(1) Introduction

In the spring 1997, Det norske Veritas made a ”study of the art”, ref. BGN-R397138, regarding the perils involved in the use of various kinds of pipe connections. The study was carried out on behalf of Norsk Hydro A.S. The aim of the study was to increase the knowledge on flanged pipe joints and thereby to increase the basis for finding the optimal pipe connection in a production line environment.

To estimate leak frequencies for different types of joints as compared with the standard ANSI, a modified FMEA (= *failure mode evaluation analysis*) was carried out. The modification consisted of involving the distribution of causation factors to differentiate the failure modes.

In our study, which follows, we have applied the DnV pattern although with some additions.

In the DnV study there are three Frequency Groups. We have added a fourth for the case, when ”*The probability of occurrence during the lifetime can be excluded*.” The probability of gasket dislocation, for instance, can be excluded, as with VCF-joints there are no gaskets to become dislocated.

We also have added a few parameters, missing in the DnV-study, such as sub-quality bolting and insufficient load capacity.

By comparing the resulting probability factors for a conventional, gasketed ANSI joint with that for a modern, non-gasketed VCF joint, the level of functional safety for the latter becomes quantified. Although a specific figure may be derived, it does suffice with a strong basis for the judgement, whether a VCF-joint is ”Better” or ”Worse” in comparison with a conventional ANSI-joint.

(2) Theory

(2.1) Preface

(The following text is cited almost verbatim from Chapter 5 in the DnV Report, **Ref. 1**).

The overall aim for applying modern, VCF-joints is to increase safety by reducing the likelihood for leakage. Replacement of ”known” technology requires a thorough description of the new product. Data, such as leak frequency and leak rates, is gained through years of use. It is difficult to put forward this kind of information for new products. Based on known data for an ANSI-joint together with a qualitative analysis, it has become possible to give an estimate of increased or decreased safety by using modern, VCF-joints.

A qualitative comparison of the flanges and connectors is performed by dividing the features concerned into four categories related to:

- Design and fabrication
- Storage and handling
- Installation
- Normal operation

Each of these categories is subdivided in possible failure modes for evaluation. The methodology for evaluation is based on frequency grouping and consequence rating, as show in the tables below:

(2.2) Frequency grouping

Frequency (Probability)	**Probability**
1	Expected to occur several times during the lifetime of the field
2	Likely to occur once during lifetime
3	The probability of occurrence during lifetime cannot be excluded
4	The probability of occurrence during lifetime can be excluded

(2.3) Consequence grouping for use in FMEA tables

Consequence	Seriousness
1	Occurrence is likely to cause significant leakage
2	Occurrence is likely to cause minor leakage
3	Occurrence will probably not cause leakage, but reduce safety factor or require maintenance

(2.4) Criticality factors

The criticality factor is defined as the frequency group multiplied with the consequence group, as shown in the following table, where ”1” is very critical and ”12” is not critical, **Ref. 2**.

	Frequency			
Frequency Consequence	**1**	**2**	**3**	**4**
1	1	2	3	4
2	2	4	6	8
3	3	6	9	12

(2.5) Baseline

The baseline for the conventional ANSI-joint is given by the equation presented below:

$F(d) = 2,0 \cdot 10^{-3} \cdot d^{-1,25} + 1,8 \cdot 10^{-5}$

It is modified by a set of factors, hereafter denoted P-factors. These P-factors are determined by introducing the distribution of causation reported in **Ref. 3**.

The weight factors are 0,16 0,1 0,3 and 0,44 -- their sum adding up to 1,00.

Because 44% of all reported incidents occurred during normal operation, the weight factor for normal operation is set equal to 0,44. Approximately 22% of the incidents occurred during reinstatement and start-up mode. It is believed, that flanged joints are quite sensitive to installation in order to work properly. Hence, the weight factor is rounded up to 0,30. The design and fabrication related aspects are given more weight = 0,16 than storage and handling = 0,10.

