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Limitations and Applicability of WRC 107/537, WRC 297, and WRC 368 for Nozzle Load Evaluation in Pressure Vessels

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Abstract: *The Welding Research Council (WRC) bulletins WRC 107 (superseded by WRC 537), WRC 297, and WRC 368 are widely used for evaluating local stresses in pressure vessel nozzle-to-shell intersections subjected to external piping loads [1-4]. These methods provide simplified analytical procedures for estimating local membrane and bending stresses in the vicinity of vessel attachments. However, the applicability and accuracy of these bulletins depend strongly on geometric limitations, loading assumptions, and the treatment of stress concentration factors (SCFs).*

This paper discusses the limitations associated with the use of WRC-type bulletins for nozzle load evaluation, with particular emphasis on the influence of shell and nozzle SCFs, software-dependent implementation approaches, and the treatment of pressure-induced stresses and reinforcement effects [1-12]. Special attention is given to WRC 368[3] which introduced improved treatment of local shell stress behaviour and pressure stress interaction effects compared with earlier WRC methods [3].

The paper compares the stress evaluation methodologies used in WRC 107/537, WRC 297, and WRC 368 and highlights the importance of finite element analysis (FEA) for configurations outside the validity range of the bulletins [13-15]. Recommendations are provided for the appropriate use of WRC methods in engineering practice and for identifying cases where advanced numerical analysis becomes necessary.

Keywords: *WRC 107/537, WRC 297, WRC 368, pressure vessel nozzles, nozzle-to-shell intersection, external piping loads, stress concentration factors (SCFs), local stress analysis, finite element analysis FEA.*

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I. INTRODUCTION

The evaluation of nozzle loads in pressure vessels is a critical aspect of mechanical design in the process, petrochemical, power generation, and offshore industries. External piping reactions impose localized stresses at nozzle-to-shell intersections, which may lead to excessive deformation, fatigue damage, leakage, or local structural failure if not adequately assessed

To facilitate practical engineering calculations, the Welding Research Council developed a series of bulletins for evaluating local stresses caused by external loads acting on vessel attachments. Among these, WRC 107 [1], its successor WRC 537, WRC 297, and WRC 368 [2-4] remain widely adopted in industry software and design procedures.

WRC 107/537 [1,4] provides analytical solutions for attachments on cylindrical and spherical shells, whereas WRC 297 [2] specifically addresses cylindrical nozzle-to-cylinder intersections and includes nozzle neck stress evaluation. Despite their widespread use, these bulletins are based on semi-empirical formulations and idealized assumptions that may not adequately represent actual vessel geometries, fabrication details, or complex loading conditions [8-9].

WRC 368 [3] introduced additional refinements for evaluating local stresses in cylindrical shells subjected to external nozzle loadings. The bulletin incorporates improved formulations for local shell stress distributions and pressure stress interaction effects, thereby extending the analytical treatment of nozzle-to-shell intersections beyond the assumptions used in earlier WRC methods. Although modern finite element methods increasingly supersede simplified analytical procedures, WRC 368 [3] remains influential in commercial nozzle analysis software and engineering practice.

In modern engineering practice, nozzle load evaluations are frequently performed using commercial software packages such as PV Elite, COMPRESS, NozzlePRO, and FE/Pipe [13-15]. However, significant differences may arise depending on how these programs implement stress concentration factors, pressure stress interactions, reinforcement effects, and allowable stress criteria.

This paper reviews the applicability boundaries and limitations of WRC-type bulletins and discusses the influence of SCFs, pressure effects, reinforcement considerations, and finite element methods on nozzle load assessments.

II. OVERVIEW OF WRC BULLETINS

2.1 WRC 107 / WRC 537

WRC 107 [1], later updated and expanded as WRC 537 [4], provides analytical procedures for evaluating local stresses in cylindrical and spherical shells subjected to external forces and moments acting on attached nozzles or structural attachments.

