Summary of Findings on Failed Gas Valves

This note summarises our findings on the failure of gas valves associated with hydrogen embrittlement of bolts used in the assembly of the valve.

Background

Hydrogen embrittlement (HE) is a well-established phenomenon; while it can occur in many alloys, it is most frequently a problem with high strength steels. It arises when hydrogen dissolved in the steel collects at regions of high tensile stress and facilitates cracking. The susceptibility of a steel to HE is strongly affected by the strength; lower strength steels are essentially immune to HE, while higher strength steels can be very susceptible. The strength above which HE becomes a problem is dependent on a number of factors, including the hydrogen concentration in the steel and its chemical composition and microstructure, but it is typically in the region of 1000 MPa. Steel bolts are classified by a code of the form *xx.y*, where *xx* is a number corresponding to the specified minimum ultimate tensile strength (UTS) in units of 100 MPa, while *.y* is the specified minimum yield stress (SMYS) divided by the UTS and rounded to one digit. Thus class 12.9 bolts have a specified minimum UTS of 1200 MPa and an SMYS of 1080 MPa (1200 MPa x 0.9), and are potentially susceptible to HE.

Hydrogen can be introduced into steel by many means, including pickling, electroplating and corrosion. In the case of electrogalvanised high strength bolts, it is known that hydrogen enters the steel during pickling prior to electroplating and during the electroplating itself. In order to remove the hydrogen, treatment specifications require that the bolts are baked after (or sometimes during) plating to remove the hydrogen. In order to be effective the baking should occur immediately after plating. There are consequently a number of ways for flaws in the plating process to result in defective bolts that will fail under stress due to hydrogen introduced during production. Failures due to hydrogen introduced during production are known as Internal Hydrogen Embrittlement (IHE). High strength bolts can also fail as a result of hydrogen produced by corrosion in service; in this case the phenomenon is known as Environmental Hydrogen Embrittlement (EHE).

The zinc coating on electrogalvanised bolts has a number of effects – it leads to the introduction of hydrogen during the coating process, it acts as a barrier against hydrogen entering or leaving the steel (since hydrogen diffuses much more slowly in zinc than it does in iron), and it provides corrosion protection for a period, though once the steel is exposed it will tend to increase the local rate of hydrogen entry compared to uncoated steel. Hydrogen embrittlement due to hydrogen present in the bolts from manufacture, IHE, is typically relatively rapid (of the order of days, weeks or months), although the time to failure will depend on the stress applied to the bolts and the hydrogen concentration. Thus tests for potential hydrogen embrittlement of fasteners apply high loads for a short period; ISO 15330 "*Fasteners. Preloading test for the detection of hydrogen embrittlement. Parallel bearing surface method*" specifies a minimum test duration of 48 hours. The failure time for hydrogen entering as a result of corrosion, EHE, depends on the corrosion processes occurring and can be much longer, especially for galvanised bolts, where little hydrogen will enter the steel until corrosion penetrates the zinc coating.

The Failures

The observed failures consist of broken bolts holding the bonnet to the body, or in one case the gland seal to the bonnet, of a gas valve; if sufficient bolts break the valve will leak. Consequently two classes of failure can be considered:

- bolt failure - failure of an individual bolt without regard to other bolts in the valve
- valve failure - failure of sufficient bolts in a valve for leakage to occur.

Reported valve failures are listed in Table 1.

It is generally agreed that the bolt failures are primarily a result of HE, although some bolts may fail by mechanical overload once the majority of bolts in a valve have failed.

In addition to failed valves, in which all or most bolts have failed, some isolated bolt failures have been observed during valve inspections, either in service or in unexposed valves in storage.

Bolt failures observed in storage are clearly a result of IHE, since little or no corrosion will occur in a dry storage environment. Failures occurring in service could be a result of IHE or EHE, although long times to failure and evidence of corrosion are suggestive of EHE.