The modified equation is:

$F(d)=[2,0\cdot 10^{-3}\cdot d^{-1,25}+1,8\cdot 10^{-5}]\cdot P_{design}\cdot P_{handle}\cdot P_{install}\cdot P_{normal}$

$P_{ANSI} = P_{design}\cdot P_{handle}\cdot P_{install}\cdot P_{normal} = 1,00$

Consequently, if the product of P-factors is = 1,00, then the functional safety of the joint in question is considered as equal to an ANSI-joint. Below 1,00 means ”better” and above 1,00 means ”worse”.

The matrix parameters of the FME-analysis are presented in the following tables.

The calculation of P_{normal} for VCF-joints may be used as an example. By referring to the Subtotal row of the Normal Operation block, the P_{normal} is calculated as follows:

$$P_{normal} = 1 + \left\{\frac{52 - 85}{52}\right\}\cdot 0,44 = 0,72$$

(3) FMEA Matrix Parameters

(3.1) Design and fabrication related

	ANSI			VCF		
	Freq	Cons	Crit	Freq	Cons	Crit
Seal ring material	1	2	2	4	3	12
Flange material	3	3	9	3	3	9
Quality of bolting	1	2	2	3	3	9
Surface treatment	3	3	9	3	3	9
Deviation in tolerance	3	3	9	3	3	9
Sub total:			**31**			**48**

W-factor: 0,16	P-factor:1,00	P_{design} = 0,91

Comments:

VCF-joints have no gaskets such as RTJ, IX, HX, Flange-Plus or Destec. It follows, that problems with gasket material can not possibly occur with VCF-joints.

The likelihood for flange material failures and tolerances for the material composition, are assumed to be equal for the ANSI-joint and for the VCF.

Bolting commonly is furnished from neighbour stores and with vague requirements on quality. In the VCF System emphasis is made not only on material but also on mechanical properties, origin of manufacture and veracity of installation by means of the VERAX Calibration Unit available to customers.

For two flanges in metal-to-metal contact to seal, the geometry and the finish of the surfaces are vital to the function. With the ANSI-joint contact pressure is all important. With the VCF-joint it is not.

(3.2) Storage and handling

	ANSI			VCF		
	Freq	Cons	Crit	Freq	Cons	Crit
Mechanical impact	2	2	4	3	3	9
Transport	2	2	4	3	1	3
Sub total:			**8**			**12**

W-factor: 0,10	P-factor:1,00	P_{handl} = 0,95

Comments:

The term mechanical impact may include a drop to the floor. In this context, the weight of the joint becomes important. An ANSI joint is larger and very much heavier a VCF one.

Commonly, individual ANSI flanges are shipped without protection. In contrast, VCF joints are shipped assembled and with special packing to protect damageable points.

(3.3) Installation

	ANSI			VCF		
	Freq	Cons	Crit	Freq	Cons	Crit
Misalignment	1	1	1	2	2	4
Gasket dislocation	2	2	4	4	3	12
Damage to gasket/flange	3	2	6	3	2	6
Non uniform preload	2	2	4	3	3	9
Lack of preload	2	1	2	3	3	9
Too high preload	2	2	4	4	3	12
Sub total:			**21**			**52**

W-factor: 0,30	P-factor:1,00	$P_{install}$ = 0,56

Comments:

Commonly, ANSI-flanges are mated only after being welded to pipe. VCF-joints in principle are installed as units, what eliminates the problem of mis-alignment. When broken, there ought to be no difficulty in re-assembly.

Gross damage to sealing surface or to flange is not acceptable, as it is not consistent with a no-leak requirement. This is true both for conventional joints and for modern ones.

In general, ANSI-joints typically have few, heavy bolts, while VCF-joints have several, light ones. It follows, that non-uniform bolt preload is more of a problem with the former type.