The method calculates local shell stresses only and does not explicitly determine nozzle neck stresses. The analytical formulation is based on thin-shell theory and is applicable primarily to geometries that satisfy specified dimensional limits.

The bulletin evaluates membrane and bending stresses generated by external loads acting at the nozzle attachment location and is commonly used for preliminary assessments and standard pressure vessel configurations.

2.2 WRC 297

WRC 297 [2] extends the analytical approach specifically to cylinder-to-cylinder intersections and includes evaluation of both vessel shell stresses and nozzle neck stresses.

Compared with WRC 107/537, WRC 297 [1,2,4] generally provides a more realistic assessment for nozzle load evaluation because the nozzle neck frequently becomes the governing component under external piping loads, particularly when the nozzle wall thickness is smaller than the vessel shell thickness.

The bulletin also introduces stress indices and stress concentration approaches for evaluating local stresses at the shell and nozzle junction.

2.3 WRC 368

WRC 368 [3] provides analytical procedures for evaluating local stresses in cylindrical shells subjected to external nozzle loadings while incorporating improved treatment of pressure stress interactions and local shell behaviour.

Compared with WRC 107/537 [1,4], the bulletin extends the analytical basis for evaluating local shell stresses near nozzle intersections and provides more refined stress formulations for combined loading conditions.

Unlike WRC 107/537 [1,4], which primarily evaluates local shell stresses caused by external loads alone, WRC 368 [3] partially incorporates the interaction between pressure stresses and externally induced local stresses. The methodology therefore represents an intermediate step between simplified analytical methods and more advanced finite element approaches.

WRC 368 [3]remains based on idealized shell geometries and is therefore subject to applicability limitations similar to those of other WRC-type bulletins.

The bulletin is frequently implemented within commercial pressure vessel software and is often combined with finite element–derived stress concentration approaches.

III. STRESS CONCENTRATION AND THEIR INFLUENCE

3.1 Importance of Stress Concentration Factors

Stress concentration factors (SCFs) significantly influence calculated stresses in nozzle load evaluations [10-12]. In practical applications of WRC 297 and WRC 368 [2,3], both shell SCFs and nozzle SCFs may require definition or interpretation .

The calculated local stresses are highly sensitive to these factors, and relatively small variations in SCF values may produce substantial differences in the final stress results and code utilization ratios.

Likewise, WRC 368 [3]incorporates pressure stress interaction formulations that inherently account for localized stress intensification effects associated with nozzle-to-shell intersections. Consequently, stress predictions obtained using WRC 368 [3] may differ significantly from those obtained using WRC 107/537 [1,4] or WRC 297 [2] depending on the treatment of pressure-induced stresses and shell flexibility effects.

3.2 Variations in SCF Determination

Different engineering approaches and software platforms determine SCFs differently. These variations may lead to inconsistent stress predictions between analysis methods and software packages [10-15].

Commonly used approaches include:

- empirical formulations,
- pressure stress interaction methods,
- finite element–derived stress intensification factors,

- experimentally derived correlations, and
- user-defined SCFs.

Commercial software packages implementing these methods include:

- PV Elite,
- COMPRESS,
- NozzlePRO,
- FE/Pipe, and
- other FEA-based tools.

The NAM standard NSS 12-D-4-05 [12] is a company standard used in industry practice and explicitly calculates both shell and nozzle stress concentration factors (SCFs). Likewise, WRC 368 [3] incorporates pressure–stress interaction formulations that inherently account for SCF effects.

Technical discussions regarding SCF determination methodologies are available in:

- the Dekker–Stikvoort paper [10] on SCFs, and
- publications by Bozkurt [11] related to stress concentration evaluation.

  Different engineering approaches and software platforms determine SCFs differently. These variations may lead to inconsistent stress predictions between analysis methods and software packages [10–15]. The definition of SCFs is not standardized across industry software, leading to potential variability in calculated nozzle stresses.