Review of valve failure data suggested that a cluster of failures had occurred in valves manufactured in early 2010. Therefore, available data on failed and unfailed bolts and valves was collected and analysed in collaboration with Professor Patrick Laycock. The analysis was based on bolt and valve failure information collected by AVK. Unfortunately the data are somewhat distorted, since valve failures are essentially self-selecting (i.e. a failed valve reveals itself by leaking) whereas failure of one or two bolts on a valve (which would not cause valve failure) is revealed only if the valve is inspected.

In summary, the statistical analysis, last updated in March 2014, suggests that there were one or more 'bad' batches of bolts, supplied by one manufacturer (TVS) that had a higher than normal susceptibility to IHE, and gave rise to a cluster of failures in weeks 11 to 14 in 2010. This is shown in Figure 1, which plots the estimated probability of bolt failure as a function of the date of valve production. Three estimates of bolt failure probability are shown:

- Raw failure rate - this is simply the number of failed bolts divided by the number of bolts examined. Owing to the small number of bolts from some periods (especially outside the known 'at risk' period), this may under-estimate the true failure probability.
- Best estimate failure rate - this assumes that the next bolt to be examined will have failed. This will typically over-estimate the failure rate, especially when no failures are observed.
- 95% confidence estimate - this provides a very conservative estimate of the possible failure rate.

To a first approximation the probability of multiple bolt failures in a single valve are given by the product of the probabilities of individual bolt failures. Thus if the probability of a bolt failure is 1% (0.01), the probability of failure of 3 bolts in a single valve will be 0.001^3 or 1 in 1 million. In practice the situation will be complicated by corrosion effects (which will typically be the same for a given valve) and the increase in stress in intact bolts that will occur when a bolt fails (which will increase the probability of failure of intact bolts once one or more bolts have failed). These factors may explain why no valves have been found with 4, 5 or 7 failed bolts. In statistical terms the effect of corrosion is to lead to a lack of homogeneity in the failure probability, while the effect of increasing stress as bolts fail will lead to a lack of independence in the failure probability.

Based on Figure 1, assuming that at least three bolts must fail for a valve to fail, and ignoring deviations from homogeneity and independence, a bolt failure probability of 1 % leads, as explained above, to a valve failure probability of 1 in 1 million, which can reasonably be considered as acceptable. From the data of Figure 1 it can be seen that there is a significantly enhanced probability of valve failure in weeks 11 to 14, as is found for actual valve failures. Week 16 also has an apparently high failure probability, but this is based on very limited data, with only one failed bolt in a sample of 96. This highlights the difficulty of obtaining adequate data for reliable statistical analysis when the probabilities of failure are low.

Three valve failures occurred in valves manufactured prior to 2010. One of these, S/N 12720, manufactured on 29 April 2008, used black (i.e. not zinc plated) bolts; these are unlikely to suffer from IHE, and there was evidence of corrosion, indicating that the probable failure mechanism was EHE resulting from corrosion in service. Valves S/N 100586 and S/N 103303 manufactured on 25 June and 30 July 2009 respectively, used zinc plated bolts, so IHE was possible. However, in the case of S/N 100586 there were a number of factors that suggested that the failure was due to EHE resulting from corrosion rather than IHE:

- The broken bolts were situated at the 'corners' of the valve, and were therefore somewhat more exposed to corrosion than the two unbroken bolts in the middle of the long sides.
- Of the three bolts that I was able to examine, the two broken 'corner' bolts showed more corrosion and loss of zinc than the 'middle' bolt.
- The time to failure was relatively long.
- There is no evidence of any other broken bolts from this period of production (other than S/N/ 103303).

In the case of S/N 103303 I have less information, but the time to failure and date of production suggest that this failure was also due to EHE.

Subsequent to these investigations a valve failure was reported for a valve (S/N 123643) that was produced in July 2010; after the period associated with a high failure probability. This valve had all but one of the bolts broken, and the remaining bolt displayed signs of cracking at the root of the unengaged threads. Examination of the bonnet and the failed bolts revealed significant corrosion, and it is probable that this failure was due to EHE induced by corrosion, rather than IHE.