Lack of preload is primarily the effect of gasket creep and plasticity. As a result of the mechanism being completely different, loss of preload is no problem with VCF-joints.

With conventional, raised face flanges, a too high preload does induce warping of the flanges, concentrated bending in the bolts and non-uniform gasket pressure. In a modern bolted joint, this is not the case.

(3.4) Normal operation

	ANSI			VCF		
	Freq	Cons	Crit	Freq	Cons	Crit
Fatigue	3	3	9	4	3	12
Vibration	1	2	2	4	2	8
Stress corrosion	3	2	6	4	2	8
Erosion / wear	3	3	9	4	2	8
Interface corrosion	1	2	2	4	3	12
Bolt preloading	2	2	4	2	2	4
Creep of gasket	3	3	9	4	3	12
Lack of maintenance	3	3	9	4	3	12
Load capacity	1	2	2	3	3	9
Sub total:			**52**			**85**

W-factor: 0,44	P-factor:1,00	$P_{install}$ = 0,72

Comments:

In any ANSI-joint a dynamic mode does rule, with concentrated stress in the fillet between the neck and the flange itself plus strain well up in the plastic region under the bolt head and in the first thread outside of the nut. In any VCF-joint a static mode does rule with no concentrated stresses, no bending of the bolts and no risk of fatigue.

Vibration has no ill effect on VCF-joints.

The conventional design leaves the strained shanks of the bolts exposed to the surrounding environment and therefore to the possibility of failure due to stress corrosion. In a VCF-joint the bolt is totally enclosed in a room isolated from the surrounding environment, what eliminates such a risk.

Wear implies a dynamic situation. Accordingly, it can not possibly impair the functional safety of a VCF-joint.

As there is no split between the flange faces of a VCF-joint, interface corrosion need not be apprehended.

In order for to facilitate bolt preloading, VCF-joints are delivered complete with proper tools. This means ring spanners with extra long handles for bolt sizes up to and including M16.

Hydraulic stud tensioners are provided for heavier bolts.

With ANSI-joints creep of the gasket used to be a serious problem. With VCF-joints it is not.

It is appreciated, that ANSI-joints need maintenance, while VCF-joints do not.

When building a bolted joint, the most important part of the work is to establish the nature and magnitude of loads acting on it. It follows that the parameter of max. working pressure does not suffice. VCF-joints are selected based on superimposing various load-cases.

(3.5) Result

As a result of the above grading of various events, which possibly may occur, a P_{VCF} now can be calculated as follows:

$$\mathbf{P_{VCF}} = P_{design} \cdot P_{handle} \cdot P_{install} \cdot P_{normal} = 0{,}91 \cdot 0{,}85 \cdot 0{,}56 \cdot 0{,}72 = \mathbf{0{,}31}$$

(3.6) Extreme operational incidents

DnV in its study did not involve an evaluation of the properties in extreme operational conditions, such as under fire exposure. The reason is, that the base-line is based on a data collection, which is gathered under normal operational conditions. Consequently, an FMEA with an evaluation of extreme operational failure modes would not be suitable for modifying the base-line.

However, the properties of a pipe connection in extreme conditions are important. The fire resistance of the joints should be at least equal to, or better than that of the pipe itself.

In a complete evaluation of the functional safety of a modern pipe joint, it is considered of paramount importance, that also the effects of extreme operational incidents be accounted for.

(4) Conclusion

It is concluded, that the functional safety of modern, non-gasketed pipe joints acc. to the VERAX Compact Flange System is better than that of the conventional, gasketed ones acc. to ANSI.

(5) Literature references

1. DnV Report BGN-R397138, Det norske Veritas, P O Box 60, N-5031 LAKSEVÅG, Norway
2. Angelsen, S & Mellem, T: Bolted piping connection systems a comparative study, Technical report nr: 89-3074, 1989
3. Offshore hydrocarbon releases statistics. Health and Safety Executive, Report OTO 96 954, Oct 1996.