IV. LIMITATIONS OF WRC 107/537 AND WRC 297

4.1 Limitations of WRC 107/537

Although WRC 107/537 [1,4] is widely used, several important limitations must be recognized:

1. Only shell stresses are calculated.
2. Nozzle neck stresses are not evaluated.
3. Reinforcement pad effects are not considered.
4. Internal pressure stresses are excluded.
5. The method assumes idealized shell geometry.

If the nozzle-to-shell thickness ratio (t/T) is less than 1.0, nozzle neck stresses often govern the design. In such cases, WRC 107/537 [1,4] may produce un-conservative results because nozzle stresses are not evaluated directly.

4.2 Limitations of WRC 297

Although WRC 297 [2] improves upon WRC 107/537 [1,4] by including nozzle stresses, it also has important limitations:

1. Applicable only to cylinder-to-cylinder intersections.
2. Does not explicitly account for reinforcement pads.
3. Limited to specified geometric ratios.
4. Assumes isolated nozzles without nearby discontinuities.
5. Pressure stresses require separate consideration.

Furthermore, local stress results may vary considerably depending on the selected SCFs and software implementation method.

V. APPLICABILITY LIMITS

Applicability limits for WRC 107/537 [1,4]and WRC 297 [2] must be satisfied for valid use .

5.1 Applicability Limits for WRC 107 / WRC 537

The following geometric requirements should be satisfied before applying WRC 107/537 [1,4]:

1. $d/D < 0.33$
2. $Dm/T=(D-T)/T > 50$

where:

- d= nozzle outside diameter,
- D = vessel outside diameter,
- T = vessel shell thickness,
- Dm = mean vessel diameter.

These limits ensure that shell behaviour remains within the assumptions used in the derivation of the bulletin equations.

5.2 Applicability Limits for WRC 297

The following conditions apply for WRC 297 [2] usage:

1. $d/D \leq 0.5$
2. $20 \leq d/t \leq 100$
3. $20 \leq D/T \leq 2500$
4. $d/T \geq 5$
5. The nozzle must be isolated from nearby discontinuities:
    - not within $2\sqrt{(DT)}$ on the vessel shell,
    - not within $2\sqrt{(dt)}$ on the nozzle neck.

where:

- d= nozzle diameter,
- t = nozzle thickness,
- D= vessel diameter,
- T = vessel shell thickness.

Violation of these limits may invalidate the assumptions of the bulletin and reduce the reliability of the stress predictions.

VI. PRESSURE EFFECTS AND PRESSURE THRUST FORCES

Neither WRC 107/537 [1,4] nor WRC 297 [2] directly includes stresses due to internal pressure in the local stress calculations. However, pressure stresses may significantly interact with external load stresses at nozzle intersections and may influence both local membrane and peak stress distributions.

Pressure thrust forces [5,6], generated by internal pressure acting on the projected nozzle area, must also be included in the nozzle load assessment where applicable. Failure to include these forces may lead to underestimation of local stresses, nozzle reactions, and support loads.

WRC 368 [3] partially addresses pressure stress interactions through pressure stress intersection formulations that inherently include SCF effects and shell flexibility influences.

In practical engineering applications, the interaction between pressure-induced stresses and externally applied piping loads may become especially important in:

- high-pressure vessels,
- thin-wall shells,
- cyclic loading applications,
- fatigue-sensitive services, and
- elevated temperature operation.

VII. FINITE ELEMENT ANALYSIS AND ADVANCED METHODS

With increasing vessel complexity and higher design requirements, finite element analysis (FEA) has become an essential tool for nozzle load assessment.

FEA methods provide significant advantages in cases involving:

- reinforced nozzles,
- thick-wall vessels,
- large nozzles,
- closely spaced nozzles,
- thermal gradients,
- transient loading conditions,
- local discontinuities,
- non-standard geometries, and
- nonlinear material behaviour.