Another valve (S/N 119460) that was produced in May 2010 failed after a silicone sealant had been applied following an inspection. This produced acetic acid during the curing process, and the acidity was considered to be responsible for the production of hydrogen and the subsequent EHE.

Since the main period of my investigations in 2014, there have been two further failures, S/N 103303 (discussed above) and 119890. The latter, manufactured at the end of June 2010, was inspected and found to be intact in June 2013, but subsequently failed in November 2015. The absence of early failure and the apparent absence of corrosion protection strongly suggests that this failure was EHE resulting from corrosion.

In addition to the strong effects of bolt manufacturer and date of production on the probability of bolt failure, there was also a weaker effect of service environment, with buried valves having a higher probability of failure. This may be indicative of an environmental effect on failure, but it may also be the result of a differing proportion of unfailed valves being examined, since the examination of buried valves is significantly more difficult.

Conclusions

It is clear that there was a faulty batch of bolts in early 2010 that lead to the cluster of failures in valves produced in weeks 11 to 14 of 2010 (the primary 'at risk' period). This failure was primarily a result of IHE, although there may have been some environmental effects.

Some failures occurred outside the 'at-risk' period. It is considered to be most probable that these failures occurred as a result of EHE due to corrosion, although this cannot be proved conclusively.

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Exeter 4 February 2017.

Table 1 - Valve Failures

Failure Date	Test Number	Valve Test Date	Customer	Size	Location	Comments
Jan-14	100586	25/06/2009	SSE	100mm	Ham Lane Longham Dorset	SSE reported as 4 bolts failed and bonnet lifted and leaked at 2 bar. Commisioned 16th Nov 2009. Longham Dorset.
Aug-15	103303	30/07/2009	NG	80mm	Manley Grove Hyde	Kevin Boland at National Grid reported all 6 bolts failed on LP system
Sep-12	115757	08/03/2010	NG	150mm	Connaught Road London City Airport	Bolt exchange by Nat Grid near London City Airport. When excavated both gland bolts found broken and valve leaking. (3.5 bar). Clamp fitted to B/B Joint (original bolts left in)
Nov-13	116095	20/03/2010	SSE	80mm	Hamilton	Failed in Hamilton. SGN
Apr-13	117713	22/03/2010	SSE	100mm	Didcot/Oxford	Failed in Oxford. SGN
Aug-11	117714	22/03/2010	SSE	80mm	Reading	(TVS) Reading valve all bolts broken. Hydrogen embrittlement due to plating.
Jul-12	117747	22/03/2010	SSE	80mm	Tunbridge Wells	Tunbridge Wells Kent (SSE), Repaired by customers engineer (studs and Bolts?) under an emergency operation due to gas leak being reported. All bolts reported as being broken. A Bite and customer engineer returned to the site and found 1.5 bolts thrown / disguarded on the ground at the site location these were returned to AVK. Fasteners returned are TVS grade 12.9 plated. Proper bolt exchange carried out 8/8/12, valve fitted with grade 8.8 & witnessed by RM/RCS
May-12	117309	09/04/2010	NG	200mm	Stoke	National Grid Valve (Stoke) Failed on 6.9 bar. 8 bolts fratured, 2 remain intact. (TVS). Heads of broken bolts not found. Gland bolts unknown
Mar-13	119460	11/05/2010	BG	90mm	Ireland	Bord Gais - Outside of date range. See seperate report - Failed after remediation
Dec-13	123643	03/07/2010	Nat Grid	150mm	Dorney AGI	Reported as bonnet lifted and valve leaks (7 bar) 7 of the 8 bonnet bolts broken. Repaired by fitting 8.8 bolts. Bolts sent by NG to HSE for investigation. Liquid coated to CW5 instead of being wrapped
Nov-15	119890	17/06/2010	SSE	200mm	Manor Way Enrith	The valve was installed in Church Manor Way, Eritch, South East London (just south of the Thames near Dagenham) [originally listed as failing in 2013)
Aug-13	12720	29/04/2008	Nat Grid		Leamington	Valve installed in approx March 2009
Jul-13	117755	22/03/2010	NG	80mm	Stockport	The valve was below ground on low pressure and unwrapped. All 6 fasteners had failed

