Stainless Steel Fatigue Curve (ASME III - Appendix I-9.2M)

Appendix 5 | Results presentation

A5.1 Benchmark 1

Name (First - Last)
Company
Country
Participant number

Benchmark 1 results
Rev. 2 from Sept. 17, 2016

Benchmark 1.0	elastic codified approach for P=17MPa											
Sections (on figure 9)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Pm (≤ Sm = 184 MPa)												
PL (≤ 1.5 Sm = 276 MPa)												
PL + Pb (≤ 1.5 Sm = 276 MPa)												
	max 1	location 1	max 2	location 2	max 3	location 3						
$\sigma_I+\sigma_{II}+\sigma_{III}$ (≤ 4Sm = 736 MPa)												

Benchmark 1.1	Plastic collapse and local failure under pressure load					
limit load Pressure (S_y): C_{L1}		location				
elastic-plastic (double slope): C_{L2}						
elastic-plastic (max strain 0,5%): C_{L3}						
for elastic-plastic (0,5%)	max 1	location 1	max 2	location 2	max 3	location 3
$\sigma_I+\sigma_{II}+\sigma_{III}$ outer						
$\sigma_I+\sigma_{II}+\sigma_{III}$ inner						

Benchmark 1.2	Plastic instability under pressure load	
limit load Pressure ($(S_y+R_m)/2$): C_{l1}		location
elastic-plastic (5%): C_{l2}		
elastic-plastic (10%): C_{l3}		

Benchmark 1.3	Piping load effects on Benchmarks 1.0 and 1.2											
Piping (axial force on piping Fx = 10^6 N) load for max pressure of 17MPa												
	Piping load effects on Benchmarks 1.0 - Level D criteria											
Sections (on figure 9)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Pm (≤ 2.4 Sm = 441 MPa)												
PL (≤ 3.6 Sm = 662 MPa)												
PL + Pb (≤ 3.6 Sm = 662 MPa)												
	Piping load effects on Benchmarks 1.2: max pressure reduction											
limit load ($(S_y+R_m)/2$): C'_{l1}		location										
elastic-plastic (5%): C'_{l2}												
elastic-plastic (10%): C'_{l3}												

Benchmark 1.4	3D effects on Benchmarks 1.1: plastic collapse	
only Fx =106 N (to be confirmed)	Set 1	
limit load Sy: C''_{L1}		location
elastic-plastic max strain 0.5%: C''_{L3}		
	3D effects on Benchmarks 1.3: plastic instability	
F, M in 3 directions	Set 2	
limit load (Sy+Rm)/2: C''_{l1}		location
elastic-plastic max strain 5%: C''_{l2}		

Codified Stress classification	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Pt 1 inner surf.-Elast. VonMises												
Pt 1 inner surf.-ElastPlast VonMises												
Pt 2-Elast. VonMises												
Pt 2-ElastPlast VonMises												
Pt 3-Elast. VonMises												
Pt 3-ElastPlast VonMises												
Pt 4-Elast. VonMises												
Pt 4-ElastPlast VonMises												
Pt 5 outer surf.-Elast. VonMises												
Pt 5 outer surf.-ElastPlast VonMises												

A5.2 Benchmark 2

Name (First - Last)
Company
Country
Participant number

Benchmark 2 results
Rev. 2 from Sept. 17, 2016

Benchmark 2.0 MCL Nozzle – Codified Elastic Fatigue analysis

	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor
Transient 1	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner Ke RCCM																				
inner Ke ASME																				
outer Ke RCCM																				
outer Ke ASME																				
Transient 2	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner Ke RCCM																				
inner Ke ASME																				
outer Ke RCCM																				
outer Ke ASME																				
Combined Transients 1+2	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner Ke RCCM																				
inner Ke ASME																				
outer Ke RCCM																				
outer Ke ASME																				

Benchmark 2.1 MCL Nozzle – Fatigue simplify non-linear analyses using finite element analysis of Ke

	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor	Ke	Usage factor
Transient 1	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner new Ke																				
outer new Ke																				
Transient 2	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner new Ke																				
outer new Ke																				
Combined Transients 1+2	S20		S21		S22		S23		S24		S25		S26		S27		S28		S29	
inner new Ke																				
outer new Ke																				

Benchmark 2.2 Cyclic Plastic Shakedown Analysis: few cycles + extrapolation rules

will be defined later

Benchmark 2.3 Cyclic Plastic Fatigue Analysis: few cycles + extrapolation rules

will be defined later

Benchmark 2.4 3D effects on benchmarks 2.0 to 2.4

will be defined later

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