Advanced tools such as NozzlePRO [15] and detailed FE/Pipe [15] analyses can provide more realistic stress distributions than simplified WRC methods by explicitly modelling shell flexibility, local geometric discontinuities, reinforcement details, and weld transition effects.

Finite element analysis also enables:

- evaluation of peak stresses,
- fatigue assessment,
- nonlinear elastic-plastic analysis,
- thermal stress analysis,
- creep evaluation, and
- assessment of combined mechanical and thermal loading.

For critical applications, FEA should therefore be used either:

- to validate WRC results, or
- as the primary design method where WRC assumptions are not satisfied.

FEA is generally required when WRC applicability limits are exceeded or when a higher-fidelity stress evaluation is needed.

Note that PASS/NOZZLE-FEM Stress and Flexibility Finite Element Analysis of Pressure Vessel and Piping Components is considered equivalent to FE/Pipe.

VIII. ENGINEERING CONSIDERATIONS FOR PRACTICAL APPLICATIONS

In practical engineering work, WRC-based calculations should not be interpreted as exact stress solutions but rather as simplified engineering approximations derived from shell theory and semi-empirical correlations.

The following considerations are important during practical implementation:

1. Different software packages may apply different SCFs, pressure interaction models, and allowable stress criteria.
2. Results obtained from different programs should therefore not be expected to match exactly.
3. Conservative interpretation is necessary when nozzle loads approach allowable limits.
4. Reinforcement pads and local stiffening may significantly alter stress distributions beyond the assumptions of simplified WRC methods.
5. Fatigue-sensitive services require particular attention because local peak stresses may not be adequately represented by simplified analytical methods.

Engineering judgment remains essential when interpreting WRC-based results and determining whether additional analysis is required.

Significant differences between software implementations arise due to SCF treatment and pressure interaction models [13–15]. Engineering judgement is required when interpreting results [10–12].

IX. REINFORCEMENT PADS AND THEIR INFLUENCE ON WRC-TYPE ANALYSIS

Reinforcement pads (re-pads) are widely used in pressure vessel construction to compensate for shell material removed by nozzle openings and to improve local structural stiffness at nozzle-to-shell intersections. Although reinforcement pads may significantly influence local stress distributions under external piping loads, their structural effects are only partially represented — or entirely neglected — in classical WRC-type analytical methods [1–4].

In practical engineering applications, reinforcement pads modify the local shell flexibility, alter membrane and bending stress distributions, and may reduce local deformation at the nozzle attachment region. However, the simplified shell-theory assumptions used in WRC 107/537 [1,4], WRC 297 [2], and WRC 368 [3] generally assume idealized shell intersections without explicit modelling of local reinforcement geometry.

9.1 Reinforcement Pads in WRC 107/537

WRC 107/537 [1,4] does not explicitly include the effect of reinforcement pads in the analytical stress formulations. The method assumes a relatively smooth shell geometry and evaluates local shell stresses generated by external loads acting on attachments.

Consequently, the following limitations apply when reinforcement pads are present:

1. Local shell stiffening effects are neglected.
2. Changes in shell flexibility caused by the pad are not represented.
3. Weld geometry and local discontinuities introduced by the pad are ignored.
4. Peak stresses near pad edges are not evaluated.
5. Stress redistribution between shell, nozzle neck, and reinforcement region is not captured.

In some practical cases, the omission of reinforcement effects may produce conservative results because the reinforcement locally increases stiffness and reduces shell deformation. However, in other cases, local peak stresses generated at reinforcement pad welds or geometric transitions may become significant and remain undetected by the simplified analytical approach.

9.2 Reinforcement Pads in WRC 297

WRC 297 [2] includes nozzle neck stress evaluation and therefore provides a more realistic representation of nozzle behaviour compared with WRC 107/537 [1,4]. Nevertheless, the bulletin still does not explicitly model reinforcement pads or local reinforcement geometry.