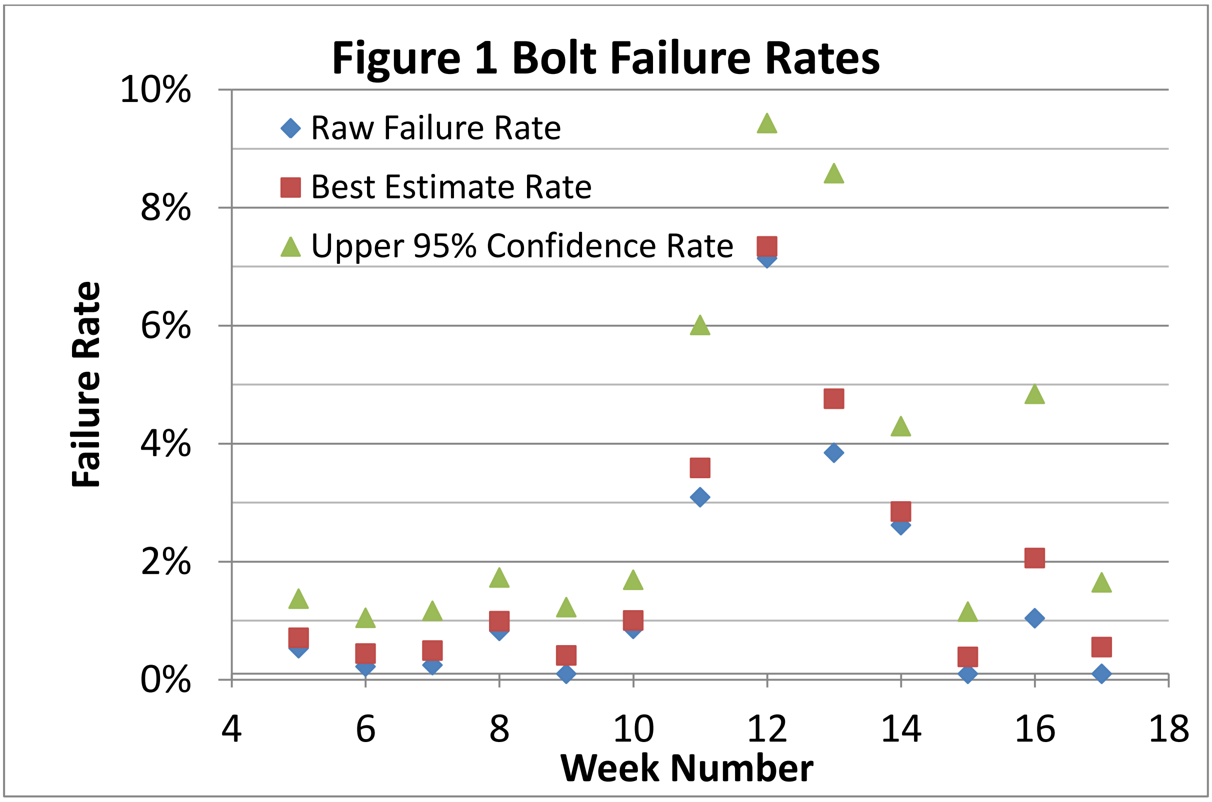
Figure 1 Bolt Failure Rates
Failure Rate
10%
8%
6%
4%
2%
0%
4
6
8
10
12
14
16
18
Week Number
Raw Failure Rate
Best Estimate Rate
Upper 95% Confidence Rate