The presence of a reinforcement pad may influence:

- local shell stress distributions,
- nozzle neck flexibility,
- local bending behaviour, and

- stress concentration factors (SCFs).

Because WRC 297 [2] was derived using idealized cylinder-to-cylinder intersections, the analytical assumptions may become less representative when substantial local reinforcement is present. The influence of reinforcement pads therefore depends strongly on:

- reinforcement geometry,
- pad thickness and diameter,
- weld configuration,
- shell thickness ratio, and
- external loading direction.

Large or thick reinforcement pads may substantially alter local stiffness behaviour beyond the assumptions inherent in the bulletin derivation.

9.3 Reinforcement Effects in WRC 368

WRC 368 [3] introduced improved treatment of local shell behaviour and pressure stress interaction effects compared with earlier WRC methods. Although reinforcement pads are still not explicitly modelled, the improved shell interaction formulations may partially reflect the influence of local stiffness changes associated with reinforced nozzle regions.

Nevertheless, WRC 368 [3] remains fundamentally based on simplified shell-theory assumptions and therefore cannot fully represent:

- local three-dimensional stress gradients,
- weld toe stress concentrations,
- reinforcement pad edge effects,
- nonlinear local stiffness behaviour, or
- fabrication-induced geometric discontinuities.

As a result, reinforced nozzle configurations remain approximate when evaluated using WRC 368 [3].

9.4 Influence on Stress Concentration Factors

Reinforcement pads may significantly influence both shell and nozzle stress concentration factors (SCFs). Depending on geometry and loading conditions, reinforcement may either:

- reduce overall membrane and bending stresses through local stiffening, or
- increase localized peak stresses near weld transitions and pad terminations.

This behaviour is particularly important for:

- cyclic service conditions,
- thermal loading applications,
- fatigue-sensitive equipment, and
- high-pressure vessels.

Because SCF treatment varies among commercial software implementations [10–15], reinforced nozzle assessments may produce substantial variability between different analysis programs.

Some software packages incorporate empirical stiffness corrections or finite element–derived SCFs for reinforced nozzles, whereas others continue to rely primarily on classical WRC formulations with limited reinforcement consideration.

9.5 Need for Finite Element Analysis

For reinforced nozzle configurations subjected to significant external piping loads, finite element analysis (FEA) frequently becomes necessary to obtain reliable stress predictions.

FEA is particularly recommended for cases involving:

- large reinforcement pads,
- thick reinforcement plates,
- high local thermal gradients,
- fatigue-sensitive applications,
- closely spaced nozzles,
- high external moments,
- non-standard reinforcement geometries, or
- complex weld configurations.

Unlike simplified WRC methods, FEA can explicitly model:

- local reinforcement geometry,
- weld transition profiles,

- shell flexibility changes,
- nonlinear stress redistribution, and
- local peak stresses.

Modern software tools such as NozzlePRO, PV Elite, COMPRESS, and detailed finite element models may therefore provide significantly more realistic stress assessments for reinforced nozzle intersections than simplified WRC-based procedures.

9.6 Engineering Considerations

In practical design work, reinforcement pads should not automatically be assumed to improve nozzle load capacity without detailed evaluation. Although reinforcement may reduce gross shell deformation, it may also introduce elevated local peak stresses and increased structural discontinuity effects.

Engineering judgement is therefore required when interpreting WRC-type nozzle load results for reinforced nozzles, particularly when:

- allowable stress limits are approached,
- fatigue loading is significant,
- thermal cycling occurs, or
- nozzle flexibility strongly influences piping reactions.

X. CONCLUSIONS

WRC 107/537, WRC 297, and WRC 368 [1-4] remain valuable engineering tools for preliminary and routine nozzle load evaluations. However, their use requires careful consideration of geometric applicability limits, stress concentration factors, omitted effects such as reinforcement and internal pressure stresses, and software-dependent implementation differences. WRC methods remain valuable but require careful application within their validity limits. FEA should be used for complex or critical cases [13–15].

WRC 107/537 [1,4] may be inadequate when nozzle stresses govern the design, particularly when the nozzle thickness is smaller than the shell thickness. WRC 297 [2] provides a more comprehensive assessment by including nozzle stresses, but its accuracy remains highly dependent on SCF selection and implementation methodology.

WRC 368 [3] improves the analytical treatment of pressure stress interaction effects and local shell behaviour but remains limited by the assumptions inherent in simplified shell-theory formulations.

Differences among commercial software packages and analytical procedures may lead to significant variations in predicted stresses. Consequently, engineering judgment is required when interpreting WRC-based results.

For complex geometries, fatigue-sensitive applications, or critical service conditions, finite element analysis should be considered necessary to ensure accurate and reliable nozzle load evaluation.

XI. CLOSING REMARKS

The continued use of WRC 107/537, WRC 297, and WRC 368 in modern pressure vessel engineering demonstrates the lasting practical value of these analytical methods for nozzle load evaluation. Despite the availability of advanced computational techniques, WRC-based procedures remain widely applied because they provide efficient and reasonably conservative engineering solutions for many standard nozzle configurations.

Nevertheless, the applicability of these methods is inherently limited by the simplifying assumptions used in their derivation. The accuracy of the calculated stresses depends strongly on geometric validity limits, stress concentration factor (SCF) treatment, pressure stress interaction assumptions, and software-specific implementation methodologies. Reinforcement effects, local discontinuities, weld geometries, thermal loading, and complex structural interactions may significantly influence actual stress behaviour beyond the capabilities of simplified analytical procedures.

Among the evaluated methods, WRC 107/537 remains useful for preliminary shell stress evaluation but may become inadequate when nozzle neck stresses govern the design. WRC 297 provides a more complete assessment by including nozzle stresses, while WRC 368 offers improved treatment of local shell behaviour and pressure stress interaction effects. However, none of these methods fully captures the complex three-dimensional stress distributions that may occur in reinforced or highly loaded nozzle intersections.

For critical applications, fatigue-sensitive service, non-standard geometries, or cases exceeding the established applicability limits, finite element analysis (FEA) should be regarded as the preferred engineering approach. Advanced software tools such as NozzlePRO, FE/Pipe, and PASS/NOZZLE-FEM enable more realistic modelling of local stress behaviour, shell flexibility, reinforcement effects, and weld transition stresses.

Ultimately, reliable nozzle load evaluation requires not only appropriate analytical methods but also sound engineering judgement. Engineers should recognize the limitations of simplified WRC procedures, understand the assumptions embedded within commercial software implementations, and apply advanced numerical analysis where necessary to ensure safe and reliable pressure vessel design.

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AUTOBIOGRAPHY

Walther Stikvoort is an independent consultant specializing in pressure equipment integrity, pressure vessel design, and mechanical stress analysis, based in Assen, The Netherlands. His work focuses on the evaluation of nozzle loads, stress concentration factors (SCFs), and structural integrity assessment of pressure vessels and piping systems used in the process, petrochemical, power generation, and offshore industries.

Stikvoort has contributed to engineering research and technical publications related to Welding Research Council (WRC) methods, nozzle-to-shell intersections, and finite element analysis (FEA). His expertise includes the application and limitations of WRC 107/537, WRC 297, and WRC 368 methodologies, advanced nozzle load evaluation techniques, and the interpretation of software-based stress analysis tools such as PV Elite, COMPRESS, NozzlePRO, and FE/Pipe.

His publications emphasize the importance of understanding geometric applicability limits, pressure effects, reinforcement considerations, and software-dependent implementation differences when assessing local stresses in pressure vessel attachments. He advocates the use of finite element analysis for complex geometries and critical service conditions where simplified analytical methods may not provide sufficient accuracy.